UPDATE REPORT ON SPENT NUCLEAR FUEL MANAGEMENT AND CLOSURE DATE COST COMPARISON AT THE COLUMBIA GENERATING STATION

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October 24, 2017

Summary

This study provides preliminary cost estimates for the storage and geological disposal of spent nuclear fuel (SNF) at the Columbia Generating Station (CGS) in Washington, a boiling water power reactor (BWR) operated by Energy Northwest. Based on data from Energy Northwest, nuclear industry sources and recent U.S. Department of Energy (DOE) reports, costs are compared between the closure of CGS in 2019 and 2043 when the reactor's operating license expires.

In April 2017, the U.S. Government Accountability Office (GAO) informed Congress that "spent nuclear fuel can pose serious risks to humans and the environment and is a source of billions of dollars of financial liabilities for the U.S. government. According to the National Research Council and others, if not handled and stored properly, this material can spread contamination and cause long-term health concerns in humans or even death."[1]

For illustrative purposes, this study is based, in large part, on a major assumption, currently adopted at closed reactors, that all spent nuclear fuel will remain on site, until the year 2026 when, according to the DOE's strategic plan, a consolidated storage site will be opened, followed by the opening of a geologic disposal site in 2048. Costs of transportation are included as are the rates of removal from the reactor to the consolidated storage site and then to the repository.

Storage and disposal costs of 891 metric tons of spent nuclear fuel following closure of the CGS in 2019 range from approximately $711 million to $1.56 billion. If the reactor operates until 2043, storage and disposal costs of a projected 1,539 metric tons of spent nuclear fuel range from

$1.17 billion to $2.74 billion. Potential cost savings, if the reactor is closed in 2019, are between $459 million and $1.18 billion.

As reflected in these wide ranges in cost estimates, large cost uncertainties remain. For instance, if the cancelled Yucca Mountain repository project is reactivated, it is designed to hold less than half of the total currently projected spent fuel to be generated in the United States at a total cost of $113 billion.

Significant uncertainties surround prolonged storage of high-burnup spent nuclear fuel. This fuel generally contains a higher percentage of uranium 235, allowing reactor operators to effectively double the amount of time the fuel can be used. Once it is used, high burnup significantly boosts the radioactivity in spent fuel and its commensurate decay heat. Of concern is the damage that high-burnup fuel may have on the cladding of the fuel. The Nuclear Regulatory Commission (NRC) and the nuclear industry do not have the necessary information to determine if prolonged storage of high-burnup fuel may damage fuel cladding and create leakage. Currently, the Columbia Generating Station is not authorized by the NRC to store high-burnup spent nuclear fuel in dry casks. Since, the NRC concedes that "data is not currently available" supporting the safe transportation of high-burnup spent nuclear fuel,[2] U.S. Energy Department researchers suggested it may be "trapped" at reactor sites for a significant period before removal. By 2043, when the CGS operating license expires, high-burnup spent nuclear fuel will increase from about 23.5 percent of the total generated at the CGS to approximately 60 percent.

Dry cask storage systems currently deployed are not licensed for disposal and were chosen primarily as an economical means of surface storage. Existing large canisters can place a major burden on a geological repository, such as: handling, emplacement and post closure of cumbersome packages with higher heat loads, radioactivity and fissile materials. "Waste package sizes for the geologic media under consideration …are significantly smaller than the canisters being used for on-site dry storage by the nuclear utilities," Energy Department researchers conclude. Technical advisors to the DOE find that, "repackaging the SNF may be a lengthy process and could impact operational schedules at the utility sites, at a consolidated storage facility, or at the repository, depending on where repackaging is performed." At the CGS, 10 times as many canisters than currently projected - each holding a much smaller number of spent fuel assemblies - may be required for disposal. Repackaging could add as much as $915 million to pre-disposal costs for the CGS.

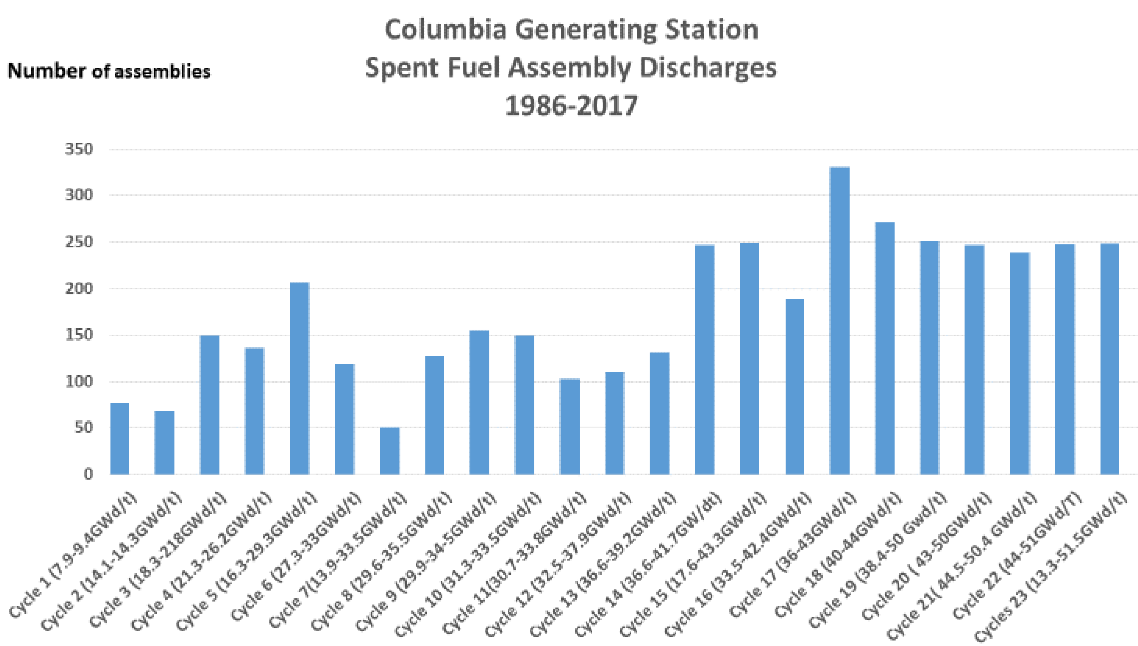
The continued failure to establish a geological disposal site for the DOE to take custody of spent nuclear fuel, shifts storage costs to the U.S. taxpayer. In 2010, Energy Northwest recovered nearly $56.9 million from the U.S. Treasury for the delay in opening a repository. Future taxpayer liability by the time the CGS license expires in 2043 for on-site storage, could be in the range of $200 million or even more. Adding to this expense is the practice of longer irradiation times in reactor cores, which makes spent fuel much more radioactive and vulnerable during storage.

In the end, electricity ratepayers and taxpayers will be saddled with very large costs for management and disposal of the spent nuclear fuel generated by the Columbia Generating Station. The basic statistical trend in this complex situation remains quite simple: the more spent nuclear fuel that is generated, the more ratepayers and taxpayers will pay for its disposition.

Introduction

The Columbia Generating Station (CGS) is a 1,190 Megawatt boiling water power reactor (BWR) located on the U.S. Department of Energy's (DOE) Hanford Site in Washington State. Over the past 33 years, the CGS has generated 4,321 spent nuclear fuel (SNF) assemblies containing approximately 400,000 spent fuel rods (Figure 1). The rods contain about 100 million ceramic uranium pellets. As of 2017, about 42.42 percent of the SNF (1,873 assemblies) is in the reactor spent fuel pool, while the remaining 57.58 percent (2,448 assemblies) is in 36 dry casks (Figure 2). The quantity of spent nuclear fuel is estimated by Energy Northwest to nearly double to 8,316 spent nuclear fuel assemblies when the operating license for the CGS expires in 2043.[3] After bombardment with neutrons in the reactor, about 5 to 6 percent of the uranium fuel pellets are converted to a myriad of radioactive elements with half-lives ranging from seconds to millions of years (Table 1). Standing within a meter of a typical unshielded spent nuclear fuel assembly, even ten or twenty years after removal from the reactor, guarantees a lethal radiation dose in minutes. One hundred years after removal from the reactor standing within a meter of this same unshielded spent nuclear fuel assembly would result in a lethal dose to an individual within 14 minutes. Spent nuclear fuel at the Columbia Generating Station contains roughly 300 million curies of long-lived radioactivity. [4] The estimated concentration of long-lived radionuclides in spent power reactor fuel at CGS is approximately 170 percent greater than stored in Hanford's radioactive waste tanks from decades of plutonium production for weapons.

Figure 1



Heat from the radioactive decay in spent nuclear fuel is also a principal safety concern. For example, several hours after a full reactor core is offloaded to a spent nuclear fuel pool, it gives off enough heat from radioactive decay to melt and ignite the fuel's reactive zirconium cladding, should water from the pool drain away for any reason. The physical heat of this offloaded spent nuclear fuel remains extremely high for several years, depending upon its makeup and how long it was in the reactor, until it is relatively cool enough to be moved into air-cooled dry casks. By 100 years, decay heat and radioactivity drop substantially but still pose life-threatening hazards.

Because of these extraordinary hazards spent nuclear fuel is required under federal law (the Nuclear Waste Policy Act) to be disposed in a geological repository to prevent it from escaping into the human environment for tens of thousands of years. For these reasons, the US Government Accountability Office (GAO) informed the Congress in April 2017 that "spent nuclear fuel can pose serious risks to humans and the environment and is a source of billions of dollars of financial liabilities for the U.S. government. According to the National Research Council and others, if not handled and stored properly, this material can spread contamination and cause long-term health concerns in humans or even death." [5]

Table 1 Estimated Radioactivity in a BWR spent fuel assembly

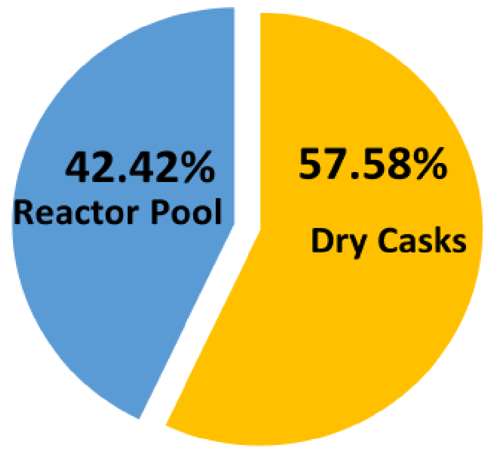
(4.0% enriched with 49,170 MWd/MTU burnup, 10-yr decay)

Radionuclide	Half-Life	Curies	Radionuclide	Half-Life	Curies
Am 241	430 yr	373.00	Pa-231	33,000yr	0.00
Am-242	16 hr	2.87	Pd-107	6,500,000 yr	0.03
Am-242m	150 yr	2.88	Pm-147	2.62 yr	2110.00
Am-243	7,400 yr	8.63	Pr-144	17.28 min	17.30
Cs-134	2.1 yr	1310.00	Pu-238	88yr	1020.00
Cs-135	2,300,000 yr	0.18	Pu-239	24,000yr	54.10
Cs-137	30 yr	24100.00	Pu-240	6,500yr	127.00
Ba-137m	2.6 min	22700.00	Pu-241	14yr	15700.00
C-14	5700 yr	0.21	Pu-242	380,000yr	0.71
Cd-113m	14yr	22700.00	Ru-106	376days	90.50
Ce-144	284.3 days	17.30	Sb-125	2.77yrs	120.00
Cl-36	300,000 yr	0.00	Se-79	65,000yr	0.02
Cm-242	160 days	2.38	Sm-151	90yr	67.30
Cm-243	29yr	5.55	Sn-126	100,000yr	0.16
Cm-244	18yr	923.00	Sr-90	29.12yr	16600.00
Cm-245	8,500yr	923.00	Tc-99	213,000yr	3.88
Cm-246	4,700yr	0.04	Th-230	77,000yr	0.00
Eu-154	8.8 yr	192.00	U-232	72yr	0.01
H-3	12.3yr	105.00	U-233	159,000yr	0.00
I-129	16,000,000yr	0.01	U-234	244,000yr	0.24
Kr-85	11yr	1170.00	U-235	703,000,000yr	0.00
Nb-93m	16.13yr	0.16	U-236	23,400,000yr	0.07
Nb-94	20,300yr	0.00	U-238	4,470,000,000yr	0.06
Np-239	400 days	8.63	Y-90	64hr	16600.00
Np-237	2,100,000 yr		Zr-93	1,530,000yr	0.35
			TOTAL		127,056.67

Source: USNRC, Characteristics for the Representative Commercial Spent Fuel Assembly for Preclosure Normal Operations, 2007

As of 2017, 1,833 spent nuclear fuel assemblies are in the reactor spent fuel pool, while the remaining 2,448 assemblies are stored in 36 dry casks. (See Figure 2). 64.81percent of the spent fuel inventory in the reactor pool is high burnup (see figure 5)

Figure 2 Spent Nuclear Fuel Storage at the Columbia Generating Station



Onsite Storage Costs

Energy Northwest does not have an estimated time-frame before its spent nuclear fuel will be shipped for consolidated storage or disposal. “Columbia’s used nuclear fuel can stay in dry-cask storage indefinitely, until the U.S. industry begins reprocessing it for reuse as fuel, or brings advanced nuclear plants online that can reuse it without reprocessing,” concludes Energy Northwest, “[and we are] supportive of completion of the NRC’s review of the Yucca Mountain license application and publication of its results and, as a near-term solution, development of regional, interim storage facilities across the U.S. that can hold used nuclear fuel until a permanent facility is agreed upon.” [6] However, a nuclear industry consultant recently suggested that “Nuclear operators will be more comfortable with shipping SNF [spent nuclear fuel] once the plant has retired.”[7]

When the reactor is permanently shut down, freshly discharged and high heat spent fuel requires further cooling in the reactor’s storage pool before being placed in dry storage canisters. Minimum cooling times before all spent fuel can be loaded into a dry cask depends on the amount of time it has been irradiated in the reactor core before discharge. For instance, six years of cooling in the storage pool at the Vermont Yankee plant, a recently closed boiling water reactor of similar design to the CGS, is expected prior to loading the balance of spent nuclear fuel in dry casks, which is expected to cost $149 million.

Energy Northwest estimates that the CGS will require a total of 123 casks to hold 8,316 spent nuclear fuel assemblies on 7 concrete pads by the time its license expires in 2043.[8] By contrast, if the reactor is closed in 2019, a total of approximately 71 casks holding 4,185 assemblies would be required. This would result in a cost savings of $112.9 million for dry cask procurement, loading and pads (Table 2). Assuming the spent fuel can be shipped for consolidated storage prior to disposal, approximately $183 million in overall cost savings could result.

Table 2
Onsite Storage Costs for the Columbia Generating Station
(Consolidated Storage site opens in 2026)

COST CATEGORIES	REACTOR OPERATES UNTIL 2043	REACTOR OPERATES UNTIL 2019
Planning and Preparations	$23,727,000	$23,727,000
Dormancy w/Wet Fuel Storage (6 years)	$149,000,000	$149,000,000
Dry Cask Procurement	$118,114 ,000	$48,026,600
Dry Cask Loading	$34,071,000	$13,850,000
Storage Pads	$39,620,000	$16,980,000
M&0 for ISFSI	$140,060,000	$70,300,000
Total	$504,592,000	$321,884,000

Centralized Interim Storage Costs

Recent reactor closures, largely due to age and economics are generating a growing backlog of "orphan" wastes at decommissioned sites. One third of the U.S. reactor fleet is more than 40 years old. [9] Given these circumstances, this study assumes an interim storage site opening by the year 2026, as was assumed by Entergy Corporation in its 2014 Post Shutdown Decommissioning Activities Report, for the Vermont Yankee Nuclear Power Station.[10] Since Vermont Yankee is the first large single unit boiling water reactor, similar in design to CGS, to undergo decontamination and decommissioning, it can serve as a template for onsite cost estimates.

Based on research by the nuclear industry sponsored by the U.S. Department of Energy,[11] a large-scale consolidated storage site with a capacity of 100,000 metric tons might be opened by the year 2026. Based upon the Vermont Yankee study, removal of spent fuel would take 38 years to complete after plant closure. If the reactor is closed in 2019, $182.7 million in 2017 dollars for spent nuclear fuel management would be saved (See Table 3).

The Energy Department indicates that the cost for a centralized interim storage facility capable of holding 100,000 Mt of spent fuel for 40 years would range from $7.2 to $21.7 billion, with a schedule of about 15 years for design, licensing and construction. When these estimates are applied to an estimated 1,538.4 MT (8,316 assemblies) of spent nuclear fuel generated at CGS until its license expires in 2043, the costs range from $110.8 million to $333.8 million. If the reactor is closed in 2019, there would be a cost saving that range from $46.6 million to $140.5 million. Under current law these additional costs are not covered under the Nuclear Waste Policy Act Fund and are to be borne by the utility and its ratepayers.

Table 3
Consolidated Storage Costs at another Location
(including transportation)

REACTOR OPERATES UNTIL 2043	$110,764,800-$333,832,800
REACTOR OPERATES UNTL 2019	$ 64,152,000-$193,347,000

Repackaging for Disposal

Dry cask storage systems are either single purpose (storage only) or dual purpose (storage and transportation). None are currently licensed for disposal. "Direct disposal of the large canisters currently used by the commercial nuclear power industry is beyond the current experience base globally," a 2013 DOE study observes, "and represents significant engineering and scientific challenges."[12] A 2013 report by the staff of the Nuclear Waste Technical Review Board concludes, "repackaging the SNF may be a lengthy process and could impact operational schedules at the utility sites, at a consolidated storage facility, or at the repository, depending on where repackaging is performed."[13]

Under the Nuclear Waste Policy Act (42 USC 10101), which sets forth the process for disposal of high-level radioactive wastes, the U.S. Government cannot accept title to spent nuclear fuel until it is received at an open permanent repository site. According to the law, "the persons owning and operating civilian nuclear power reactors have the primary responsibility for providing interim storage of spent nuclear fuel from such reactors." [14]The U.S. Government Accountability Office reported in 2014: "per DOE, under provisions of the standard contract, the agency does not consider spent nuclear fuel in canisters to be an acceptable form for waste it will receive. This may require utilities to remove the spent nuclear fuel already packaged in dry storage canisters".[15]

In 2012, Energy Department researchers concluded that "waste package sizes for the geologic media under consideration …are significantly smaller than the canisters being used for on-site dry storage by the nuclear utilities."[16] A nuclear industry study concluded in 2014 that " casks and canisters being used by the power utilities will be at least partially, and maybe largely, incompatible with future transport and repository requirements, meaning that some if not all, of the [used nuclear fuel] that is moved to dry storage by the utilities will ultimately need to be repackaged."[17]Existing large canisters can place a major burden on a geological repository, such as: handling, emplacement and post closure of cumbersome packages with higher heat loads, radioactivity and fissile materials. Repackaging expenses rely of the transportability of the canisters, but more importantly on the compatibility of the canister with heat loading requirement for disposal. In terms of geologic disposal, decay heat over thousands of years can cause waste containers to corrode, negatively impacting the geological stability of the disposal site and enhancing the migration of the wastes.[18]

According to DOE research the costs of repackaging at a centralized storage site are large.[19] The estimates in this study are based on a small (9 assemblies), medium (32 assemblies) and large (44 assemblies) standardized transportation and disposal canister (STAD) for a boiling water reactor. When applied to the Columbia Generating Station, assuming it will operate until 2043, this could involve cutting open 120 dry casks and repacking approximately 8,160 spent fuel assemblies into casks suitable for disposal. Due to this difficult and expensive possibility, the additional costs range from $272 million to $915 million. (Table 4). A decision on the type of geologic repository will help determine the size of the repackaged canisters. Based on the Energy Department's strategic plan to open a repository by the year 2048, the per assembly cost would be approximately $33,400 (large STAD) to $112,000 (small STAD) in 2015 dollars. The estimated cost of managing low-level radioactive waste from removing spent fuel to new canisters is estimated by the DOE at $9,500 per assembly and could be more than the cost to load the assembly in any canister.[20]

For purposes of this study, it is assumed that the reactor will maintain its spent fuel pool for reloading dry casks after its operating license expires in 2043. Otherwise, a hot cell or a new transfer pool would have to be built to safely repackage the high-level radioactive waste. The DOE has not yet decided to proceed with a decision on repackaging largely because of the lack of a technical basis that will be heavily influenced by a decision over a repository siting.

Table 4 Estimated costs for repackaging spent nuclear fuel generated by the Columbia Generating Station for disposal *

16 large STADS (44 assemblies)	Canister	$127,361,640.00
	Overpack	$64,618,818.00
	transfer cask	$726,560.00
	Subtotal -Cask system	$192,776,215.00
	total -loading cost	$2,295,470
	Low-level waste	$77,520,000.00
	Grand Total	**$272,591,685.00**
255 Medium STADS (32 assemblies)	Canister	$126,988,215.00
	Overpack	$80,886,765.000
	transfer cask	$725,560.00
	Subtotal Cask System	$208,601,540.00
	Loading Cost	$2,765,272
	Low-level waste	$77,520,000.00
	Grand Total	**$288, 886,812.00**
907 small STADS 9 assemblies	Canister	$508,139,494.00
	Overpack	$326,520,000.00
	Subtotal - cask system Loading Cost	$834,659,494.00 $3,083,969.00
	Low-level waste	$ 77,520,000.00
	Grand Total	**$915,263,918.00**

*Sources: DOE: Task Order 21: Operational Requirements for Standardized Dry Fuel Canister Systems, (2015) Tables 7-5 and 7-6., & DOE-NWTRB, June 2015.

Costs for repackaging of spent nuclear fuel for disposal have been developed by the U.S. Department of Energy. [21] Based on DOE's cost estimates, if the Columbia Generating Station of closed in 2019, cost savings may range from $114.7 million to $440.2 million (Table 5)

Table 5

SPENT NUCLEAR FUEL REPACKAGING COSTS FOR DISPOSAL

TRANSPORTATION AGING AND DISPOSAL CANISTERS (STAD) (e)	REACTOR OPERATES UNTIL 2043	REACTOR OPERATES UNTIL 2019
Large STAD (44 Assemblies)	$272,591,685	$157,864,545
Medium STAD (32 assemblies)	$288,886,812	$167,301,453
Small STAD (9 assemblies)	$915,263,918	$ 475,021,533

Disposal Costs

DOE assumes that a projected amount of 140,000 MT of spent nuclear fuel would require 16 years to transport and 50 years for total emplacement in the repository. The repository would be permanently closed after 150 years. By 2043, when the license for the CGS expires, a total of approximately $492 million is projected to be collected from ratepayers to cover permanent disposal costs of CGS' spent nuclear fuel. These costs assume that the repositories do not have a significant interim storage and repackaging infrastructures, and that the packages arriving are ready for disposal.

Energy Northwest still anticipates potentially reprocessing and recycling spent nuclear fuel prior to disposal,[22] but the Electric Power Research Institute cautions: "Near-term US adoption of spent fuel processing would incur a substantial cost penalty...processing would have to be accompanied by deployment of fast reactor plants. But demonstration fast reactor plants to-date has mostly proved expensive and unreliable, which aggravates processing's economic handicap."[23] Cost estimates developed by EPRI suggest that reprocessing spent fuel estimated to be generated at CGS would cost approximately $7.8 billion - more than three times the projected cost for direct disposal.[24]

In 2013, after the Yucca Mountain site was cancelled, the DOE estimated that the range of cost for the disposal of 140,000 Metric Tons (MT) of commercial power reactor spent fuel is between $25 billion to $85 billion (2016 dollars).

Under the Nuclear Waste Policy Act, the cost for disposal is to pay by a fee levied on consumer of nuclear powered electricity of one mill ($0.001) per kilowatt-hour. Based on recent data, Energy Northwest collects an average of $8.1 million per year. As of 2014, Energy Northwest had collected approximately $200 million in fees for disposal of its spent nuclear fuel inventory (2017 dollars). [25] [26]

In addition to savings of $8.1 million per year in disposal fees, and based on DOE's most recent estimate of total cost to construct, operate and close a geological repository, were Energy Northwest to close the Columbia Generating Station in 2019 instead of waiting until 2043, between $121 million and $421 million would be saved (see Table 6).

The revival of the Yucca Mountain site is being promoted by the Trump Administration and some members of the U.S. Congress, with proponents seeking to reactivate its licensing process to approve construction in the next several years. Given DOE's previous estimates of costs at the problematic Yucca Mountain site, going with that site would greatly increase the cost of disposal.

Based on DOE's previous assumed time-frames, if the Yucca Mountain proposal overcomes its obstacles, the timing for opening would roughly match the DOE's 2013's plan to open a repository by 2048. In 2007, the DOE issued a revised life-cycle cost estimate totalling $113 billion (2016 dollars) for the disposal of 70,000 metric tons of commercial power reactor spent fuel at the Yucca Mountain site. Under the Nuclear Waste Policy Act, the Yucca Mountain site was designed to hold no more than 70,000 MT of high-level radioactive wastes. Because this is only half of the 140,000 MT that DOE claims will be disposed of in a national repository by 2048, more spent nuclear fuel than that 70,000 MT amount would have to be disposed in an as-yet-undetermined second disposal site. For purposes of this study, we have assumed the less costly option range for disposal is correct, rather than use the more expensive Yucca Mountain figures.

Table 6
DISPOSAL COSTS
(including transportation)

U.S. ENERGY DEPARTMENT DISPOSAL ESTIMATES	REACTOR OPERATES UNTIL 2043	REACTOR OPERATES UNTIL 2019
Repository Cost= $89B (140,000 MT)	$978,363,846	$566,421,174
Repository Cost=$26B (140,000MT)	$285,814,285	$165,471,428

CHALLENGES AND UNCERTAINTIES

Spent Fuel Pool Storage Concerns

In its most recent analysis in 2014, the NRC estimates that a spent fuel pool fire in the United States could release 100 times more Cesium-137 than from the Fukushima accident, but asserts that the probability of such a fire is very low. Such a fire, depending upon the location of the reactor and its spent fuel pool, and the direction of fallout from it, could displace millions of people and render an area uninhabitable that more than 20 times larger than that the exclusionary zone created by the 1986 Chernobyl nuclear reactor meltdown in Ukraine.

The CGS spent fuel pool is located about 5 stories above ground. The CGS pool was originally designed to hold about three times less than its current capacity and was intended for a 5-year storage period. Although about half of the total number of spent fuel assemblies in the GCS storage pool are high burnup, they make up about 80 percent of the total amount of long-lived radioactivity.

Because it was originally designed for relatively short-term storage, the CGS pool lacks the same "defense in depth" protection as the reactor core. For instance, the CGS spent fuel pool is not under thick and heavy secondary containment that covers the reactor vessel, and does not have its own independent backup power or water supply. According to the Nuclear Regulatory Commission, the Columbia Generating Station is one of ten BWRs in the U.S. which, "are more reliant on infrequently operated backup cooling systems than other similar plants because of the absence of an onsite power supply for the primary SFP [spent fuel pool] cooling system or low relative capacity of the primary cooling system."

After the Fukushima nuclear disaster, the NRC required Energy Northwest to provide a strategy to address the loss of water to the GCS spent fuel pool in case of a beyond design basis accident, such as a highly destructive earthquake. Energy Northwest's strategy to replace spent fuel pool water involves a pumper truck connected to the reactor's two spray ponds. Over 600 feet of hosing carrying 300 to 600 gallons per minute is required to reach the spent fuel pool located 195 feet above the ground.

The stress on storage pools never originally designed to hold significant larger, more radioactive and thermally hotter spent fuel is of special concern due to problems associated with aging and deterioration. A study done for the U.S. Nuclear Regulatory Commission by the Oak Ridge National Laboratory concluded that age-related deterioration and leaks at reactor spent nuclear fuel handling and storage areas "are occurring at an increasing rate" The study finds it "is often hard to assess their in-situ condition because of accessibility problems."

These concerns were given greater prominence in May 2016 by a National Academy of Sciences panel established by Congress to review the response of the NRC to the Fukushima nuclear accident. In its report, the panel stated that the near miss of the loss of spent fuel pool cooling at the Fukushima site, "should serve as a wake-up call to nuclear plant operators and regulators about the critical importance of having robust and redundant means to measure, maintain, and, when necessary, restore pool cooling." The panel also urged the NRC to "ensure that power plant operators take prompt and effective measures to reduce the consequences of loss-of-pool-coolant events in spent fuel pools that could result in propagating zirconium cladding fires."

Long-Term Storage Issues

Because the proposed Yucca Mountain nuclear waste repository was cancelled by the Obama administration and is by no means assured of revival in the coming years, and all other storage plans remain speculative, these wastes may remain in interim storage at the reactor sites for the indefinite future. There is no definitive answer as to how long spent nuclear fuel generated at the

CGS will remain in storage before either centralized interim storage or geological disposal are available. "At present, the United States does not have a designated disposal site for used nuclear fuel," states a 2014 U.S. Department of Energy (DOE) study," the nation therefore faces the prospect of extended long-term storage (i.e., >60 years) and deferred transportation of used fuel at operating and decommissioned nuclear power plant sites."[27]

The U.S. Department of Energy (DOE) has produced a plan to open a spent nuclear fuel geological repository in 2048,[28] fifty years after the original opening date. In recognition of major uncertainties, the agency also states that "extended storage, for periods of up to 300 years, is being considered within the U.S." [29]

The U.S. Nuclear Regulatory Commission's (2014) "Waste Confidence" rule establishes that, in the short term, the spent nuclear fuel "can be stored safely [at reactor sites] for at least 60 years beyond the licensed life for operation." [30] In the long-term, the NRC ruled that spent nuclear storage at reactor sites can extend for an additional 100 years to the indefinite future. For the Columbia Generating Station, this suggests that the time a repository to dispose of spent nuclear fuel might be available ranges from the year 2048 to the 24th century and beyond.

A nuclear industry expert suggests that unless the federal government finds a way to restart efforts to site a repository quickly, the DOE program may never have to take spent fuel from an operating site."[31]

Assuming the Energy Department opens a geologic repository by the year 2048, the costs for onsite storage for the U.S. reactor fleet are estimated to be quite large. According to researchers at DOE's Sandia National Laboratory and the University of Oklahoma:

> "In 2048, the cumulative storage costs at reactors are projected to be $26 billion. The costs continue to grow even after 2048 because it takes time to unload the sites. The analysis used an unloading rate of 3000 MTHM (Metric Ton Heavy Metal)/yr. The final cost is $60 billion in 2095, more than 100 years after storage began at most reactors."[32]

The Quest for Centralized Interim Storage

After more than four decades of failure in establishing a centralized storage facility, there are major uncertainties about the actual location, timing and perhaps, most important, political acceptance.

In 2013, the U.S. Department of Energy DOE planned for an interim pilot storage facility with a capacity of 500 dry casks for spent fuel at closed nuclear sites, also known as "stranded wastes." Once the pilot facility is operational, DOE plans for a large interim storage facility that could accept spent nuclear fuel by 2026. Much of what must be accomplished to establish an interim storage site, is outside of the authority of the DOE.

With the continued operation of several more reactors in doubt, the backlog of stranded wastes could double over the next decade – comprising more than a third of the current nuclear power generated spent nuclear fuel. The DOE' s proposed schedule for establishing a pilot interim storage site has slipped. By the time a centralized interim storage site may be available, DOE is expecting a "wave" with as many as 60 reactor shutdowns that could clog transport and impact the schedule for a centralized storage operation.[33] Among the uncertainties identified by DOE include:

- Transportation infrastructures at or near reactor sites are variable and changing;
- Each spent nuclear fuel canister system has unique challenges. For instance, the CGS has some dry casks that are licensed for at-site storage only and not for transport.[34]
- There are at least 10 different alternatives for a future storage facility that has yet to be selected.[35]
- The requirements for a geological repository are unknown. Site-based constraints on decay heat from spent nuclear fuel can impact the timing of shipping.
- The pickup and transportation order of spent fuel has yet to be determined. It has been assumed that the oldest would have priority, leaving sites with fresher and thermally hotter fuel that may be "trapped" at sites to cool down further.
- Packaging of transport containers could have a major impact. As many as 11,800 storage canisters may have to be reopened. [36]

High-burnup spent nuclear fuel

This reality of indefinite onsite storage raises an important concern regarding the storage of high-burnup nuclear fuel (HBU). Burnup is the amount of energy extracted per unit mass of the fuel. Typical units for burnup of commercial SNF are gigawatt-days per ton of uranium originally contained in the fuel (GWd/t). The NRC considers high burnup to be at or greater than 45GWd/t.

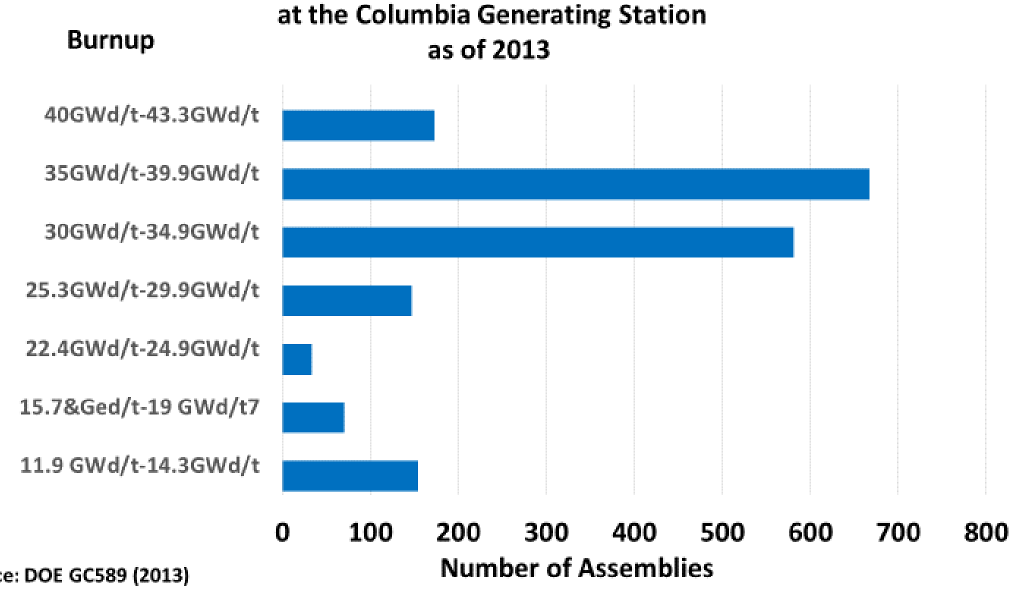
US commercial nuclear power plants use uranium fuel that has had the percentage of its key fissionable isotope—uranium 235—increased, or enriched, from what is found in most natural uranium ore deposits. In the early decades of commercial operation, the level of enrichment allowed US nuclear power plants to operate for approximately 12 months between refueling. In recent years, however, US utilities have begun using what is called high-burnup fuel. This fuel generally contains a higher percentage of uranium 235, allowing reactor operators to effectively double the amount of time the fuel can be used, reducing the frequency of costly refueling outages. The switch to high-burnup fuel has been a major contributor to higher capacity factors and lower operating costs in the United States over the past couple of decades.

Research shows that under high-burnup conditions, the zirconium cladding of the fuel rods may not be relied upon as a key barrier to prevent the escape of radioactivity, especially during prolonged storage in the "dry casks" that are the preferred method of temporary storage for spent fuel. High-burnup waste reduces the fuel cladding thickness and a hydrogen-based rust forms on the zirconium metal used for the cladding, which can cause the cladding to become brittle and fail. In addition, under high-burnup conditions, increased pressure between the uranium fuel pellets in a fuel assembly and the inner wall of the cladding that encloses them causes the cladding to thin and elongate. In addition, the same research has shown that high burnup fuel temperatures make the used fuel more vulnerable to damage from handling and transport; cladding can fail when used fuel assemblies are removed from cooling pools, when they are vacuum dried, and when they are placed in storage canisters.

High-burnup spent nuclear fuel is proving to be an impediment to the safe storage and disposal of spent nuclear fuel. For more than a decade, evidence of the negative impacts on fuel cladding and pellets from high burnup has increased, while resolution of these problems remains elusive. High-burnup significantly boosts the radioactivity in spent fuel and its commensurate decay heat. Data provided to the US. Department of Energy, indicates that since 2009, the CGS has been generating high burnup spent nuclear fuel as defined by the NRC. About 23.5 percent of the total amount of spent nuclear fuel at CGS is high burnup (1017 out of a total of 4321 spent nuclear fuel assemblies).

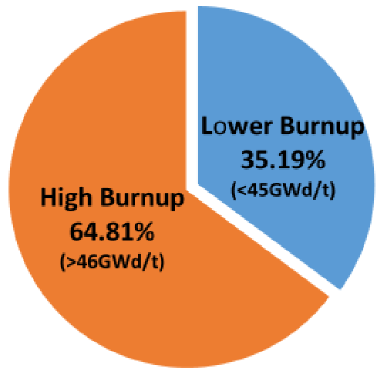
Since 2009, nearly all spent nuclear fuel discharges at the CGS are high-burnup. (See Figure 1) Currently, the General License issued by the NRC for the CGS' Independent Sent Fuel Storage Installation (ISFI) is among 37 reactor sites that lack approval for storage of high-burnup SNF in dry casks.[37] None of the spent nuclear fuel stored in dry casks at CGS is high-burnup (see Figure 4). The NRC has not approved the storage of high-burnup SNF generating at CGS in dry storage canisters, [38] and so all high-burnup SNF is stored in the reactor pool, which will continue to increase in volume as additional high-burnup SNF is placed there during every two-year refueling cycle. [39] Currently, 23.5 percent of the spent fuel at CGS falls under NRC's definition of high burnup. All high burnup SNF is stored in the CGS storage pool and makes up 64.81 percent of the pool's inventory. (See figure 5)

Figure 4 Spent Nuclear in Dry Casks at the Columbia Generating Station as of 2013



Source: DOE GC589 (2013)

Figure 5 Spent Nuclear Fuel in the CGS pool (2017)



Based on the last seven years of reactor discharges, by the year 2043, when the CGS license expires, about 60 percent of total amount of spent fuel generated by CGS is expected to be high burnup. The amounts of long-lived radioactive fission products in spent nuclear fuel increase significantly with high burnups. Given this trend, we can expect this will significantly increase the concentration of radioactivity in the CGS' spent fuel pool over time, particularly cesium-137, and decay heat. (see Table 1)

Heat from the radioactive decay in spent nuclear fuel is also a principal safety concern. Several hours after a full reactor core is offloaded, it can initially give off enough heat from radioactive decay to match the energy capacity of a steel mill furnace. This is hot enough to melt and ignite the fuel's reactive zirconium cladding unless cooled by water. Over time, even after decades of cooling, the excess heat remains a danger to destabilize a geological disposal site it is placed in. By 100 years, decay heat and radioactivity drop substantially but remain dangerous. For these reasons, the US Government Accountability Office (GAO) informed the Congress in 2013 that spent nuclear fuel is "considered one of the most hazardous substances on Earth."[40]

It will take the Energy Department at least a decade to complete a study involving temperature monitoring in a specially designed dry cask containing high-burnup fuel.

DOE research also indicate that smaller casks could hold significantly fewer high burnup assemblies which could allow for transport after five years following discharge from the reactor. This would require newer designs than those currently deployed at CGS, involving possibly dozens to hundreds of additional casks, to accommodate spent nuclear fuel generated during the licensing period.[41]

Appendix A

Cost Assumptions
(2017 dollars)

Dry Cask Procurement (a)	$960,521 per cask
Dry Cask Loading (a)	$277,000 per cask
Storage Pads (b)	$5,660,000 each
Planning and Preparations (c)	$23,727,000
Dormancy w/Wet Fuel Storage (c)	$149,000,000
Annual ISFSI M&O (d)	$1,850,000
Consolidated SNF Storage Opens in 2026 (100,000 Mt) (e)	$74,000 -$223,000 per metric ton
Large Standardized Aging and Disposal(STAD) Canister (44 assemblies) (f) (g)	$33,690 per assembly
Medium Standardized Aging and Disposal (STAD) Canister (32 assemblies) (f) (g)	$30,737 per assembly
Small Standardized Aging and Disposal (STAD) Canister (9 assemblies) (f) (g)	$51,994 per assembly
DOE Opens Repository in 2048 (140,000 Mt) (h)	$185,714 - $635,714 per metric ton

(a) The United States Court of Federal Claims, No 0410C, Energy Northwest v the United States, February 26, 2010. http://www.uscfc.uscourts.gov/sites/default/files/opinions/DAMICH.ENERGY022610.pdf

(b) United States Government Accountability Office, Outreach Needed to Help Gain Public Acceptance for Federal Activities That Address Liability, GAO-15-141, October 2014. http://www.gao.gov/assets/670/666454.pdf

(c) Entergy Corporation, Post Shutdown Decommissioning Activities Report, Vermont Yankee Nuclear Power Station, December 19, 2014. https://www.nrc.gov/docs/ML1435/ML14357A110.pdf

(d) Energy Northwest, 2015 Annual Report. https://www.energy-northwest.com/whoweare/finance/Documents/2015%20Energy%20Northwest%20Annual%20Report.pdf

(e) U.S. Department of Energy, Office of Nuclear Energy, Task Order 11: Development of Consolidated Fuel Storage Facility Concepts Report, February 12, 2013. https://curie.ornl.gov/system/files/documents/not%20yet%20assigned/AREVA%20-%20TO11%20-%20FINAL%20REPORT_0.pdf

(f) DOE: Task Order 21: Operational Requirements for Standardized Dry Fuel Canister Systems, (2015) Tables 7-5 and 7-6.

(g) DOE: J. Jarrell, Standardized Transportation, Aging, and Disposal (STAD) Canister Design, presentation to the Nuclear Waste Technical Review Board June 24, 2015. http://www.nwtrb.gov/meetings/2015/june/jarrell.pdf

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