SCALE ECONOMIES IN EXTENDED SNF STORAGE

G.S. Rothwell
Nuclear Energy Agency/Organisation for Economic Cooperation and Development (retired)
Paris, France
Email: geoffreyrothwell@yahoo.com

Abstract

Fuel is periodically replaced in nuclear power plants (NPPs). Irradiated or Spent Nuclear Fuel (SNF, where SNF could be used nuclear fuel if reprocessing facilities are available) cools in suitable facilities, where the type and the length of time depend on plans for the ultimate disposition of the SNF, for example, reprocessing or permanent long-term storage ("extended" implies storage longer than 50 years). The paper attempts to calculate the relationships between the costs and the sizes of on-site wet and on-site/off-site dry storage facilities. This is done by estimating reduced-form equations based on publicly available data, which can be modified with more recent, detailed, or proprietary data to update or extend the analysis: the values reported here should not be considered as the only possible outcomes; they are used here to understand relative NPP SNF owner economic incentives. The paper finds that once the NPP has been decommissioned, and only the on-site dry storage remains, there might not be a cost reason (from the point of view of the NPP owner/operator) to move the SNF to consolidated facilities. However, there is a consensus that consolidated facilities (a) would be more safe and secure than dispersed on-site storage locations, (b) would facilitate final disposal, and (c) can reduce the risks perceived by local communities near SNF storage facilities.

1. INTRODUCTION

Understanding the costs of managing Spent Nuclear Fuel (SNF) is becoming more important because of planning for Nuclear Power Plant (NPP) decommissioning, and the ultimate disposal of SNF, and/or their residuals from reprocessing, in deep geologic repositories (DGRs). (The paper will refer to irradiated fuel as SNF without any judgement as to whether it is waste or potential fuel.) The two primary alternatives for interim storage of SNF are wet (pool) storage and dry (cask) storage at either NPPs or at Consolidated Interim Storage Facilities (CISFs). Also, pool storage is often used at reprocessing plants because it facilitates retrieval of specific fuel assemblies for batch reprocessing. (The paper focuses on SNF from Pressurised Water Reactors, PWRs, and Boiling Water Reactors, BWRs, particularly in the US, because cost data are more available for US nuclear fuel storage facilities than for these facilities in other countries.)

To determine the economic incentives of adding capacity to an existing facility or constructing new capacity, for cost minimisation, one needs to know the relationship between total cost (*TC*), average cost (*AC*), and the size of the facility (*SIZE*). *AC* is calculated by dividing *TC* by *SIZE*:

$$AC = TC / SIZE \,. \tag{1}$$

AC (for example, the average cost per metric tonne or kilogram of storage) is often used in evaluating SNF management and disposal alternatives, instead of using net present value, because it is difficult to determine what the value might be of the discounted returns to investment in SNF management facilities (hence, most studies analyse the difference between alternatives, for example, once-through versus twice-through versus a closed fuel cycle). Many cost estimates assume a constant relationship between *AC* and *SIZE*. However, with high fixed costs, *AC* is likely to decline with increases in *SIZE* until technological, management, or regulatory constraints cause *AC* to rise. To address this, one approach is to separate (a) fixed capital (*FixedCapital*) and annual fixed O&M (*FixedO&M*), i.e., those costs that do not vary with the size of the facility, such as site licensing fees and (b) variable capital (*UnitCapital*) and annual variable O&M (*UnitO&M*), i.e., those costs that vary with the size of the facility. By distinguishing between fixed and variable costs, *TC*, becomes:

$$\begin{aligned} TC = {} & FixedCapital + (UnitCapital \times SIZE) \\ & + [FixedO\&M + (UnitO\&M \times SIZE)] \times (1/\mathrm{CFR})\text{ , where} \end{aligned} \tag{2}$$

$$CFR = \Sigma_t\,(1 + r)^{-t} = r \cdot \{\, [(1 + r)^T] \,/\, [(1 + r)^T - 1] \,\} \,, \tag{3}$$

where *CFR* is the Capital Recovery Factor and *r* is the *real* discount rate, assumed to be 3% for all facilities [1, p. 6], and *T* is the lifetime. Here, the default lifetime of a storage facility is 40 years (which is usually the licensed lifetime, but not necessarily the economic or actual lifetime). Unless otherwise stated, the *CFR* is equal to 4.33% (where $r = 3\%$ and $T = 40$ years) and $(1/CFR) = 23.11$. (*CRF* increases with *r* and decreases with *T*.)

The economics textbook *AC* curve has a U-shape and is derived from a quadratic (or higher order) total cost equation (this is a reduced form of Equation 2). The associated *AC* is given in Equation (5):

$$TC \quad = \quad a_0 + a_1\,SIZE + a_2\,SIZE^{\,2}\,, \qquad (4)$$

$$AC \quad = \quad (TC\,/\,SIZE) \;=\; (a_0 + a_1\,SIZE + a_2\,SIZE^{\,2})\,/\,SIZE \;=\; (a_0\,/\,SIZE) + a_1 + a_2\,SIZE\,. \qquad (5)$$

In Equation (4) a_0 represents fixed cost (*FC*), costs that do not vary with capacity, and ($a_1\,SIZE + a_2\,SIZE^2$) represents variable costs (*VC*), costs that vary with capacity (*VC* is a quadratic function in $SIZE^2$ if *VC* increases above a specific size; if not, a_2 is insignificant). In Equation (5) average fixed cost (*AFC*) is (a_0 / *SIZE*) and average variable cost (*AVC*) is ($a_1 + a_2\,SIZE$). With calculated costs for different-sized facilities, the relationship between *AC* and *SIZE* can be estimated. If the parameter a_2 is insignificant, the estimated equation reduces to a *reciprocal* form, where *AFC* declines to zero as size increases and a_1 is the asymptotic cost:

$$AC \quad = \quad a_1 + (a_0\,/\,SIZE)\,. \qquad (6)$$

This paper estimates average costs as a function of storage facilities sizes, in other words, “scale economies,” for (a) on-site wet (pool) storage, analysed in Section 2; (b) on-site dry (cask) storage, analysed in Section 3; and (c) off-site dry (cask) storage, analysed in Section 4; see [2, p. 93] on scale economies. To distinguish between sizes of each type of facility, *SIZE*, and estimated parameters are subscripted with 1, 2, or 3. To avoid double counting, the paper assumes that SNF is loaded into dual-purpose canisters (DPCs) as a part of the on-site dry storage system and these DPCs are transported to off-site facilities, such that the costs of loading them into transportation overpacks, transportation, and repackaging at the off-site facility (either at a CISF, short-term storage at a reprocessing facility, or at a DGR) are considered in the costs at the off-site facility.

The proposed models can be modified with more recent, detailed, or proprietary data to update or extend the analysis: the values reported here should not be considered as the only possible outcomes for a particular NPP and are used here to understand relative NPP SNF owner economic incentives. *(The dollar sign, $, is used if the value is in 2017 dollars; if not, the term USD-year is used for US dollars of a particular year.)*

2. ON-SITE WET STORAGE IN REACTOR FUEL POOLS

For a cost comparison with dry storage, this section estimates the cost of NPP (on-site) fuel pool capacity. In the fuel pool cooling is provided by demineralised water. Integrity of the fuel cladding material is maintained by keeping the temperature of the fuel cladding low: water provides cooling and shielding. The SNF is stored in racks that separate the fuel assemblies and can provide additional neutron absorption to prevent criticality. Fuel pools are used at all currently operating light water reactors.

There is little publicly available information on the specific cost of NPP fuel pools, particularly with the incorporation of lessons learnt from the Fukushima Dai-ichi accident [3]. For example, Idaho National Laboratory’s most recent *Advanced Fuel Cost Basis Report* states, “In 2012 it was decided to discontinue this [SNF fuel pool] module since wet [pool] storage of SNF is generally part of reactor O&M costs.” [4, p. E1-3] However, to estimate the cost of the SNF pool, much of the pre-Fukushima cost can be accounted for in the Code of Accounts in [5, pp. 145-147]: Account 217−Fuel Service Building includes “the spent fuel pool, cask loading and decontamination areas, new fuel receipt and inspection areas, and the necessary truck locks and handling equipment.” Account 225−Fuel Handling Systems includes “fuel handling and storage equipment, such as cranes, fuel handling tools, service platforms, and fuel cleaning and inspection equipment.” These costs are given in [6, pp. 43, 56-57] in USD_{2011}. The overnight costs can be translated into total capital investment costs in $\mathrm{USD}_{2017,}$ as in [7, p. 27], updated with US Federal Reserve’s GDP implicit price deflator of 1.176 [8].

However, the costs of building structures for SNF cooling are more a direct function of the surface area of the pool than the Metric Tonnes of Heavy Metal (MTHM) they can hold. The cost of providing storage for 600 MTHM, or for a generic 4-loop Westinghouse PWR (3,417 MWth/1,144 MWe), is about $135M from [6] where these costs include direct, indirect, owners' costs, contingency, and Interest During Construction. The total capital cost of building a pool big enough for 2 units would be about $209M, such as at TVA's Watts Bar Unit 1, anticipating the operation of Watts Bar Unit 2.

To estimate scale effects, if one third of the assemblies are replaced with each reload, then the maximum number of reloads is equal to the licensed original size of the fuel pool divided by one-third of the number of assemblies in the core. The minimum number of reloads for NPPs in the US in the late 1980s was 10 [9, Table 4.2.1]. The smallest fuel pool in the US NPP fleet in the late 1980s (when it was assumed that US DOE would take possession of SNF in 1998) was 4.3 m x 11.9 m x 11.9 m, which could hold 230 MTHM. Assume that the cost of the smallest pool would be about $72M (this would be the *fixed capital cost*) and an additional $63M would be required to build a pool to hold 600 MTHM (this is the approximate size of the fuel pool described in [6]). Therefore, each additional square meter of surface area (greater than the surface area of the smallest pool equal to 336 m^2) would require an investment (*unit capital cost*) of about $258k/$m^2$ of pool surface area.

Added to these capital costs are annual O&M costs. The annual O&M cost model here is based on [10], which presents estimates of annual costs of operating a 750 MTHM SNF pool. There, the cost model was based on General Electric's Morris Operation and was modified to reflect average storage capacities at generic US NPP fuel pools. Other cost data came from Duke Power based on SNF pool storage costs at its NPPs. The model in [10] assumed personnel costs are independent of reactor type *and* fuel pool size (for pools that are similar in size to those at existing NPP sites). The personnel costs for operating a pool were calculated to be annually 2,159,400 USD_{1989} (x 1.757 = $3,788k, where 1.757 is the US Federal Reserve's GDP implicit price deflator [8]); so *fixed O&M total costs* per year would be about $3.8M. If each pool is about 1,200 m^3 storing 750 MTHM, the non-personnel costs (*variable O&M costs*) are about 2,870 USD_{1989}/MTHM (= 2,154,400 USD_{1989}/750 MTHM). The present value of these costs over a 40-year life would be 23.11 times these values, or $88M plus $66,300/MTHM. These can be updated to 2017 USD and added to capital and D&D costs: Assuming decommissioning for a 1,000 MWe NPP are $1B [11], the pro rata share of the costs of the D&D NPP fuel pools are about [6] (1.09% + 1.35% = 2.44%) x $1B = $24.4M for a 600 MTHM SNF pool. Estimated total and average cost per kgHM for an on-site SNF pool are estimated in Equation (7). Fuel pool costs, as calculated here, have an inverse relationship with their licenced maximum MTHM storage capacity. This is a specific version of Equation (6). The average cost of on-site pool storage can be represented as

$$AC_1 = \$248 + (\$130\text{k} / SIZE_1)\ . \tag{7}$$

The lowest value of AC_1, as size increases to the largest possible capacity, approaches an asymptote of $248/MTHM. This is equal to the value of the constant, $a_{1,1}$ in the Ordinary Least Squares (OLS) estimate of the statistical relationship between AC_1 and $SIZE_1$ from calculated cost data. The cost of building a fuel pool to store up to 600 MTHM is estimated to be about $465/kg. (For a graphic representation of AC_1, see Figure 1, below.)

Regarding the use of data from the 20th century to forecast costs in the 21st century, see [12, on website]: As a consequence of the accident at the Fukushima-Dai-ichi NPP, the Czech Republic agreed to perform stress tests required by the European Council of SNF storage pools for each unit at the Dukovany and Temelín NPPs. On-site dry storage facilities were not subject to European Council stress tests because these facilities were not seriously affected by earthquakes in Japan: "There was no release of radioactive substances to the environment from these facilities. *In this way it was demonstrated that especially dry cask storage facilities due to their passive safety features are sufficiently robust and resistant to withstand even some beyond design basis accidents*" [*emphasis added*]. Therefore, estimates for the average cost per MTHM for wet on-site storage should be considered minimum costs rather than mean, median, or best estimate costs.

3. ON-SITE DRY STORAGE OF SNF

NPP fuel pools were originally designed to temporarily store SNF, allowing the irradiated fuel to cool before being sent to a reprocessing facility to chemically separate and recover valuable uranium and plutonium. Because of government policies, a commercial reprocessing industry never developed outside France, the Russian Federation, and the UK (reprocessing has been discontinued in the UK). By the time these policies were re-evaluated, reprocessing was not considered economic by the NPP owner/operators. Therefore, SNF has been stored on-site at NPPs for much longer than originally anticipated. For example, in the US in the 1990s many fuel storage pools were beginning to approach their licensed capacities. In response to this situation, NPP owner/operators began to replace existing storage racks with high-density storage racks [13]. Simultaneously, NPP owner/operators were developing plans to move older SNF out of pools and into dry casks for on-site storage facilities, sometimes referred to as Interim Spent Fuel Storage Installations (ISFSIs, also known in IAEA documents as Interim Spent Fuel Storage Facilities, ISFSFs).

In assessing GE-Hitachi's proposal to build an Advanced Boiling Water Reactor (ABWR) in the UK, the UK Office of Nuclear Regulation described the steps required to build an on-site ISFSI [14, p. 3]: "Hitachi-GE's proposed strategy for managing the UK ABWR spent fuel consists of the following main steps:" (a) When decay heat has fallen sufficiently, SNF assemblies are loaded into a multi-purpose canister (MPC) within a transfer cask, inside the fuel pool. (b) Once loaded, the MPC and transfer cask are lifted onto a cask stand outside the fuel pool and the MPC internals are dried, pressurised with an inert gas, and a lid welded to the MPC. (c) The MPC and cask are moved from the fuel pool building on a cask transporter to an on-site storage area. (d) The MPC is removed from the transfer cask and placed inside a large concrete over-pack on a concrete pad, which might be in a structure or inside a structure. (e) When a CISF or DGR is available, the MPCs can be moved to the site. The SNF can be stored at the CISF or re-packaged into disposable containers and placed inside the DGR. The remainder of this section describes dry cask technology and provides a cost estimate for building, populating, and operating an on-site ISFSI.

As an example of a dry cask storage system, hundreds of CONSTOR® casks (made with a ductile cast iron body) have been manufactured by Gesellschart fuer Nuklear-Behaelter mbH (GNB) for Bulgaria (CONSTOR® 440/84), Lithuania (CONSTOR® RBMK 1500), and for many other NPPs [15]. The Dry Spent Fuel Storage Facility at the Bulgarian Kozloduy (a VVER) NPP was completed in 2011 with financial support from the European Bank for Reconstruction and Development. After commercial operation of the Ignalina NPP there were about 22,000 fuel assemblies with about 2,500 MTHM, of which about 700 MTHM had been moved to on-site dry cask storage (CONSTOR® casks). The CONSTOR® casks were designed for long-term storage (up to 50 years) of RBMK half-height fuel assemblies with an initial enrichment of 2%, a burnup of 20 GWd/MTU, and 5 years of cooling in a fuel pool, according to [15, p. 4]. These casks are stored in a building; see, for example, the one at Ignalina (www.iae.lt/en/news/press-releases, 24 January 2019), which is similar to the inside of the SNF storage building at Gorleben, Germany [16]. Also, consider the similar GNB CASTOR® storage system made with a stainless steel body (used, for example, at the Surry NPP in the US starting in 1986).

Dominion Energy's Kewaunee NPP entered retirement in May 2013 after 39 years of operation. In December 2013, NAC International was awarded a contract for the turnkey dry storage project including (a) site engineering, (b) expansion of the plant's ISFSI with 24 of NAC's MAGNASTOR® casks, and (c) pool-to-pad equipment and loading services. The entire SNF inventory is being stored in 24 MAGNASTOR® casks and 14 legacy NUHOMS® (NUtech HOrizontal Modular System), which is a horizontal storage system supplied by Transnuclear's (TN of Orano, formerly Areva).

Another popular storage system in the US is the Holtec HI-STORM UMAX®. For example, at Callaway's ISFSI there are 48 5.2 m canister containers in a 7.6 m deep excavation. Around these canister containers is more than 7,500 m^3 of concrete. Each container can hold a canister with 37 used PWR fuel assemblies. The ISFSI provides storage for 1,776 used fuel assemblies or about 888 MTHM. US utilities have implemented dry cask storage at a rate of about 200 new loaded casks per year. The dry cask systems are diverse because the three major cask vendors (Orano TN, Holtec International, and NAC International) have introduced new designs to improve operational efficiencies; [17] discusses the different cask systems used by the US utilities. According to [17, p. 2], "Because of the large volume and diverse systems, nationwide [US] SNF management through its final disposition [will be] a complex undertaking."

The costs of building the ISFSI at Haddam Neck Plant (HNP) were discussed in [18]. Construction of a storage pad and vertical SNF storage casks was completed in 2002. Transferring the fuel from the fuel pool to dry storage in DPCs began in the first quarter of 2004 and was finished one year later. There are 43 dry storage casks on the 21.3 m by 69.5 m (1,480 m^2) 60-cm-thick concrete pad (about 900 m^3 of reinforce concrete). Forty of the casks contain SNF assemblies and three casks contain sections of the reactor internals classified as Greater-Than-Class-C waste. (Each cask is on a pad of 34.5 m^2 ≈ 6 m x 6 m). Each concrete cask has a 9 cm steel liner surrounded by 53 cm of reinforced concrete and, when loaded into a DPC, weighs 126 tonnes. The entire ISFSI construction (procuring materials, fabricating the fuel canisters and casks, constructing the storage pad and facility, and transferring the fuel) took three years.

According to [18, p. 4-26], the cost of the HNP ISFSI from 1999 to 2007 was 144.6M USD$_{2010}$ or \$162M, with the bulk of this (98%) spent between 2001 and 2005. Further, [18 p. 4-27] states: “While the decommissioning of the HNP is completed…, the HNP ISFSI continues to be licensed under the HNP 10 CFR Part 50 license. Consequently, [Connecticut Yankee Atomic Power Company] is maintaining a decommissioning fund of 152.9M USD$_{2008}$, 145.4M USD$_{2008}$ for ISFSI operations, and 7.5M USD$_{2008}$ for ISFSI decommissioning.” Therefore, the present value of monitoring and maintaining the ISFSI for 40 years from 2007 to 2067 is about \$168M. There is an implicit expectation that \$6.2M would be spent annually for monitoring and maintaining the ISFSI. (Sixty years is the time limit on decommissioning an NPP in the US, which assumes at least one renewal of the ISFSI’s operating license from the US NRC.)

In 2007 one of the most complete accountings of capital cost data for a dry-cask storage project at an *operating* reactor was done for the “Certificate of Need,” filed 18 January 2005, by Xcel Energy with the Minnesota Public Utility Commission for a dry cask storage facility with 30 NUHOMS® casks near the reactor building of the Monticello NPP. Each cask is designed to hold 61 BWR SNF assemblies containing about 11 MTHM (about 180 kgHM per BWR assembly). The total construction was 55M USD (assumed to be in 2005 USD), which when converted to mid-2017 USD by multiplying by the US GDP implicit price deflator of 1.230 [8] yields \$68M. Of this, about 20M USD$_{2005}$ (or about \$25M; see estimate of \$23.7M from [19]) represents *fixed* one-time costs that are independent of the number of casks on the site storing up to 2,000 MTHM, and the remainder is about 110k USD$_{2005}$/tonne of SNF. If additional SNF dry casks were to be added later, only the incremental (variable) capital cost of about 110k USD$_{2005}$, or \$135,300/tonne would be required. Subtracting \$25M from \$82.07M, 64 casks would imply a cost of \$892k per cask, and \$16.62M for cask handling, which could be included in “ISFSI Operations” in [20, p. 53].

For a dry-cask storage facility at an operating NPP, the incremental annual security and maintenance costs are less than at a retired NPP, because personnel are working at the NPP. [21, p. 16] relied on a consultant’s estimate that the annual operating cost was about 1M USD$_{2005}$ (\$1.23M) per year at an operating NPP. (Compare this to the estimate of annual O&M of \$1.85M in [22, p. 16].) For costs at a closed facility, there are data provided by the Maine Yankee NPP in its license termination plan for storage of 543 tonnes of SNF. There, the calculated annual operating costs (for staffing, security, insurance, various state and US NRC fees, etc.) are slightly under 5M/year in nominal year US dollars (or about \$6M/year).

If operating costs are independent of the number of casks (and the MTHM in those casks) at an on-site ISFSI, the average cost per unit of storage capacity can be summarised as

$$AC_2|_{\mathbf{S=1}} = (\$25\text{M} + \$135{,}300 \text{ x } SIZE_2 + \$1.23\text{M x } 23.11)/SIZE_2 = \$135{,}300 + \$53.43\text{M}/SIZE_2\,, \tag{8}$$

$$AC_2|_{\mathbf{S=0}} = (\$25\text{M} + \$135{,}300 \text{ x } SIZE_2 + \$6\text{M x } 23.11)/SIZE_2 = \$135{,}300 + \$163.69\text{M}/SIZE_2\,, \tag{9}$$

where **S = 1** if the NPP is operating or being decommissioned and there is an administrative, technical and security staff, and **S = 0** if the NPP is not operating or not being actively decommissioned. The amount of SNF in dry storage in year *t*, $MTHM_t$, grows until (at least) six years after shutdown (in “safe storage”) when it is assumed that the fuel pool has been emptied. Based on OLS estimate Equations (8) and (9), the asymptotic cost is \$135,000/MTHM (= \$135/kgHM) with approximately \$217/kgHM without an ISFSI staff for 2,000 MTHM and approximately \$162/kgHM with an ISFSI staff for 2,000 MTHM. (See representation in Figure 1.)

4. OFF-SITE DRY STORAGE OF SNF

About a dozen consolidated interim dry cask storage facilities are in operation, being built, or planned in countries with NPPs; [23] identifies many of them. Regarding two US facilities, the license for the Holtec International CISF in Lea County, New Mexico, was submitted to the US NRC in 2017. The Waste Control Specialists’ (WCS) licence application was resubmitted to the US NRC in 2018. In June 2018 WCS created a joint venture with Orano USA, Interim Storage Partners LLC, to build the storage facility in Andrews County, Texas. (A cost estimate of a generic US CISF is available in [24].)

These US facilities would be reviewed as applications for a specific license under 10 CFR 72 and, as proposed, are not co-located with an NPP. If the application is approved, the US NRC would issue a license that would be valid for up to 40 years. A SNF storage license contains technical requirements and operating conditions (for example, fuel specifications, cask leak testing, and surveillance) for the CISF and specifies what the licensee is authorised to store at the site. The WCS CISF is similar to the Private Fuel Services (PFS) Facility in Utah, licensed by the US NRC in 2006 to store 40,000 MTHM for 20 to 40 years [25].

Assuming a “moving storage” scenario where a host community agrees to only 40 years of hosting the CISF, 40,000 MTHM of SNF flow into and out of a series of CISFs (until a DGR or reprocessing facility is opened) under the following assumptions: (a) Cooled SNF from ISFSIs begin arriving at the facility in 2026 with an annual fill rate of 4,000 MTHM; filling the facility by the end of 2035. (b) 40 years after it first arrives at the facility, the SNF begins to be moved out of the facility to a new facility; all the SNF leaves the first facility before 2075. (c) Every 40 years a new facility is developed, built, filled, monitored, emptied, and decommissioned. (d) To facilitate average cost calculations, the costs of MTHM storage are discounted to 2018 using USD_{2017} with a 3% discount rate. (This is equivalent to calculating the present value that would be necessary to pay all future program costs from a fund with a real rate of return of 3%.) (e) Finally, the cost of transport to the first CISF is primarily equal to the handling costs: the transfer of DPCs at an on-site ISFSI from concrete overpacks to (reusable) transportation overpacks, and the transfer of DPCs from transportation overpacks to the CISF storage pad. This is because moving costs are small compared to the handling costs: “shipments of SNF and MOX will be relatively insensitive to shipment distance or to weight-related shipping costs.” [4, p. O1-22] Next, the paper discusses the costs associated with the first two of these 40-year CISFs. These costs are repeated such that each SNF canister spends only 40 years at a particular CISF. There is an overlap of costs when the subsequent facility is being prepared and the SNF is moved.

As discussed in [25], the following analysis is based on [26], which describes seven cost categories: (a) Public management costs (at all government levels); (b) Private development and construction costs; (c) Overpack construction costs; (d) Cask handling costs; (e) Administration and security costs (salaries, wages, and benefits for employees working in the Canister Transfer building are accounted for in the cask handling charge), see organisational chart in [7, Annex E]; (f) Taxes or payments in lieu of taxes from [27, p. 111]; and (g) Decontamination and demolition (decommissioning) costs from [26, p. 1-7]. These investments and expenses are added in each year and discounted to 2018. In 2056 private development costs start again to prepare for the second CISF if there is no DGR or reprocessing facility. The present value of these expenses from 2018 through 2056 is about \$2,500M. This is for one set of 40,000 MTHM. Hence, in years 2066 to 2075 the SNF is being moved from the first CISF to the second CISF. The OLS estimated parameters for the reduced form equation for average costs for CISF dry storage in a PFS-like facility through the end of the 21st century are

$$AC_3 = \$164 + (\$1{,}826\text{k} / SIZE_3)\,. \tag{10}$$

(See Figure 2.) At the minimum efficient scale (MES [2, p. 187]) of 100,000 MTHM, the average cost is about \$182/kgHM, which is similar to the cost of on-site dry storage with an operating NPP: \$162/kgHM for on-site dry storage facilities of 2,000 MTHM, however, the cost would be much higher if only 2,000 MTHM were stored at the CISF. (The MES is that size at which the cost is within 10% of the expected minimum asymptotic cost, where 10% was chosen because there could be 10% error in forecasting the minimum asymptotic cost.) Because of the similarity of these average costs, the first part of Section 5 compares the average costs of on-site wet and dry storage, and the second part compares average costs of on and off-site dry storage.

5. COMPARING ESTIMATED COSTS FOR WET & DRY STORAGE

Comparing on-site wet and dry storage after the NPP has been built is complex. The capital construction costs for a specific size of fuel pool are sunk. (Sunk costs are those that cannot be recovered once construction is complete; here, it is possible that the owner of fuel from another NPP could lease the extra space in the fuel pool, but this alternative makes the analysis more economically and legally complex.) Because the size of the fuel pool at an advanced water reactor is essentially fixed, the only alternative is dry storage. Figure 1 compares (a) AC_1/kgHM from Equation (7) with a solid line; (b) non-sunk costs (the present value of annual O&M and D&D costs), $\underline{AC_1}$/kgHM, derived from Equation (7), with a broken line; (c) $AC_2|_{S=1}$/kgHM from Equation (8) with a dotted line before the NPP is shutdown or during decommissioning when there is an on-site staff; and (d) $AC_2|_{S=0}$/kgHM from Equation (9) with a dashed line when there is no administrative and security staff.

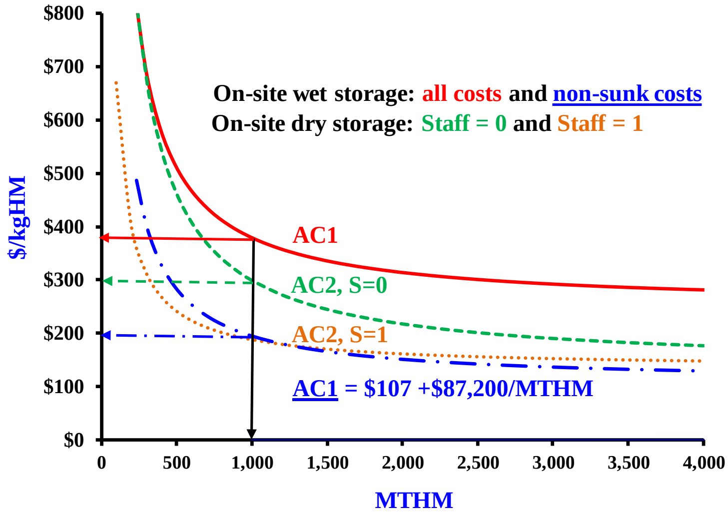

FIG. 1. Comparing on-site wet and dry storage. Source: Equations (7), (8), and (9).

The first observation is that the highest cost alternative is building and operating wet storage where 80% of the economies of scale are exhausted at 2,000 MTHM for a large, twin-NPP operating for 40 to 50 years. *Average costs of operating* the fuel pool (once it has been built) are almost identical to the *average construction and operating costs of dry storage*. Hence, there is no economic reason not to transfer to on-site dry cask storage. However, these generic costs are primarily based on 20th century regulatory filings using HI-STORM UMAX®, MAGNASTOR®, and/or NUHOMS® storage systems, and might not represent current regulatory requirements, so further research should be done to identify required post-Fukushima upgrades.

Although comparing on-site wet and dry storage is complex, comparing on-site and off-site dry storage is relatively simple. Off-site dry storage is always more expensive than on-site dry storage, primarily because of the development costs and multiple handling costs (not considering the compatibility of the canisters with transportation equipment). In Figure 2 the maximum size for on-site dry storage was assumed to be 4,000 MTHM, equal to 4 NPPs generating 20 MTHM for 50 years. The maximum size for off-site dry storage was assumed to be 100,000 MTHM, although there might not be a technical size limit to off-site storage of non-damaged SNF (damaged SNF might require specialised facilities for transfer into standardised canisters and casks). On-site dry storage facility for 1,000 MTHM (one NPP for 50 years) would cost approximately \$300/kgHM, whereas this same amount in an off-site dry storage facility would cost approximately \$2,000/kgHM.

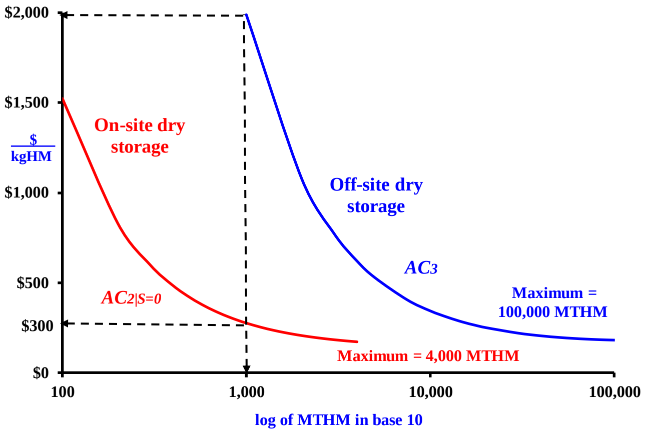

FIG. 2. Comparing on-site and off-site dry storage (MTHM in log base 10). Source: Equations (9) and (10).

Because of these relative costs, there must be non-economic reasons for moving SNF from on-site to off-site dry storage: (a) local community concerns about the SNF storage in their locale, particularly after the decommissioning of the local NPP, the staff has been reduced to a few dozen people, and the site is no longer contributing much in the way of taxes to the community; (b) restrictions on the land on which the ISFSI is located might limit potential economic development in the area; (c) preparation for the disposal of SNF in a DGR (or for reprocessing) with a CISF near the site of the DGR (or reprocessing facility), where there is minimal transportation from the CISF to the DGR; and/or (d) national regulatory requirements.

The final issue is whether countries with small NPP fleets should build CISFs (and DGRs) for SNF generated by NPPs in their country. This is a politically sensitive issue given the *Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management*, as discussed in [28, p. 5]: “The Convention imposes obligations on Contracting Parties in relation to the transboundary movement of spent fuel and radioactive waste based on the concepts contained in the IAEA Code of Practice on the International Transboundary Movement of Radioactive Waste.” The *Joint Convention* essentially requires each country to provide management facilities for SNF generated in their country. A case in point is the management of SNF from Krško, a 730 MWe Westinghouse NPP, in Slovenia that is jointly owned by the nationally-owned Slovenian and Croatian electric power companies. The fuel pool at Krško has the capacity (about 600 MTHM) to store all SNF assemblies until the end of plant life in January 2023 (but its life could be extended by 20 years). Croatia is obliged to take ownership of one half of the SNF and nuclear waste by 2025.

The economic conundrum posed by the *Joint Convention* is that countries with small NPP fleets will eventually need to provide CISFs after their NPPs are decommissioned. The unit cost of small CISFs is much larger than for large CISFs, as can be seen in Figure 2. (Although not discussed in this paper, the costs of small DGRs are several times more expensive per MTHM than larger DGRs due to the high fixed costs of site licensing, site preparation, and site construction.) Because of these large costs, many countries with small fleets (and/or non-favorable geologies) have chosen the “wait and see” strategy where they are waiting for countries with larger fleets to build CISFs and DGRs. Unfortunately, the siting of the DGR, and hence the siting of a CISF near a DGR, has been used as a political football, kicked across the field by political parties out of power to gain advantages through perceived fear of radioactive “waste” or kicked down the field to the next generation. The Finnish government (with only two NPPs and a third planned) is now closest to making its goal of an indigenous DGR with Sweden and France close behind. In any event, we must see more pre-DGR SNF storage capacity whether the nuclear fuel cycle is open or eventually closed.

6. SUMMARY AND CONCLUSIONS

According to [29, pp. 68-69] (post-dating the attacks of 11 September 2001 and pre-dating the accidents at Fukushima Dai-ichi on 11 March 2011), regarding the potential advantages of dry over wet storage: “The following statements can be made about the comparative advantages of dry-cask storage and pool storage”…: Less SNF is at risk in an accident or attack on a dry storage cask facility than on a fuel pool. An accident or attack on a dry cask storage facility would likely affect at most a few casks and put a few tens of metric tons of SNF at risk. An accident or attack on a fuel pool puts the entire inventory of the pool, potentially hundreds of metric tons of SNF, at risk (as was experienced at Fukushima Dai-ichi). The potential consequences of an accident or attack on a dry cask storage facility are lower than those for a fuel pool.

The paper attempted to calculate the relationships between the sizes and costs of on-site wet and on-site/off-site dry storage facilities for SNF. It found that once the NPP fuel pool is built, the cheapest solutions are to use the fuel pool until it is full and move the SNF to on-site dry storage *while* there is staff on-site to monitor and secure this form of storage. Once the NPP has been decommissioned, and only the on-site dry storage remains, there might be no cost reason (from the point of view of the NPP owner/operator) to move the SNF to consolidated facilities due to the high costs of loading and unloading SNF. Hence, *there is a stable equilibrium to leave the SNF on-site, particularly in countries with small NPP fleets*. However, there appears to be a consensus that consolidated facilities (a) would be more safe and secure than dispersed on-site storage locations, (b) would facilitate final disposal, and (c) might reduce the risks perceived by local communities.

7. REFERENCES

[1] Rothwell, G.S. “Sustainable Development and the Application of Discounting to the Calculation of the Levelised Costs of Electricity,” Nuclear Energy Agency, OECD, Paris, France (2018), http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=NEA/NDC/R(2018)1&docLanguage=En

[2] Rothwell, G., *Economics of Nuclear Power*, Routledge Publishers, London and New York (2016). https://issuu.com/johna.shanahan/docs/161031_future_of_nuclear.

[3] TVA (Tennessee Valley Authority), “Spent Fuel Pool Evaluation Supplemental Report for Watts Bar Nuclear Plant, Units 1 and 2 - Response to NRC Request for Information Pursuant to Title 10 of the Code of Federal Regulations 50.54(f) Regarding Recommendation 2.1 of the Near-Term Task Force Review of Insights from the Fukushima Daiichi Accident,” Docket Nos. 50-390 and 50-391 (22 December 2016). www.nrc.gov/docs/ML1635/ML16357A578.pdf.

[4] INL, *Advanced Fuel Cycle Cost Basis*, INL/EXT-17-43826, Idaho National Laboratory, Idaho Falls, ID (September 017). www.researchgate.net/publication/323557503_Advanced_Fuel_Cycle_Cost_Basis_-_2017_Edition.

[5] GIF/EMWG (Generation IV International Forum/Economic Modelling Working Group), *Cost Estimating Guidelines for Generation IV Nuclear Energy Systems*, GIF/EMWG/2007/004 (2007). www.gen-4.org/gif/jcms/c_40408/cost-estimating-guidelines-for-generation-iv-nuclear-energy-systems.

[6] ORNL, *Advanced High Temperature Reactor Systems and Economic Analysis*, ORNL/TM-2011/364, prepared by Oak Ridge National Laboratory under the direction of UT-Battelle, Oak Ridge, Tennessee, US (2011). info.ornl.gov/sites/publications/files/Pub32466.pdf.

[7] NEA, *Measuring Employment Generated by the Nuclear Power Sector*, Nuclear Energy Agency, OECD, Paris, France (2018). www.oecd-nea.org/ndd/pubs/2018/7204-employment-nps.pdf

[8] US Federal Reserve (US Federal Reserve Bank of St. Louis), “Gross Domestic Product: Implicit Price Deflator, Index 2009=100, Quarterly, Seasonally Adjusted.” St. Louis, Missouri, US (2018). fred.stlouisfed.org/series/GDPDEFGraph Observations

[9] US NRC, *Regulatory Analysis for the Resolution of Generic Issue 82, Beyond Design Basis Accidents in Spent Fuel Pools*, NUREG-1353, Division of Safety Issue Resolution, Office of Nuclear Regulatory Research, US Nuclear Regulatory Commission, Washington, DC (1989). www.nrc.gov/docs/ML0823/ML082330232.pdf

[10] Rod, S., “Cost Estimates of Operating Onsite Spent Fuel Pools after Final Reactor Shutdown,” PNL-7778, Pacific Northwest Laboratory, Richland, Washington, US (August 1991). www.osti.gov/biblio/5349359

[11] NEA, *Costs of Decommissioning Nuclear Power Plants*, Nuclear Energy Agency, OECD, Paris (2016). https://www.oecd-nea.org/ndd/pubs/2016/7201-costs-decom-npp.pdf

[12] SUJB, “Spent Fuel Management,” State Office for Nuclear Safety, Prague, Czech Republic (2018). https://www.sujb.cz/en/nuclear-safety/spent-fuel-management/

[13] Dominion, “Millstone Nuclear Power Station, Unit Nos. 2 and 3 10 CFR 50.59 and Commitment Change Report for 2000” a letter to the US NRC (2 July 2001). adamswebsearch2.nrc.gov/webSearch2/view?AccessionNumber=ML011900320

[14] ONR, “Step 4 Assessment of Spent Fuel Interim Storage for the UK Advanced Boiling Water Reactor,” ONR-NR-AR-17-030, Office of Nuclear Regulation, UK (2017). www.onr.org.uk/new-reactors/uk-abwr/reports/step4/onr-nr-ar-17-030.pdf

[15] Poskas, P., Simonis, V., Smaizys, A., “Comparison of the main characteristics for CASTOR and CONSTOR casks loaded with spent RBMK-1500 nuclear fuel,” IAEA-CN-102/33, presented at IAEA, Vienna, Austria (2003). www.iaea.org/inis/collection/NCLCollectionStore/_Public/34/047/34047327.pdf?r=1

[16] Jussofie, A., “Spent fuel management and storage in Germany,” GNS presented at *International Seminar on Interim Storage of Spent Fuel*, Tokyo (15-17 November 2010). criepi.denken.or.jp/result/event/seminar/2010/issf/pdf/1-10_powerpoint.pdf

[17] Banerjee, K., Robb, K., Radulescu, G., Cuta, J., Miller, P., Liljenfeldt, H., Scaglione, J., “UNF-ST&DARDS: A Unique Tool for Automated Characterization of Spent Nuclear Fuel and Related Systems,” Oak Ridge National

Laboratory, *Proceedings of the 18th International Symposium on the Packaging and Transportation of Radioactive Materials PATRAM 2016* (18-23 September). Kobe, Japan (2016). tech-showcase.ornl.gov/wp-content/uploads/2018/08/TIP-Used-Nuclear-2018.pdf

[18] PNNL, *Assessment of the Adequacy of the 10 CFR 50.75(c) Minimum Decommissioning Fund Formula* (November). Pacific Northwest National Laboratory, Richland, Washington, US (2011). www.nrc.gov/docs/ML1306/ML13063A190.pdf.

[19] Entergy Corp, "Post Shutdown Decommissioning Activities Report, Vermont Yankee Nuclear Power Station," (2014). www.nrc.gov/docs/ML1435/ML14357A110.pdf

[20] IAEA, *Costing of Spent Nuclear Fuel Storage*, IAEA Nuclear Energy Series, No. NF-T-3.5, International Atomic Energy Agency, Vienna, Austria (2009). www-pub.iaea.org/MTCD/Publications/PDF/Pub1398_web.pdf

[21] APS (American Physical Society), *Consolidated Interim Storage of Commercial Spent Nuclear Fuel: A Technical and Programmatic Assessment* (2007). www.aps.org/policy/reports/popa-reports/upload/Energy-2007-Report-InterimStorage.pdf

[22] Alvarez, R., "Update report on Spent nuclear fuel management and closure date cost comparison at the Columbia Generating Station," Institute for Policy Studies (24 October 2017). https://d3n8a8pro7vhmx.cloudfront.net/oregonpsrorg/pages/45/attachments/original/1508967118/Robert_Alvarez_CGS_SNF_Update___Cost_Study_-_10-24-17.pdf?1508967118

[23] IAEA, *Nuclear Fuel Cycle Information System*, International Atomic Energy Agency, Vienna, Austria (2018). infcis.iaea.org/NFCIS/Facilities

[24] EPRI, *Cost Estimate for an Away-From-Reactor Generic Interim Storage Facility (GISF) for Spent Nuclear Fuel*, Electric Power Research Institute Technical Update 1018722, Palo Alto, CA (May 2009). www.epri.com/#/pages/product/1018722/?lang=en

[25] Rothwell, G., "Scale Economies in a Series of Generic Interim SNF Storage Facilities," *Proceedings of the International Congress on Advances in Nuclear Power Plants*, ICAPP 2015, Nice, France (3-5 May 2015). www.sfen.fr/ICAPP

[26] Private Fuel Services (PFS) LLC, *Application for a License to Construct and Operate a Spent Fuel Storage Facility*. Docket No. 72-22, US Nuclear Regulatory Commission (June 1997). pbadupws.nrc.gov/docs/ML0103/ML010320524.pdf

[27] Bunn, M., Holdren, J.P., Macfarlane, A., Pickett, S.E., Suzuki, A., Suzuki, T., and Weeks, J., *Interim Storage of Spent Nuclear Fuel: A Safe, Flexible, and Cost-Effective Approach to Spent Fuel Management* (Cambridge, MA: Managing the Atom Project, Harvard University, and Project on Sociotechnics of Nuclear Energy, University of Tokyo, June 2001. bcsia.ksg.harvard.edu/BCSIA_content/documents/spentfuel.pdf).

[28] Pellaud, B. "International Monitoring of Storage and Disposal Facilities." *Setting the Stage for International SNF Storage Facilities: International Workshop Proceedings*, National Research Council, Washington, DC (2008). www.nap.edu/read/12191/chaper/3

[29] National Research Council, *Safety and Security of Commercial Spent Nuclear Fuel Storage: Public Report.* National Academy Press, Washington, DC, US (2006). www.nap.edu/catalog/11263/safety-and-security-of-commercial-spent-nuclear-fuel-storage-public

ACKNOWLEDGEMENTS

I thank M. Baryshnikov, S. Bilbao-y-Leon, K. Büttner, B. Dixon, C. Evans, E. Gomez-Belinchon, J. Ha, J. Harris, J. Jarrel, A. Khaperskaya, D. Kerr, D. Korn, A. Larsson, V. Lebedev, C. McCombie, M. Molina Martin, O. Nevander, M. Pieraccini, W. Roberts, J. Sorjonen, R. Sloan, P. Standring, T. Wood, H. Zaccai, and E. Zurbenko for their comments, references, and support. This paper is based on work done for the Nuclear Technology and Economics Division (NTE) of the Nuclear Energy Agency (NEA) of the Organisation for Economic Cooperation and Development (OECD). The paper reflects the views and conclusions of the author.