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Options for Future Fuel/Basket Modifications for DPC Disposition

Spent Fuel and Waste Disposition

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Acronyms

ANA	Advanced Neutron Absorber
APSRA	Axial Power Shaping Rod Assembly
BPRA	Burnable Poison Rod Assembly
BWR	Boiling Water Reactor
CoC	Certificate of Compliance
CRA	Control Rod Assembly
DCRA	Disposal Control Rod Assembly
DPC	Dual-Purpose Canister
GTCC	Greater-than-Class-C waste
ID	Inner Diameter
MPC	Multi-Purpose Canister
MTU	Metric Tons Uranium
NSA	Neutron Source Assembly
OD	Outer Diameter
ORA	Orifice Rod Assembly
PWR	Pressurized Water Reactor
RCCA	Rod Cluster Control Assembly
SNF	Spent Nuclear Fuel
TAD	Transport-Aging-Disposal canister
TPA	Thimble Plug Assembly
VSI	Vibration Suppression Insert
WABA	Wet Annular Burnable Absorber

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Options for Future Fuel/Basket Modifications for DPC Disposition

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Deliverable Description: Identify and evaluate options for fuel and basket modifications, for dual-purpose canisters (DPCs) to be loaded in the future, that would substantially reduce the probability of postclosure criticality after waste package breach and flooding with ground water. Planned work in FY20 will examine the feasibility of criticality control features, particularly neutron absorbing inserts or replacement channels for boiling water reactor (BWR) fuel assemblies. The expected outcome is additional engineering information that can be used to guide the R&D program, and to support future stakeholder interactions. This document will be incorporated into planned deliverable *DPC Disposal Concepts of Operation* (M3SF-20SN010305052, 18Sep20).

Objective: Definition of fuel/basket modification options, to support future engineering analysis (e.g., worker dose, postclosure criticality).

Approach: The following discussion describes the hardware geometry and composition, and provides a preliminary scoping description of neutron absorber configuration and cost. Previous studies and patents are mentioned where applicable. Costs for fuel/basket modifications are estimated using material and fabrication estimates, and separate labor estimates for time and costs associated with installation activities in spent fuel pools.

Assumptions are made to generate cost estimates, such as the average capacities of future DPCs that will be in use when fuel/basket modifications are started. Notably, the assumed numbers of fuel assemblies or basket fuel cells that need to be modified to control postclosure criticality, and their placement in the DPC basket, need to be verified by analysis.

The general approach is to focus on fuel or basket modifications that do not require potentially significant changes to existing dual-purpose canister (DPC) basket designs, although additional analysis and licensing would be required. Avoidance of "significant" design changes would help ensure that the same modifications could be applied across the industry without favoring one DPC vendor over another. Some possible basket modifications are identified in Section 2.2 that would require significant basket redesign, and are not analyzed further.

This report does not deal with other criticality control and management strategies being investigated by the R&D program, such injectable fillers and criticality consequence analysis.

1. Fuel Assembly Modifications

This section explores several different options for adding disposal criticality control features to spent fuel assemblies. The addition of control rods to pressurized water reactor (PWR) spent nuclear fuel (SNF) assemblies is discussed first, followed by a similar discussion for BWR SNF assemblies. This is followed by discussion of BWR re-channeling, zone loading, and rod consolidation.

1.1 PWR Disposal Control Rods

Adding control rods to PWR fuel assemblies for *disposal* criticality control, was described and analyzed by EPRI (2008, 2009a) and has been studied as a solution for SNF in the present R&D program (SNL 2020; Alsaed 2019). It would require minimal modifications to fuel assemblies and no modification of existing basket designs. There are two major technical aspects associated with implementation: 1) feasibility of disposal control rod assembly (DCRA) operations in spent fuel management facilities; and 2) behavior of disposal control rods after waste package breach, in the disposal environment. This report addresses the feasibility aspect, while the long-term degradation of fuel assemblies in a repository is being addressed by a parallel investigation (see SNL-ICG 2019).

Similar applications for criticality control in storage and transportation have been developed (and patented) before. As discussed by EPRI (2009b):

> "…In a collaborative offering with [Babcock & Wilcox (B&W)] Fuel Company (now [ORANO]), [Advanced Refractory Technologies, Inc. (ART)] offered boron carbide/alumina pellets encapsulated in stainless steel cladding as neutron absorber inserts for the guide tubes of PWR fuel assemblies…These absorber rods would be used to compensate for the degraded neutron absorber in fuel racks and to provide additional reactivity hold-down to accommodate fuels with higher U-235 enrichments.
>
> "The matrix of the pellets is sintered alumina. The boron carbide content of the pellets can be adjusted to provide the required reactivity control, but typically ~15.0 [weight percent] boron carbide would provide adequate control. This is a decided advantage over borated stainless steel rods, which are normally limited to 1.75 [weight percent] boron. As discussed previously, the use of absorber rodlets for reactivity control is probably viable only in the Combustion Engineering fuel assemblies that have large guide tubes."

The B &W/ART product announcement was made in 1995 (EPRI 2009b). Note that it was specific to pool storage.

A patent was issued to Framatome in 2001 (U.S. 6,327,321 B1) for borated aluminum rodlets that would occupy guide tubes or instrumentation tubes, for criticality control during storage and transportation. For extending the reactivity range of wet storage racks, supplemental control rods of solid borated stainless steel, and sealed tubes containing B_4C and alumina powders, have also been proposed (EPRI 2009b).

Once a waste package breaches in a repository, and floods with ground water, the DPC basket and fuel will begin to degrade. The reactivity of the substantially intact configuration will remain analyzable by the same means for many thousands of years because the fuel assembly materials, and possibly basket materials, are corrosion resistant. It is important that for the majority of DPC baskets that use stainless steel as structural material, that the structure will outlast the aluminum-based neutron absorbers by many thousands of years.

Over the very long term after waste package breach (e.g., longer than 10,000 years exposure to ground water) the fuel and basket components may lose structural integrity, allowing the fuel array to collapse and consolidate. For DCRAs to continue to inhibit criticality after collapse, the disposal control rods would move with the fuel array as it begins to collapse, so that they remain intimately located with and distributed within the fuel mass. Eventually fuel collapse is likely to consolidate the fuel and basket to an extent at which the hydrogen fraction is decreased to the point where criticality is no longer possible even without neutron absorbers. Fuel/basket collapse will not necessarily occur uniformly, and DCRAs would be designed to control heterogeneous consolidation (e.g., localized void expansion). Modeling of fuel/basket degradation is underway, with the goal to generate collapsed and partly collapsed configurations for neutronic analysis (SNL-ICG 2019).

One early mode of fuel assembly degradation could be parting of fuel rods from the top and bottom nozzles (PWR fuel). The guide tubes ("thimbles") hold the assemblies together axially, and if the guide tubes or their nozzle connections fail then the nozzles can shift and fuel rods can pull out (fuel assemblies are made so that the top nozzle can be removed on-site to replace individual fuel rods). In a horizontal orientation, fuel rods that are unsupported at the ends will sag at the ends and begin to consolidate. Another potential area of mechanical degradation is the spacer grids, which are typically made from Zircaloy but are built up from thin pieces that could corrode rapidly relative to nozzles and fuel rods (two-sided corrosion in the presence of tensile stress).

Detailed description of PWR fuel assembly components and geometry is beyond the scope of this report, and many important details such as material thicknesses and fabrication steps tend to be proprietary. Generally, PWR fuel assembly configurations evolved from 14x14 through 17x17 arrays early in production (Weihermiller and Allison 1979) all of which are now represented in the spent fuel inventory. These configurations have varying numbers of guide tubes but the same basic design approach (top and bottom nozzles, spacer grids, guide thimble connections, etc.). Design improvements have continued, but recent PWR fuel assembly designs retain the basic thimble functionality (e.g., Robust Fuel Assembly and Next Generation Fuel; Westinghouse 2008).

For DCRA implementation some of the potentially important differences between fuel assembly designs are guide tube diameter, dashpot sections, thimble plug geometry, and characteristics such as irradiation damage and corrosion resistance that could impact long-term degradation in a repository. One major difference is the larger diameter of guide tubes in standard 14x14 and 16x16 designs from Combustion Engineering, which occupy four fuel rod positions and accommodate one or more control rods that are significantly larger than typical Westinghouse designs (Kennard and Harbottle 2000; EPRI 2009b). Notably, the materials used in fuel cladding and guide tubes (i.e., Zr-alloy or stainless steel), the robustness of guide tubes and their connections at the nozzles, and the connections between fuel rods and nozzles (where applicable), can affect the manner and rate of fuel assembly degradation.

The DCRA concept was originally analyzed ("surrogate control rods") with potential application to a repository in unsaturated tuff, as part of a study that compared different possible postclosure criticality control methods (EPRI 2008, 2009a). The following approaches were investigated in that study for two typical as-loaded 32-assembly PWR DPCs: 1) burnup credit analysis (reactivity margin); 2) moderator displacement credit for wet-annular burnable absorber assembly rods (WABAs) and burnable poison rod assemblies (BPRAs); 3) loading maps optimized for lower canister reactivity; and 4) disposal control rods containing B_4C in the guide tubes of the four central assemblies or in all 32. Using as-loaded fuel characteristics it was found that burnup credit lowered k_{eff} by 5 to 10% depending on how many nuclides were included. More recent analysis of more than 700 as-loaded DPCs with updated burnup credit methodology (using a more complete inventory of fission products; Clarity et al. 2019) shows that this range can be extended by a few percent. In the EPRI (2008, 2009a) study, moderator displacement by depleted poison rods had a worth of approximately 2 to 3%, while optimized loading was worth 1 to 2%. Disposal control rods in the central four assemblies had a worth of 4%, while using them in all 32 assemblies was worth 35%.

Neutron-induced changes in B_4C absorber composition and properties are not expected to occur in DCRAs because the neutron fluence during the postclosure time period (nominally 10,000 years) will be much less than in-reactor. Hence, any neutron absorbing material could be used that satisfies capture cross-section requirements based on analysis, and is stable in the disposal environment particularly to gamma radiation (up to 50 MGy dose). Natural boron carbide ceramic (B_4C) is such a material and may also be attractive from a cost perspective. Fretting of DCRAs during transportation of DPCs is not expected to occur as the control rods would be contacted only by guide tubes, and fretting of fuel rods and guide tubes was not observed in a recent multi-modal long-distance SNF transport demonstration (Salzstein, personal communication, March 19, 2020).

There are three major configurations of PWR fuel assemblies available for modification to DCRAs at reactor discharge:

- Fuel assemblies containing reactor control cluster assemblies (RCCAs).
- Fuel assemblies containing burnable poison rods arranged with "spider" fixtures (i.e., BPRAs) for insertion into guide tubes. Note that BPRAs may contain fewer poison rods than there are guide tubes (Figure 1), in which case the open guide tubes have thimble plugs to prevent reactor coolant bypass.
- Fuel assemblies containing only thimble plugs in the guide tubes, which may also be arranged with "spider" fixtures, i.e., thimble plug assemblies (TPAs).

The RCCAs, BPRAs, and TPAs are the most numerous types of control components that may be present in fuel assemblies off-loaded for pool storage. Other control components may also be present including control rod assemblies (CRAs), axial power shaping rod assemblies (APSRAs), orifice rod assemblies (ORAs), vibration suppression inserts (VSIs), neutron source assemblies (NSAs) and neutron sources (see for example, NRC 2017).

RCCAs consist of neutron absorbing rods (24 in a typical 17×17 PWR assembly) attached to a common spider and hub assembly. RCCAs have fixed alignment with control rod drive openings in the reactor vessel head (Figure 1) and are inserted into guide tubes in fuel assemblies. When assemblies are shuffled during refueling, RCCAs are moved to new locations and reused, or after many cycles they may be moved to spent fuel storage (and stored in spent fuel assemblies). Reconfiguration of RCCAs (e.g., transfers between fuel assemblies) is done in the fuel canal using the refueling machine, RCCA change fixture, and specialized long-handled tools (Westinghouse 1984).

BPRAs are distributed throughout the reactor core (Figure 1) to control long-term variations of reactivity, along with boron dissolved in the coolant. Burnable poison rods are generally depleted in one reactor fuel cycle, can be removed during refueling outages, and are present in many final-cycle discharged assemblies which are then moved to spent fuel storage. Whereas Figure 1 represents a typical first PWR core at startup (loaded entirely with fresh fuel), subsequent core designs can use fewer BPRAs (or fewer poison rods within BPRAs). For convenience in refueling, depleted poison rods may be left in the BPRAs for multiple cycles and ultimately discharged with the spent fuel.

As indicated in Figure 1 not all guide tube locations in BPRA fuel assemblies are occupied by burnable poison rods. To limit bypass coolant flow through open guide tubes during reactor operation, thimble plugs are installed from the top. For the minority of fuel assemblies that have neither RCCAs or BPRAs, thimble plugs are installed in each open guide tube. Thimble plugs may also be installed with RCCAs and BPRAs, if any guide tubes remain open. Thimble plugs that are present at discharge are not removed without reason such as reuse for cost avoidance, and eventually they are moved with spent fuel assemblies to spent fuel storage.

The feasibility of the disposal control rod approach depends in part on the availability of undamaged fuel assemblies with unused guide tubes for rod installation, and the characteristics of irradiated fuel in those fuel assemblies. (Damaged fuel assemblies might also be modified with DCRAs, depending on the type and extent of damage.) To the extent possible, thimble plugs would be removed for DCRAs in lieu of BPRAs or RCCAs, because the plugs represent a smaller volume of separate waste. In general these would be discharged assemblies with BPRAs and possibly some thimble plugs, or assemblies with TPAs and no poison rods. Removing RCCA hardware or burnable poison rods from discharged fuel assemblies would not be preferred because of the need for other means of storage and disposal of the irradiated hardware. Disposal control rods would be configured in DCRAs using a standardized configuration to the extent possible, and installed using specialized long-handled tools in a manner similar to BPRAs. A cluster fixture ("spider") could be prepared for each DCRA in advance, containing the necessary disposal control rods. Specialized DCRA tools could be developed to remove thimble plugs and burnable poison rods, and install disposal control rods in the required configuration. The DCRA station would be located in the fuel pool, outside the reactor containment.

In addition, a few primary and secondary neutron source rods are distributed among the BPRAs, or as secondary source assemblies, and these generally remain in the assemblies at discharge except when the secondary sources are reloaded (Cf-252 primary sources generally decay in one cycle). Instrumentation installed in the central tubes in each assembly is not addressed in this discussion, and would generally be removed and replaced at each refueling outage.

The fuel description information needed to identify which fuel assemblies contain RCCAs, BPRAs, or TPAs is obtainable from the periodic GC-859 survey of utility fuel owners. The criteria for survey response include, but are not limited to, the following information for all fuel in the pool: 1) a count of fuel assemblies at the site containing PWR control hardware (Section E.1); and 2) a specific tie between the fuel assembly ID and the control hardware it contains, if any (Section E.2). Whereas the GC-859 survey is updated every 5 years or so, more current information would presumably be available to the utility for loading DCRAs.

Additional GC-859 information on loading of DPCs is available to assess how many DCRAs *could have* been loaded, and where in the DPC basket. Such analysis could support *a posteriori* analysis of DCRA emplacement feasibility.

Location of control hardware within a DPC is controlled by the canister Certificate of Compliance (CoC), and typically constrains control components to central locations, which likely overlaps with desired locations for DCRAs. For example, the following constraints exist:

- Holtec MPC-32 (CoC 72-1014; NRC 2000a) allows for loading control components in only 12 central storage locations (earlier amendments only allowed for loading in four central locations).
- NAC CY-MPC (Connecticut Yankee) (CoC 72-1025; NRC 2000b) allows for loading of control components in all (24 or 26) locations, within intact fuel assemblies only.
- NAC YANKEE-MPC (Yankee) (CoC 72-1025; NRC 2000b) does not allow for loading of control components in any of the 36 locations.

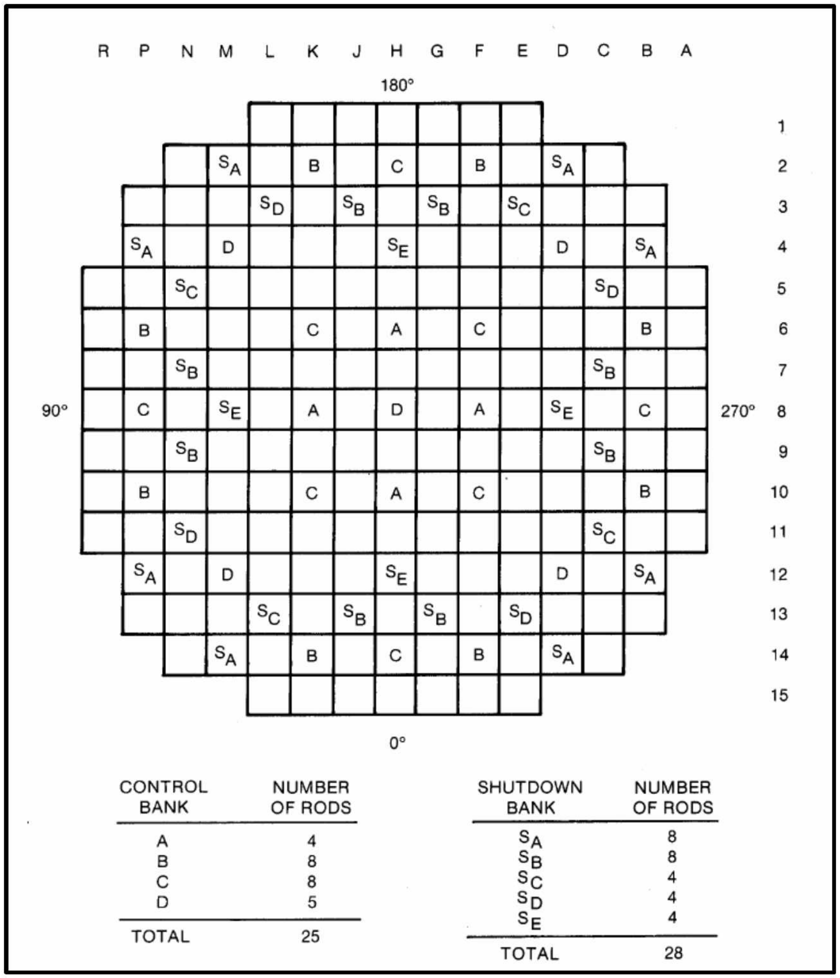
- NAC Magnastor 37-PWR basket (CoC 72-1031; NRC 2009) restricts loading of control components to the center nine fuel locations.
- Transnuclear NUHOMS DSC-24P (CoC 72-1004; NRC 2017) does not allow for loading of control components. The same CoC does allow for loading control components in all locations in the DSC-24PHB and -24 PTH canisters, all 32 locations in the DSC-32PT and -32PTH1 canisters, and all 37 locations in the DSC-37PTH canister.

The principal reason for restricting the locations for loading of control hardware is shielding of radiation from activated metal in those components. The specifications cited above are for storage licenses, but other, more restrictive specifications are possible for transportation. These specifications would not apply to PWR DCRAs directly, but they could impact the locations that are readily available for DCRAs. Importantly, if RCCAs and BPRAs are removed to accommodate DCRAs in a DPC, either they would be reinserted into other fuel assemblies where allowed, or a separate waste stream would result. This discussion is offered here to frame the complexity that could arise in loading design for DPCs with DCRAs. The inventory of PWR fuel assemblies at each utility site containing BPRAs, WABAs, and other devices, is needed to simulate DCRA implementation. Loading of DCRAs would be licensed for disposal of course, and it is possible that the CoCs for DPC storage and transportation would also need to be amended prior to implementation.

A typical 4-loop PWR with 193 fuel assemblies has RCCAs in 53 locations (Figure 1). From geometrical considerations approximately 16 DCRAs would be needed for large PWR DPCs (e.g., with capacity for 32 or 37 assemblies). This estimate is based on a checkerboard arrangement that excludes locations at the edges and corners. Alternatively, EPRI (2008, 2009a) analyzed the reactivity for a 32-assembly DPC with DCRAs in only the four innermost positions, or in all 32 positions, as discussed previously. To determine the number, locations, and neutronic properties of DCRAs requires k_{eff} analysis. Analysis of feasibility should also consider the availability of open guide tubes, and the isotopic content (enrichment, burnup) of the available fuel assemblies.

Dewatering of DPCs containing DCRAs would not differ from dewatering with RCCAs or BPRAs left in place for disposal. This will be addressed in a plan for testing to support evaluation of fuel/basket modifications (planned milestone M3SF-20SN010305054).

The cost of a single PWR disposal control rod would be approximately \$476 based on: 1) approximately \$276 for B_4C pellets (natural B); and 2) assumed cost of \$200 for thin-wall metal tubing plus fabrication and inspection (Table 1). A range of materials could be suitable for tubing, since the guide tubes are typically zirconium alloy and already provide structural performance comparable to fuel rods. Material selection criteria would include welding, size/flexibility, and slow corrosion so that B_4C pellets are retained, and corrosion products do not cause failure of the guide tubes after many thousands of years exposure to ground water. Note that the B&W/ART announcement proposed stainless steel tubing (EPRI 2009b). Extrapolating to 16 DCRAs each with 24 disposal control rods, and including installation labor, the total cost would be \$187k per DPC (Table 1). Backup information for these calculations includes assumed parameter values (Table 2) and development of labor cost estimates (Table 3). Cost estimates in this report do not include licensing activities.



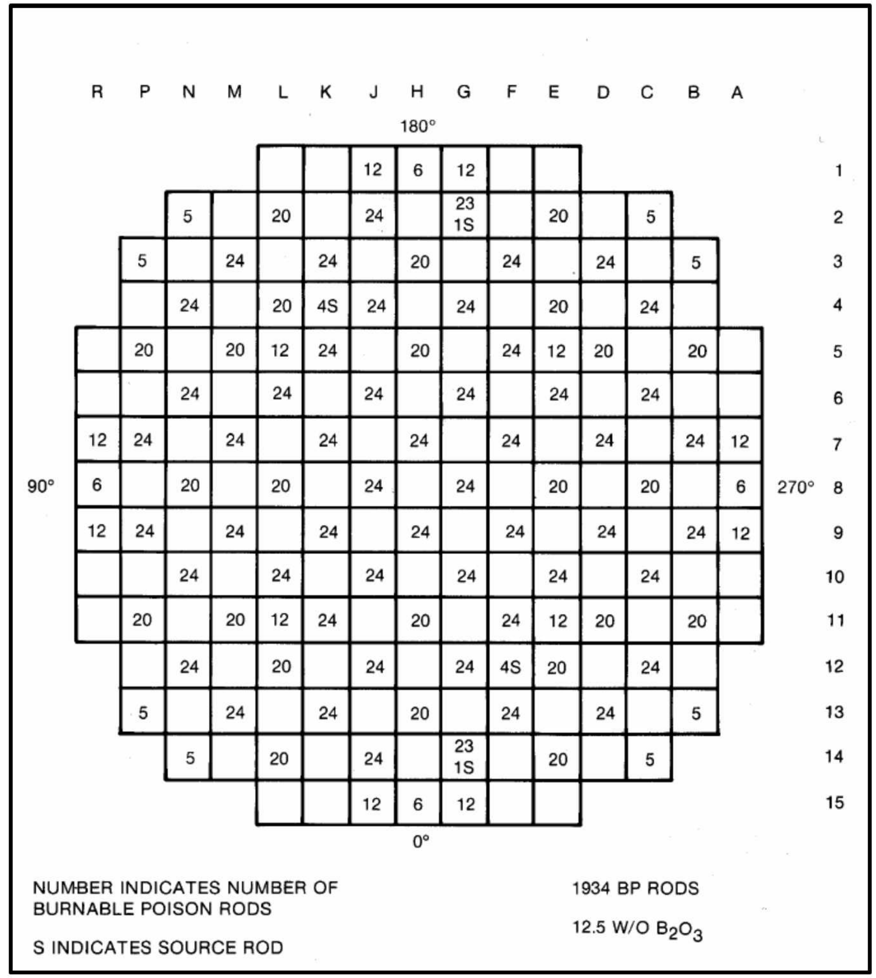


Figure 1. (left) Typical distribution of RCCAs in a first load core. (right) Distribution of BPRAs in a typical first load PWR core with 17x17 assemblies. (Figures 2-7 and 2-9 from Westinghouse 1984)

Table 1. Fuel/basket modification rough-order-of-magnitude cost calculations.

Proposed Modification	Description	Fuel Type	# Modified Assemblies per DPC [A]	Hardware Cost per Assy. Modified [B]	Hardware Cost per DPC [B,C]	Labor Cost per DPC [B,D]	Total Cost per DPC [B]	Avg. Total Cost per MTU [E]	Annual Cost to Modify Projected New DPCs, 2020 $ [F]
PWR Disposal Control Rods	Place sealed metal tubes with B_4C pellets into each of 24 guide tubes.	PWR	~16	$11k	$183k	$4.4k	$0.19M	$13k	$25M
BWR Assembly Re-channeling	Replace channels with 3-mm thick advanced neutron absorbing (ANA) material	BWR	~29	$8.5k	$246k	$12k	$0.28M [G]	$23k [G]	$24M [G]
Chevron Inserts	Insert 3-mm bi-fold plate into each basket cell modified	PWR	~25	$4.4k	$109k	$2.8k	$0.11M	$7.8k	$15M
Chevron Inserts	Insert 3-mm bi-fold plate into each basket cell modified	BWR	~51	$3.2k	$165k	$5.8k	$0.17M	$14k	$15M

Notes:
[A] Based on geometry; see text.
[B] Rough-order-of-magnitude cost estimates, rounded to 2 significant figures; see text.
[C] Assume 32-PWR DPC or 68-BWR DPC as average fleet-wide future capacities, as applicable.
[D] See Table 3.
[E] Assume 0.45 MTU/PWR assembly, or 0.18 MTU/BWR assembly, for all assembles in a DPC (modified or not).
[F] Assume 3,000 MTU/yr is loaded into DPCs (1,950 MTU of PWR and 1,050 MTU of BWR SNF) each year.
[G] Includes disposal cost for original channels based on Section 1.3 and unit rate for LLW disposal in Table 2. Disposal of channels as GTCC waste would increase these cost figures for re-channeling by 14% (assuming no consolidation of waste volume).

Proposed Modification	Description	Fuel Type	# Modified Assemblies per DPC [A]	Hardware Cost per Assy. Modified [B]	Hardware Cost per DPC [B,C]	Labor Cost per DPC [B,D]	Total Cost per DPC [B]	Avg. Total Cost per MTU [E]	Annual Cost to Modify Projected New DPCs, 2020 $ [F]
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[A] Based on geometry; see text.
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[G] Includes disposal cost for original channels based on Section 1.3 and unit rate for LLW disposal in Table 2. Disposal of channels as GTCC waste would increase these cost figures for re-channeling by 14%.

Table 2. Assumed parameter values for fuel/basket modification cost calculations.

Assumed SNF inventory (MTU fraction)	65% PWR, 35% BWR
Assumed annual dry storage throughput	3,000 MTU (long-term average projected for 2030-2050; Gunter and Hardin, 2018)
DPC capacity	32-PWR or 68-BWR (used as a representative future average)
MTU per assembly	0.45 MTU (typical PWR), 0.18 MTU (typical BWR, e.g., GE-4 8x8)
Absorber rod or plate length	4 m
DCRA control rods per PWR assembly	24 (estimated)
B_4C pellet diameter	8.4 mm
B_4C pellet density	2,500 kg/m^3 (typical)
B_4C pellet volume per rod	2.22x10^{-4} m^3 (per 4 m length)
B_4C pellet mass per rod	0.552 kg
B_4C pellet cost per kg [A]	$500 (assumed)
Incidental cost per rod [A]	$200 (tubing and end plug material, machining, welding, inspection)
Rod tubing OD, m	0.00988
Rod tubing ID, m	0.00888
Tube weight with ends, kg	0.500
Chevron insert half-width, PWR	0.200 m
Chevron insert half-width, BWR	0.142 m
Number of inserts per DPC (estimated)	25 (PWR) or 51 (BWR)
Number of re-channels per DPC (estimated)	29
Re-channel width	0.142 m
Absorber thickness	3 mm (for re-channel or insert; see text)
ANA density	8,690 kg/m^3
ANA plate cost	$93/kg (Alloy 22 with 2% Gd_2O_3, milled; shipping + admin.)
Re-channel fabrication cost [B]	$3,000 (assumed)
Chevron insert fabrication cost [B]	$500 (assumed)
GTCC waste disposal cost (solid)	$27,000/m^3 (Shropshire et al. 2009, Module G5)
LLW disposal cost (solid) [C]	$10,000/m^3 (EnergySolutions 2013)

Notes:

[A] Cost estimates based on industrial grade (stainless steel) or scientific reagent grade (B_4C) materials, with a ~200% allowance for handling, machining, administration, and quality assurance/quality control (QA/QC; quantity pricing).

[B] Estimates for bending, forming, welding (as needed), inspection, shipping, administration, and QA/QC (quantity pricing).

[C] Based on historical charges at the Clive, UT disposal facility. This is at the lower end of the range of disposal cost considered.

Table 3. Utility cost estimates for fuel/basket modifications (author's engineering judgment).

PWR DPC Disposal Control Rod Assembly Installation		Resource	Quantity	Cost ($/hr)	Comments
Installation Rate (DCRAs/hour)	3	Fuel Handling Supervisor	1	$ 90	
Scope (DCRAs)	16	Fuel Handler	4	$ 280	
Duration (hours)	9	Crane Operator	1	$ 70	Duration adjusted by efficiency factor (10/6)
		Rad Prot Tech	1	$ 60	
Labor Cost ($)	$ 4,444		Total	$ 500	

BWR Fuel Rechanneling		Resource	Quantity	Cost ($/hr)	Comments
Rechannel Rate (pairs/hour)	2	Fuel Handling Supervisor	1	$ 90	A "pair" consists of removal/storage of old channel and installation of new channel
Scope (pairs)	29	Fuel Handler	4	$ 280	
Duration (hours)	24	Crane Operator	1	$ 70	Duration adjusted by efficiency factor (10/6)
		Rad Prot Tech	1	$ 60	
Labor Cost ($)	$ 12,083		Total	$ 500	

BWR DPC Chevron Installation		Resource	Quantity	Cost ($/hr)	Comments
Installation Rate (chevrons/hour)	5	Fuel Handler	3	$ 210	
Scope (chevrons)	51	Crane Operator	1	$ 70	
Duration (hours)	17	Rad Prot Tech	1	$ 60	Duration adjusted by efficiency factor (10/6)
Labor Cost ($)	$ 5,780		Total	$ 340	

PWR DPC Chevron Installation		Resource	Quantity	Cost ($/hr)	Comments
Installation Rate (chevrons/hour)	5	Fuel Handler	3	$ 210	
Scope (chevrons)	25	Crane Operator	1	$ 70	
Duration (hours)	8	Rad Prot Tech	1	$ 60	Duration adjusted by efficiency factor (10/6)
Labor Cost ($)	$ 2,833		Total	$ 340	

1.2 BWR Control Rods

This option is an extension of the PWR DCRA concept, and has only been studied in the present R&D program. Like the PWR approach, it would require minor modification of spent fuel assemblies and no modification of existing basket designs.

Water rod geometry resembled fuel rods in the original GE fuel designs, but more recent designs have larger diameter cavities containing multiple tubes, some of which have variable diameter (Figure 2). Unlike the PWR DCRA concept, individual BWR fuel assemblies are not designed for insertion of control elements. Reliance on cruciate control blades for disposal criticality control would require redesign of DPC baskets (Section 2.2). Also, PWR reactor sites all currently have tools for insertion and removal of internal control rods, whereas such tools would need to be developed for BWR DCRAs. Note that multiple BWR fuel assembly types may be used at a utility site, increasing the variation of tooling and disposal hardware that could be needed.

Detailed description of BWR fuel components and geometry is beyond the scope of this report, and much of the detail is proprietary information. BWR fuel assembly configurations have evolved from 6x6 through 11x11 arrays (Weihermiller and Allison 1979), with 10x10 fuel commonly used today, and 12x12 fuel proposed for advanced designs. Whereas the basic design is similar among all current vendors (tie plates, fueled tie rods, partial fuel rods, water rods, grid spacers, channel, nose piece, handle) the water rod geometry has evolved since the first 8x8 fuel which had a single water rod (replacing one fuel rod, GE-4 series). The GE-4 and later fuel designs were typically retrofitted to all Gen-II BWRs, so that much, but not all of the fuel that has arisen from production BWRs has at least one water rod.

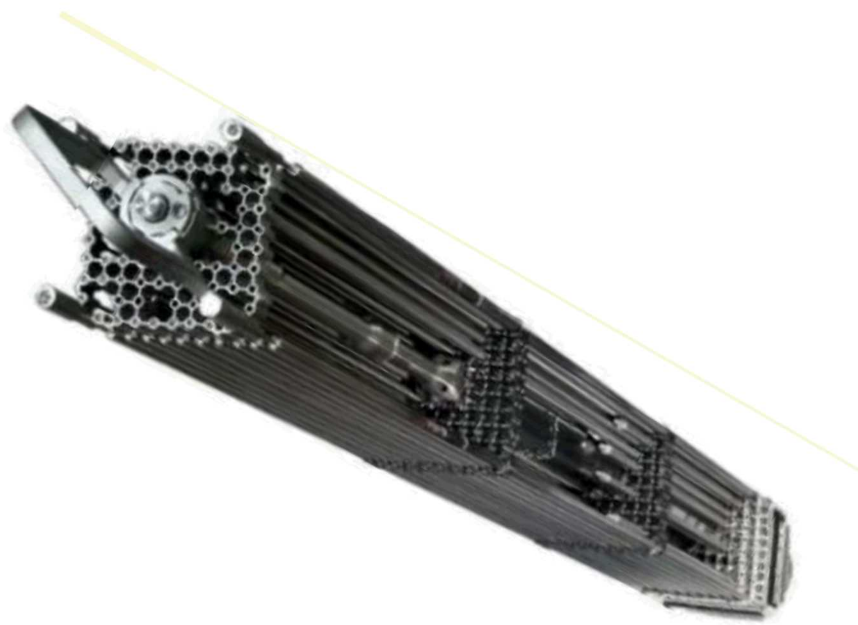

Figure 2. Recent BWR fuel assembly (Framatome/Areva Atrium 10XM®) cutaway with channel removed, showing the single large water rod with fitting on the top.

The neutronic feasibility of the disposal control rod approach depends on access to water rods for installing disposal control rods, and on sufficient neutron absorption worth from one or two rods per assembly. Like the PWR DCRA approach, disposal control rods would be installed mainly in undamaged BWR fuel assemblies using specialized long-handled tools. A cluster fixture would probably not be used since only one or two disposal rods would be installed per assembly. The DCRA station would be located in the fuel pool, outside the reactor containment. The BWR assembly bail handle is always located above the water rod openings, so the handle would probably need to be removed for rod installation.

From geometrical considerations a significant number, perhaps dozens, of BWR DCRAs would be needed for large BWR DPCs (e.g., with capacity of 68 or 89 assemblies), depending on the worth of the DCRAs in a DPC basket configuration. The number, location, and neutronic properties of DCRAs in a DPC would require analysis of degraded geometry, and k_{eff} analysis.

The option for BWR DCRAs has a number of challenges that will likely disqualify it from implementation. First, it doesn't provide a solution for the perhaps hundreds of 6x6 and early 7x7 GE fuel assemblies which contained no water rods (these typically have low enrichment, and may not require modification to remain subcritical in a repository anyway). Second, many assembly types have water rods that lack large openings in the axial direction to accommodate insertion of a disposal control rod. Third, to access the water rod, the fuel channel and upper tie plate assembly must be removed (Figure 3).

Removal of fuel channels and replacing them with new fuel channels is a fairly routine operation at a number of operating reactors, to manage channel distortion caused by corrosion or differential fluence. The fuel assembly is first placed in the fuel preparation machine and the channel clip located on an upper corner of the fuel assembly is unbolted. The fuel channel is then lifted off the top of the fuel bundle and placed in a nearby storage location. A replacement fuel channel is then placed over the fuel bundle and a new channel clip is bolted in place.

BWR fuel disassembly beyond fuel channel removal is not recommended. To access the water rod, the upper tie plate (BWR analog of the PWR upper nozzle) must be removed. This requires removal of the nuts from the eight tie rods, removal of the nut capture hardware, and removal of the upper tie plate. This process has damaged the tie rods from the torque used to remove the nuts, which can break the fuel cladding at any weak location along the length of the rod, in particular at lower end plug welds or where defects may exist along the cladding surface. Fuel reassembly proceeds in the reverse sequence. The upper tie plate is re-seated on the top of the fuel rods, new tie rod nut capture hardware and tie rod nuts are installed, and a fuel channel is placed over the fuel bundle and a new channel clip is bolted in place. The fuel assembly can then placed in its storage location in the pool, or in a DPC.

Because of feasibility questions the BWR DCRA option is unlikely to be implemented especially if better options are available (i.e., re-channeling or chevron inserts).

1.3 BWR Fuel Re-Channeling

All BWR assembly designs use channels to mechanically protect the fuel, control coolant flow, and guide the control blades. The re-channeling approach for disposal criticality control would replace the fuel channels (Figure 3) on selected BWR assemblies, with channels fabricated from corrosion-resistant advanced neutron absorbing (ANA) material. The approach is potentially applicable to all BWR fuel designs, and all DPC basket designs with sufficient clearance for the required disposal channel thickness. The original fuel channels could be removed from above, with the assembly in a fuel preparation machine, and replaced by the ANA channels. Thus the installation would be done in the spent fuel pool, separate from refueling or DPC loading activities. The ANA disposal channels would be designed to interface with the assembly tie plate geometry and mounting points in the same way as the original channels, which vary across fuel assembly vendors and designs.

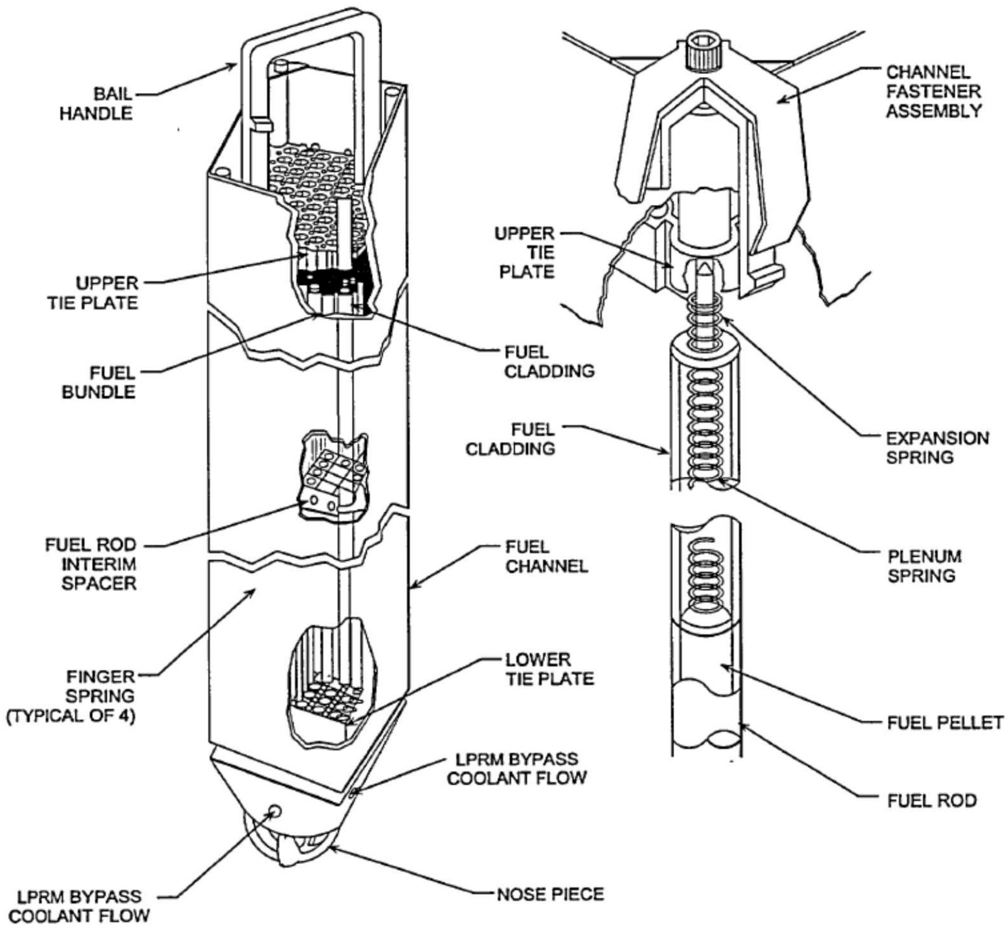

Figure 3. BWR fuel assembly schematic showing fuel channel and channel fastener (Figure 2.2-1 from NRC 2006).

Note that BWR fuel modification may not be needed if as-loaded BWR DPCs can be shown to have sufficient reactivity margin. Such a result depends on the outcome of enhanced BWR fuel burnup analysis (discussed in Section 3).

The re-channeling approach requires availability of a proven ANA material with sufficiently slow general corrosion in the disposal environment. The Hastelloy-based ANA developed in the 2000's and currently being investigated (Blink et al. 2019) is similar in composition to Alloy C-4 and Alloy C-22 (Ni-Cr-Mo) with inclusions of Gd-based absorber (2.0 wt. % natural Gd). An alternative could be a modern borated stainless steel, possibly using highly enriched boron to improve corrosion resistance by decreasing the metallurgical effects from boron. In order for re-channeling to be effective and licensable for a range of generic (non-site specific) disposal environments, its corrosion resistance must be demonstrated for a wide range of potential ground water compositions. Also, ductility, strength, rolling, and welding properties of ANA would be important for fabrication, and prototype testing and examination would be needed.

Required thickness of ANA can be estimated from the absorber plate configuration developed for the triple-purpose canister proposed for the repository in unsaturated tuff (DOE 2008a,b). The basket in that specification would use borated Type 304 stainless steel (304B4, nominally 1.2 wt. % natural B) with a required minimum thickness of 6 mm. The required ANA thickness (2 wt. % natural Gd) for an equivalent thermal neutron absorption cross-section is approximately 1 mm (by analogy to Gd-stainless steel analyzed by Mizia et al. 2001). Additional ANA thickness of approximately 2 mm or more would be added for corrosion allowance (depending on the disposal environment and measured rates of general corrosion). For example, two-sided general corrosion totaling 2 mm in 10,000 years corresponds to an allowable maximum rate of 100 nm/yr. Hastelloy compositions and stainless steel formulations have been demonstrated to corrode this slowly in various environments, but testing continues (Blink et al. 2019).

The channel on BWR-2 through -5 generation fuel assemblies has an inner width of 5.278 in. (nominal), and a wall thickness of 0.80 to 0.120 in (2 to 3 mm; see Moore and Notz 1989). Using the maximum channel wall thickness, the overall width is nominally 5.52 in. As an example, the fuel cell width for the Holtec UMAX MPC-89 DPC basket is 5.99 in. (min. nominal; NRC 2014), leaving a total clearance of 12 mm in the x- and y-directions. For this example the use of 3 mm thick channels would leave 6 mm clearance in both directions. Another 1 mm of channel thickness, if needed for additional corrosion allowance, might be obtained by reducing the 6 mm clearance values to 4 mm. Note that re-channeling could correct issues caused by distortion of the original channels (and re-channeling could be applied selectively to assemblies with distorted fuel channels).

The number, location, and neutronic properties of re-channeled assemblies in a DPC would require analysis of degraded geometry, and k_{eff} analysis (planned milestone M3SF-20OR0103050126). From geometrical considerations approximately 29 re-channeled assemblies would be needed for the BWR DPC (e.g., MPC-68 or MPC-89). This arrangement would ensure one re-channeled wall thickness between any two adjacent assemblies, except where one of those assemblies has two external surfaces, or one external surface with absorber plate on two other surfaces. Ongoing modeling studies are intended to evaluate whether degradation of fuel assemblies and the DPC basket would occur in a manner that preserves the interposition of the ANA fuel channels between fuel assemblies (SNL-ICG 2019).

Dewatering of re-channeled BWR assemblies would not differ much from assemblies with the original channels, if the new channels have the same configuration and similar surface properties.

The cost of Alloy 22 with 2% Gd addition is approximately $93 per kg, delivered as 3 mm thick sheets (Haynes International communication, April 8, 2020). This is based on a quoted cost for ingot-prepared Alloy 22 of $40/kg, an assumed cost increase of 50% for Gd addition and waste scrap, and a cost of $33/kg for shipping, storage, and inspection. The 2 wt. % Gd addition itself increases the cost only slightly.

The cost estimates for re-channeling as reported in Table 1 are based on disposal of old channels as unconsolidated low-level waste (LLW). Each channel occupies a volume of approximately

81 liters leading to 2.35 m^3 per DPC (29 channels), and a cost of $23.5k (see Table 2). Disposal as greater-than-Class-C (GTCC) waste would add approximately 14% to the indicated cost estimates in Table 1. Consolidation of these channels by pressing could reduce their volume by 6-fold (by analogy to reduction of non-fuel products of rod consolidation; IAEA 1992) and thereby decrease re-channeling cost by a few percent.

With an assumed fabrication cost of $3,000 per channel, the overall hardware cost for each BWR assembly is estimated to be $8k, and the cost for one DPC (29 re-channeled assemblies in a large capacity basket) would be approximately $322k (see Tables 1 and 2; includes disposal of 29 unconsolidated original channels as GTCC).

1.4 Zone Loading to Limit Reactivity

Zone loading strategy would be a refinement of the reactivity margin approach to analyzing the potential for postclosure criticality, which has already been demonstrated for a significant fraction of the existing fleet of as-loaded DPCs (Clarity et al. 2019). Implementation of zone loading would involve only analysis of postclosure criticality for loading maps, and recertification of loading protocols. These steps are inherent to all fuel/basket modification alternatives. Shuffling of assembly loading in DPCs is inherent to other options including PWR DCRAs and possibly BWR re-channeling or chevron inserts, since there may be tradeoffs between assembly locations and the number and distribution of added absorber features.

As noted previously, analysis of as-loaded 32-PWR assembly DPCs suggested that only a 1 to 2% reduction in k_{eff} could be expected (EPRI 2008, 2009a). Such reduction would be small, but this result does not factor in: 1) the range of as-loaded fuel characteristics possible in DPCs to be loaded in the future; and 2) the possibility of selecting low-reactivity assemblies from the fuel pool during DPC loading. A wider range of reactivity reduction from rearranging assemblies in DPCs (up to approximately 10%) is supported by the misload analyses from Clarity et al. (2019, Appendices C and D). For idealized zone loading, selected low-reactivity assemblies would go into central basket positions, thereby making some DPCs loaded at a site directly disposable by limiting the likelihood of postclosure criticality even for degraded disposal conditions. How many DPCs loaded at a site would be subcritical depends on the site inventory.

There are potential complications with the approach: 1) vendor-specific loading maps show thermal power limits for loading positions (e.g., NRC 2014) that may not correspond to criteria for low reactivity, particularly if thermal management loading choices conflict with low-reactivity choices; 2) worker dose is generally a greater priority to utility operators than other factors, within the requirements of the CoCs, and although loading choices for shielding may be similar to choices for low reactivity, there may be conflicts; and 3) utilities may already have loaded older, colder, lower-enrichment, lower-reactivity, less radioactive fuel (or some combination of these qualities) into dry storage because of past loading strategies, and also that much of the oldest fuel now in pools may include "damaged fuel" which has particular loading requirements (e.g., basket locations, and assuming fresh fuel for reactivity analysis).

Zone loading analysis would likely rely on the same stylized degradation cases (loss of absorbers, and loss of basket with absorbers) that have been used in reactivity margin calculations (Clarity et al. 2019). These are conservative configurations in that basket components are fully degraded while fuel pitch within each assembly is unchanged. The approach may be consistent with configurations described in a topical report developed in the early 2000s for purpose-designed canisters (DOE 2003), but the subject is complex and the analysis of postclosure criticality for as-loaded DPCs has never been subjected to regulatory review. It should also be noted that a zone-loading strategy could complicate probabilistic misload analysis that would be required to support risk-informed licensing. Analysis of zone-loading for a particular site, accounting for fuel inventory available for DPC loading, is needed to evaluate feasibility (planned milestone M3SF-20OR0103050127).

1.5 Rod Consolidation

Both PWR and BWR fuel assemblies can be disassembled, and the rods re-packed closely at minimum pitch (~2:1 volume reduction). Rod consolidation was investigated extensively in the 1980's and early 1990's as a solution to the emergent problem of spent fuel pool capacity, but was supplanted by dry storage technologies. It has the significant advantage over disposal of intact fuel assemblies, that consolidated fuel is less reactive and neutron absorbing materials are not required for packaging.

Fuel disassembly would necessarily involve control of contamination from release of corrosion products (primarily from BWR fuel) and from damage to fuel rods as they are extracted from the spacer grids and end plates/nozzles. If done dry, then a hot cell would be required such as the pilot-scale consolidation plant built at Gorleben, Germany (Baier et al. 1999) which has never operated "hot." Alternatively, disassembly could be done wet which could require intensive filtration for maintaining pool conditions, beyond what is needed only for fuel storage. Non-fuel components from disassembly can be compacted by approximately 6:1 compared to the original assembly volume (IAEA 1992). Non-fuel components could then be disposed of along with consolidated rods in spent fuel waste packages, in a manner similar to damaged fuel assemblies.

Chopping of fuel assemblies could avoid dealing with "stuck" fuel rods during disassembly, but would significantly increase contamination and would not achieve the same reduction in fuel volume (or reduction in reactivity). It would be costly and could increase worker dose. Disposal packaging would be similar to packaging of damaged fuel.

Rod consolidation as an alternative to future loading of DPCs has significant disadvantages that were understood in the early 1990s when the utilities turned to dry storage. It would require pool equipment modification and redesign of storage systems, in many utility locations. It would lack key advantages of other fuel modification approaches, principally the use of existing canister and basket designs from multiple vendors.

2. Basket Modification

This section describes modifications to DPC baskets that could be made external to fuel assemblies, for control of disposal criticality. The discussion below describes insert hardware that would not require changing current basket designs, and also direct basket modifications that would involve significant design changes.

2.1 Absorber Plate Replacement (Basket Redesign)

Replacing Boral®, Metamic-HT® or other aluminum-based materials in DPC baskets with more corrosion resistant ANA materials, would require basket redesign and changes to DPC specifications. This outcome is beyond the objective of this assessment to identify fuel/basket modifications that could work with any baskets from any vendor, without significant redesign or reanalysis. However, once ANA material becomes available for use in DPC criticality control, it is likely that new versions of existing basket designs would be developed by vendors.

There are three basic functions for basket materials: structural, heat rejection, and neutron absorption. Aluminum-based metal-matrix-composite (MMC) materials combine these functions, and no known class of corrosion-resistant materials can replace aluminum MMCs in the recent designs with MMC baskets. Instead, ANA material would likely replace Boral® absorber sheets in some designs with stainless steel baskets, and would be added to MMC basket structure. We note that ANA materials (Ni-Cr-Mo-Gd as described in Section 1.3, or other corrosion resistant materials such as borated stainless steel) will likely be lesser conductors of heat than aluminum MMCs or ceramic-metal composites, which could lead to significant basket redesign or changes in heat rejection specifications.

A previous study presented specifications for design of a standardized triple-purpose canister suitable for a range of repository geologic settings (ORNL 2015a, 2015b). The specification described a large canister for commercial SNF (21 PWR or 44 BWR assemblies) that would use borated stainless steel for both preclosure and postclosure criticality control. Another study (RWM 2014) also describes a relatively large (12-PWR) triple-purpose canister with borated stainless steel plates. These studies could be a starting point for DPC absorber plate modifications, as required to achieve disposal criticality control in one or more geologic repository settings. Improvement on corrosion performance of borated stainless steel may be achieved using ANA materials as discussed previously (Blink et al. 2019).

Early dry storage canister and cask designs also used borated stainless steel for neutron absorption. Examples include the FuelSolutions® W74 series canisters, the Castor V/21 and X/33 dry storage casks, and the TN-REG and TN-BRP storage and transport casks. These were generally not intended for disposal except for the W74M, which is a weld-sealed canister for 64 BWR assemblies that is licensed for storage and transport but not disposal (Greene et al. 2013).

Another possible basket redesign concept is to allow the use of BWR control blades for postclosure criticality control. However, BWR control blades are typically stainless steel clad hafnium plates or stainless steel encased B_4C-filled rods. Existing reactor control blades would likely need to be modified to ensure longevity in the disposal environment, such that they would resemble absorber plates. There is no precedent for installing control blades in DPC baskets resembling current designs, and placement of control blades between assemblies (or groups of four) could involve significant changes to basket designs. Required changes might also include disassembly or other post-irradiation modifications to the control blade assemblies themselves, since BWR control blade assemblies are designed to actuate from below whereas DPCs are loaded from above. Overall, the modification of BWR DPCs to accommodate control blades for postclosure criticality control, would involve extensive basket redesign and other technical challenges that would be infeasible compared with alternative fuel/basket modification approaches.

2.2 Chevron Insert Absorber Plates

Chevron-shaped inserts (longitudinal bi-fold plates; Figure 4) were invented to supplement neutron absorption in spent fuel pool racks after degradation of polymeric boron-containing absorber material. Basket inserts could be used with either PWR or BWR fuel, and require only that there be sufficient clearance in the basket fuel cell. The insert concept has been effective for retrofitting fuel racks in pools, but widespread use could be subject to operational sensitivity from bowed or twisted fuel assemblies (particularly BWR fuel with distorted channels).

Inserts for DPCs are posited here as a technical solution for: 1) use with baskets made from aluminum-based MMC materials; or 2) any difficulties that might arise with replacing absorber plates (Section 2.1). Both applications may be considered as retrofits, just as inserts have been used in the past to retrofit racks in spent fuel pools. Aluminum-based baskets so-equipped could have the advantages of the MMC material (light weight, heat rejection) combined with improved postclosure criticality control.

According to EPRI (2009b):

> "…a chevron shaped insert called a NETCO-Snap-In® absorber is elastically deformed as it is inserted into a storage cell and locks in place when fully inserted. Semi-scale inserts have been fabricated and tested. A full scale demonstration has been completed and production-scale fabrication has started…Another supplemental absorber system, called Racksaver, is a chevron that fits onto spent fuel assemblies and has an upper fitting that rests on the upper fuel assembly nozzle."

Holtec International markets a chevron insert system (Dream® inserts) and holds a related patent (U.S. 8,158,962 B1) for storage and transportation applications. An example Holtec insert (Figure 3) is made from Metamic® absorber material and is designed to be inserted into a fuel rack position after the fuel assembly is inserted, and hang from the top. Another example from a 1998 patent (U.S. 5,841,825) is designed to be attached to a fuel assembly before insertion into a fuel rack (Figure 3). Other patents (U.S. 5,629,964; U.S. 6,741,669 B2; others) also pertain to chevron inserts for spent fuel pool storage racks.

Chevron inserts could be inserted in every cell of a DPC basket (except those at the edges where they may not be needed for reactivity control) without changing the basket design, if there is sufficient clearance. Chevron inserts could reduce fuel cell clearance by 3 to 4 mm in both the x- and y-directions (assuming at least 3 mm ANA thickness is needed). Inserts could be designed for installation in DPC baskets before the canisters are delivered to the spent fuel building, i.e., prior to immersing a new canister in the fuel pool. For BWR assemblies with fuel channels, inserts could be readily installed in baskets after loading fuel, since the fuel channel could act as a guide for the insert.

For situations where inserts would leave insufficient clearance for BWR fuel, the original fuel channels could be removed (Section 1.3) to provide additional clearance of 0.160 to 0.240 in (4 to 6 mm; twice the channel thickness range identified previously). Removing irradiated fuel channels would create a new waste stream (LLW, or possibly GTCC; see Section 1.3), and would warrant a close feasibility comparison between inserts and re-channeling for BWR SNF.

Specifying the number and location mapping of inserts requires k_{eff} analysis (planned milestone M3SF-20OR0103050126). From geometrical considerations approximately 25 chevron inserts would be needed for a PWR DPC (32-assemblies) and 51 for a BWR DPC (68 assemblies). Geometric estimates are generated by neglecting those edge cells with two external surfaces, or with one external surface and absorber plates on at least two other faces.

The cost of ANA sheet (discussed above for re-channeling) would be approximately $93 per kg. The overall cost of 25 inserts for a 32-BWR DPC, each weighing 41.7 kg, and including labor for installation, would be approximately $112k per DPC (Table 1). The overall cost of 51 inserts for a 68-BWR DPC, each weighing 29.7 kg, would be approximately $171k per DPC, including labor (Table 1). The impact of additional weight from criticality control features on DPC hoisting in existing fuel management facilities is discussed in Section 3.

The insert approach depends on the availability of corrosion resistant ANA material as discussed above for re-channeling, with ductility, strength, and rolling properties suitable for fabrication. Welding properties could also be important for attachment of clips, guides, etc. needed to handle the inserts and retain them in place in the basket. As stated previously, prototype testing and examination would be needed.

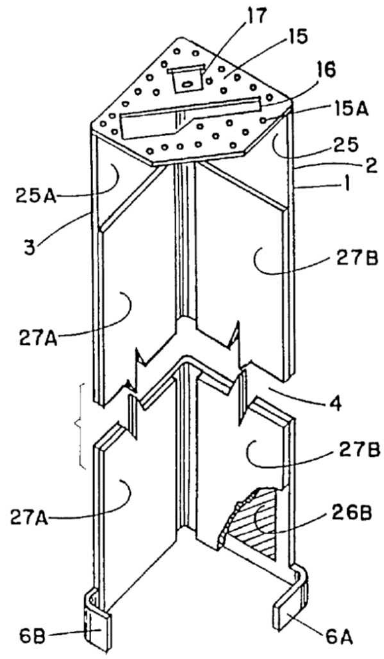

Figure 4. (left) Holtec Dream® C1 insert for storage racks at the Turkey Point and St. Lucie plants (Holtec Tech. Bulletin HTB-012). (right) Chevron insert sketch from 1998 US Patent 5,841,825. (Note that features of these systems are subject to copyrights and patents.)

Dewatering of DPCs with many chevron inserts installed could differ from dewatering without inserts because of additional surface area, and the area of insert contact with BWR and PWR basket features and BWR fuel channels. For example, the impact of the chevrons during helium circulation using the Holtec-proprietary Forced Helium Dehydration system would have to be considered. This will be addressed in preparation of a plan for testing to support evaluation of fuel/basket modifications (planned milestone M3SF-20SN010305054).

3. Discussion, Conclusions, and Recommendations

3.1 Hook Load Limits

A key constraint on fuel pool DPC operations is the primary crane hook load limit. Each of the fuel/basket modification solutions identified here would add weight to DPCs (Table 4). Allowable weight increases vary by site and must be evaluated to determine feasibility.

The following discussion focuses on utility fuel pools with the common hook load capacity of 125 short tons (250 kip). Some facilities have larger cranes, but most have at least 125-ton capacity if they are loading 24-PWR/56-BWR or larger DPCs.

The description of DPC systems by Greene et al. (2013) allows a preliminary comparison of loaded transfer cask weight (containing a loaded canister, plus filled with water as it is hoisted from the pool). For many transfer casks, the maximum loaded weight (dry) is reported (Table 5).

Table 4. Rough-order-of-magnitude DPC weight increase from fuel/basket modifications.

	Plate Mass, kg	Total Added Mass of Modifications, kg per DPC [A]	Total Weight of Modifications, lb per DPC
PWR DCRA		404 [B]	889
BWR Re-channel	59.3	422 to 855 [C]	928 to 1,881 [C]
PWR Insert	41.7	1,043	2,294
BWR Insert	29.7	1,513	3,329

Notes:
[A] Assume typical DPC capacities and assumed modifications described in Table 1.
[B] Neglect weight decrease from any RCCAs or BPRAs removed.
[C] Assume both the original and ANA replacement channels are 3 mm thick. For fuel with thinner original channels (e.g., 2 mm) the added mass would be approx. 855 kg (1,881 lb) for 29 ANA replacement channels.

For the NUHOMS series, it is necessary to add the empty transfer cask weight with the maximum loaded canister weight (Table 5). The goal of the exercise is to determine which DPC systems can be loaded with fuel/basket modifications totaling approximately 3,500 lb or less (bounding Table 4), plus approximately 13,200 lb. (6,000 liters) of water, and still meet a 125 ton hook limit. Many DPCs are smaller and contain less water, but the 13,200 lb. figure is bounding for a greater set of existing DPC designs. (No attempt to calculate the void volume of DPCs was made for this study.) The resulting maximum dry weight for transfer cask + loaded DPC is 233.3 kip, and the larger capacity transfer cask-canister combinations that are most likely to exceed this value are indicated in Table 5.

For heavier canisters up to approximately 13,200 lb. additional margin might be obtained by draining the fuel canister of water before it is hoisted out of the pool. By pumping out the water, the dry limit of cask + loaded canister for which fuel/basket modifications could be accommodated with a 250 kip hook load limit, could be extended as high as approximately 246 kip. The practice is apparently routine for loading of large DPCs at some sites, but the feasibility of applying it to support fuel/basket modification on a system-wide basis is beyond the scope of this report.

For the NUHOMS canisters from Transnuclear (ORANO) the weights of empty transfer casks and loaded fuel canisters are reported separately and must be added. Hence, empty cask weight values from Greene et al. (2013) are added to the bounding loaded canister weights in each capacity range from the same source (Table 6), to arrive at the dry weights for NUHOMS systems in Table 5.

The preliminary analysis represented by Tables 5 and 6 is intended to be bounding, but it lacks detail as to what canisters and transfer casks are actually being deployed at individual sites, and the hook load limits at those sites. Special variants of canisters and casks are in use across the utility industry. Site-specific analysis of hook load margins could support estimates for the numbers of sites that can accommodate additional canister weight in the form of disposal criticality control hardware. At the same time, more detailed specification of the control features such as dimensions and the number needed for each DPC, would produce better estimates of proposed weight increases. Note that this analysis does not account for other weight factors such as rigging, and that any practice that increases hook loads in any licensed facility would require regulatory review.

Table 5. Estimated maximum loaded dry weight for transfer casks containing loaded canisters (data from Greene et al. 2013).

Transfer Cask	Vendor	Compatible Canisters	Loaded Dry Wt., kip	Compatible Canisters	Loaded Dry Wt., kip	Compatible Canisters	Loaded Dry Wt., kip	Compatible Canisters	Loaded Dry Wt., kip
HI-TRAC 100	Holtec	MPC-24	≤ 194.5	MPC-32	199.0	MPC-68	196.5		
HI-TRAC 125	Holtec	MPC-24	≤ 240.5	***MPC-32***	***245.0***	***MPC-68***	***242.5***		
HI-TRAC 125D	Holtec	MPC-24	≤ 231.5	***MPC-32***	***236.0***	MPC-68	233.5		
HI-TRAC VW (min. Pb shielding)	Holtec	MPC-37	186.0	MPC-89	186.0				
HI-TRAC VW (max. Pb shielding)	Holtec	***MPC-37***	***270.0***	**MPC-89**	**270.0**				
Class 1	NAC	Class 1 (24-PWR)	182.9						
Class 2	NAC	Class 2 (24-PWR)	190.1						
Class 3	NAC	Class 3 (24-PWR)	192.2						
Class 4	NAC	Class 4 (56-BWR)	193.0						
Class 5	NAC	Class 5 (56-BWR)	196.2						
MTC	NAC	Magnastor 37	212.0	Magnastor 87	213.0				
OS197	Transnuclear	24XXX (PWR)	205.0	32XX (PWR)	221.3	52XX (BWR)	186.2	61XXX (BWR)	204.4
OS197H	Transnuclear	24XXX (PWR)	205.0	32XX (PWR)	221.3	52XX (BWR)	186.2		
OS197FC	Transnuclear	24XXX (PWR)	205.0						
Standard	Transnuclear	24XX (PWR)	207.2	52XX (BWR)	188.4				
MP187 (transport + transfer cask)	Transnuclear	***24XX (PWR)***	***252.3***						
OS187H	Transnuclear	32XX (PWR)	229.9						
OS200	Transnuclear	***32XX (PWR)***	***240.3***	61XX (PWR)	223.4				
OS200FC	Transnuclear	***32XX (PWR)***	***240.3***	***37XX (PWR)***	***239.6***				

Notes:
1. Canister-transfer cask combinations shown in ***bold italics***, would potentially exceed a 250 kip hook load limit, with added features and filled with water.
2. Use maximum weights for families of canister systems were applicable.
3. Weight precision approx. the same as Greene et al. (2013)
4. For NUHOMS, add empty transfer cask plus loaded canister. Use heaviest canister in each size range (see Table 6).

Table 6. Bounding of maximum fuel canister loaded dry weight (compiled from Greene et al. 2013).

Canister loaded weights (lb):		Minimum in size range:	Maximum in size range:
NUHOMS 24PS	78,128	75,794	93,700
NUHOMS 24PL	75,794		
NUHOMS 24PHBS	78,128		
NUHOMS 24PHBL	75,794		
NUHOMS 24PTH-S	92,400		
NUHOMS 24PTH-L	93,700		
NUHOMS 24PTH-LC	89,500		
NUHOMS 24PT2S	84,319		
NUHOMS 24PT2L	81,968		
NUHOMS 24PT1	78,400		
NUHOMS 24PT4	85,000		
NUHOMS FO-DSC (24 PWR)	80,710		
NUHOMS FC-DSC (24 PWR)	81,120		
NUHOMS 32PT-S100	88,150	88,150	110,000
NUHOMS 32PT-S125	100,380		
NUHOMS 32PT-L100	89,140		
NUHOMS 32PT-L125	101,380		
NUHOMS 32PTH-XX	108,850		
NUHOMS 32PTH1	108,850		
NUHOMS 32PTH2	110,000		
NUHOMS 37PTH-S	108,100	108,100	109,300
NUHOMS 37PTH-M	109,300		
NUHOMS 52B	74,925	74,925	74,925
NUHOMS 61BT	88,390	88,390	93,120
NUHOMS 61BTH	93,120		

3.2 Postclosure Degradation of Fuel, Baskets, and Criticality Control Features

Many DPC basket designs rely on stainless steel structural components that could withstand thousands of years exposure to ground water without collapse, even though aluminum-based neutron absorbing components (e.g., Boral® absorber plates) fail from corrosion. This means that added disposal control features could function in non-collapsed configurations throughout the period of regulatory concern (thousands of years). On the other hand, some of the newer basket designs consist mostly of aluminum (e.g., Metamic-HT®) which could maintain structural integrity for only a few tens to hundreds of years in ground water. Also, if the period of regulatory concern is extended to tens of thousand of years, with extended basket exposure to ground water, then any DPC could suffer basket collapse. To understand the configuration of fuel and neutron absorbers for collapse conditions, additional modeling of fuel/basket degradation is needed.

A promising approach is to compare the mechanical lifetime of ANA components (typical thickness of 3 mm or greater) with that of other components of the fuel and basket. For some fuel and basket components the mechanical lifetime may be significantly less than for disposal criticality control features. Components such as thin Zircaloy used in spacer grids, Metamic-HT® used in egg-crate style baskets, and welded stainless steel, carbon steel, aluminum, or other materials used in basket construction, could degrade faster than fuel rods or disposal criticality control features. Consolidation of the SNF would commence before corrosive degradation of added neutron absorbing components. Mechanistic models could show how degradation leads to collapse and consolidation of the fuel (decreasing moderation), while control features such as DCRAs, and channels or inserts made from ANA would remain intact and distributed throughout the fuel mass.

Once the modeling and analysis case is made for disposal criticality control using fuel/basket modifications, a regulatory review is needed. This could take the form of a generic topical report, or it could be initiated by vendors for licensing of specific systems.

3.3 Conclusions and Recommendations

The foregoing sections lead to the following conclusions regarding measures to limit the likelihood of postclosure criticality, to facilitate direct disposal of commercial SNF in DPCs of existing designs:

- Disposal control rods (DCRAs) for PWR fuel could be closest to being realized, among the alternatives discussed here. Analysis of k_{eff} is needed for as-loaded canisters with DCRA designs distributed in various ways within the DPCs. CoC restrictions on control component placement in DPCs need to be studied to determine availability of basket locations for DCRAs. Added weight from PWR disposal control rods could approach 1,000 lb. depending on particular aspects of control rod design (size, tubing weight, etc.).

- Re-channeling of BWR fuel is a workable solution that is technically feasible for any BWR fuel assembly. Design and performance modeling of replacement channels (here called "re-channels") depends on testing of corrosion resistant absorber materials. For application in a range of generic (non-site specific) disposal environments, the materials need to show general corrosion rates less than 100 nm/year. Prototype demonstration of fabrication properties is also needed. Net weight change from installing re-channels may be small or zero, depending on the characteristics of ANA channels.

- Chevron inserts for BWR or PWR fuel are potentially useful for baskets made of aluminum-based materials, and could also be used to retrofit any DPC of an existing design that used aluminum-based absorber plates. The success of inserts would depend foremost on the clearance available in DPC basket cells. Design and performance modeling of inserts also depends on corrosion testing for representative geologic disposal environments, and prototype demonstration. The potential added weight from inserts is greatest among the options considered here, and could be more than 3,000 lb. per DPC.
- Replacement of absorber plates made from Boral® or other aluminum-based materials, in DPC baskets of existing designs, is a potentially feasible change that would add cost and weight similar to chevron inserts (the amount of absorber material would be comparable). It is possible that once corrosion testing of ANA and other materials is complete, that such baskets would become available. Further analysis would be provided by DPC vendors, and is not included in this report.
- Analysis of zone loading at particular spent fuel pools, accounting for the fuel inventory available for selection, could expand applicability of the reactivity margin strategy. Previous analysis has shown that 10% to 15% improvement in k_{eff} might be realized, although it is not clear how many DPCs could be effectively loaded this way with the available low-reactivity fuel assemblies. Implementation would require re-licensing of loading protocols, with control of worker dose and DPC temperatures.

The information needs identified in this study to further evaluate these options, are summarized and compared in Table 7.

Each of the alternative fuel/basket modification approaches requires reactivity analysis to verify how it would limit the likelihood of postclosure criticality. Configurations to be analyzed include: 1) degraded basket features but intact fuel assemblies and intact disposal criticality control hardware; and 2) degraded basket features and degraded fuel assemblies, and intact disposal criticality control hardware.

Note that as-loaded BWR DPCs are generally less reactive than PWR DPCs for stylized degradation cases (Clarity et al. 2019). BWR DPCs (or most of them) might be shown to have sufficient reactivity margin to remain subcritical in a repository, with enhancements to the burnup credit methodology. BWR burnup credit methodology will require closer attention to reactor operation history, and is the subject of ongoing interest in the R&D community.

The fuel/basket modifications identified here could be implemented in DPC basket construction, or prior to DPC immersion in fuel pools for chevron inserts. Zone loading would require new fuel selection/canister loading protocols but no modification to hardware.

Hook load is a potentially significant constraint on addition of disposal criticality control hardware. Resolving the impact of hook load limits on fuel/basket modification options, requires more detailed description of the hardware, and site-specific analysis of hook load margins.

The rough estimates of cost (Table 1) indicate a range from approximately $112k to $282k per DPC. The DCRA estimate ($187k per DPC, Table 1) is consistent with a previous estimate of $200k for DCRAs (Alsaed 2019). Estimated cost per MTU for the four solutions described in Table 1 ranges from $8k to $23k. Labor costs for installation of these four modifications are estimated based on engineering judgment and found to be small compared to hardware costs.

For hypothetical future loading of 3,000 MTU/yr of SNF into DPCs (a long-term average projected for 2030 to 2050) the annual cost for implementing postclosure criticality control measures would be approximately $15M to $25M for PWR fuel, and $15M to $24M for BWR fuel (calculated on an average per MTU basis; see Table 1). These estimates include labor, and would represent a small fraction (a few percent) of current costs for procuring DPCs and loading of 3,000 MTU of SNF in the U.S.

The ultimate efficacy of fuel/basket modification for future DPCs depends on timely implementation. Given that half of the commercial SNF that will ever be produced by the current fleet of U.S. reactors is projected to be in sealed DPCs by around 2030, timely implementation (including non-technical factors that are beyond the scope of this report) means 5 to 10 years from now. Accordingly, it is recommended that R&D proceed to: 1) study modification options to determine location, spacing, and other aspects of control feature design; 2) model fuel/basket degradation with control features, and the impacts on reactivity; and 3) investigate ANA material corrosion for a range of representative disposal environments, as well as ANA properties important to fabrication.

Finally, this report has considered other solutions (BWR control rods or blades, rod consolidation) and concludes that they are impractical, and would require disassembly of fuel assemblies, and/or significant redesign of existing DPC baskets. The ultimate goal of this approach to DPC disposition is to minimize the effort needed to re-engineer and re-license new basket configurations, while providing solutions that can in principle be used in any DPC produced by any vendor. That said, we note that every solution discussed in this report would likely require regulatory certification, to include amendments to existing CoCs for storage and transportation.

Table 7. Summary of fuel/basket modification option technical challenges.

<table>
<tr><th>Studies Needed >>></th><th>Postclosure Criticality Analysis</th><th>Postclosure Degradation Analysis</th><th>Absorber Development & Prototyping</th><th>Dimensional Clearance Analysis</th><th>Hook Weight Analysis</th></tr>
<tr><td>PWR DCRA</td><td rowspan="5">Determine practical composition, number, and locations for disposal criticality control features in different DPC types and capacities.</td><td rowspan="5">Evaluate corrosion impacts on neutron absorber distribution, for >10^4 yr exposure to ground water</td><td>Use well-studied absorber material</td><td>Not an issue</td><td rowspan="5">Evaluate site-specific hook load margins (especially for DCRAs and inserts)</td></tr>
<tr><td>BWR Re-channel</td><td rowspan="3">Evaluate ductility for fabrication, and corrosion types and rates</td><td>Unlikely to be an issue</td></tr>
<tr><td>PWR Insert</td><td rowspan="2">Evaluate fuel types & baskets at specific sites</td></tr>
<tr><td>BWR Insert</td></tr>
<tr><td>Absorber Plate Replacement</td><td>Evaluate corrosion types and rates</td><td>Unlikely to be an issue</td></tr>
<tr><td>Zone Loading</td><td>Evaluate reactivity margin attainable, and associated impacts on worker dose and thermal limits, for quantities of fuel at specific sites</td><td>Depends on degraded fuel/basket configurations assumed</td><td colspan="3">Not applicable</td></tr>
</table>

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