The Hazards of High-Level Radioactive Waste in the Pacific Northwest:

A Review of Spent Nuclear Fuel Management At the Columbia Generating Station

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Glossary of Acronyms

ACRS –Advisory Committee on Reactor Safeguards
ALARA – As low as reasonably achievable
Bq – becquerel
BRC – Blue Ribbon Commission on America's Nuclear Future
BWR – boiling water reactor
CGS – Columbia Generating Station
Ci – curie
CLIC – crud-induced-localized corrosion
Co-60 – cobalt 60
Cs-137 – cesium 137
CRUD – Chalk River unidentified debris –radioactive corrosion products
DOE – Department of Energy
EPRI – Electric Power Research Institute
EPZ – emergency planning zone
Fe-55 – iron 55
Fe-59 – Iron 59
FP – fission product
FSAR – Final Safety Analysis Report
Cr-51- chromium 51
GE – General Electric
GW - gigawatt
H-3- tritium
HLW – high-level waste
IAEA – International Atomic Energy Agency
ISFSI – Independent Spent Fuel Storage Installation
MCi – million curies
MW – megawatts
MTU – metric ton of uranium
NCRP – National Council on Radiation Protection and Measurements
NEA – Nuclear Energy Agency
NEI – Nuclear Energy Institute
Ni-16- nitrogen 16
NPP –nuclear power plant
NRC- Nuclear Regulatory Commission
PWR – pressurized water reactor
RCC – reactor cooling water
rem – radiation equivalent man
SCRAM – forced reactor shutdown
SFP –spent fuel pool
TRU - transuranic

Summary and Recommendations

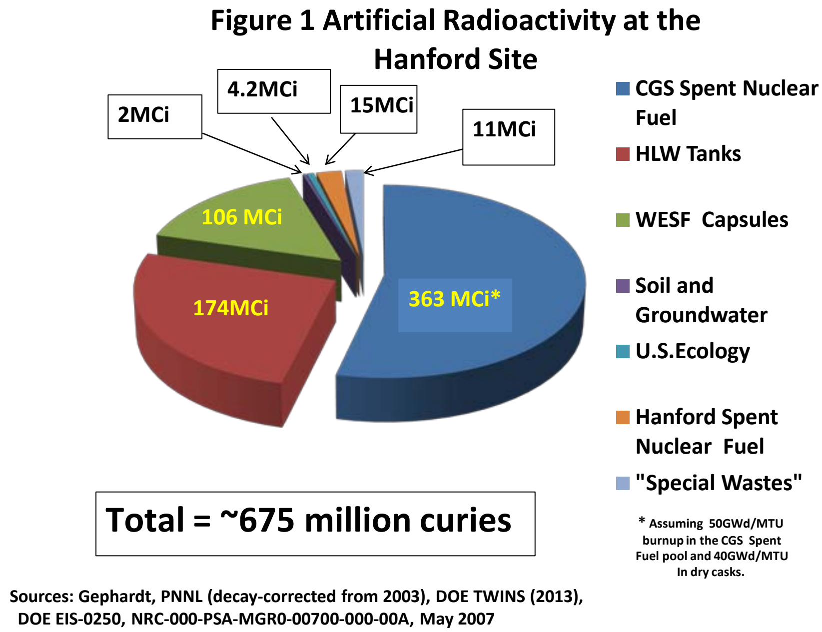
The Columbia Generating Station (CGS) is a 1,170 Megawatt boiling water power reactor (BWR) located on the U.S. Department of Energy's Hanford Site in Washington State. Beginning operation in 1984, in addition to generating electricity, CGS has become a major radioactive waste production and storage facility.

It will take several decades, at the minimum, before a permanent disposal site for high level radioactive waste will be available, says the Energy Department, which estimates a permanent repository might open by the middle of this century. Given that more than 50 years have already passed in the quest for a permanent geological disposal site in the U.S., citizens of the Pacific Northwest should be prepared for the growing possibility that spent nuclear fuel generated by the Columbia Generating Station, and the Energy Department's large amount of high-level radioactive defense wastes will remain on the Hanford site for an indefinite period.

Safely securing spent nuclear fuel that is currently being held in a vulnerable, high density pool, storage at CGS is a major public safety priority. Energy Northwest has made some progress in addressing this concern by placing approximately 60 percent of its spent fuel in durable, dry casks.

However, because of allowable increases in irradiation times for reactor fuel (high burnup), current and future spent fuel inventories in the storage pool are likely to contain larger concentrations of fission products than in dry casks and pose a significant additional hazard.

Over the past 30 years, CGS has generated approximately 320,000 spent fuel rods (3,992 assemblies) containing roughly 273 to 363 million curies of long-lived radioactivity (See table 1). About 40 to 54 percent is stored in the reactor spent fuel pool. CGS has generated about 150 to 200 percent more radioactivity than contained nearby in Hanford's 177 defence high-level radioactive tanks from 40 years of plutonium production for nuclear weapons. Currently CGS has generated approximately half of the total concentration of radioactive wastes on the Hanford site (See Figure 1).

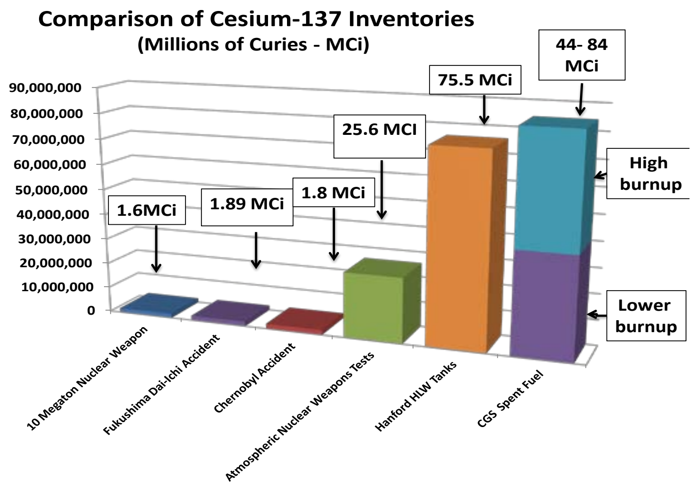


As the last remaining operating reactor at the site, over the next 30 years, the CGS is projected to generate 300 to 400 percent more long-lived radioactivity than currently in Hanford's HLW tanks.

Transferring spent nuclear fuel to dry casks reduces some of the risks and consequences of storage. In 2004, a panel of the National Academy of Science informed the U.S. Nuclear Regulatory Commission (NRC), that a "partially or completely drained spent fuel pool could lead to a propagating zirconium cladding fire and release large quantities of radioactive materials to the environment…Such fires would create thermal plumes that could potentially transport radioactive aerosols hundreds of miles downwind under appropriate atmospheric conditions."

Fallout from a spent fuel pond fire containing cesium-137 is of key concern because of its large quantity and toxicity when released into the environment. With a half-life of 30 years, Cs-137 gives off external penetrating radiation and accumulates in the environment as if it were potassium. The National Council on Radiation Protection and Measurements (NCRP) concludes that, "Cs -137 has often proven to be the most important long-term contributor to the environmental radiation dose received by humans as a result of certain human activities." The amount of Cs-137 in the CGS pool is about 2 to 3 times more than released by all atmospheric nuclear weapons tests (See Figure 2) and about 24 to 45 times more than released by the Chernobyl accident.

Figure 2



Dr. Allison Macfarlane, Chairman of the U.S. Nuclear Regulatory Commission (NRC) noted in April, 2014 that “land interdiction [from a spent nuclear fuel pool fire at the Peach Bottom Reactor in Pennsylvania] is estimated to be 9,400 square miles with a long term displacement of 4,000,000 persons [See Attachment 1].” By comparison, the Fukushima nuclear disaster resulted in eviction of approximately 160,000 people from their homes, food restrictions, and the costly and uncertain remediation of large areas.

Like the reactors at the Fukushima accident site, the CGS pool is elevated several stories above ground and currently holds the equivalent of roughly two spent reactor cores – more than the Fukushima Unit No. 4, which held the largest inventory among the damaged reactors and still poses an accident risk. 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. As a result, the 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 BWR,’s 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.”

Overheating of the spent fuel pool could generate radioactive vapors that threaten the habitability of working areas. As of February 2014, Energy Northwest had not performed the necessary calculations of the time when boiling in the pool would occur from emergency emplacement of a full irradiated core in the pool – three times the amount normally discharged every two years. According to Energy Northwest, this would add roughly three times more decay heat than a normal refuelling. Despite this, the NRC exempts Energy Northwest from having back-up for a single failure of one of its two spent fuel pool heat exchangers, “based on the expected infrequent performance of a full core offload." Full core offloads are not rare at U.S. nuclear reactors and the NRC has yet to establish a requirement for operating reactors to safely reserve pool space for full irradiated cores.

Instead of formal requirements for emergency response for accidents involving spent fuel pools, the NRC relies on voluntary guidelines suggested by the Nuclear Energy Institute (NEI), an organization run by the commercial nuclear industry. The NEI guides are very general and do not address the site-specific designs, seismic circumstances, and other potential vulnerabilities, especially a major accident involving the reactor itself. In terms of water makeup capabilities to mitigate leaks and drainage from the CGS pool, Energy Northwest's plan consists of using water from a fire hydrant, a fire "pumper" truck, or hoses from the reactor's spray water ponds.

Dry Storage at CGS

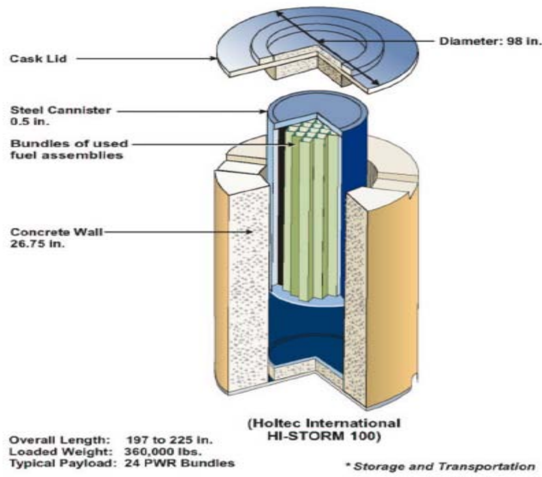
As of May 15, 2014, Energy Northwest has placed 36 dry casks on two concrete pads in its Independent Spent Fuel Storage Installation (ISFSI) under license with the NRC. The total casks contain an estimated 168 million curies of long-lived radioisotopes. Each canister is encased in thick concrete and holds 68 spent fuel assemblies- approximately 9 percent a full reactor core. Dry storage is estimated by Energy Northwest to be able to expand to a total of 90 casks.

Dry-cask storage offers several advantages over high density pool storage but lacks the long term safety that is provided by underground repositories. Dry casks rely on passive, natural air circulation for cooling, rather than requiring large amounts of water to be continually pumped into cooling pools to replace water lost to evaporation. Also, the inventory of spent fuel is divided among a number of discrete, robust containers, rather than being concentrated in a single pool.

The Holtec Hi-Storm 100 model dry cask system is used at CGS, in which casks are vertically placed on concrete pads and are designed to be "dual purpose," for storage and transportation (See Figure 3.) The high-storm casks can withstand a horizontal ground motion from an earthquake without tipping over (0.397g) - 158 percent more than from the design basis earthquake (0.25g) for the CGS spent fuel pool. However it must be noted that new seismic information uncovered by the US Department of Energy and the US Geological Survey for this area has required buildings to withstand the forces of 0.6 g, [1] a standard which neither the reactor building, the spent fuel pool, nor the Holtec dry casks are designed to meet. To further mitigate seismic impact, additional steps were taken to attenuate the rocking motion beneath the casks during an earthquake.

The radiological consequences of a dry cask rupture are estimated by the NRC to be orders of magnitude smaller than a spent fuel pool fire. Often overlooked is the fact that despite the significant destruction of the Fukushima nuclear site caused by a major earthquake and tsunami, all 9 dry spent fuel storage casks at the site were unscathed.

Figure 3 Holtec Hi-Storm 100 Dry Cask

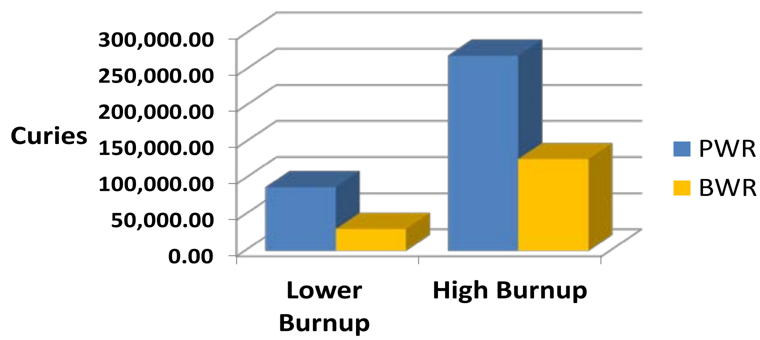


High Burnup Spent Power Reactor Fuel

Since the 1990's, U.S. reactor operators, were permitted by the U.S. Nuclear Regulatory Commission (NRC) to effectively double the amount of time nuclear fuel can be irradiated in a reactor, by approving an increase in the percentage of uranium-235, the key fissionable material that generates energy. Known as increased "burnup" this practice is described in terms of the amount of electricity in megawatts (MW) produced per day from a metric ton of uranium.
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. "The technical basis for the spent fuel currently being discharged (high utilization, burnup fuels) is not well established," notes an expert with the National Academy of Engineering in 2012. "The NRC has not yet granted a license for the transport of the higher burnup fuels that are now commonly discharged from reactors. In addition, [high burnup] spent fuel that may have degraded after extended storage may present new obstacles to safe transport." For instance the NRC's dry cask peak cladding temperature limit of 400 degrees C, was established nearly 15 years ago and is not based on high burnup data. High burnup fuel will likely require more restrictive limits on temperatures during dry storage.

The amounts of long-lived radioactive fission products in spent nuclear fuel increase significantly with high burnups (See Figure 4). If the current inventory in the spent fuel pool is high burnup, and subsequent discharges add more, this will significantly increase the concentration of radioactivity, particularly cesium-137, and decay heat.

Figure 4 Estimated radioactivity in a U.S. spent nuclear fuel assembly



Sources: DOE EIS-0250, Appendix A, http://energy.gov/sites/prod/files/EIS-0250-FEIS-01-2002_0.pdf
NRC http://pbadupws.nrc.gov/docs/ML0907/ML090770390.pdf

Because Energy Northwest currently has not revealed the burnup history and radiological contents of spent fuel currently in the CGS pool, this report provides a range of estimated radioactivity based on generic calculations developed by the U.S. Department of Energy and the Nuclear Regulatory Commission and U.S. industry wide burnup trends published by the Electric Power Research Institute and the International Atomic Energy Agency. Burnup data for spent fuel in dry casks at CGS have been made public by the NRC – indicating that assemblies are below the high burnup threshold of 45,000 MWD/MTU.

Corrosion Problems

Increases in reactor fuel burnup also exacerbates corrosion problems that can affect reactor safety and pose worker radiation exposure risks. For decades, the Columbia Generating Station has experienced problems associated with the build-up of highly radioactive debris and rust particles on spent fuel cladding and reactor internals. The build-up and deposit of debris, known as "crud," on spent fuel also impacts the integrity of the zirconium alloy cladding – a primary barrier preventing the escape of radioactivity. The build-up of corrosion products has led to fuel failure at CGS, which resulted in the leakage of fission products in the reactor system.

CGS has altered the chemistry of the reactor coolant several times to mitigate corrosion, which has in some instances increased radiation exposure levels to workers. "Numerous attempts to prevent and control crud formation and circulation by changing the water chemistry have been made; none has been fully successful," concludes researchers at DOE's Idaho National laboratory. "There is little fundamental understanding of what crud is, how it forms, and how its characteristics might be modified to make crud less damaging to plant operation and worker health."

Radioactive crud deposits can dislodge due to mechanical disturbances, creating "crud burst events" spreading high doses-rates in an unexpected manner. The CGS has experienced numerous events which dislodged crud deposits. For instance, an NRC inspection report found that, "several crud burst causing evolutions occurred [at CGS] around the June to July 2007 time frame and there was no process in place for radiation protection to be informed so that they could adequately monitor for changing radiological conditions throughout the plant.”

In 2011, Energy Northwest replaced its steam condenser at CGS, considered to be a significant source of radioactive corrosion products because of years of operating while damaged. It remains to be seen if this will translate into a reduction in plant corrosion hazards, especially given the lapses in radiation protection of the reactor workers.

Occupational Radiation Protection

The NRC reports that radiation exposures to workers at BWR’s in the United States in 2011 was more than two and a half times higher than at pressurized water reactors (PWR). This is because of the single loop coolant design which allows BWR’s to contaminate larger amounts of plant equipment than Pressurized Water Reactors.

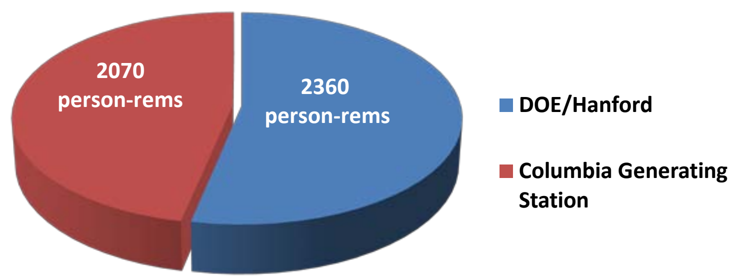
To keep individual exposures down, Energy Northwest employs a large number of transient workers in order to spread the dose over a larger number of people. The average annual number of workers with measurable exposures at CGS from 1985 to 2011 was nearly four times the number of full-time employees. The goal is to reduce both individual and collective dose with the implementation of the As Low As Reasonably Achievable (ALARA) principle.

NRC inspection reports between 2003 and 2014 reveal several lapses in which:

- Worker doses exceeded exposure limits ,
- Job planning, inadequate radiological surveys, and posting of radiation hazards were inadequate;
- Area radiation monitoring was non-functional ;
- Supervisors failed to inform workers about radiological hazards.

As a result, workers at the Columbia Generating Station had the third largest collective exposure among the 28 currently operating single unit reactors in the U.S. between 1997 and 2011 (See figure 15). Moreover, from 1999 to 2011, the Columbia Generating station was responsible for nearly half of the collective worker dose of all facilities located on the Hanford site, including Energy Department facilities (See figure 5). As noted in a December 2011 NRC inspection report, "the willingness to work around substandard procedures was a long-standing operator behavior."

Figure 5 Collective Occupational Radiation Doses for DOE/Hanford and the Columbia Generating Station Person-Rems (1999-2011)



Sources: NUREG-0713, DOE Occupational Radiation Exposure (1999-2011)

The 300-618-11 Burial Ground

The parking lot of the Columbia Generating Station adjoins the Energy Department's 300-618-11 Burial ground which received wastes from several facilities that handled millions of curies of high-level radioactive wastes from Hanford tanks, as well as transuranic wastes, and spent fuel from Hanford production and commercial nuclear power reactors (See figure 6). Intrusive characterization of the site began in 2011 and the start of remediation has not been announced.

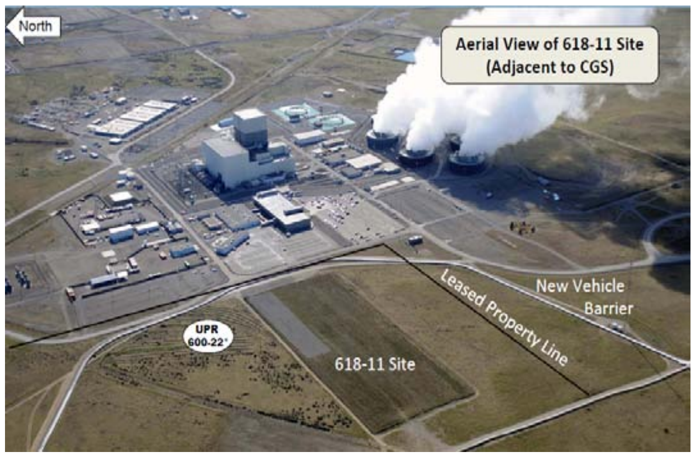
Described by the NRC as containing "high-level wastes," dozens of containers have potentially lethal radiological concentrations. Kilogram quantities of plutonium wastes along with thousands of curies of mixed fission products were disposed in trenches at the site including very high dose items. Recently, a DOE site contractor warned its employees that the burial ground "holds some of the highest-hazard materials we've encountered at Hanford."

Nearly all records documenting the shipment of wastes to the burial ground as well as some of the site's engineering drawings were destroyed. Roughly half of the waste containers are estimated to contain combustible materials including flammable gases. Several years after the disposal site was closed in 1967, there were several events involving exposure to workers and the spread of radioactivity.

In response, Energy Northwest installed a new vehicle barrier between the parking lot and the disposal site and received a belated license amendment in 2010 from the NRC to address its potential hazards. Apparently, close proximity to a high hazard radioactive disposal site was not considered in approving the construction and operation of CGS at this location.

DOE contractors estimate a high accident probability impacting CGS workers in the range of 1 in 100. Under the environmental compliance agreement with the State of Washington, the 300-618-11 Burial Ground is to be remediated by 2018. Energy Northwest has established an emergency response plan in coordination with the DOE. Given the risk uncertainties from remediation, potential disruption of operation at CGS from a mishap at the DOE's adjoining high-level radioactive waste disposal site should not be discounted.

Figure 6 Location of the Hanford 300-618-11 Burial Ground



Source: Energy Northwest (2012)

RECOMMENDATIONS

1. Energy Northwest has transferred a significant amount of spent nuclear fuel to safer dry storage casks – and should be encouraged to transfer more with the goal of eliminating high density storage and establishing an open rack configuration. This would increase air convection in the event of unplanned pool drainage and decrease zirconium cladding ignition risks in a loss-of-coolant accident.

2. As a precautionary measure, high burnup spent fuel greater than NRC Technical Specification limit of 45,000 MWd/MTU should be considered *a priori* damaged and placed in cans specifically designed for damaged fuel, prior to emplacement in a dry cask. According to the Energy Department, the shuttered Maine Yankee and Zion reactor sites are the only ones in the United States storing high burnup spent fuel in dry casks. In order to eliminate concern over safe transport, the spent fuel assemblies at these sites are packaged or will be packaged in cans designed to hold damaged fuel.

3. Energy Northwest should reveal the burnup history as well as an estimate of the radioactive inventory of its spent nuclear fuel current stored in the CGS pool. The NRC should require operators at all reactors storing spent fuel in pools to do the same.

4. Shifting the risk from individual full time employees to a much larger group of transient workers is not a responsible form of health protection and does not conform to the ALARA principal of radiation protection. Otherwise, the NRC would not place such emphasis on reducing collective doses. The Nuclear Regulatory Commission and Energy Northwest should make reduction in occupational radiation exposures a high priority. While the NRC has documented several lapses of worker radiation protection at CGS, it routinely assigns them a low safety priority, without regard for potential long-term health consequences. Although enhanced engineering and administrative controls are important, a reduction in the burnup of reactor fuel will reduce corrosion and more importantly radiation exposures to workers. Energy Northwest should establish a clearly measurable goal of significantly reducing collective radiation exposure to workers.

5. The characterization and remediation of the Energy Department's adjoining 300-618-11 Burial Ground, yards away from the CGS, officially considered to be among the most hazardous landfills on the Hanford site poses potential significant hazards to workers at the CGS and should require enhanced emergency preparedness and response activities. Furthermore, Energy Northwest and the DOE should take steps to determine if any of the contaminants from this waste site have migrated onto the CGS property and if it requires remediation or other protective measures.

COLUMBIA GENERATING STATION

HIGH-LEVEL RADIOACTIVE WASTE INDEX

Number of spent fuel rods generated by years of reactor operations: ~320,000

Amount of radioactivity in the spent fuel rods: 273 to 363 million curies

Amount of spent fuel to be stored in cooling pools: about 40 percent

The amount of radioactivity in
spent nuclear fuel at CGS exceeds that in 177 waste tanks at the Hanford site: by 150 to 200 %

Percentage of radioactivity in CGS waste that is Cs-137, the most risky form: 43

Number of times the radioactivity in Cs-137 at CGS
exceeds all that released in atmospheric nuclear weapons tests: 2-3

Number of times it exceeds that released at Chernobyl: 24-45

Table 1

Indicator	Columbia Generating Station
Rated power of reactor	1,170 MW/t (a)
Number of fuel rods per assembly	91 (b)
Number of assemblies in reactor core	764 (b)
Typical period of full-power exposure of a "lead" fuel assembly (assuming refueling outages of 2-month duration at 24-month intervals, discharging 72 assemblies, capacity factor of 0.9 between outages)	6 years (b)
Typical burn-up of fuel assembly at discharge	40,000 to 50,000 MWt/d (c) (d)
Enrichment (U-235 % by weight)	>5.0 %(e)
Maximum Burnup at Discharge	65,550 MWD/t (f)
Typical Cs-137 inventory in fuel assembly at discharge	0.0029 to 0.0054 MCi (d)
Cs-137 inventory in reactor core	18.2 MCi (g)
Capacity in spent fuel pool	2658 assemblies (h)
Fuel Core Reserve in pool	764 (h)
Number of assemblies in pool	1544 assemblies (f) (g)
Number of assemblies in dry casks	2448 assemblies (k)
Cs-137 inventory in spent fuel pool (assuming space for full core unloading.	44 to 84 MCi (c) (d)
Cs-137 Inventory in a dry storage cask	2.0 MCi (d)
Total Cs-137 inventory in dry casks	70.2 MCi (d)
Projected Cumulative Spent Fuel Discharge to 2043	7525 Assemblies (f)
Current Estimated Long-lived Radioactivity in Spent Fuel	273 to 363 MCi (c) (d)
Projected Total Estimated Long-lived Radioactivity in Spent Fuel 2043	585-684MCi (c) (d) (f)

(a)U.S. Nuclear Regulatory Commission, Safety Evaluation Report, Office of Nuclear Reactor Regulation, February 2012, http://pbadupws.nrc.gov/docs/ML1205/ML12059A357.pdf
(b) Energy Northwest, Final Safety Analysis Report.
(c) U.S. Department of Energy, Final Environmental Impact Statement, for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada, 2002, Appendix A, Tables A-10 and A-13
(d) U.S. Nuclear Regulatory Commission, Characteristics for the Representative Commercial Spent Fuel Assembly for Preclosure Normal Operations 000-PSA-MGR0-00700-000-00A, May 2007, Table 20. http://pbadupws.nrc.gov/docs/ML0907/ML090770390.pdf
(e) U.S. Nuclear Regulatory Commission, Amendment to Facility Operating License, Amendment No. 163, May 23, 2000. http://pbadupws.nrc.gov/docs/ML0037/ML003719838.pdf
(f) U.S. Department of Energy, Inventory and Description of Commercial Reactor Fuels within the United States, SRNL-STI-2011-00228, March 31, 2011, P. 27. http://sti.srs.gov/fulltext/SRNL-STI-2011-00228.pdf
(g) Nuclear Energy Institute, Spent Nuclear Fuel data as of December 31, 2011.
(g) Mark T. Leonard, Randall O. Gauntt and Dana A. Powers, Accident Source Terms for Boiling Water Reactors with High Burnup Cores Calculated Using MELCOR 1.8.5, Sandia Report, SAND2007-7697 November, 2007, Table 5. http://prod.sandia.gov/techlib/access-control.cgi/2007/077697.pdf
(h) .S. Nuclear Regulatory Commission, WNP2 –Issuance of Amendment Re: Technical Specification 4.3, "Fuel Storage" (TAC No. MA7228, May 23, 2000.
(j) Energy Northwest, Columbia Generating Station Begins Refueling and Maintenance Outage Saturday, News Release 13-11, May 9 ,2013.
(k) Energy Northwest, Columbia Generation Station, Docket No. 50-397 and 72-35, Registration of Spent Fuel Cask Use, May 15, 2014.

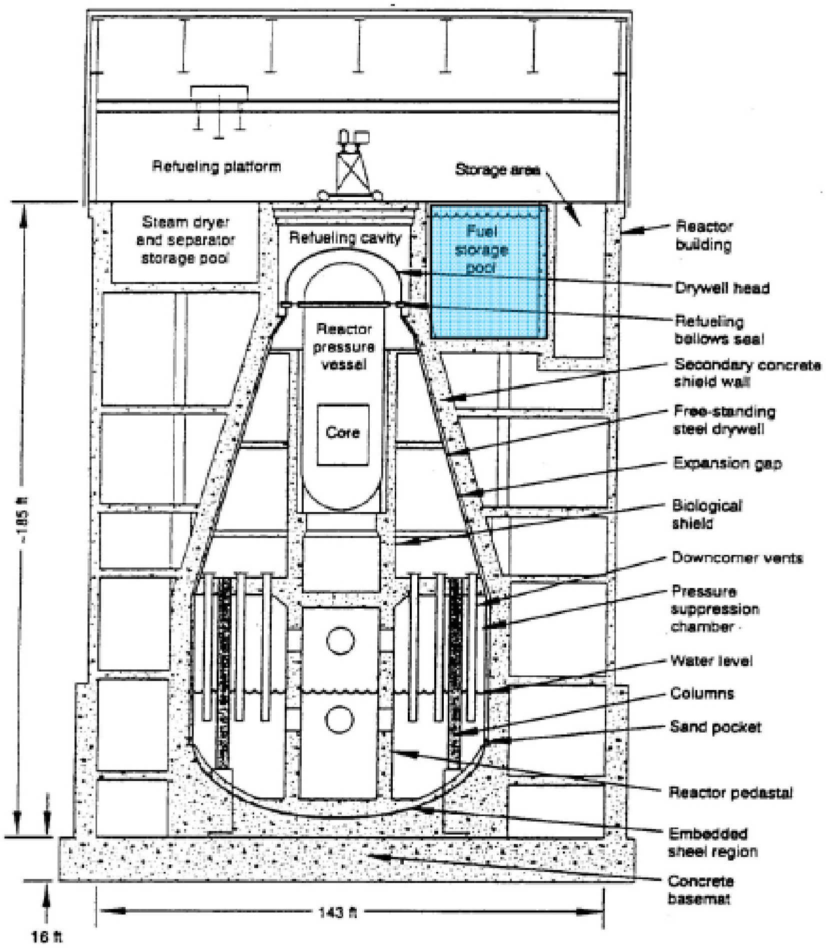
The CGS Spent Fuel Pool

The spent fuel storage pool is located at the top of the reactor building adjacent to the reactor vessel outside of the reactor containment. The pool is above grade with the bottom of the pool elevated at approximately 195 feet. It is a reinforced concrete structure with a stainless steel liner. The pool is approximately 40 feet long by 40 feet wide and 40 feet deep and contains 350,000 gallons of water. [2] Spent fuel racks are located near the bottom of the pool (See figures 7 and 8). A minimum of 22 feet of water is maintained above the tops of the spent fuel assemblies. The total amount of water required for removal of spent fuel, emplacement and pool storage is 853,600 gallons.[3]

The pool does not have its own back-up water or power supply. In case of a loss of water in the pool, the reactor relies on a diesel-powered Standby Service Water (SSW) system, which is also called upon to remove residual decay heat from the reactor during emergencies as well as to provide water for the reactor fire protection system. According to the Nuclear Regulatory Commission, CGS 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."[4]

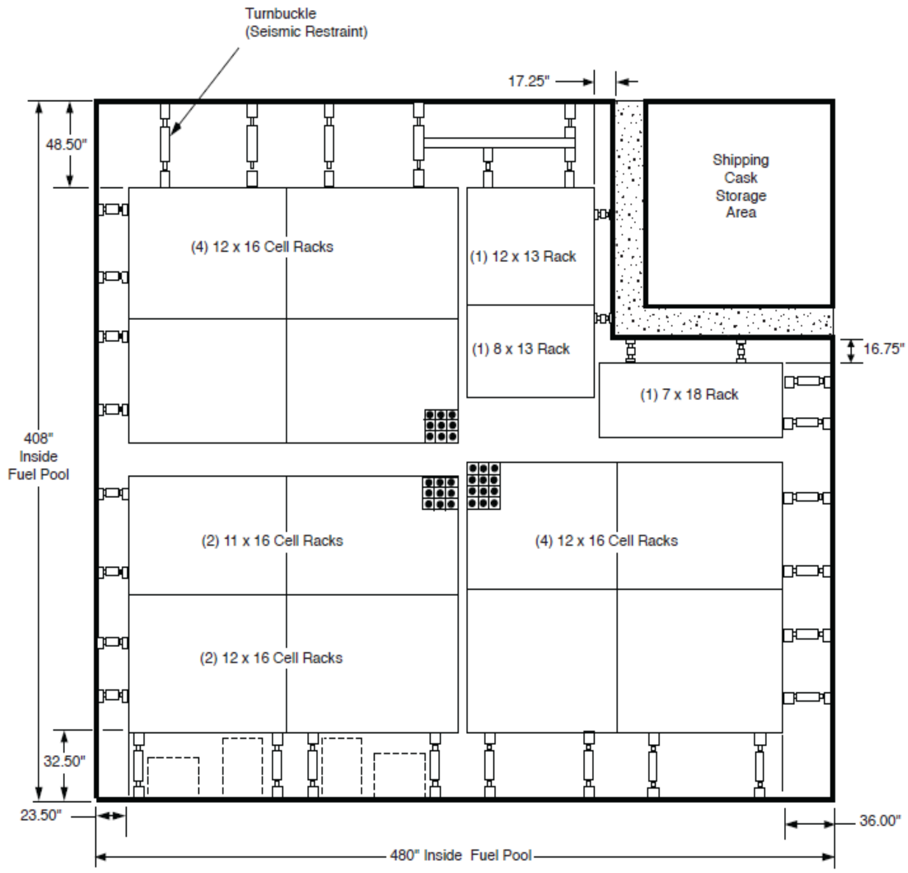
The CGS spent fuel pool has instrumentation that is 15 feet 11 inches from the bottom of the pool (gamma scan collimator) that "extends through the side." This enables plant operators to analyze the enrichment, power distribution and fission product content of individual assemblies. [5]

Figure 7 CGS Spent Fuel Pool System



(Source: CGS FSAR-2011)

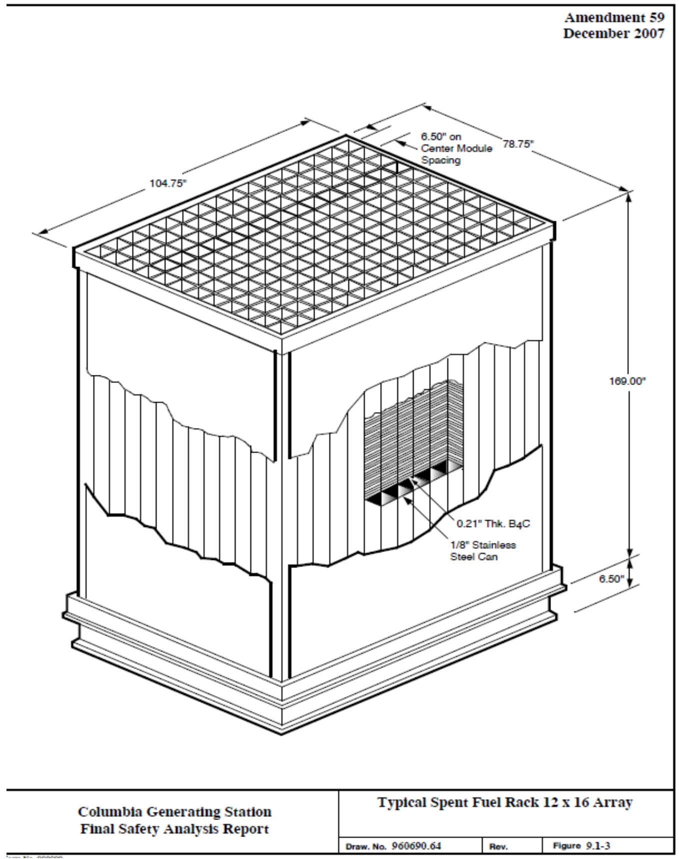
Figure 8 CGS Spent Fuel Pool Storage Racks



(Source CGS FSAR- 2011)

Prior to startup in 1984, the original spent fuel pool racks were designed to hold 1,020 fuel assemblies, but were substituted with high density racks that accommodate 2,652 assemblies. [6] There are 15 racks distributed into 5 storage regions for different sized spent fuel assemblies. The racks contain a total of 693 box-like slots, in which assemblies are loaded from the top using an overhead crane capable of handling as much as 125 tons. The center-to-center spacing between fuel assemblies is 6.5 inches with neutron absorbing plates surrounding each stored fuel assembly (See figure 9).

Figure 9 CGS Storage Rack



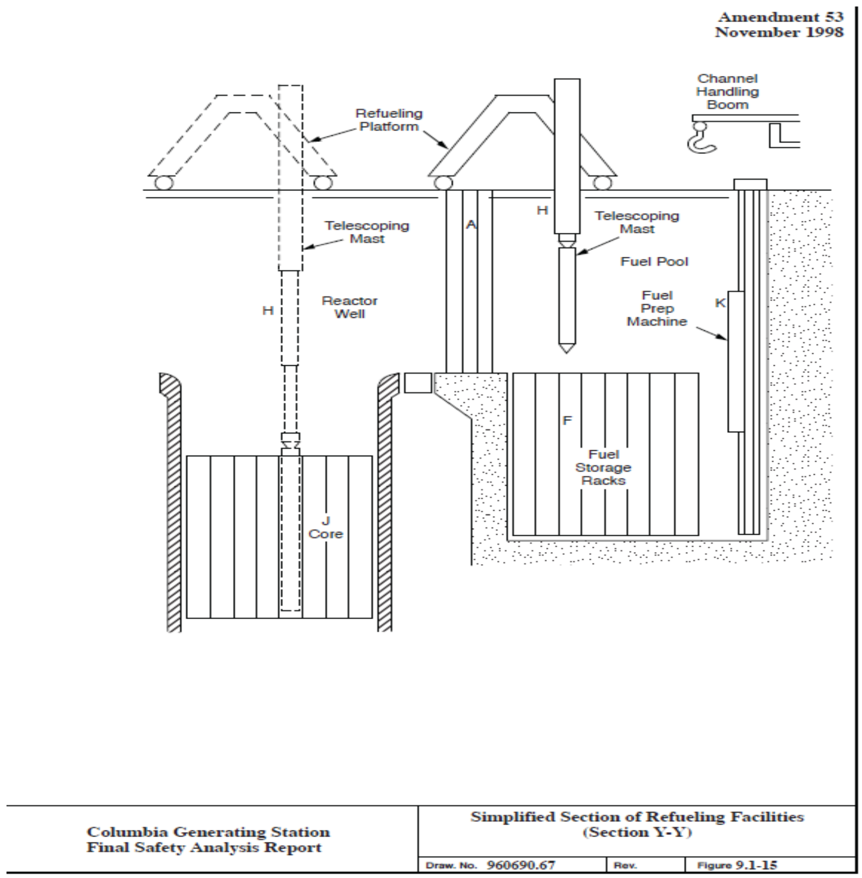
CGS also has a relatively new concrete storage vault next to the pool that holds enough fresh, unirradiated fuel for a full core.[7]

Usually, after 24 months, the CGS discharges about 240 to 252 spent fuel assemblies or approximately one third of the full core. The spent fuel is removed and replaced with fresh fuel assemblies by removal of the reactor vessel top, using the reactor building crane rated at carrying 125 tons. The crane is positioned over the reactor vessel and special tensioners are attached to loosen and remove the nuts securing the vessel head.

Once the nuts are removed, the vessel head is transported by the crane to a pedestal on the refueling floor. Before the fuel is moved between the pool and vessel, the refuelling cavity above the reactor core is filled with water. It has two gates that are opened which connect the shute-like canal to the spent fuel storage pool and the reactor well.

Spent and fresh fuel is moved using a grapple from the reactor core under water to maintain cooling and shielding from high levels of radiation. During a normal outage, approximately one third of the fuel is removed from the reactor vessel, one third of the fuel is reconfigured (generally from the center to the peripheries) and one third new fuel is installed. The platform runs on rails over the fuel pool and the reactor well. Once discharge, refueling and other maintenance, replacement and repair activities are completed, the reactor head is secured again on to the top of the vessel (See figure 10).

Figure 10 CGS Spent Fuel Handling System



To maintain required water temperatures, the pool has two heat exchangers that are also part of the pool cleaning system designed to remove debris using filters and to maintain water chemistry, to inhibit re-criticality, debris build-up, and corrosion. The fuel pool pumps and heat exchangers are located in an enclosed room beneath the pool.

Because of the large amount of decay heat generated by the spent nuclear fuel, the pool is required to keep the over-all water temperature below 150 degrees F –about 40 percent hotter than the original maximum pool temperature. According to the CGS Final Safety Analysis Report (FSAR), revised in 2009, which provides the "safety envelope" for the reactor, when a full irradiated core is placed in the pool the temperature of the water exiting from the hottest storage location should not exceed 175°F, assuming full cooling capacity. [8]

The decay heat loads, especially during refueling outages, has increased after CGS was permitted by the NRC to increase its power output and a doubling of the original time period that fuel would undergo irradiation in the reactor. These changes resulted in a significant increase in the highly radioactive fission products that have created a commensurate increase in the heat load of the pool – resulting in an additional burden on the pool heat removal and cleaning system.

The fuel pool cooling system was originally designed to maintain the pool at a temperature of less than or equal to 125°F during refueling activities with both trains of fuel pool cooling in operation and reactor cooling water (RCC) at 95°F. However, the Final Safety Analysis Report (FSAR) for the Columbia Generating Station, which defines the boundary for safe operation, does not address the temperature limits for an unanticipated full core offload, in which one of the two heat removal systems is disabled. The NRC exempts Energy Northwest from having back-up for a single failure of one its two heat exchangers, "based on the expected infrequent performance of a full core offload."[9]

However, in January 2014, when pressed about this matter by the NRC, Energy Northwest revealed that the heat in the SFP will be "on the order of three times greater than that of a normal refueling," after discharge of a full irradiated core. NRC also noted that Energy Northwest had not performed the necessary calculations of the time when boiling in the pool would occur from emplacement of a full irradiated core in the pool.[10]

Instead of formal requirements regulating emergency response to accidents involving spent fuel pools, the NRC relies on voluntary guidelines proposed by the Nuclear Energy Institute (NEI), an organization run by the nuclear energy industry. The NEI guides are very general and do not address the site-specific designs, seismic circumstances, and other potential vulnerabilities, especially a major accident involving the reactor itself.[11]

In terms of water makeup capabilities to mitigate leaks and drainage from the CGS pool, Energy Northwest's plan consists of using water from a fire hydrant, a fire "pumper" truck or hoses that have to be connected to the reactor's spray water ponds. [12]

By January 2014, the Columbia Generating Station had not yet implemented the NEI's guidance to prevent or mitigate steam and condensate from a boiling spent fuel pool. Such an event would create a radioactive environment that would prevent access to the pool area and create equipment problems in other parts of the plant. [13]

Under normal reactor operating conditions, most of the tritium (H-3) gas, a radioactive isotope of hydrogen, is produced and released routinely to the atmosphere at CGS and comes from the spent fuel pool. Spent reactor fuel pools are estimated to be the largest source of atmospheric tritium releases to the environment. [14] Tritium gas release increases as more spent fuel is added and stored for several years. Fuel cladding defects and the mixing of irradiated water from the reactor containment with the spent fuel pool during refueling also increases the amount of tritium released to the environment.

Reactor Spent Fuel

As uranium fuel is irradiated in the reactor core at CGS, radioactive elements are created when the atoms of uranium-235 and other heavy isotopes are split (fission) as well as by absorption (activation) of neutrons in the atoms of many other isotopes (See Table 2). The CGS uses fuel that is enriched above its naturally-occurring fraction of 0.7 percent of U-235 to as much as 5 percent so it can serve as the primary isotope needed for fission and thus, the generation of energy.

Table 2 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

Over the years, the Columbia Generating Station has relied on four different fuel assembly designs with the objective of increasing the length of time during irradiation (burnup). Currently, the CGS core has 764 fuel assemblies and is a mixture of Atrium-10 and GE-14 fuel assemblies. [15]

- The Atrium-10 fuel assembly contains 91 rods and is approximately 14.5 feet long, 5.5 inches across and weighs about 500 lbs (See Figure 11).
- GE-14 assembly contains 92 rods, is approximately 14.5 feet long, 5.5 inches across and weighs about 715 lbs.

The Atrium-10 and GE-14 assemblies are deployed for higher burnups with increased U-235 enrichment and spend as long as 6 years undergoing irradiation.[16] [17] About one third of the reactor core (240-252 assemblies) is replaced with fresh fuel when the reactor is shut-down every two years. Although information regarding burnup is publically available for spent fuel in dry casks at CGS, the current level of burnup of spent fuel in the reactor pool remains unavailable to the public on the grounds that it is proprietary information. [18]

When the reactor is shut down for refueling, the spent fuel being removed contains a myriad of radioactive isotopes with different half-lives including longer lived radioisotopes, notably cesium-137 (half-life=30 years), along with very long-lived fission products (i.e. iodine-129, technetium-99, cesium-135) and actinides (plutonium-239, americium-241) that have half-lives ranging from tens of thousands to millions of years.

Figure 11 Atrium 10 Fuel Assembly

(Source: NEI)

Radioactivity of Spent Nuclear Fuel

Spent fuel contains materials that are radiotoxic, meaning that they create biological damage based on their radioactive properties alone. The most immediate and severe form of harm is direct exposure to a spent nuclear fuel assembly at a near distance. For instance, a freshly discharged spent fuel assembly at CGS would give off more than 10,000 rems per hour (100 Sv/hr) in the form of external penetrating radiation.[19] A person standing within 3 feet of this assembly would receive a lethal dose within minutes. For the next 100 years, it would give off life threatening doses at this distance.[20] Long-term effects from lower doses include cancers, other diseases, and lasting genetic damage, including congenital abnormalities, chromosomal disorders, and a range of diseases.[21]

From the perspective of public safety, the cesium-137 content in spent fuel at CGS is an important radioisotope of concern. With a half-life of 30-years, the National Council on Radiation Protection and Measurements (NCRP) believes that "Cs -137 has often proven to be the most important long-term contributor to the environmental radiation dose received by humans and other organisms as a result of certain human activities.[22]" Large-scale environmental contamination by Cs-137 during reactor accidents at Chernobyl, Ukraine in 1986 and the Fukushima Dai-Ichi site in Japan in March 2011, underscores our concern for public safety if a similar accident were to occur at the Columbia Generating Station.

Approximately 43 percent of the intermediate and long-lived radioactivity in the spent nuclear fuel at CGS is Cs-137. Thus, CGS has generated about 118 to 157 million curies (4.366E+18Bq-5.809E+18 Bq) of Cs-137. Of that, between 44 and 84 million curies of Cs-137 are in the spent fuel pool. By comparison, this quantity is about 2 to more than 3 times the amount released by all atmospheric nuclear weapons tests. (See figure 2).

Decay Heat

As mentioned previously, after removal from the reactor core, the spent fuel gives off a significant amount of heat as the radioisotopes decay. The offload of a full reactor core at CGS is estimated to create a heat load in the spent fuel pools of about 36.2 MBTU/hr (10.6 million watts).[23] Within one year the heat output of the spent fuel diminishes by about ten times. After 10 years it drops by another factor of ten. By 100 years the decay heat has dropped another five times, but still gives off significant heat.[24] However, the decay heat remains substantially high throughout the operation of the reactors and long after they are closed.

Control of decay heat is a key safety factor for spent fuel storage and its final disposal in a geological repository. Storage of spent nuclear fuel in pools requires continuous cooling for an indefinite period to prevent decay heat from igniting the zirconium cladding and releasing large amounts of radioactivity into the environment.

Zirconium cladding of spent fuel is chemically very reactive in the presence of uncontrolled decay heat. According to the National Research Council of the National Academy of Sciences the build up of decay heat in spent fuel in the presence of air and steam:

> " is strongly exothermic – that is, the reaction releases large quantities of heat, which can further raise cladding temperatures… if a supply of oxygen and or steam is available to sustain the reactions...The result could be a runaway oxidation – referred to as *a zirconium cladding fire* – that proceeds as a burn front (e.g., as seen in a forest fire or fireworks sparkler)...As fuel rod temperatures increase, the gas pressure inside the fuel rod increases and eventually can cause the cladding to balloon out and rupture.[original emphasis] "[25]

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 enhance the migration of the wastes.[26] At the now cancelled Yucca Mountain geological disposal site in Nevada decay heat from spent fuel would require approximately 2,500 cubic feet of storage space and ventilation, for each cubic foot of spent fuel.[27]

High Burnup Nuclear Fuel

For some 16 years, U.S. reactor operators, including CGS have been permitted by the NRC to double the amount of time nuclear fuel can be irradiated in a reactor, by approving an increase in the percentage of uranium-235, the key fissionable material that generates energy. In doing so, NRC has bowed to the wishes of nuclear reactor operators, motivated by economics rather than by safety margins in spent nuclear fuel storage and disposal. Based on data from the International Atomic Energy Agency it is not unreasonable to assume that the major preponderance of the spent fuel remaining in the pool at the CGS is high burnup (>45,000MWd/MTU).

In 2012 the National Academy of Engineering of the National Academy of Sciences raised concern about the viability of high burnup fuel by noting, "the technical basis for the spent fuel currently being discharged (high utilization, burnup fuels) is not well established… the NRC has not yet granted a license for the transport of the higher burnup fuels that are now commonly discharged from reactors. In addition, spent fuel that may have degraded after extended storage may present new obstacles to safe transport."[28]

Known as increased "burnup" this practice is described in terms of the amount of electricity in megawatts (MW) produced per day with a ton of uranium. As of 2008, the NRC allows reactors using uranium fuel to operate at the highest burnup rates of any country in the world.[29]

In 1999, CGS was permitted by the NRC to increase burnup by moving from an 18 month to a 24 month fuel cycle. This allows a fuel assembly to remain as long as six years in the reactor core and for shutdowns for refueling to be extended from one to two years. CGS is permitted to reach a maximum burnup of 62,000MWd/MTU. [30]

High burnup spent fuel contains substantially more high activity radiation –dramatically increasing the radionuclide inventory (especially Cs-137) of spent fuel and subsequent decay heat (See figure 4). The NRC and reactor operators, including Energy Northwest, have not revealed to the public the site-specific radioactive inventories and burnup histories of spent fuel currently being stored in their spent fuel pools.

However, given these uncertainties the U.S. Department of Energy (DOE) and the NRC have provided general estimates of the radionuclide content of spent nuclear fuel based on current and previous burnup assumptions. According to DOE the estimated average long-lived radioactivity for a typical PWR and BWR assembly having lower burnup at the time of geological disposal are 88,173.69 curies and 30,181.63 curies respectively.[31] For current burnups the NRC estimates that the post discharge radioactive inventory of spent fuel for typical PWR and BWR assemblies are 270,348.26 curies and 127,056.67 curies respectively (See figure 4).[32] Approximately 43 percent of the total estimated radioactivity in a BWR assembly, including both the lower and high burnup fuel is from Cs-137.

Even NRC admits, "there is limited data to show that the cladding of spent fuel with burnups greater than 45,000 MWd/MTU will remain undamaged during the licensing period." [33]

In allowing increased burnup at power reactors the NRC has taken a leap of faith with respect to the safe operation of reactors, and the safe and secure storage and disposal of spent nuclear fuel. With higher burnup, nuclear fuel rods undergo several risky changes that include:

- Increasing oxidation, corrosion and hydriding of the fuel cladding. Oxidation reduces cladding thickness, while hydrogen (H3) absorption of the cladding to form a hydrogen-based rust of the zirconium metal from the gas pressure inside the rod can cause the cladding to become brittle and fail.[34]
- Higher internal rod gas pressure between the pellets and the inner wall of the cladding leading to higher fission gas release. Pressure increases are typically two to three times greater.[35]
- Elongation or thinning of the cladding from increased internal fission gas pressure.[36]
- Structural damage and failure of the cladding caused by hoop (circumferential) stress. [37]
- Increased debris in the reactor vessel, damaging and rupturing fuel rods.[38]
- Cladding wear and failure from prolonged rubbing of fuel rods against grids that hold them in the assembly as the reactor operates (grid to rod fretting).[39]
- A significant increase in radioactivity and decay heat in the spent fuel. [40]
- A potentially larger number of damaged spent fuel assemblies stored in pools.[41]
- Requiring upgraded pool storage with respect to heat removal and pool cleaning.[42]
- Requiring as much as 150 years of surface storage before final disposal. [43]

There is growing evidence that as a result of higher burn-ups nuclear fuel cladding cannot be relied upon as a primary barrier to prevent the escape of radioactivity, especially during dry storage. This has not been lost on the nuclear industry and staff of the NRC for several years now. Damage in the form of pinhole leaks, and small cracks that could lead to breaching of fuel cladding is "not explicitly defined in [NRC] Regulations, staff guidance or standards." [44]

As of 2012, the spent fuel placed in dry storage at CGS does not appear to exceed 45,000 MWd/MTU.[45]

Fuel Rod Corrosion and Damage

Despite efforts to mitigate this problem, for the past 25 years, fuel cladding corrosion, known as "crud", has been a significant challenge at CGS. For decades, the Columbia Generating Station has experienced chronic problems associated with the build-up of these radioactive debris and rust particles on spent fuel cladding and reactor internals. The control of corrosion in reactor water is highly important for the performance and safety of BWRs. Because of the single loop coolant design, BWR's contaminate larger amounts of plant equipment, than Pressurized Water Reactors, and can expose workers to unacceptably high doses of radiation. The build-up of highly radioactive crud can also interfere with heat transfer and operation of plant equipment.

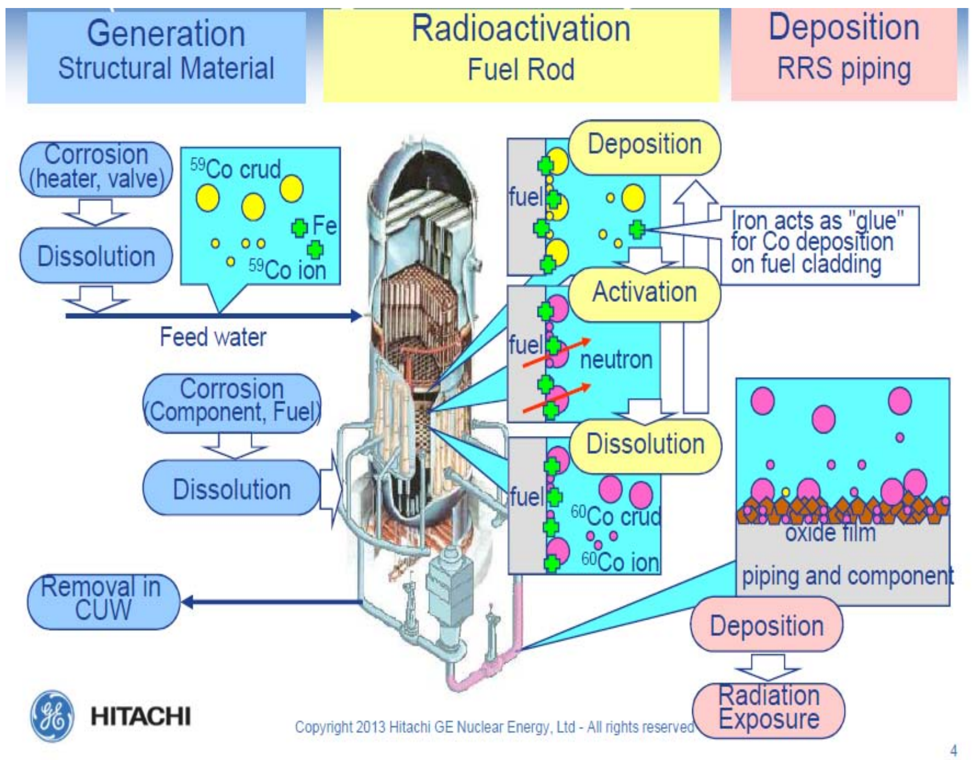
Crud can be flaky, porous, or hard depending on its chemical make-up. It is a mixture of iron, nickel, chrome and other trace elements along with their corresponding activated forms (Co-58, Co-60, Fe-55, Fe-59, Cr-51 etc.) thought to have leached out of reactor equipment being bombarded by neutrons. These chemicals concentrate and combine atop hotspots on the fuel rods. Crud deposits promote local corrosion that can create a rupture in the cladding, causing fission products to be released. Crud layers during storage in pools have been shown over time to loosen and dislodge which can impact pool operation, and spent fuel removal to dry casks.

In most cases, "crud" reduces the power output of nuclear reactors – the deposits absorb the neutrons that keep the fission reaction going. It is considered by Energy Department nuclear research experts at the Idaho National Laboratory to be "a major problem in commercial power-producing nuclear reactors." They report that, " numerous attempts to prevent and control crud formation and circulation by changing the water chemistry have been made; none has been fully successful…there is little fundamental understanding of what crud is, how it forms, and how its characteristics might be modified to make crud less damaging to plant operation and worker health." [46](See figure 12).

According to a 2006 study done by Energy Northwest, "copper's substantial negative impacts on reactor fuel integrity were identified in the early days of Boiling Water Reactors. A phenomena, known as Crud Induced Localized Corrosion (CILC), is caused by copper entering the reactor, attaching itself to the fuel corrosion layer, and causing localized corrosion and high temperature areas on the fuel cladding. The eventual outcome is often loss of clad integrity and long axial splits of the clad. That allows fission products to spread throughout the plant and ultimately cause increased release rates to the environment. CILC has rendered large quantities of fuel unusable, costing tens of millions of dollars and extended reduced power operation at some units. …..The industry has substantially lessened, but not eliminated, CILC failures by removing copper from their condenser materials or adding deep bed demineralizers. Columbia has done neither, leaving us susceptible to CILC fuel failures." [47]

The Nuclear Energy Agency (NEA) of the international Organization for Economic Co-operation and Development concluded in 2012 that crud buildup constitutes a significant problem for US BWR plants. However the NEA reports that "firm (safety) limits on crud deposition are not defined, although the amount of crud deposited and its composition can be significant to the corrosion performance of the cladding." Following severe crud build-up episodes since 2002 that impacted the operation of at least eleven U.S. BWR's (the most recent in 2009), the NRC rejected efforts to establish a crud build-up limit for safe reactor operation. [48]

Figure 12 Formation and Migration of Radioactivity in a Boiling Water Reactor



On October 2, 2002, during a meeting at NRC headquarters, Energy Northwest provided the NRC staff with an update on the status of increased fuel corrosion indications initially discovered during fuel inspections in 2001 (Refueling Outage R-15 -Spring 2001). Follow-up inspections performed to date included visual examinations, measurements of fuel oxide thickness, and analyzing fuel crud samples.

Energy Northwest reported it found "high levels of nodular corrosion … Some spallation observed on 4th burned bundles … Accelerated copper deposition occurring [and] thicker oxide (corrosion) and crud layers than found during previous Columbia experience." [49] In 2005, The Electric Power Research Institute (EPRI) performed a "poolside" analysis, in which samples from spent fuel that has undergone a single irradiation cycle, were collected. EPRI reported: "a large number of debris formations," with a chemical composition close to the La Salle reactor spent fuel, that experienced severe corrosion (see Figure 13). [50]

A year later, Energy Northwest research stated, "during 2001, Columbia found that some of its fuel had thicker than expected oxide layers. A root cause team, with industry expertise, studied the previous operating cycle and fuel scrapings. The fuel had higher than normal levels of copper and iron deposits. Concerns over probable fuel damage were high. Spallation (similar to concrete spallation where material falls off) was identified on Columbia fuel…. The root cause was determined to be poor demineralizer performance, coinciding with a chemical intrusion due to condenser system leakage. Had the condenser not leaked this challenge to the fuel would not have occurred."[51]

Figure 13 Crud buildup on CGS spent fuel

Source: EPRI (2006)

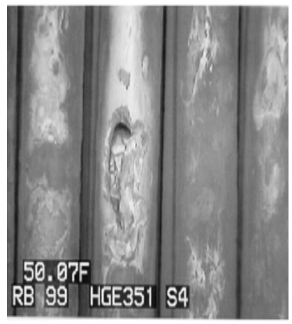
In particular, "poor chemistry control in the early years of Columbia's operations caused corrosion of the condenser tubes. One result is a phenomenon, called dezincification, which caused pits in the admiralty bronze condenser tube metal. The pits remain and provide initiation sites for localized corrosion and subsequent tube leaks/failures (See Figure 14)."[52] The study also raised concerns that the CGS was an "outlier" of the nuclear industry, which, if action was not taken to correct its damaged steam condenser, could threaten industry self-regulation, and "can have downside risks not only to individual stations, but the nuclear industry as a whole."

"A single failed BWR rod" states a study by the International Atomic Energy Agency, "can cost more than US $1,000,000 (2004) in outage time, fuel and power replacement costs. Failures affecting the larger fraction of a reload — such as crud or corrosion failures — can easily run into the tens of millions of dollars."[53]

To address the problem of controlling crud, Energy Northwest has adopted numerous changes in reactor coolant chemistry, and in 2011 replaced the interior structure of a major piece of equipment (steam condenser), which was considered a major crud source, because of its damage during early operation of the reactor. [54]

Figure 14

Failed Fuel at CGS due to crud and accelerated corrosion (1999)



Source: CGS 2006

Occupational Radiation Exposure

As mentioned previously, BWR’s render larger amounts of plant equipment radioactive, and because of its single cooling loop design, are prone to corrosion. These factors can expose workers to unacceptably high doses of radiation. According to the NRC,” *BWRs generally have higher collective doses due to the fact that the steam produced directly from the reactor is used to drive turbines to produce electricity. This results in radioactivity being present in both the reactor and power generation components of the systems, while PWR [pressurized water reactor] systems are designed to keep the radioactivity within the reactor vessel and primary system and not in the turbine system.”* [55] The dose to workers at BWR’s is mostly from gamma radiation – a form of external penetrating radiation that often requires heavy shielding. As a result in 2011, the average collective radiation dose to workers at BWR’s in the United States was 258 percent greater than at PWR’s. [56]

According to the Final Safety Analysis Report for CGS, maintenance personnel such as mechanical, electrical, and instrument craftsmen, who make up the largest single group of workers at the plant, are expected to receive more than 60 percent of the total collective radiation dose. Other groups such as plant operations personnel, health physics engineers and supervisors are expected to receive the remaining balance of radiation exposures. [57]

Other sources of worker exposure at BWRs include gamma radiation in the main steam lines mostly emanating from the isotope nitrogen-16 (N-16). At BWRs hydrogen is injected to retard the oxidation of iron. This, however, increases the radiation hazard because hydrogen combines with nitrogen to form a radioactive ammonia compound. With a half-life of 7.13 seconds, N-16 is continuously produced by the irradiation of reactor water with neutrons. Because of its very short half-life, N-16 emits intensely penetrating radiation at energy levels about 150 times greater than a diagnostic X-ray machine. For this reason lead blankets are often used on the outside of piping. [58]

The largest increases in occupational radiation exposures tend to occur during the process of shutdown for refueling, and maintenance or equipment replacement. During the shutdown process radioactive particles and debris are dislodged within the reactor system. As the reactor vessel top is removed and the reactor cavity is flooded, reactor coolant containing radioactive cobalt, iron and more than a dozen activated elements can emit significant doses. Radioactive corrosion products such as cobalt (Co-58 and Co-60), Iron (Fe-59), manganese (Mn-54), zinc (Zinc-65), and chromium (Cr-51) concentrate in piping and equipment. For instance, the elbow of a pipe builds up more radioactive particles and requires posting notices and shielding if workers go near. Of particular concern is when corrosion "crud" particles build up and are suddenly dislodged from the core and piping and cause increased dose rates in wider areas of the plant. [59]

During refueling, poor water clarity is a safety concern in terms of increased doses from suspended radioactive particles in the reactor coolant, which also can make spent fuel less visible for removal. Most of the worker exposures at BWRs in the U.S. are related to the removal and replacement of the reactor vessel head during outages.

"Crud burst events" during shutdowns and scrams, release significant quantities of activated corrosion as well as Fission Products (FP) and can create higher station-wide or localized radiation areas, as well as reactor cooling water clarity problems, which affect visibility and increases worker exposure. Crud bursts are common during planned and unplanned shutdowns because they can dislodge a significant amount of radioactive particles from reactor system piping resulting in increased radiation doses in the affected areas where it is relocated. Often curd bursts are deliberately induced by injection of chemicals in conjunction with administrative controls to limit personnel access to high dose areas. Bursts also can occur with unexpected consequences due to vibration and other mechanical disturbances during shutdowns, startups, and scrams. The CGS has experienced 23 forced shutdowns (SCRAMS), which were likely to dislodge crud deposits and lead to increased radiation doses throughout the reactor building. For instance at CGS, "several crud burst causing evolutions occurred around the June to July 2007 time frame and there was no process in place for radiation protection [personnel] to be informed so that they could adequately monitor for changing radiological conditions throughout the plant." [60]

In order to reduce radiation levels BWR operators, including CGS, implemented the practice of injecting zinc to offset the accumulation of cobalt-60. According to the Electric Power Research Institute this, "has resulted in several instances of tenacious crud formation on fuel cladding surfaces. At one plant, these formations have led to fuel failures." [61] In 2013 EPRI reported that an examination of spent fuel at CGS, did not immediately translate to a substantial change in deposit composition" of tenacious crud buildup following a reduction in zinc injection into the reactor coolant. [62]

Lapses in worker radiation protection

To keep individual exposures from increasing, Energy Northwest has employed an increasingly large number of temporary workers, significantly exceeding the estimated 323 full-time employees at the site. A review of the NRC's 44th Annual Report of Occupational Radiation Exposure at NRC Licensed Facilities, indicates that the average annual number of transient workers with measurable exposures at CGS from 1985 to 2011, was three to four times the number of full-time employees estimated in the CGS Final Safety Analysis Report. [63] [64]This practice has the effect of reducing exposures to the individual full-time worker while shifting the risk to larger numbers of temporary employees. Between 1985 and 2011, the total collective exposure at CGS totaled 8,108 person-rems.[65]

NRC inspection reports between 2003 and 2014 reveal at least on several occasions,[66] that:

- Worker doses exceeded administrative limits by as much as 2-3 times,
- Job planning, radiological surveys, and posting of radiation hazards were found to be inadequate;
- Area radiation monitoring for several areas were non-functional ;
- Radiation monitoring equipment was not properly calibrated; and
- Supervisors failed to inform workers about radiological hazards.

These lapses are reflected in data collected by the NRC of the 28 currently operating single unit reactors in the U.S. – indicating that workers at the Columbia Generating station accumulated the third largest collective exposure from 1997 to 2011. (See figure 15). Moreover, between 1999 and 2011, CGS was responsible for 47 percent of the total collective occupational radiation dose for all nuclear facilities located on the entire Hanford site. [67] [68]During this period a total of 4,430 person-rems were reported at the Hanford site, including CGS, which reported a total of 2,027 person-rems. (See figure 5.) As noted in a December 2011 NRC inspection report, "the willingness to work around substandard procedures was a long-standing operator behavior." [69]

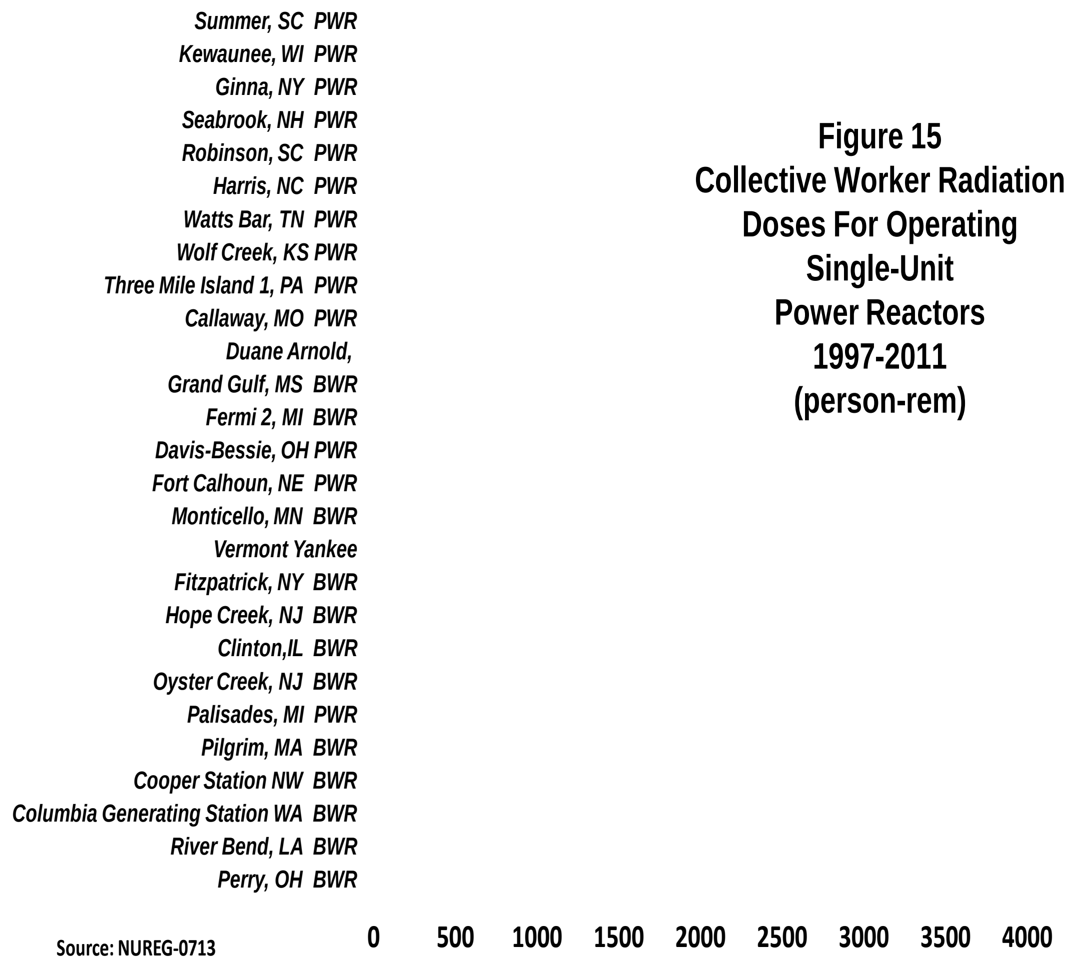


Figure 15
Collective Worker Radiation Doses For Operating Single-Unit Power Reactors 1997-2011 (person-rem)

The 300-618-11 Burial Ground – Proximity to CGS

The parking lot of the Columbia Generating Station adjoins the US Department of Energy's 300-618-11 Burial Ground which received wastes from several facilities that handled and processed mega-curie quantities of high-level radioactive wastes from Hanford tanks and spent fuel from Hanford production and commercial nuclear power reactors (See figures 6 and 16).[70] Energy Northwest has installed a new vehicle barrier between the parking lot and the disposal site. According to a Hanford site contractor, in a message to its employees in 2012 the burial ground "holds some of the highest-hazard materials we've encountered at Hanford."[71] The Energy Department describes it as one its "most challenging remediation projects." Characterization of the site began in 2011 and a completion date for remediation has not been announced. [72]

Figure 16 aerial view of the 300-618-11 burial ground

Source: DOE

Because all records documenting the shipment of wastes to the burial ground were destroyed in 1988, official estimates of the quantities of radioactive and other hazardous wastes and their potential consequences contain elements of speculation. For instance, there are no reliable engineering drawings of the burial ground.

Nevertheless, according a 1993 document prepared for the US Department of Energy's Office of Environmental and Waste Management, it is known that "as high-level radiochemical operations got underway in the 325 and 327 Buildings [at Hanford] in 1953, solid waste burial practices for the 300 Area began to change. High radiation levels in and near Burial Ground 618-2, generated by 325 and 327 building's waste concerned site monitors. On their recommendation, Burial Ground 618-10, known as '300 North' opened in 1954 about 4.3 miles northwest of the 300 27 buildings, cardboard containers and gunk catchers [lead pans] were replaced by the milk pail disposal system. Radioactive wastes were collected in operations buildings in 5 to 6 gallon aluminum milk pails. A commercial gelatin was poured in to seal the top, and each milk pail was placed in an individual cask containing lead shielding surrounded by an aluminum shell. These casks were transported to 300 North, and after 1962, to the Wye Burial Area [now known as the 618-11 burial ground]. Until it was phased out of operation between 1962 and 1964, this burial ground [618-10] consisted of trenches and rows of burial caissons known as 'pie fields.'...Beginning about 1960, after waste became hotter in the 325 and 327, ground where milk pails (not casks) were disposed of in the buried caissons and covered with sand and concrete. The Wye Burial Ground (also known as 618-11) was active from 1962 to 1970...The...Wye burial grounds also received 1-quart 'grape juice cans' that held used, highly radioactive charcoal filters from the operations buildings."[73]

Despite the absence of specific data regarding the types and quantities of radioactive and non-radioactive hazardous materials at these burial grounds, DOE contractors have concluded that the probability of an accident resulting in a dose of 1,000 millirem/year is calculated to be in the range of 1 in 100.[74] Energy Northwest has established an emergency response plan in coordination with the DOE.

Several years after the disposal site was closed in 1967, there were numerous events involving excessive exposure to workers and the spread of radioactivity from this dump site. Dozens of containers were reported to have radiological concentrations greater than 1,000 curies per cubic meter. About 50 percent of the waste containers are estimated to contain combustible materials.[75]

Nonetheless, DOE downgraded the hazard category of the disposal site even though estimated doses to employees at the CGS from an accidental release to the environment from a fire at the burial ground exceeds the annual dose limit.

The history the 300-Area radiochemical facilities clearly indicate that wastes sent to the 300-618-11 Burial Ground resulted from handling and processing mega-curie quantities from Hanford high-level waste tanks and from spent fuel from weapons material production and commercial power reactor fuel. [76] As such, the contents of this landfill clearly fit the legal definitions of high-level radioactive and transuranic waste requiring geologic disposal.[77] The Nuclear Regulatory Commission apparently agrees with this definition by describing the site as a "High-Level Waste Burial Ground."[78]

Apparently, the close proximity to the remediation of a high hazard radioactive disposal site was not considered in the decision to site the CGS. Despite uncertainties that remain to be addressed relative to the hazards of this landfill, in October 2010, the NRC permitted Energy Northwest to amend its license to accommodate its potential nearby risk by concluding "that: (1) there is reasonable assurance that the health and safety of the public will not be endangered by operation in the proposed manner."[79]

Wastes sent to the 8.6 acre disposal site were in several containers that are known to have accumulated hydrogen and pose a risk of fire and explosion. A waste drum fire occurred in January 2014 at the 618-10-10 burial ground, which received comparable wastes, less than a mile Northwest of the CGS. [80]

Dry Cask Storage at CGS

As of June 2014 , Energy Northwest has placed 36 dry casks on two concrete pads in its Independent Spent Fuel Storage Installation (ISFSI) under license with the NRC. Each canister holds 68 spent fuel assemblies.[81]

The Columbia Generating Station uses the Holtec Hi-Storm 100 model dry casks system in which casks are vertically placed on concrete pads (See figure 3). The Hi-Storm 100 cask is designed to be “dual purpose,” meaning that it can also be transported. According to Holtec’s Certificate of Compliance with the NRC: “The HI-STORM 100 Cask System (the cask) consists of the following components: (1) interchangeable multipurpose canisters (MPCs), which contain the fuel; (2) a storage overpack (HI-STORM), which contains the MPC during storage; and (3) a transfer cask (HI-TRAC), which contains the MPC during loading, unloading and transfer operations. The cask stores up to 32 pressurized water reactor fuel assemblies or 68 boiling water reactor fuel assemblies.” [82]

According to Holtec in 1998, “Even though the casks are installed as free-standing structures in relative close proximity to each other, their kinematic stability under earthquake loadings has not been a matter of in-depth assessment and inquiry on the part of the cask designers or the NRC. This is partly because the casks are relatively stubby structures, which makes them reasonably stable under moderate seismic events. In addition, the ISFSI installations to date have been located primarily in regions of the country that have low "design basis earthquakes" (DBE). Upon further analysis, Holtec engineers conclude: “all safety factors exceed 1.0 [g] so that structural integrity requirements under the conservatively developed high seismic event are met or exceeded.” [83]

However, research done in 2004 at the Massachusetts Institute of Technology, finds that in Holtec’s Final Safety Evaluation Report to the NRC that the Hi-Storm 100 system cannot withstand a horizontal ground motion from an earthquake with a magnitude rating of 7.3 on the Richter scale.[84] The high-storm casks can withstand a horizontal ground motion from an earthquake without tipping over (0.397g) - 158 percent more than from the design basis earthquake (0.25g) for the CGS spent fuel pool. However it must be noted that new seismic information uncovered by the US Department of Energy and the US Geological Survey for this area has required buildings to withstand the forces of 0.6 g, [85] a standard which neither the reactor building, the spent fuel pool, nor the Holtec dry casks are designed to meet. To mitigate earthquake impacts at CGS, Holtec has placed low friction material interposed between the slab and the overpack and its support surface to attenuate the rocking motion during an earthquake. [86]

Consequences of a Spent Fuel Pool Fire at a Nuclear Reactor

For the past 30 years, nuclear safety research has consistently pointed out that severe accidents could occur at spent fuel pools resulting in catastrophic consequences. A severe pool fire could render about 188 square miles around the nuclear reactor uninhabitable, cause as many as 28,000 cancer fatalities, and spur $59 billion in damage, according to a 1987 report for the NRC by Brookhaven National Laboratory.[87]

If the fuel were exposed to air and steam, the zirconium cladding would react exothermically, catching fire at about 800-1000 degrees Celsius. Particularly worrisome is the large amount of cesium-137 in spent fuel pools, which contain anywhere from 44 to 84 million curies of this dangerous isotope. With a half-life of 30 years, cesium-137 gives off highly penetrating radiation and is absorbed in the food chain as if it were potassium.

The damage from a large release of fission products, particularly cesium-137, was demonstrated at Chernobyl. More than 100,000 residents from 187 settlements were permanently evacuated because of contamination by cesium-137. The total area of this radiation-control zone is huge: more than 6,000 square miles, equal to roughly two-thirds the area of the State of New Jersey. During the following decade, the population of this area declined by almost half because of migration to areas of lower contamination.

In 2004, the National Academy of Sciences reported that U.S. pools were vulnerable to terrorist attack and to catastrophic fires. According the Academy:

> "A loss-of-pool-coolant event resulting from damage or collapse of the pool could have severe consequences…It is not prudent to dismiss nuclear plants, including spent fuel storage facilities as undesirable targets for terrorists…under some conditions, a terrorist attack that partially or completely drained a spent fuel pool could lead to a propagating zirconium cladding fire and release large quantities of radioactive materials to the environment…Such fires would create thermal plumes that could potentially transport radioactive aerosols hundreds of miles downwind under appropriate atmospheric conditions."[88]

The NRC's response was to withhold the Academy's report, and issue its own analysis which disputed the report's findings. William Colglazier, executive officer of the Academy said the NRC's response was misleading and warned that the public needed to learn about the report's findings. According to Colglazier, "There are substantive disagreements between our committee's views and the NRC. If someone only reads the NRC report, they would not get a full picture of what we had to say." [89] Eventually a declassified version of the panel's report was made available.

Current NRC Chair, Allison Macfarlane recently stated, in June 2014 that "land interdiction [from a spent nuclear fuel pool fire] is estimated to be 9,400 square miles with a long term displacement of 4,000,000 persons..." (See attachment 1)

This fact has been recognized by the NRC's Office of Nuclear Security and Incidence Response for several years, which has published findings to this effect. [90] As an important part of its preparedness and response capabilities, the NRC emergency operations center relies on a computer code to provide a rapid evaluation of the radiological impacts from accidents at nuclear power plants, spent fuel storage pools and casks. This code is a key element in deployment of emergency responders and evacuation of people within and beyond the NRC's 10-mile radius Emergency Planning Zone (EPZ).

According to a 2007 NRC analysis of a spent fuel pool fire at the San Onofre Nuclear Generating Station in southern California - within 6 hours of the pool drainage the spent fuel cladding would

catch fire releasing approximately 86 million curies into the atmosphere. Of that about 30 percent of the radioactive cesium in the spent fuel (roughly 40 million curies) would be released – significantly more than released by all atmospheric nuclear weapons tests. [91]
The resulting doses to people within 1, 5 and 10 miles of the release are calculated at 5,200 rems (1 mile), 1,200 rems (5 miles) and 450 rems (10 miles) respectively. These are considered to be life-threatening doses. Thyroid doses from inhalation of radioactive iodine are calculated at 39,000 rems (I mile), 8,900 rems (5 miles) and 3,500 rems (10 miles) respectively. Doses this high from exposure to radioactive iodine would be enough to cause this organ to be destroyed (See Table 3). We would expect similar disastrous consequences in the event of a spent fuel pool fire at the Columbia Generating Station.

Table 3
NRC Estimation of Radiation Release from at Spent Fuel Pool Fire

Total amount of radioactivity released to the atmosphere	86,000,000 curies (30% release fraction)

	1 mile	5 miles	10 miles
Total Estimated Dose Equivalent (rem)	5,200	1,200	450
Thyroid Committed Dose Equivalent (rem)	39,000	8,900	3,500

Source: NUREG-1889

By contrast the radiological consequences of a dry cask rupture are significantly less. According to the same 2007 NRC analysis, a cask rupture would result in the release of 34,000 curies of radioactivity, with a total effect dose equivalent of 5.3 rems and 2.6 rems at 0.1 miles and 0.2 miles respectively. The thyroid dose would be 4 and 1.9 rems at the same respective distances. Thus, the radiological release from a pool fire would be more than 2,500 times larger than a cask rupture. Doses within one mile from the pool fire would be nearly 1,000 times higher.

NRC's Response Regarding Spent Fuel Pools to the Fukushima Accident

In July 2011 the NRC's Near-Term Task Force assembled in response to the Fukushima Dai-Ichi nuclear disaster, issued several recommendations to upgrade safety at U.S. nuclear power stations.[92] Of the twelve recommendations, several specifically addressed spent fuel pools. The Task Force made it a top priority for reactor operators to:

- install safety-related instrumentation to monitor pool levels, temperature and radiation levels from the reactor control room;

- ensure there are reliable water make-up systems that are capable of withstanding earthquakes and floods
- Ensure pool cooling systems are powered by emergency back-up generators in case of the loss of off-site power.

By December 2011, the Commission approved the staff's recommendations for the prioritization and implementation of the Near-Term Task Force's recommendations, with some changes. Significantly, the Commission voted to reject a staff and Task force recommendation for all post Fukushima upgrades to be mandatory for "adequate protection" of the public under the Atomic Energy Act. The Commission only required that pool water level instrumentation be placed in reactor control rooms, while fending off any further spent fuel pools upgrades.

In March 2012, the NRC issued an order for "enhanced fuel pool instrumentation" because, "the spent fuel pool level instrumentation at U.S. nuclear power plants is a typically narrow range and, therefore, only capable of monitoring normal and slightly off-normal conditions".

The NRC stated that "During the events in Fukushima, responders were without reliable instrumentation to determine water level in the spent fuel pool...This caused concerns that the pool may have boiled dry, resulting in fuel damage." Numerous attempts were made to refill the spent fuel pools, which diverted resources and attention from other efforts. The events at Fukushima demonstrated the confusion and misapplication of resources that can result from beyond-design-basis external events when adequate instrumentation is not available.

The lack of information on the condition of the spent fuel pools contributed to a poor understanding of possible radiation releases and adversely impacted effective prioritization of emergency response actions by decision makers.

Reliable and available indication is essential to ensure plant personnel can effectively prioritize emergency actions."[93]

As important as this water level monitoring system is, considering that the water makeup capabilities to mitigate drainage from the CGS pool consists merely of using water from a fire hydrant, a fire "pumper" truck or hoses that have to be connected to the reactor's spray water ponds, CGS has only been ordered to have the enhanced instrumentation in place by May 2015.

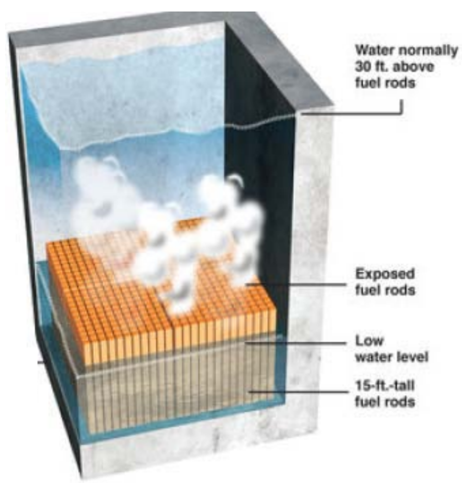
In November 2013 the Nuclear Regulatory Commission issued a final "*Consequence Study of a Beyond-Design-Basis Earthquake Affecting the Spent Fuel Pool for a U.S. Mark I Boiling Water Reactor."* According to the study, *"The study compares high-density and low-density loading conditions and assesses the benefits of post 9/11 mitigation measures...This study's results are consistent with earlier research conclusions that spent fuel pools are robust structures that are likely to withstand severe earthquakes without leaking."* [94]

In June 2014 four out of five Commissioners endorsed the study and its recommendation to not proceed with a policy requiring accelerated removal of spent fuel from reactor pools.

There are several issues which the study did not address:

Partial water loss from a pool with high density racks could be more consequential than complete pool drainage. The NRC ignores the more likely hazards of partial pool drainage. This problem was underscored by a panel of the National Academy of Sciences in 2006, which concludes: "For a partial-loss-of-pool-coolant event, the analysis indicates that the potential for zirconium cladding fires would exist for an even greater time (compared to the complete-loss-of-pool-coolant event) after the spent fuel was discharged from the reactor because air circulation can be blocked by water at the bottom of the pool."[95] (See Figure 17).

Figure 17 Spent Nuclear Fuel Pool Partial Drainage



- **Aging and deterioration of Spent Fuel Pool Systems –** The NRC staff dismissed this problem by ignoring a 2011 NRC-sponsored study, which concludes," *as nuclear plants age, degradations of spent fuel pools (SFPs), reactor refueling cavities…are occurring at an increasing rate, primarily due to environment-related factors. During the last decade, a number of NPPs* [nuclear power plants] *have experienced water leakage from the SFPs [spent fuel pools] and reactor refueling cavities.*[96] Instead the NRC staff points to a study done 24 years ago, before aging effects were being observed.

- **The study did not include a full core offload –** Although NRC requires reactors to maintain space for full core offloads, which add a significant concentration of radioactivity to the spent fuel pool, it did not include this factor in its study. This is of particular significance, since the earthquake and tsunami that impacted Fukushima occurred when Dai-ichi Unit 4 had a full core offload.

- **Failure to address the central purpose of the study to compare the risks of high density versus open rack configurations.** The National Academy panel concluded in 2004 that *"[high density] configuration inhibits water or air circulation more than the earlier [open rack] configuration."*[97] The draft study dismisses consideration of an open-rack configuration out of hand. Open rack configuration has the benefit of spreading out the assemblies without having to place them in neutron absorbing boxes. Despite the National Academy's recommendations, the NRC staff stated that, "*re-racking the pool would represent a significant expense, along with additional worker dose, and was not felt to be the likely regulatory approach taken based on consultation with the Office of Nuclear Reactor Regulation."*[98]

Underscoring these issues are dissents by two NRC staff members as well as the Chair of the Commission. As noted previously, radioactive plumes from a spent fuel fire could impact areas hundreds of miles away. This flaw in the study was pointed out by an NRC staff member before the Advisory Committee on reactor Safeguards in October 2013.

> "The Regulatory Analysis shows that expedited movement of fuel older than 5 years from spent fuel pools to dry cask storage does not provide a substantial safety enhancement. ***It is important for the reader to understand that the significance of the safety enhancement has been judged based solely on the risk to individuals living in close proximity to a nuclear power plant.*** *[emphasis added.]* This means that risk to an individual is assumed to be a reasonable surrogate for cumulative human health risk, even though the events in question are known to have widespread effects in the unlikely event they occur."

The staff dissent also found that the, "regulatory analysis does not consider related alternatives (e.g., expedited movement of fuel older than ten years, refinement of spent fuel pool heat load management requirements) that might be more cost-beneficial**."** [99]

A second staff dissent was presented to the Commission in January 2014, which also challenged the study's basic framework:

"The regulatory analysis uses a 50-mile truncation as a baseline …For SFP accidents in high density pools, which are expected to release [to the environment] much more material than reactor accidents, this truncation can decrease the calculated consequences by nearly a factor of 10. This truncation is arbitrary and technically indefensible…spent fuel pool accidents in high density pools can lightly contaminate very large areas, displacing millions of people and requiring extensive protective actions"[100]

Finally in her 11-page opinion disapproving the NRC staff recommendation, NRC Chair Allison Macfarlane, a professional geologist, noted:

"We have a limited seismic record and limited database to make severe earthquake forecasts. The inability of seismologists to predict the Tohoku earthquake off the east coast of Japan is a case in point. In terms of human-induced initiators… it is not possible to apply the same risk and cost-benefit analyses to quantify security risks in a similar manner as safety risks. As a result it is not feasible to determine the cumulative probability of all initiators, and completely assess the numerical and total risks for each unique spent fuel pool in the nation." Macfarlane also underscored the NRC staff dissenter, stating, "expedited transfer of spent fuel, is a collateral impact of the inability of the federal government to successfully site a repository for nuclear waste disposal." She also noted that, "land interdiction [resulting from a high density spent fuel pool fire at the Peach Bottom Reactor in Pennsylvania] is estimated to be 9,400 square-miles with a long-term displacement of 4,000,000 persons."[101]

The Collapse of the Disposal Framework

The framework of the 1982 Nuclear Waste Policy Act (NWPA) for ultimate disposal of high-level radioactive waste, one of the planets most dangerous human-made substances, has collapsed. Several events are converging that pave the way to reopen this law. They include:

- Abandonment of the proposed Yucca Mountain high-level radioactive waste geologic disposal site underscored by the 2012 elections;
- Recommendations of the Blue Ribbon Commission on Americas Nuclear Future (BRC). The panel, convened in 2010 by President Obama after cancelling the Yucca Mt. project, calls for a major institutional overhaul of storage and disposal site selection expected to take several decades to implement if adopted;
- Rejection of the U.S. Nuclear Regulatory Commission's Waste Confidence Rule by the Federal Appeals Court of the District of Columbia for failure to thoroughly evaluate the environmental, safety and health impacts from spent nuclear fuel storage, as a result of an uncertain disposal future;
- Maximum high-density spent fuel pool storage capacity is expected by the NRC to be reached by all operating U.S. power reactors by 2015[102]; and
- Economic impacts from cheap abundant natural gas on aging nuclear power stations vulnerable to increased expenses associated with expanding dry storage of spent fuel.

After the Obama administration cancelled the Yucca Mt. project a Presidential Blue Ribbon Commission on America's Nuclear Future was tasked with coming to terms with the country's five-decade-plus quest to store and dispose of its high-level radioactive waste. In January 2012, the Panel recommended, among other things:

- developing a "new consent-based process... for selecting and evaluating sites and licensing consolidated storage and disposal facilities in the future:"
- establishing "a new waste management organization" to replace the role of the Energy Department with "a new independent, government-chartered corporation…"

The bottom line is that, optimistically, these recommendations will take several decades before consolidated storage and disposal can occur.

Spent fuel with burnups higher than 45GWD/t should be stored in canisters as *a priori* damaged fuel. According to the Energy Department in 2011, the shuttered Maine Yankee and Zion reactor sites are the only two sites in the United States that are storing high burnup spent fuel in dry casks. In order to eliminate concern over safe transport, the spent fuel assemblies at these sites are packaged or will be packaged in fuel cans used for damaged fuel. [103]

The National Academy of Sciences has concluded that dry-cask storage offered several advantages over pool storage. Dry-cask storage is a passive system that relies on natural air circulation for cooling, rather than requiring water to be continually pumped into cooling pools to replace water lost to evaporation caused by the hot spent fuel. Also, dry-cask storage divides the inventory of spent fuel among a large number of discrete, robust containers, rather than concentrating it in a relatively small number of pools.

Despite the major damage caused by the earthquake and tsunami at the Fukushima Dai-ichi nuclear site, nine dry casks holding 408 spent nuclear fuel assemblies were unscathed.

Spent Fuel Pool Aging Concerns

Wet storage operating costs do not factor in potential safety problems associated with age and deterioration of spent fuel pool systems, especially at closed reactors. In 2011 a study done for the U.S. Nuclear Regulatory Commission by the Oak Ridge National Laboratory concluded:

> *"As nuclear plants age, degradations of spent fuel pools (SFPs), reactor refueling cavities, and the torus structure of light-water reactor nuclear power plants (NPPs) are occurring at an increasing rate, primarily due to environment-related factors. During the last decade, a number of NPPs have experienced water leakage from the SFPs [spent fuel pools] and reactor refueling cavities [See table 4]."*[104]

The authors of this report note that*: "it is often hard to assess their in situ condition because of accessibility problems…. Similarly, a portion of the listed concrete structures are either buried or form part of other structures or buildings, or their external surfaces are invisible because they are covered with liners."*

Table 4. Spent Fuel Pool System Leaks Between 1997-2005

Category	Reactor Refueling Cavity Leakage	Spent Fuel Pool Leakage	Torus Corrosion and Cracking	Age-Related Concrete Degradation
No. of Occurrences	11	12	7	26
No. of NPPs	11	12	7	21
No. of Sites	8	10	7	16
No. of Case Studies*	7	9	7	0
Appendix Location*	A	B	C	N/A

NUREG-CR-7111 (2011)

Endnotes

[1] Youngs, R.R, 2007, Updated site response analysis for the Waste Treatment Plant, DOE Hanford Site, Washington: prepared by Geomatrix Consultants, Inc., for the Battelle Pacific Northwest National Laboratory, Richland, Washington, PNNL-16653 (GMX- 9995.002-001), 41-43p. http://www.pnl.gov/main/publications/external/technical_reports/PNNL-16653.pdf
[2] Columbia Generating Station, Final Safety Analysis Report, Amendment 61, December 2011, http://pbadupws.nrc.gov/docs/ML1401/ML14010A304.pdf
[3] Ibid.
[4] Nuclear Regulatory Commission, Memorandum to: Chairman Jackson Commissioner Rogers Commissioner Dicus, From: James M. Taylor, Executive Director to for Operations, Subject: Resolution of Spent Fuel Pool Storage Action Plan Issues, July 26, 1996. http://pbadupws.nrc.gov/docs/ML0905/ML090510286.pdf
[5] Op Cit Ref. 2,
[6] U.S. Nuclear Regulatory Commission, Spent Fuel Project Office, WNP-2 Spent Fuel Storage, September 1999. http://pbadupws.nrc.gov/docs/ML1312/ML13126A169.pdf
[7] Ibid.
[8] Ibid.
[9] Op. Cit. Ref. 2 p. 9.1-27.
[10] U.S. Nuclear Regulatory Commission, Interim Staff Evaluation and Audit Report by the Office of Nuclear reactor Regulation Related to Order EA-12-049 Modifying Licenses With Regard to Requirements For strategies for Beyond-Design-Basis External Events, Energy Northwest, Columbia Generating Station, Docket No. 50-397. http://pbadupws.nrc.gov/docs/ML1333/ML13337A266.pdf
[11] Nuclear Energy Institute, Diverse and Flexible Coping Strategy (FLEX) Implementation Guide, Rev. B-1, May 2012. http://pbadupws.nrc.gov/docs/ML1214/ML12143A232.pdf
[12] Op Cit Ref. 6.
[13] Ibid.
[14] Jason T. Harris, Tritium Releases from Nuclear Power Plants, Idaho State University, July 24, 2012, http://hpschapters.org/sections/envrad/2012AMpresentations/Harris%20HPS%20Tritium_2012.pdf
[15] Energy Northwest, Columbia Generating Station, Final Safety Analysis Report, Amendment 61, December 2011. http://pbadupws.nrc.gov/docs/ML1201/ML12011A158.pdf

16 International Atomic Energy Agency, Impact of High Burnup Uranium Oxide and Mixed Uranium Plutonium Oxide Water Reactor Fuel on Spent Fuel Management, IAEA Nuclear Energy Series, No. NF-T-3.8, Vienna, (2011). P. 6, /MTCD/Publications/PDF/Pub1490_web.pdf

[17] A.N.T. International, High Burnup Fuel Design Issues and Consequences, October 2012. https://www.antinternational.com/fileadmin/Products_and_handbooks/sample/IZNA12/IZNA12_STR_HiBu_sample.pdf
[18] Personal communication with Charles Johnson, May 15, 2014

19 International Panel on Fissile Materials, Managing Spent Fuel from Nuclear Power Reactors, September 2011, P. 7, Fig. 1-41-4. http://www.princeton.edu/sgs/publications/ipfm/Managing-Spent-Fuel-Sept-2011.pdf
20 Ibid.
21 National Research Council, Board on Radiation Effects, Division of Earth and Life Studies, Committee to Ass Health Risks from Exposure to Low Levels of Ionizing Radiation, Health Risks from Exposure to Low Levels of Ionizing Radiation BEIR VII, Phase II, National Academies Press, 2006), P. 96 Table 4-1. https://download.nap.edu/openbook.php?record_id=11340&page=1
22 National Council on Radiation Protection and Measurements, Cesium-137 in the Environment: Radioecology and Approaches to Assessment and Management, NCRP Report No. 154, November 2006, p.1.
23 Op Cit ref 2
24 Op Cit Ref. 19
25 National Research Council, Board on Radioactive Waste Management, Committee on the Safety and Security of Commercial Spent Nuclear Fuel Storage, National Academes Press (2006), p. 38-39. http://www.nap.edu/openbook.php?record_id=11263&page=38 ,http://www.nap.edu/openbook.php?record_id=11263&page=39

26 R. Wigeland, T.Taiwo, M. Todosow, W. Halsey, J. Gehin, Options Study – Phase II ,Department of Energy, Idaho National Laboratory, INL/EXT-10-20439, September 2010. http://www.inl.gov/technicalpublications/Documents/4781584.pdf .

27 U.S. Department of Energy, Office of Civilian Radioactive Waste Management, Yucca Mountain Science and Engineering Report Rev. 1, Technical Information Supporting Site Recommendation Consideration, Report DOE/RW-0539-1 (North Las Vegas, NV: U.S. DOE, 2002).

28 National Academy of Engineering, Managing Nuclear Waste, Summer 2012, pp 21, 31. http://www.nae.edu/File.aspx?id=60739

29 Erik Kolstad, Nuclear Fuel Behavior in Operational Conditions and Reliability, Prepared for IPG meeting-Workshop on Fuel Behavior, Argonne National Laboratory, September 2008, p. 10

30 U.S. Nuclear Regulatory Commision, Energy Northwest, Applicant's Environmental Report Operating License Renewal Stage Columbia Generating Station Energy Northwest Docket No. 50-397 License No. NPF-21. http://pbadupws.nrc.gov/docs/ML1002/ML100250666.pdf

31 U.S. Department of Energy, Final Environmental Impact Statement, for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada, 2002, Appendix A, Tables A-10 and A-13

32 U.S. Nuclear Regulatory Commission, Characteristics for the Representative Commercial Spent Fuel Assembly for Preclosure Normal Operations 000-PSA-MGR0-00700-000-00A, May 2007, Table 20. http://pbadupws.nrc.gov/docs/ML0907/ML090770390.pdf

33 U.S. Nuclear Regulatory Commission, Standard Review Plan for Spent Fuel Dry Storage Facilities, Final Report NUREG-1567, March 2000. P. 6-15. http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1567/sr1567.pdf

34 U.S. Nuclear Regulatory Commission, Rulemaking Issue, Notation Vote, Memorandum from: R.W. Borchardt, Executive Director for Operations, Subject: Proposed Rulemaking – 10CFR 50.46c Emergency Core Cooling System Performance During Loss-of-Coolant Accidents (RIN 3150-AH42), SECY-12-0034, March 1, 2012, p. 2. http://www.nrc.gov/reading-rm/doc-collections/commission/secys/2012/2012-0034scy.pdf

35 R. Wigeland, T.Taiwo, M. Todosow, W. Halsey, J. Gehin, Options Study – Phase II ,Department of Energy, Idaho National Laboratory, INL/EXT-10-20439, September 2010. http://www.inl.gov/technicalpublications/Documents/4781584.pdf

36 Ibid.

37 Ibid

38 International Atomic Energy Agency, Impact of High burnup Uranium Oxide and Mixed Uranium – Plutonium Oxide Water Reactor Fuel on Spent Fuel Management, IAEA Nuclear Energy Series, No.. NF-T-3.8, June 2011. P. 39. http://www-pub.iaea.org/MTCD/Publications/PDF/Pub1490_web.pdf

39 Ibid.

40 Ibid.

41 Ibid

42 Ibid.

43 Zhiwen Xu, Mujid S. Kazimi and Michael Driscoll, Impact of High Burnup on PWR Spent Fuel Characteristics, Nuclear Science and Engineering, 151, 261-273 (2005), http://ocw.internet-institute.eu/courses/nuclear-engineering/22-251-systems-analysis-of-the-nuclear-fuel-cycle-fall-2005/readings/impact.pdf

44 R.E. Einsiger et al., Damage in Spent Nuclear Fuel Defined by Properties and Requirements, U.S. Nuclear Regulatory Commission, Spent Fuel Project Office, June 2006. http://pbadupws.nrc.gov/docs/ML0608/ML060860476.pdf

45 U.S. Nuclear Regulatory Commission, Columbia Generating Station – Independent Spent Fuel Storage Installation (ISFSI) Inspection report 05000397/2012008, August 24, 2012. http://pbadupws.nrc.gov/docs/ML1223/ML12236A395.pdf

46 D. L. Porter, D. E. Janney, **C**hemical Gradients in Crud on Boiling Water Reactor Fuel Elements, U.S. Department of Energy, Idaho National Laboratory, INL/CON-07-12474, April 2007. http://www.inl.gov/technicalpublications/Documents/3772059.pdf

47 W. Scott Oxenford, VP, Technical Services ,Columbia Generating Station Main Condenser, CGS Main Condenser White Paper Revision 1, June 2006.

48 Ron Adamson et al., ZIRAT-10 Annual Report, Advanced Nuclear technology International, December 2005.

49 Energy Northwest, Columbia Generating Station Docket No. 50-397, Annual Operating Report, 2002. http://pbadupws.nrc.gov/docs/ML0307/ML030730459.pdf

[50]Electric Power Research Institute, , Poolside Fuel Inspection and Fuel Deposit Evaluation at Columbia Generating Station (Cycles 16 and 17), technical Report, December 2006). http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001013431
[51] Ibid
[52] Ibid.
[53]International Atomic Energy Agency, Review of Fuel Failures in Water Cooled reactors, IAEA Nuclear Energy Series No. NF-T-2.1, (2010), p. 7. http://www-pub.iaea.org/MTCD/publications/PDF/Pub1445_web.pdf
[54] Annette Cary, Long outage scheduled at Hanford nuclear plant, Tri-City Herald, March 15, 2011. http://seattletimes.com/html/localnews/2014500495_apwanuclearplantoutage1stldwritethru.html (Correct)
[55] U.S. Nuclear Regulatory Commission, Occupational Radiation Exposure at Commercial Nuclear Power Reactors and Other Facilities 2011,Forty-Fourth Annual Report, Office of Nuclear Regulatory Research,NUREG-0713, Vol. 33. http://pbadupws.nrc.gov/docs/ML1309/ML13095A191.pdf
[56] Ibid.
[57] Columbia Generating Station, Amendment 58, Final Safety Analysis Report, December 2005, PP. 12.4-2 – 12.402-3.
[58] Stephen Lazar, Hydrogen Water Chemistry in a BWR System and its Effects on Dose Rates from Main Steam Lines, The Pennsylvania State University, Department of Nuclear Engineering, December 19, 2011. http://www.personal.psu.edu/scl5068/blogs/stephen/Research_Report.pdf
[59] U.S. Nuclear Regulatory Commission, Radioactive Waste Management Technology Chapter 3: LWR Chemistry,(undated). http://pbadupws.nrc.gov/docs/ML1215/ML12151A436.pdf
[60] U.S. Nuclear Regulatory Commission, Columbia Generating Station 1Q/2009 Plant Inspection Findings. http://www.nrc.gov/NRR/OVERSIGHT/ASSESS/2009q1/wash2_pim.pdf
[61] Electric Power Research Institute, EPRI Explores Impact of Zinc Injection on Fuel Cladding Corrosion and Crud Deposition, May 2012. http://mydocs.epri.com/docs/CorporateDocuments/Newsletters/NUC/2012-07/Zinc_injection_May2012.pdf
[62] Electric Power Research Institute, Fuel Examination and Crud Analysis from Columbia Generating Station EOC20, September 2013. http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002000355
[63] Op Cit Ref. 2
[64] Op Cit Ref. 55
[65] Ibid .
[66] U.S. Nuclear Regulatory Commission, Region IV, Columbia Generating Station4Q/2003, 1Q/2004, 1Q/2006, 2Q/2008, 1Q/2009 , 2Q/2010**,** 2Q/2013, Plant Inspection Findings, Columbia Generating Station – NRC Integrated Inspection report 05000397/2009005, February 4, 2010, Columbia Generating Station, NRC Event Number: 49702, January 8, 2014, USNRC, Region IV, Memorandum, Columbia Generating Station, Allegation Closure (RIV-2007-A-0079) September 28, 2007.
[67] Op Cit Ref. 55
[68] U.S. Department of Energy, DOE Occupational Radiation Reports for 2001, 2003,2005,2007,2009 and2011, Office of Health Safety and Security.
[69]Jacques Von Lunen, 5 violations reported during shutdown at Columbia Generating Station, Tri-City Herald, December 21, 2011. http://www.tri-cityherald.com/2011/12/21/1760578/5-violations-reported-during-shutdown.html
[70] M.S. Gerber, Multiple Missions: The 300-Area in Hanford Site History, WHC-MR-0440, September 1993, pp. 21-23.
[71] Annette Cary, Some Hanford cleanup along Columbia River to be delayed, Tri-City Herald, May 25, 2012.
[72] U.S. Department of Energy, Hanford, 618-10 and 618-11 Burial Grounds, 2014. http://www.hanford.gov/page.cfm/618BurialGrounds
[73] M.S. Gerber, Multiple Missions: The 300-Area in Hanford Site History, WHC-MR-0440, September 1993, pp. 21-23
[74] Energy Northwest, 618-11 Project Status, Presentation to the NRC, October 18, 2012. http://pbadupws.nrc.gov/docs/ML1229/ML12292A164.pdf
[75] U.S. Department of Energy, 618-10 and 618-11 Waste Burial Grounds Basis for Interim Operation, CP-14592 Revision 0, August 2003.
[76] K. D. Bazzel and B. A. Smith, River Corridor Buildings 324 and 327 Cleanup, U.S. Department of Energy, Richland Office, DOE-0312-FP, Revision 0, March 2006.
77. Nuclear Waste Policy Amendments Act of 1987, P.L. 100-203, title V, subtitle A, Sec. 5001-5065, Dec. 22, 1987, 101 Stat. 1330-227 to 1330-255. The NWPA defines HLW as: (A)“the highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material

derived from such liquid waste that contains fission products in sufficient concentrations; and (B) Other highly radioactive material that the Commission, consistent with existing law, determines by rule requires permanent isolation."

[78] U.S. Nuclear Regulatory Commission, Columbia Generating Station- Issuance of Amendment Re: Change to Final Safety Analysis Report for U.S. Department of Energy 618-11 High-Level Waste Burial Ground Remediation (TAC No. ME3862), October 25, 2010

[79] Ibid.

[80] U.S. Department of Energy, Defense Nuclear Facility Safety Board, Hanford Activity Report for the Week Ending January 31, 2014.
http://www.dnfsb.gov/sites/default/files/Board%20Activities/Reports/Site%20Rep%20Weekly%20Reports/Hanford/2014/wr_20140131_18.pdf

81 Energy Northwest, Columbia Generating Station, Docket Nos. 50-397 and 72-35, Registration of Spent Fuel Cask Use, May 15, 2014.

[82] U.S. Nuclear Regulatory Commission, Certificate of Compliance for Spent Fuel Storage Casks, Certificate No. 1014, Issued to Holtec International, Final Safety Analysis Report for the HI-STORM 100 Cask System, May 31, 2000.
http://www.balch.com/files/upload/12-6-13%20Amendment%209.pdf

[83] Holtec International, Topical Report on H0_Star and Hi _Storm 100 System Deployment at High ZPA ISFI Sites, Holtec Report No. HI-982004, Holtec Project No. 71178, Non- Proprietary Version, December 1998.
http://pbadupws.nrc.gov/docs/ML0037/ML003709644.pdf

[84] Joe Burns, On Selection and Operation of an International Storage Facility for Spent Nuclear Fuel. Massachusetts Institute of Technology, February, 2004. P. 29.
http://dspace.mit.edu/bitstream/handle/1721.1/16642/56204748.pdf?sequence=1

[85] Youngs, R.R, 2007, Updated site response analysis for the Waste Treatment Plant, DOE Hanford Site, Washington: prepared by Geomatrix Consultants, Inc., for the Battelle Pacific Northwest National Laboratory, Richland, Washington, PNNL-16653 (GMX- 9995.002-001), 41-43p. http://www.pnl.gov/main/publications/external/technical_reports/PNNL-16653.pdf

[86] Op Cit. Ref. 83.

87 V.L Sailor, K.R. Perkins, J.R. Weeks, H.R. Connell, Severe Accidents in Spent Fuel Pools in Support of Generic Safety Issue 82, Brookhaven National Laboratory, NUREG/CR-4982, July 1987.

88 National Research Council, Committee on the Safety and Security of Commercial Spent Nuclear Fuel Storage, Board on Radioactive Waste Management, The National Academies Press, Washington D.C.(2004) pp. 49, 35, & 50.

89 Shankar Vedantam, Storage of Nuclear Spent Fuel Criticized: Science Academy Study Points to Risk of Attack, Washington Post, March 28, 2005.

[90] U.S. Nuclear Regulatory Commission, Office of Nuclear Security and Incident Response, RASCAL 3.0.5 Workbook, NUREG-1889, September 2007. http://pbadupws.nrc.gov/docs/ML0729/ML072970068.pdf

91 OP Cit Ref. 22 Table 3.1, P. 52.

92 U.S. Nuclear Regulatory Commission, The Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident, Recommendations for Enhancing Reactor Safety in the 21st Century, July 2011.
http://pbadupws.nrc.gov/docs/ML1118/ML111861807.pdf

[93] US Nuclear Regulatory Commission, March 12, 2012 letter to All Power Reactor Licensees and Holders of Construction Permits in Active or Deferred Status, Subject Issuanc3e of Order to Modify Licenses with Regard to Reliable Spent Fuel Pool Instrumentation, EA-12-051, http://pbadupws.nrc.gov/docs/ML1205/ML12054A679.pdf

[94] U.S.Nuclear Regulatory Commission, Staff Evaluation and Recommendations for Japan Lessons- Learned TEIR-3 Issue on Expedited Transfer of Spent Fuel, COMSECY-13-0030, November 12, 2013. http://www.nrc.gov/reading-rm/doc-collections/commission/comm-secy/2013/2013-0030comscy.pdf

[95] Safety and Security of Commercial Spent Nuclear Fuel Storage, Public Report By Committee on the Safety and Security of Commercial Spent Nuclear Fuel Storage, Board on Radioactive Waste Management, Division on Earth and Life Studies, National Research Council, National Academies Press, 2006, p. 53.
http://www.nap.edu/openbook.php?record_id=11263&page=R1

[96] U.S. Nuclear regulatory Commission, A summary of Aging Effects and Their Management in Reactor Spent Fuel Pools, Refueling Cavities, TORI and Safety-Related Concrete Structures, NUREG/CR-7111 (2011). P. vxiii.
http://pbadupws.nrc.gov/docs/ML1204/ML12047A184.pdf

[97] Op Cit Ref. 88

98 Op Cit Ref. 94

99 Written Nonoccurrence Submitted by Brian Wagner, Office of Nuclear Regulatory Research, Division of Risk Analysis, Performance Reliability Branch to the Commission January 6, 2013

100 U.S. Nuclear Regulatory Commission, Chairman Macfarlane's Comments on COMSECY-13-0030, Staff Evaluation and Recommendation for Japan Lessons-Learned Teir-3 Issue on Expedited Transfer of Spent Fuel, April 18, 2014

101 Ibid

[102] U.S. Nuclear Regulatory Commission, Nuclear Fuel Capacity, March 29, 2012. http://www.nrc.gov/waste/spent-fuel-storage/nuc-fuel-pool.html

[103] U.S. Department of Energy, Preliminary Evaluation of Removing Used Nuclear Fuel From Nine Shutdown Sites, PNNL-22418, April 30, 2013. http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-22418.pdf

104 Op Cit. Ref. 96

Attachment 1

Chairman Macfarlane's Comments on COMSECY-13-0030
Staff Evaluation and Recommendation for
Japan Lessons-Learned Tier 3 Issue on Expedited Transfer of Spent Fuel

The issue of the expedited transfer of spent fuel from pools to dry storage is not a new one. In fact, it has been debated over many years, most recently in the 2000s as a result of concerns raised after the terrorist attacks on September 11, 2001 in the United States.[1] All reactors require pools to cool the fuel discharged from the reactor core and to shield its radiation. When light water reactors were originally designed in the United States, the fuel was only supposed to spend a relatively short time in the pool before being sent to a reprocessing facility. With the failure of reprocessing in the 1970s on security, economic, and political grounds, fuel began to build up at reactors, requiring the re-racking of spent fuel pools to accommodate additional spent fuel stocks. Congress and the Administration worked toward a solution to this build up with the enactment of the Nuclear Waste Policy Act of 1982, amended in 1987, the goal of which was to remove the spent fuel from reactor sites and emplace it in a permanent repository starting in 1998. No permanent repository exists to this day. The issue under consideration here, whether to require the expedited transfer of spent fuel, is a collateral impact of the inability of the federal government to successfully site a repository for nuclear waste disposal.[2]

The question at hand is whether spent fuel pools, often currently containing four times the originally-planned volume of spent fuel, are safe in the event of loss of coolant, or whether there are significantly safer configurations for the pools that may involve a lower volume of spent fuel, different configurations of fuel in the pool, different types of racks, or other factors that could reduce the impact of a severe pool accident. Most spent fuel pools with many cores' worth of fuel now present a source term potentially much larger than that of the core of the reactor. In the event of a loss of coolant and subsequent fire in the pool, it is theoretically possible for much more longer-lived radioactivity to be released over greater distances than from a single reactor accident alone. This realization prompted concern during the Fukushima-Dai'ichi accident in Japan in 2011. The spent fuel pool of the unit 4 reactor was relatively full with recently-discharged spent fuel from the reactor core. Although the spent fuel pools did not drain or release radioactive material, we still learned from Fukushima that the environmental and societal/human costs of land contamination from the reactor releases were extraordinarily high.

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[1] See for example: U.S. Nuclear Regulatory Commission, "Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants," NUREG-1738, February 2001; Alvarez et al, 2003, Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States, Science and Global Security, 11: 1-51; National Research Council. *Safety and Security of Commercial Spent Nuclear Fuel Storage: Public Report.* Washington, DC: The National Academies Press, 2006; Gordon R. Thompson, "Risks and Risk-Reducing Options Associated with Pool Storage of Spent Nuclear Fuel at the Pilgrim and Vermont Yankee Nuclear Power Plants," May 25, 2006; U.S. Nuclear Regulatory Commission, "Denial of Two Petitions for Rulemaking Concerning the Environmental Impacts of High-Density Storage of Spent Nuclear Fuel in Spent Fuel Pools (PRM-51-10 and PRM-51-12)," SECY-08-0036 dated March 7, 2008 and SRM-SECY-08-0036 dated June 19, 2008.

[2] It is the responsibility of the Congress and the Administration to develop a strategy for disposing of spent nuclear fuel and high-level nuclear waste; the role of the Nuclear Regulatory Commission is to regulate civilian uses of nuclear materials and facilities in order to protect human health and safety and the environment, and minimize danger to life or property, as required by U.S. law.

Background

The consequence study examines the behavior of spent fuel in a pool given a seismic event initiator and the consequences of spent fuel fires with a "high density" configuration (*i.e.*, a pool with hot fuel assemblies surrounded by four cold fuel assemblies) or a "low density" configuration (i.e., a pool with hot fuel assemblies surrounded by four empty locations). The study evaluates the robustness of the Peach Bottom spent fuel pool against seismically-induced pool damage, probabilities of a self-propagating zirconium fire, and potential contamination events for mitigated and unmitigated scenarios. The low probabilities for initiating events were calculated from the 2008 United States Geological Survey (USGS) model for a large seismic event and the point estimate frequency of an assumed cask drop into a pool.[3] The staff model suggests that there would be no significant doses to the public during or immediately after the hypothetical release because of offsite protective actions that are credited in evacuating and relocating affected populations. The cumulative doses are dominated by long-term exposure to the surrounding public that returns to live in the contaminated zone around the plant. The contamination zone is considered by staff to be habitable in the analysis once annual doses fall below 20 millisieverts (2 rem) the first year and 5 millisieverts (500 mrem) in each year thereafter.

The staff subsequently determines in the generic regulatory analysis that a pool configuration with fewer fuel assemblies (*i.e.*, "low density") did not provide a substantial safety benefit because the calculated latent cancer risk is well below the QHOs for reactors. Although a high density configuration can result in much higher consequences, it is fairly insensitive to the QHOs given the calculated low probability of a fire in spent fuel pools. Likewise, the staff determines that the low density alternative is not cost-justified because the 100 billion dollar economic cost of a release is low when weighted by the calculated frequency of a fire. This averaged cost is below the dry cask storage costs needed to maintain a low density approach.[4] The staff paper also mentions other potential options for spent fuel management. But the staff qualitatively determines that these too, provide only a limited safety benefit when using the reactor QHOs.

However, the staff consequence study and generic regulatory analysis also highlight the significant range of potential contamination events and environmental costs. These potential costs are highly influenced by the distribution of recently discharged fuel in the pool, the overall cesium content in the pool, the success of post-accident water make-up capabilities, and the successful evacuation of the surrounding population during the event sequence. Unweighted by probability, the source term in a high density spent fuel pool is assumed to range from approximately 40 to 140 million curies of cesium-137 with a nominal 40% to 75% release fraction for various fuel pool types.[5] The source term

[3] The staff notes that the regulatory analysis uses the USGS 2008 model instead of the current model under development in an on-going regulatory program. The staff notes that while the USGS model is not sufficiently detailed for regulatory decisions, it is appropriate for use in this analysis because it is the most recent and readily available hazard model for the central and eastern U.S. plant sites.

[4] The staff notes that this cost could be heavily discounted if and when the Federal Government takes possession of spent nuclear fuel at utilities.

in an assumed low density pool is approximately 2-3 times lower.[6] Based on the consequence study for Peach Bottom, a fire in a high density pool is calculated to result in a collective dose of 350,000 person-sieverts, while a low density configuration is calculated to result in a collective dose of 27,000 person-sieverts (assuming unsuccessful mitigation). The land interdiction is estimated to be 9,400 square miles with a long-term displacement of 4,000,000 persons for a high density loading. A low density loading would lead to approximately a factor of 50 reduction in interdiction and population displacement.[7 8] Similarly, a low density pool configuration could result in approximately a 100 billion dollars savings in economic costs, using the staff's current guidance for estimating cost benefits.[9]

It is important to note that the staff uses the Environmental Protection Agency (EPA) Protective Action Guidelines (PAGs) for the Intermediate Phase as the best-available metric for the analysis. The studies note that there is no Commission policy on acceptable decontamination and land reoccupation values.[10] Regardless of Commission direction on expedited transfer, the staff should not consider the EPA intermediate PAGs as an acceptable environmental policy metric, unless it is brought before the Commission as a policy matter.

Risk Perspectives and Defense in Depth

A comprehensive safety and security case for spent fuel pools should consider the full range of potential hazards (natural or human-induced) that could initiate an accident, the spectrum of potential options for addressing hazards, risk insights, defense-in-depth, scientific and engineering judgment, and other qualitative factors. I agree that probability and risk analysis are valuable tools to provide insights on safety decisions and rulemaking analysis. However, events with potentially significant consequences will always be a policy matter that requires additional consideration.

We should consider the uncertainties and limitations in predicting large earthquakes or other initiating events, and resultant consequences. We have a limited seismic record and limited database to make

[5] For comparison, various organizations have estimated that approximately 0.2 to 0.8 million curies of cesium-137 was released into the air environment from the Fukushima reactor accidents. See, for instance, "Fukushima Daiichi Status Report," International Atomic Energy Agency, June 28, 2012. The estimated fraction of source term released to the environment from a spent fuel pool fire is based in part on the assumed damage-state of the reactor building surrounding the spent fuel pool.

[6] See tables 35 and 52 of "Regulatory Analysis for Japan Lessons Learned Tier Issue on Expedited Transfer of Spent Fuel" - enclosure 1 to COMSECY-13-0030, "Staff Evaluation and Recommendation for Japan Lessons-Learned Tier 3 Issue on Expedited Transfer of Spent Fuel," November 2013.

[7] The input parameters for the consequence analyses are based on those developed for Peach Bottom for the recently completed "State-of-the-Art Reactor Consequence Analyses" research project (NUREG-1935), including site specific population distributions, meteorology, and evacuation timing parameters.

[8] See section 7.3 of "Consequence Study of a Beyond-Design-Basis Earthquake Affecting the Spent Fuel Pool for a U.S. Mark 1 Boiling Water Reactor," October 2013.

[9] I believe these economic calculations are riddled with uncertainty, given uncertainties in evacuation and reoccupation doses of a large population, the immeasurable complexity of local and regional economics, and the uniqueness of populations and environments at individual reactors.

[10] The EPA guidance also notes that the intermediate phase guidelines have an objective of limiting total dose to 50 millisieverts (5 rem) over 50 years.

severe earthquake forecasts. The inability of seismologists to predict the Tohoku earthquake off the east cost of Japan is a case in point.[11] Forecasts are subject to professional judgment and hopefully conservative risk assessments of Earth processes near each reactor plant. In terms of human-induced initiators, while our security professionals have a strong understanding of malevolent scenarios, vulnerability, and physical protection methodology, it is not possible to apply the same risk and cost-benefit analyses to quantify security risks in a similar manner as safety risks. As a result, it is not feasible to determine the cumulative probability of all initiators, and completely assess the numerical or total risks for each unique spent fuel pool in the nation. Therefore, it is important to have a continued focus on the holistic benefit of spent fuel management approaches that provide a common safety and security layer of defense against all potential initiators.

Fundamentally, spent fuel pools do not benefit from a surrounding primary containment structure to repress large releases of fission products during a loss of cooling emergency and energetic fuel damage. The consequence analysis identifies a period in which spent fuel may not be naturally air-coolable during a drain-down event without human intervention. As a result, over the life of a reactor, spent fuel pools may not have natural cooling ability for approximately 1 to 5 years of a 20-year operating life.[12] There are additional spent fuel management measures that should be evaluated to address this vulnerable state, for all types of initiating events.

The consequence study provides new, valuable insights on the importance of spent fuel loading patterns and overall cesium content, which cannot be dismissed qualitatively. For example, the consequence study reiterates the advantage associated with dispersed fuel patterns at time of discharge. The "base case" of the regulatory analysis assumes that spent fuel is discharged directly into a 1x4 loading pattern, although there is no direct requirement to do so under 10 CFR 50.54(hh). The staff implementing guidance suggests an undisclosed timeframe for achieving such a pattern.[13] In the consequence study, the staff performed a sensitivity analysis for non-dispersed patterns of the hottest fuel assemblies. It shows that deployment of water makeup capabilities is not as effective in a non-dispersed pattern as compared to 1x4 pattern. A non-dispersed pattern may also have more detrimental hydrogen combustion events than a 1x4 pattern and lead to significantly higher consequences and contamination of the surrounding environment.[14]

In contrast to the work done for the generic regulatory analysis of expedited transfer, the staff provided a comprehensive analysis on the addition of filtered containment venting systems to BWRs with Mark I

[11] Prior to the 2004 Sumatra earthquake that created the massive Indian Ocean tsunami, seismologists believed that only certain subduction zones could cause megaquakes (greater than magnitude 8.8). Only in the years after Sumatra did the seismological community begin to accept that all subduction zones of sufficient length could create megaquakes. The Tohoku quake of 2011 proved their new understanding to be correct.

[12] In the consequence study, the staff estimates spent fuel is vulnerable to ignition is between 37 – 107 days after discharge, without mitigation within 72 hours. Reactors typically discharge fuel on a one to two year cycle.

[13] The time to achieve a 1x4 pattern is security-related information.

[14] See section 9.3 of "Consequence Study of a Beyond-Design-Basis Earthquake Affecting the Spent Fuel Pool for a U.S. Mark 1 Boiling Water Reactor," October 2013.

and Mark II containments, to address lessons learned from the events at the Fukushima. For filtered vents, the staff considered both safety risk and cost benefits. To complement their analysis, the staff systematically examined qualitative factors such as providing defense in depth (including the importance of containment function), addressing significant uncertainties (frequencies and consequences), supporting severe accident management and response, improving hydrogen control, addressing external events, improving emergency planning, and addressing international experience and practices. While the staff touched upon some qualitative issues with expedited transfer, it did not provide a similar review of options and qualitative factors that are important to this decision before the Commission.

Spent Fuel Management Options

The staff should therefore consider spent fuel management actions that promote inherent defense-in-depth against accidents and events that could generate very large releases, particularly with regard to the vulnerabilities that exist in spent fuel pools during the first one to three months after fuel discharge. The staff should systematically assess these options for reducing these vulnerabilities by considering all of the following factors:

- **Longer Transfer Times to Dry Cask Storage**

The only option before the Commission is continuing the analysis of requiring the rapid defueling of all spent fuel older than five years by 2019. First, even if there is a significant safety benefit to do so, it is not clear if it is physically possible to complete such a significant task within five years - - given the current loading and handling infrastructure of individual U.S. power plants and the manufacturing capabilities of cask vendors. A study by Electric Power Research Institute on this topic, which the staff relied upon in their analysis, concluded the same and they examined transfer of fuel over longer 10-year and 15-year time frames.[15] Second, when considering consequences beyond 50 miles and a more up-to-date conversion value of $4,000 per rem, the base cases for some reactor plants are actually cost beneficial.[16] All "high cases," which are meant to use more conservative assumptions to bound possible site-specific plant configurations, are cost-beneficial even assuming an aggressive five-year schedule.[17]

The staff should further investigate the option of significantly reducing the overall cesium content in spent fuel pools, but over longer time frames, such as 10 years. This analysis may demonstrate a significant reduction in accident source terms for defense in depth, while requiring a lower number of

[15] "Impacts Associated with Transfer of Spent Nuclear Fuel from Spent Fuel Storage to Dry Storage After Five Years of Cooling," Revision 1, Electric Power Research Institute, 1023206, August 2012.

[16] See Table 10 and Tables 27 -30 of "Regulatory Analysis for Japan Lessons-Learned Tier 3 Issue on Expedited Transfer of Spent Fuel," COMSECY-13-0030, November 12, 2013.

[17] The staff considers the "high cases" to be overly conservative.

additional dry storage casks. This approach may also be more feasible when using existing dry storage cask technologies to full capacity.

- **Direct Discharge into dispersed pattern**

The consequence study illustrates the inherent value of dispersing the hottest fuel within the spent fuel pool. As noted earlier, the 1x4 pattern promotes natural cooling and reduces the likelihood and consequence of a release. As noted in the consequence study, licensees may not be directly discharging the hottest fuel from the core directly into a 1x4 pattern for some time. It appears that most licensees are achieving a 1 x4 pattern at an undisclosed time after discharge, under implementing guidance associated with the requirements of 10 CFR 50.54(hh). The staff should, at a minimum, re-examine the technical basis of the implementing guidance for 10 CFR 50.54(hh) in light of the potential benefits shown in the consequence study. The staff should survey and understand the specific discharge and spent fuel management practices of each plant as part of this examination. The staff should also consider requiring dispersed loading patterns at the time of actual discharge, when fuel is hottest and most susceptible to self-ignition without the pool coolant boundary. This requirement should be considered in conjunction with the unique attributes and vulnerabilities of each individual spent fuel pool. The staff should also evaluate the safety benefits of full core off-load capabilities during reactor operations and outages, and examine regulatory options for requiring this spent fuel management approach together with the other alternatives discussed here.

- **Alternate Dispersal Patterns (e.g. 1x8)**

Alternative loading patterns, beyond the 1x4 arrangement may provide additional margin and reduced risks. The staff sensitivity analysis shows that a 1x8 arrangement has superior heat removal capabilities compared with a 1x4 pattern. The larger mass of cold fuel in a 1x8 pattern provides a larger heat sink and results in lower heatup of recently discharged fuel in a drained pool environment. For one calculation of the 1x8 pattern, no release occurred from fuel through the first 72 hours, compared to the 1x4 pattern, which resulted in a zirconium fire that began after 40 hours and led to a 42 percent release of the cesium inventory into the environment. The Advisory Committee for Reactor Safeguards (ACRS) also notes that the 1x8 pattern can significantly reduce the consequences of seismically induced damage. The ACRS stated this approach should be further explored as a measure to provide additional defense in depth against spent fuel pool accidents. The staff should therefore pursue the option of alternate dispersal patterns (such as a 1x8) in conjunction with analyzing the benefit of directly discharging spent fuel into a dispersed pattern.

- **Alternative Storage Rack Designs**

The staff's analysis assumed the current closed, high-density rack configuration in the technical analysis. The staff's regulatory analysis estimates a significant cost for re-racking spent fuel pools to an open frame rack design. It qualitatively notes that staff believes that within the first few months after discharge, the decay heat in the freshly unloaded spent fuel is high enough to cause a zirconium fire even in the presence of convective cooling. Therefore, re-racking the spent fuel pool to install open frame racks even with BWR channel boxes removed to allow potential cross flow, would not necessarily prevent a radiological release during this time.

While this may be generally intuitive, it has not been substantively modeled or physically tested. I note that the consequence study illuminated other approaches that showed significant benefits (*e.g.*, 1x8 configuration), which may not have been intuitive at first glance. To lay this question to rest, the staff should adjust its current models to approximate the open frame rack configuration. The staff should evaluate if the additional cross-flow geometries would significantly increase time margins for mitigative actions or substantially reduce radiological consequences. The staff should also examine international spent fuel pool designs and practices to determine if alternate rack designs are being used to mitigate accident risks.

- **Longer-Term Research - Accident Tolerant Fuel**

The Department of Energy is researching accident tolerant fuel for improved reactor and spent fuel pool safety. New cladding materials and coatings for zirconium fuel are being considered as benign materials against steam reactions at high temperatures. A new generation of spent fuel with tolerant cladding is a potential passive safety measure that may significantly reduce uncertainties in both reactor and spent fuel pool loss-of-coolant accidents. The staff should support, within its regulatory role, the on-going research on accident tolerant fuel designs. This work is important as current fuel designs continue to increase to higher burnups, with growing heat loads and cesium source terms at time of discharge.

<u>Other Factors</u>

In moving forward, the staff should engage the international community in their efforts to enhance spent fuel management from a safety and security standpoint. The Commission has recently directed staff to further examine international practices for spent fuel pool management. The practices, technical analyses, and decision rationale of other nations should be considered in future work on this issue. For example, it appears that because of recent Canadian Nuclear Safety Commission's efforts to examine lessons learned from the Fukushima accident, reactor plants in Canada have apparently opted to transfer spent fuel within 7 years of discharge.[18] The staff should also consider the pending National Academy of Science's (NAS) study on this topic, and report to the Commission the NAS findings and how they comport with further work on spent fuel pool management.

I also expect that staff's work on economic consequences, qualitative factors, and recommendations for disposition of Near Term Task Force (NTTF) Recommendation 1 will lead to addressing broader framework questions for considering beyond-design basis accidents. These efforts contain regulatory elements that are integral to the NRC consideration of severe accidents for both reactors and spent

[18] Personal communication with Dr. Michael Binder, President of the Canadian Nuclear Safety Commission, January 2014.

fuel pools. Potential policy issues include systematic consideration of defense-in-depth, the use of qualitative factors, and environmental restoration and rehabitation of contaminated land.

Equally, the staff should endeavor to engage the public early in the process of examining improved spent fuel management approaches in order to garner valuable insights and ensure NRC actions are effectively communicated. This may be most beneficial in not just understanding varying technical perspectives, but also the other environmental consequences and economic impacts in local communities. I do not agree with the staff's approach in engaging the public near the very end of the current two-year regulatory review process, without the ability to fully provide input on key regulatory factors or review the draft regulatory analysis that was provided to the Commission. In accelerating this Tier 3 activity to align with the Waste Confidence environmental activities for public transparency, the staff may have ironically impeded the same public from fully vetting this issue in the safety and security arenas.

Conclusion

I appreciate the work that staff has performed thus far on spent fuel pool safety. I recognize the importance of the risk analysis and backfit analysis tools. I have also weighed some of the deterministic arguments regarding the robustness of spent fuel pools, physical security measures, and the capability of supplying supplemental cooling after a severe event. These factors provide significant comfort that we do not need to rush to take drastic actions today.

But as a precautionary principle, the Agency should continue to focus on enhancing defense-in-depth in a reasonable manner. Uncertainties in forecasting the next severe event (*e.g.*, in the assumptions and judgments that go into modeling complex scenarios), as well as in other human factors, are difficult to quantify. The potential consequences would be intolerable to the surrounding human environment. These types of environmental impacts cannot be wholly measured and evaluated through frequency weighting of dose and quantified health objectives alone. We should holistically consider safety and security concerns and further evaluate potential defense-in-depth measures to compensate for these uncertainties. This regulatory approach can be pursued at a pace that is commensurate with the calculated risks that such events pose and in parallel with broader efforts to enhance our severe accident regulatory framework.

Summary of Necessary Actions

1. The staff should provide a plan to the Commission that prioritizes spent fuel management options that may provide the greatest safety benefit and describe further research needs to determine which regulatory actions will ensure adequate defense-in-depth.

2. The staff should consider spent fuel management actions that promote inherent defense-in-depth against accidents and events that could generate very large releases, particularly with regard to the vulnerabilities that exist in spent fuel pools during the first one to three months after fuel discharge. The staff should systematically assess the following approaches for reducing these vulnerabilities:

a. Reduction of the overall cesium content in spent fuel pools by transfer to dry cask storage, but over longer time frames, such as 10 years.

b. Direct discharge of spent fuel into a dispersed pattern. The staff should re-examine the technical basis of the implementing guidance for 10 CFR 50.54(hh) in light of the potential benefits shown in the consequence study. The staff should survey and understand the specific discharge and spent fuel management practices of each plant as part of this examination. The staff should also consider requiring dispersed loading patterns at the time of actual discharge, when fuel is hottest and most susceptible to self-ignition without the pool coolant boundary. This requirement should be considered in conjunction with the unique attributes and vulnerabilities of each individual spent fuel pool. The staff should also evaluate the safety benefits of full core off-load capabilities during reactor operations and outages and examine regulatory options for requiring this spent fuel management approach together with the other alternatives discussed here.

c. Use of alternate dispersal patterns (such as a 1x8).

d. Use of alternate rack designs. The staff should adjust its current models to approximate the open frame rack configuration. The staff should evaluate if the additional cross-flow geometries would significantly increase time margins for mitigative actions or substantially reduce radiological consequences. The staff should also examine international spent fuel pool designs and practices to determine if alternate rack designs are being used to mitigate accident risks.

e. Use of accident tolerant designs. The staff should support, within its regulatory role, the on-going research on accident tolerant fuel designs.

3. The staff should engage the international community in their efforts to enhance spent fuel management from a safety and security standpoint.

4. The staff should also consider the pending National Academy of Science's (NAS) study on this topic, and report to the Commission the NAS findings and how they comport with further work on spent fuel pool management.

5. The staff should endeavor to engage the public early-on in the process of examining improved spent fuel management approaches.

6. The staff should not consider the EPA intermediate PAGs as an acceptable environmental policy metric, unless it is brought before the Commission as a policy matter.

4/8/14

Allison M. Macfarlane Date