A CASE FOR DIRECT DISPOSAL OF SNF IN EXISTING DPCS

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ABSTRACT

Commercial spent nuclear fuel (SNF) continues to accumulate in dry storage, sealed into welded dual-purpose canisters (DPCs). Direct disposal of DPCs, without cutting them open and re-packaging the fuel, is technically feasible at least for some DPCs and some disposal concepts. Options for DPC direct disposal are taking form, based on an ongoing study by the U.S. Department of Energy.

Direct disposal of DPCs should be viewed as one part of a diverse fuel management system that will eventually switch to loading standardized multi-purpose canisters (MPCs). Nearly all DPCs that are loaded before this switch could be directly disposed depending on the disposal environment selected. DPC direct disposal options have been developed for salt, crystalline and sedimentary host media. These options are suited to different populations of DPCs, ranging from those containing older, colder fuel (e.g., in sedimentary media) to all DPCs (salt).

The timing of DPC use offers an opportunity to simplify the SNF management system. Commercial SNF will be generated in the U.S. for more than 90 years, whereas facility lifetimes are typically on the order of 50 years. Efficiencies could be realized by implementing disposal in "campaigns." Additional accumulation of DPCs over the next 10 to 20 years, followed by a transition to MPCs, would define two such campaigns. A repository could first be constructed for MPCs, and disposal of DPCs could be deferred and addressed later using new, dedicated facilities. During the interim storage period DPC thermal output would decay, further expanding disposal options.

I. INTRODUCTION

At present approximately 2,000 DPCs have been loaded[1] and another 2,000 could be loaded by the time site-specific canister disposability requirements are known. This point could come in the 2030's, following the current strategy for SNF management.[2]

Technical feasibility of direct disposal of commercial SNF in DPCs continues to be investigated by the U.S. Department of Energy, Office of Used Nuclear Fuel Disposition. Technical objectives for disposal are: 1) safety of workers and the public, 2) engineering feasibility; 3) thermal management; and 4) criticality control after permanent closure of a repository. The following sections present the case for direct disposal, proposing disposal concepts, and addressing each of these objectives.

The discussion of criticality and disposal logistics includes those canisters designed for storage and transportation (DPCs) and those designed for storage only. This assumes future availability of a licensed transportation solution for storage-only canisters. Bolted-closure systems ("casks") are relatively few and can be readily opened to retrieve fuel for disposal, so they are not considered here. The discussion includes both of the two major types of baskets used in DPCs ("tube-and-spacer-disk" and "egg-crate" designs).

Each DPC (or storage-only canister) would be sealed in a purpose-designed overpack for disposal. The overpacks would be robust, and provide structural support for handling, transport underground, emplacement, and containment through the period of repository operations. The postclosure containment function of the disposal overpack would depend on the safety strategy developed for each host geologic medium that could be considered. Many possible disposal concepts have been identified[3] and the ones selected for presentation here would be implemented in rock salt, hard rock (i.e., crystalline), and argillaceous sedimentary rock.

I.A. Salt Concept

This is a repository constructed at depth in bedded or domal salt. Disposal overpacks would consist of thick carbon or low-alloy steel, and waste packages would be emplaced on the floor in drifts or alcoves, and immediately covered with crushed salt (e.g., from excavating the next drift). This concept is similar to an option developed in the German program[4] and to a concept developed for heat-generating high-level waste glass.[5] Waste packages of any size (including 32-PWR size or larger) could be used with heat output limited to approximately 10 kW at emplacement[3]). The fuel basket would be designed to meet dry storage and transportation requirements, but would not be relied upon for postclosure criticality control. Any liquid water present in the repository would be chloride brine, even in a human intrusion scenario because deep drilling in evaporites is typically done with brine. All repository openings would be backfilled at closure. Repository panels would be isolated by plugs, and shafts would be sealed.

I.B Hard Rock Unsaturated, Unbackfilled, In-Drift Concept

A repository constructed above the water table in competent hard rock (e.g., igneous intrusive or extrusive, or metamorphic), with in-drift emplacement and forced ventilation for at least 50 years. Disposal overpacks would be made from materials that resist corrosion in chemically oxidizing conditions.[6, 7] The hydrologic setting would be unsaturated, so backfill would not be needed to limit moisture movement, but other engineered barriers might be installed such as long-lived barriers to downward water percolation. Repository access drifts, shafts, and ramps would be backfilled.[3, 8, 9]

I.C. Hard Rock Saturated, Backfilled, In-Drift Emplacement Concept

A repository constructed and operated in competent, hard rock in a saturated hydrologic setting (although the concept could be used in an unsaturated setting also). This concept would also use in-drift emplacement with forced ventilation for at least 50 years. A low permeability backfill would be installed around the packages, prior to closure, to condition the waste package corrosion environment and limit groundwater flow. The backfill would be engineered to withstand potential peak temperature in the range 150 to 200°C, possibly by use of admixtures such as graphite to increase its thermal conductivity. Disposal overpacks would be corrosion resistant, and designed to perform in the disposal environment. For example, a layer of copper on low-alloy steel could be used, similar to the Swedish KBS-3 concept. Alternatively, if predicted exposure conditions warrant, the overpack could be made from corrosion-resistant, passive materials such as titanium or nickel-chromium alloys. Use of two or more separate layers could effectively eliminate the possibility of breach from defects in manufacture or damage during repository operations. Backfill could be installed remotely, or directly if waste packages are self-shielding. Repository panels would be isolated by plugs, and shafts would be sealed.[3]

I.D. Argillaceous Sedimentary Rock, Saturated, Backfilled, In-Drift Emplacement Concept

A repository constructed and operated in soft, clay-rich sedimentary rock, with in-drift emplacement and forced ventilation for ~50 years after emplacement. Drift diameter would be minimized to the extent practicable, to limit the thermal resistance of a backfill layer. All drifts would be backfilled at closure with a low-permeability engineered material[3] as described above for the hard rock backfilled concept. Backfill functions would include low permeability, and mechanical support after roof collapse to limit the extent of damage in the host formation. Backfill would be installed either remotely, or directly if waste packages are self-shielding. Disposal overpacks would be corrosion resistant, similar to the hard rock backfilled concept. Repository panels would be isolated by plugs, and shafts would be sealed.[3] Postclosure performance would be similar to a reference concept for Opalinus clay that uses in-drift emplacement.[10, 11, 12]

The foregoing set of concepts is not exhaustive, but it covers a range of behaviors potentially important to DPC direct disposal including thermal management, postclosure nuclear criticality control, and long-term opening stability. The remainder of this paper describes how these disposal concepts could be used with DPCs and storage-only canisters, to achieve the technical objectives for disposal.

II. SAFETY OF WORKERS AND THE PUBLIC

The operations needed to transfer DPCs to suitable overpacks are similar to those used upstream for DPC loading, storage and transportation. Handling and packaging would be similar for any DPC direct disposal concept, no matter where the repository is located or in what geologic host medium. Thus, although engineering details need to be worked out and universal equipment is needed to handle the range of DPC designs, there appear to be no significant technical questions concerning worker or public safety associated with repository operations until the waste is transported underground.

The postclosure waste isolation safety case for DPC direct disposal would resemble that for any repository—waste isolation would be enhanced by choosing host geology in which radionuclide transport is diffusion dominated, although disposal concepts have been developed which combine performance from natural and engineered barriers. In addition, the safety case for DPC direct disposal could benefit from the use of engineered barrier materials such as backfill, for which transport properties are insensitive to the projected temperature history.[3] Containment functions would be assigned to the overpack, and suitable materials exist for most possible disposal environments.[13]

Further analysis of postclosure waste isolation is limited without site-specific data and engineered barrier system models that support performance assessment simulations meaningful to comparison of DPC direct disposal with alternatives.[3] Performance of a repository for packaged DPCs would be similar to that for purpose-built SNF canisters, taking into account multiple engineered and natural barriers. Treatment of features, events and processes (FEPs) would be similar with the exception of postclosure criticality which is discussed further below.

III. ENGINEERING FEASIBILITY

Earlier studies have shown that DPC-based waste packages would be only slightly larger and heavier than some of those proposed for a repository in volcanic tuff.[3] Engineered solutions are available for transporting and emplacing these packages underground, although some could be the largest of their kind. For example, heavy shaft hoists have been proposed at capacities of 85 and 175 MT, and some features have been tested.[8, 14] Costs for such a hoist would constitute a small fraction of overall disposal system cost.[8] Such first-of-a-kind systems for radioactive waste handling and transport would be based on conservative design, with modern monitoring and control systems.

Developments in excavation and construction over the past 20 years suggest that repository openings could be stable for 50 years with little or no maintenance even in clay/shale rock types.[13] Repository tunneling and construction costs on the order of $10k per meter[13] are achievable and represent a small fraction of disposal system cost even with many kilometers of drifts.

IV. THERMAL MANAGEMENT

A disposal solution using larger waste packages is attractive for the U.S. which faces the disposal of more than twice as much SNF as any other nation, but the concept must manage the waste heat. The best flexibility is obtained with host rock that has both high thermal conductivity and tolerance for high peak temperatures. This is illustrated in Figure 1 which shows the average power limits per fuel assembly, for 32-PWR size packages that meet peak temperature targets for salt and hard rock (200°C), sedimentary rock (100°C), and backfill (up to 200°C). For salt and hard rock concepts, host rock peak temperature limits are readily met within approximately 100 years from fuel discharge. Accordingly, the salt repository concept and the hard rock concepts discussed above (especially the hard rock unsaturated, unbackfilled concept) are best suited for larger waste packages with higher heat output. Sedimentary host media such as shales could pose a challenge especially if they have low thermal conductivity. Significant aging (surface decay storage plus repository ventilation) would be needed to accommodate large packages of higher burnup SNF in sedimentary rock.

V. POSTCLOSURE CRITICALITY CONTROL

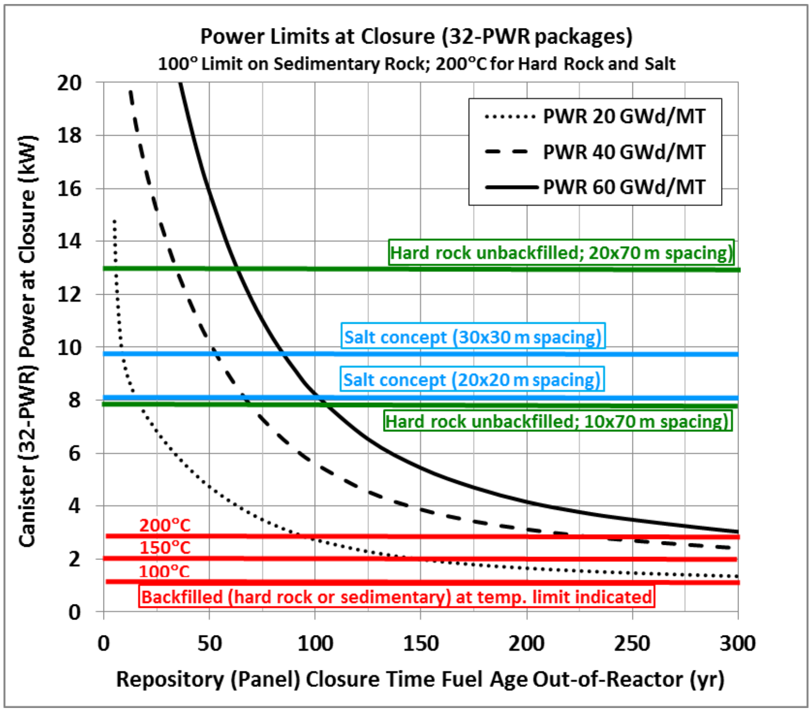
Without flooding of waste packages by ground water, criticality can never occur. However, even using corrosion resistant materials, some small number of disposal overpacks could fail during the postclosure performance period from defective manufacture, disruptive events, or possibly corrosion. Once flooded, the aluminum-based neutron absorber materials used in most DPCs would degrade readily, galvanically protecting the stainless steel. Once degraded, the configuration of neutron absorbing materials is highly uncertain. Thus, criticality control for DPC direct disposal involves analyzing reactivity without the original neutron absorbing components, possibly combined with structural collapse of the basket from corrosion. Tools available to decrease the analyzed reactivity include:

- Uncredited margin whereby the as-loaded SNF is less reactive than the fuel assumed for DPC licensing because of fuel burnup, and/or because additional burnup credit can be taken compared to what was taken in the licensing analysis.
- Neutron capture by dissolved solids in flooding ground water, such as chloride salts.

For flooding with fresh water, with loss of neutron absorbers, many DPCs (but not all of the 179 analyzed) have been shown to be subcritical using uncredited margin. Significantly fewer are subcritical if the basket also degrades (Figure 2). Thus, the materials of basket construction could be important if they fully corrode, along with the neutron absorbers, during the postclosure performance period.

Stainless steel used in basket construction could corrode slowly enough (e.g., less than 0.1 $\mu m\ yr^{-1}$ surface retreat rate) to maintain basket structural integrity throughout the postclosure performance period, especially in reducing conditions.[13] Other materials such as aluminum, carbon steel, or Metamic® would corrode faster and could not be relied on to maintain fuel configuration. Approximately 2/3 of the overall inventory of storage casks and canisters are transportable (i.e., DPCs) with basket structure made from stainless steel, while 6% are transportable but with non-stainless structural components.[13] Some stainless steel structural components are thin, such as guide sleeves used in tube-and-spacer-disk baskets. Further analysis would be needed to determine whether these components would fail from corrosion, and whether the fuel configuration can be specified if they do fail. Thus, the 2/3 estimate for disposability in fresh water environments is an upper bound.

Criticality modeling has shown that even without neutron absorbers, virtually all DPCs would be subcritical if flooded with chloride brine that would be prevalent in a salt repository. (Natural chlorine is 75.7% Cl-35, a neutron absorber.) This result is represented by a calculation whereby the fuel rods in a typical DPC are distributed throughout the canister volume in a hexagonal array with uniform pitch. Criticality analysis of this configuration, flooded with sodium chloride brine of varying strength, is summarized in Figure 3. A saturated brine (158,000 ppm NaCl as shown) could ensure that any fuel with 4% enrichment, or 5% fuel with at least moderate burnup, would be subcritical. Similarly, many



Note: Assembly power limits are shown for 32-PWR size packages in the salt repository, hard rock unbackfilled repository, and sedimentary unbackfilled repository. Where assembly power is less than these limits, before the assumed time limit for repository closure (150 yr is shown) the temperature targets can be met. Use of backfill poses the most restrictive power limits for both hard rock and sedimentary concepts.

Figure 1. Heat output per PWR fuel assembly, for three values of burnup (20, 40 and 60 GW-d/MT) showing approximate power limits (at repository closure) for disposal in 32-PWR size packages

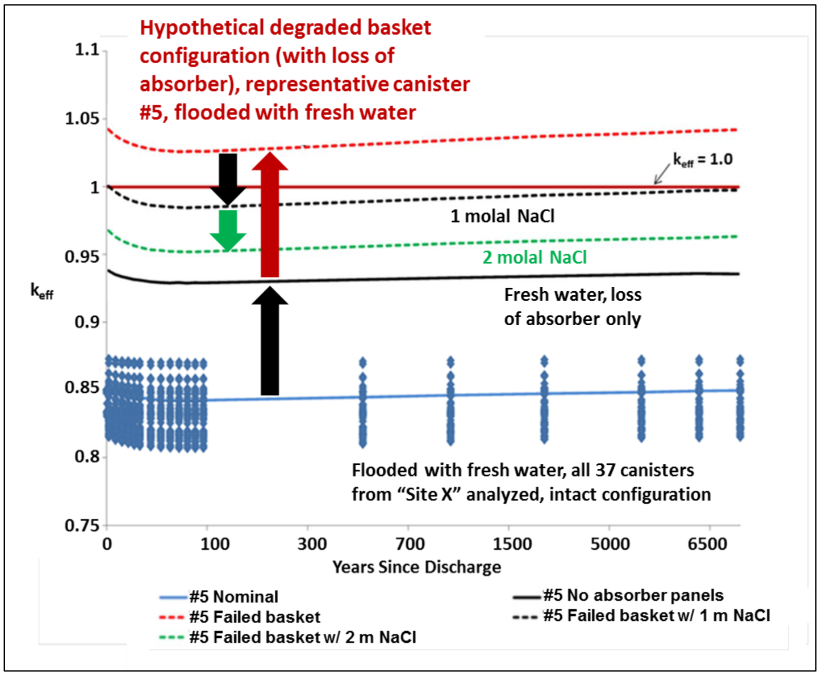


Figure 2. Neutron multiplication factor scoping results modeled using SCALE,[16] for 37 DPCs from a site in the U.S. ("Site X") with analysis of one representative canister (#5) in degraded configurations.

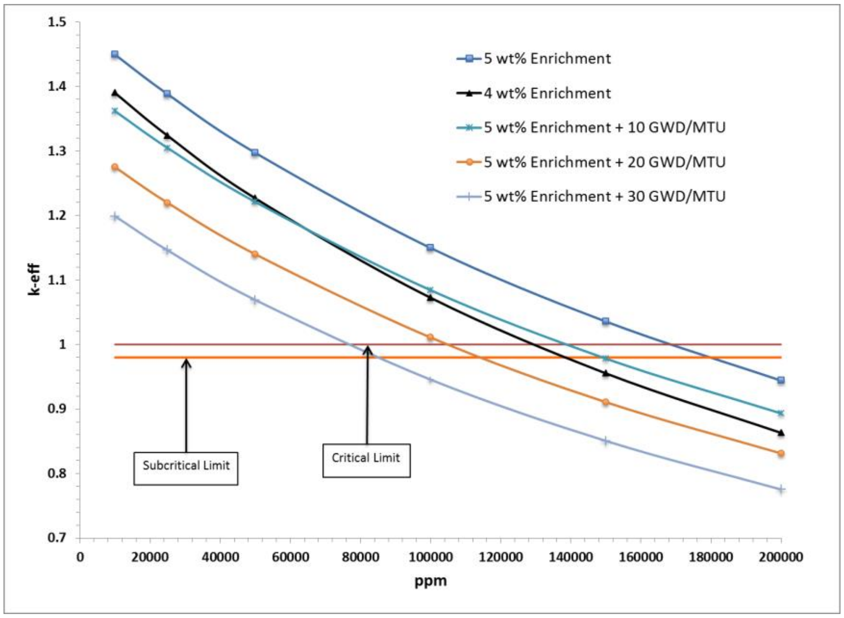


Figure 3. Neutron multiplication factor for maximally space fuel rods within a typical DPC, without a basket, as a function of NaCl concentration in ppm (a saturated 6 molal solution would be 158,000 ppm).

(but not all) DPCs would be subcritical if flooded with seawater, with loss-of-absorbers, using uncredited margin.[13] This result could be used for a repository in common marine shales or crystalline basement rock with moderately saline ground water, to select more existing DPCs for disposal than might be possible with fresh ground water.

VI. SYSTEM-LEVEL MODELING

Logistical simulations using TSL-CALVIN[13] were done to better understand the relationship between needed DPC decay storage time for disposal, and the timing of future events such as the repository opening date, or a transition to loading multi-purpose canisters (MPCs, purpose-designed for disposal) at nuclear power plants. TSL-CALVIN models all steps in managing commercial SNF from discharge until delivery to a repository, with thermal decay, for all SNF from existing and shut down power plants. Current dry-storage canister loading practices are projected into the future, assigning dates for repository opening and for transition to loading MPCs. Emplacement thermal power limits are applied, representing disposal in different geologic settings.

As time passes, more of the total SNF inventory will be in DPCs so the utility of a transition to MPCs will decline (without re-packaging of fuel from DPCs into disposal canisters, which adds costs and complications). This result emphasizes the value of timely repository siting and implementation, leading to timely decision-making on transition to disposable MPCs.

Fuel age at emplacement is also of interest to evaluate potential impacts from possible future changes in the fuel management system that limit dry storage time. The minimum fuel age at emplacement (best-case) is obtained by re-packaging all DPCs into smaller canisters for disposal, thus decreasing the required decay storage time, but increasing overall system cost by tens of billions of dollars.[3] If the nuclear utility industry transitions to smaller MPCs, and direct disposal is retained as an option for existing DPCs, the fuel age at emplacement would be comparable to the best case if: 1) the emplacement power limit is high enough to readily accommodate existing DPCs, or 2) both the MPC transition and the repository start date occur soon (e.g., a 2036 repository start date was analyzed).

A switch from loading DPCs to MPCs at power plants, once site-specific canister design requirements are known, would divide the population of canisters into two groups that could be managed separately. If the switch occurs in the late-2030's, approximately half of the total inventory of commercial SNF in the U.S. would be in DPCs, and half in MPCs (assuming 20-year life extensions and no new builds, and accounting for fuel in pools). This division offers an opportunity to structure the SNF management system, for example, based on the projected cooling histories.

TSL-CALVIN was used to evaluate when DPCs and MPCs would be cool enough for disposal, to identify controlling dates and thermal power limits that separate

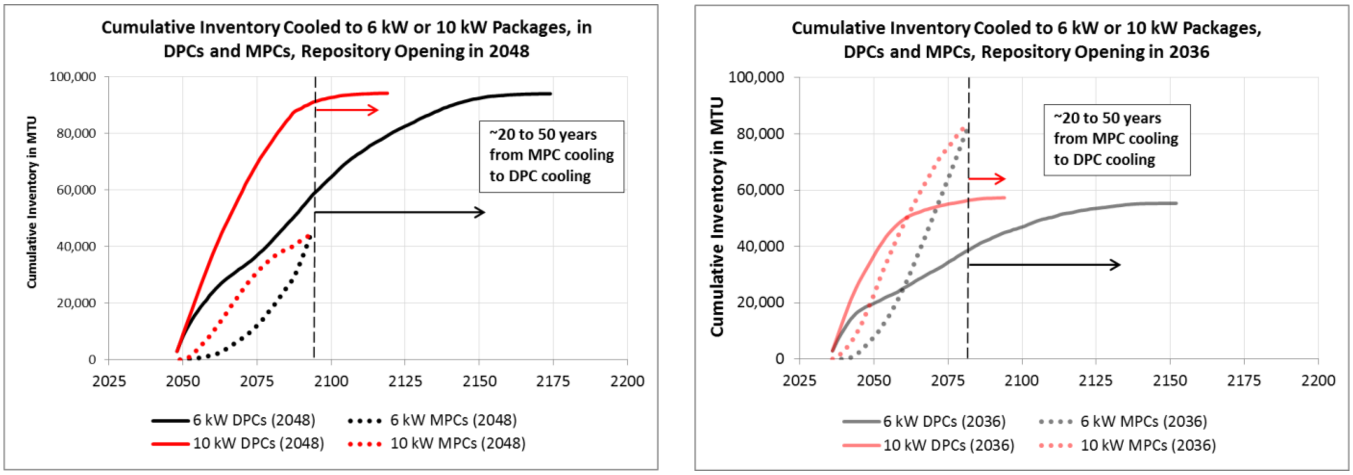


Figure 4. Available inventory that has cooled to 6 kW or 10 kW per canister (assumed for disposal), for DPCs and MPCs, with a transition to MPCs associated with the start of repository operations either in 2036 or 2048.

the availability of DPCs and MPCs in time. The simulations were repeated with disposal thermal limits of 6 kW and 10 kW, repository starting dates of 2036 and 2048, and transition to MPCs each containing ~2 MTU of SNF (e.g., 4 PWR assemblies) occurring 5 years prior to repository startup. The results (Figure 4) show that separation is greatest for the lower thermal limit (6 kW), because the aging time for DPC disposal is longer. There is also DPC-MPC separation for the upper limit implemented later (10 kW, 2048), because there are more DPCs loaded later with higher burnup fuel.

Commercial SNF will be generated in the U.S. for more than 90 years, whereas lifetimes for storage, transportation and disposal systems are typically limited to 50 years. Efficiencies could be realized by implementing disposal in "campaigns." Additional accumulation of SNF in DPCs for the next 20 years, followed by a transition to smaller, disposable MPCs would define two such campaigns. A repository could first be constructed for MPCs, and disposal of DPCs could be deferred and addressed later using different, new, dedicated facilities (even a different site). During the interim storage period DPC thermal output would decay, expanding disposal options to host media with smaller power limits.

VII. DISCUSSION

In order to exclude postclosure criticality from performance assessment on the basis of low probability, the probability that one or more packages would achieve criticality would need to be less than 10^{-4} (per repository realization; based on 10CFR63). This would apply to the aggregate of all events that could cause waste package flooding (e.g., seismic ground motion, faulting, and early overpack failure due to defective manufacture). Disruption by natural events is controlled by site-specific factors that cannot be addressed in a generic study, however, early overpack failure can be addressed. We note that excluding criticality on low probability is not the only possible approach, and that an alternative would analyze consequences from criticality events.[15] Consequence analysis could increase the proportion of existing DPCs that are deemed disposable, for disposal settings with fresh ground water.

VIII. SUMMARY

Technical analysis continues to show that direct disposal of a substantial fraction of existing DPCs is feasible. Results described in this paper are summarized in Table I. Criticality control strategy for geologic settings other than salt would depend on a combination of factors that would determine the probability of waste package breach, and the number of DPCs that could achieve criticality if breach and flooding occur. For disposal settings with fresher ground water, fewer existing DPCs could be directly disposed. Disposal in bedded or domal salt could likely accommodate virtually all existing DPCs, with favorable thermal performance and postclosure criticality control.

All of disposal concepts in Table I would benefit from site-specific information. Note that site characteristics favoring DPC direct disposal are generally more restrictive than needed for MPCs or other purpose-designed disposal canisters. MPCs could be smaller (e.g., 21-PWR size or smaller) and use long-lived neutron absorbers (e.g., borated stainless or Ni-Cr-Gd alloy). Thus, there could be a broader range of sites available for MPC disposal, if disposal planning for MPCs and DPCs is separated.

Whereas advantages from switching to MPCs (in terms of the need for decay storage) were shown to decline with time, a practical approach would be to first implement the switch to MPCs, then dispose of them and defer disposal of DPCs. The decision whether to directly dispose of DPCs or cut them open and re-package the SNF, could thereby benefit from experience with earlier repository siting and operation. If direct disposal is selected in the future, many more DPCs will have cooled enough to meet thermal constraints.

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TABLE I. Summary of DPC direct disposal prospects in different geologic settings

	Salt	Hard Rock Unsaturated[B]	Hard Rock Saturated	Sedimentary Argillaceous
Thermally Controlled Closure Time for High-Burnup SNF (years from discharge)	~75	~100	~150	~150+
Host Rock Temperature Tolerance (°C)	200	200	200	100
Host Rock Thermal Conductivity (W/m-K)	~4 to 5.5	~2.5	~2.5	~1.7
Safety (waste isolation)	✓	✓	✓	✓
Engineering Feasibility	✓[A]	✓	✓	✓
Thermal Management	✓	✓	✓[C]	✓[C]
Postclosure Criticality Control	✓	Site-specific[D]	Site-specific[D]	Site-specific[D]

Notes:

A. Heavy shaft hoist (payload ~175 MT) could be needed for DPC-based waste packages if ramp access is infeasible in bedded or domal salt.

B. See Reference 9.

C. Backfill peak temperature at waste package surface 150 to 200°C (closure at 150 year from discharge). Further away from waste packages (e.g., at 2 m) peak temperature would be < 100°C.

D. Criticality control strategy for existing DPCs would rely on a combination of:
1) multiple corrosion-resistant engineered barriers;
2) low probability or insignificant consequences of potentially disruptive natural events;
3) chloride in ground water; and/or
4) selection of DPCs with sufficient uncredited margin.