Investigations of Dual-Purpose Canister Direct Disposal Feasibility – 15106

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ABSTRACT

Direct disposal of commercial spent nuclear fuel (SNF) in dual-purpose canisters (DPCs) could avoid the cost and complexity of re-packaging spent fuel into smaller purpose-built containers, avoid disposing of the DPC hulls as low-level waste, and potentially decrease worker dose. 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 postclosure 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, and for which transport properties and pathways are insensitive to the expected temperature history. Containment functions would be assigned to the disposal overpack, and published data show that suitable materials exist for most possible disposal environments.

Earlier studies showed that DPC-based waste packages would be only slightly larger and heavier than those proposed for a repository in volcanic tuff. Engineered solutions are available for transporting and emplacing them underground, although some could be the largest of their kind. The cost of DPC direct disposal in various geologic settings has been compared to options involving a change to loading standardized multi-purpose canisters, or continuing to load DPCs and re-packaging all of them for disposal. In general DPC direct disposal would cost tens of billions of dollars less, in packaging and disposal costs.

Calculations for emplacement in hard rock and sedimentary rock show that host rock peak temperature targets of 100 to 200°C could be met by managing fuel age and burnup, with repository closure at up to 150 years from reactor discharge. For disposal in salt, DPC-based waste packages could be emplaced at only 50 to 100 years from discharge, depending on burnup. Sedimentary media such as shales pose special challenges especially if they have low thermal conductivity. If backfill is used around DPC-based packages its peak temperature could be 150 to 200°C.

Without flooding of waste packages with ground water, criticality can never occur. However, some small number of disposal overpacks could fail within the postclosure performance period due to corrosion or disruptive events. Once flooded, the aluminum-based neutron absorber materials used in most DPCs would readily degrade. Analysis has shown that even without neutron absorbers, virtually all DPCs could be subcritical if flooded with chloride brines such as would occur in a salt repository. The licensing basis for existing DPCs involves criticality analysis that may be conservative compared to fuel that is actually loaded, and the difference provides uncredited reactivity margin. Uncredited margin can offset increases in reactivity associated with flooding and basket degradation. For flooding with fresh water, with loss of neutron absorbers, many DPCs have been shown to be subcritical using uncredited margin. Significantly fewer are subcritical if the fuel basket also degrades. Thus, the materials of DPC basket construction (e.g., aluminum or carbon steel) could be deleterious if they fully corrode, along with the neutron absorbers, during the performance period.

Logistical simulations are used to better understand the relationship between the 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 (disposable) canisters at nuclear power plants. Results show that the maximum benefit from implementing a new canister design, with respect to shortening the cooling time for all SNF including that in DPCs, is associated with the earliest repository start date. As time passes more of the total SNF inventory will be in DPCs such that the value of a transition to multi-purpose canisters will decline, and the remaining options are DPC direct disposal and re-packaging in purpose-designed disposal canisters.

Fuel age at emplacement is of interest to evaluate potential impacts from future changes in the fuel management system that could place fuel age limits on dry storage or transportation. The minimum fuel age at emplacement (best-case) is obtained by re-packaging all DPCs into smaller canisters for disposal, thus drastically decreasing the needed decay storage time for any geologic disposal setting. If the industry transitions to smaller, multi-purpose canisters, and without re-packaging, the fuel age at emplacement would be comparable to the best case if: 1) the emplacement power limit is high enough, or 2) both the transition and the repository start date occur early (e.g., 2036 was analyzed).

Technical feasibility evaluation continues to show that direct disposal could be safe and cost effective, for some DPCs and in some geologic settings. Direct disposal of a substantial fraction of existing DPCs, limited mainly by thermal management, uncredited criticality margin, materials of DPC basket construction, and the salinity of ground water in the disposal environment, could be part of the overall waste management system.

INTRODUCTION

The technical feasibility of direct disposal of existing DPCs loaded with commercial SNF 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 of commercial SNF in DPCs, addressing each of these objectives.

Storage and transportation casks can be broadly subdivided into two categories, those in which used fuel is stored in thin-wall, welded metal canisters and those in which fuel is stored in heavier metal canisters with bolted closures. DPCs are welded metal canisters that can be transferred between overpacks for storage, transportation and possibly disposal. Bolted-closure systems are typically called "casks" because they are massive and self-shielding, and not used with overpacks for other purposes such as transportation. Bolted-closure systems may also be referred to as "bare-fuel casks" because they are designed for fuel assembly retrieval and cask reuse. A bolted system could, in principle, be suitable for disposal if a disposal overpack with appropriate dimensions and performance were available. Since there are relatively few existing dry storage systems in the U.S. with bolted closures, and they can be readily opened to retrieve the fuel for disposal, they are not considered further here.

The existing inventory of welded canisters was divided into those designed for storage and transportation (DPCs) and those considered to be for storage only. Canisters were considered to be transportable (and therefore DPCs) if they have a 10CFR71 certificate of compliance, or have not completed the associated licensing process. In this evaluation, for consideration of criticality control both DPCs and storage-only canisters were included, and for logistical simulation both were assumed to be transportable and disposable (assuming availability of a licensed transportation solution for storage-only canisters).

There are two major types of baskets used in DPCs: the "tube-and-spacer-disk" design (Figure 1) and the "egg-crate" design (Figure 2). The tube-and-disk design consists of a series of fuel tubes (also called guide sleeves) that maintains the position of each assembly. Fuel tubes are held in place by mechanical coupling to a set of spacer disks, which are secured by tie rods. The disks maintain the tube spacing and provide heat transfer to the canister shell. Some of the disks may be fabricated from aluminum or other materials to reduce cost or improve heat transfer. The egg-crate designs typically comprise fuel support tubes or cells made from tubing or plates welded together. The entire basket is connected to the canister by supports

attached at the basket periphery. Both types of baskets were included in this evaluation of direct disposal feasibility.
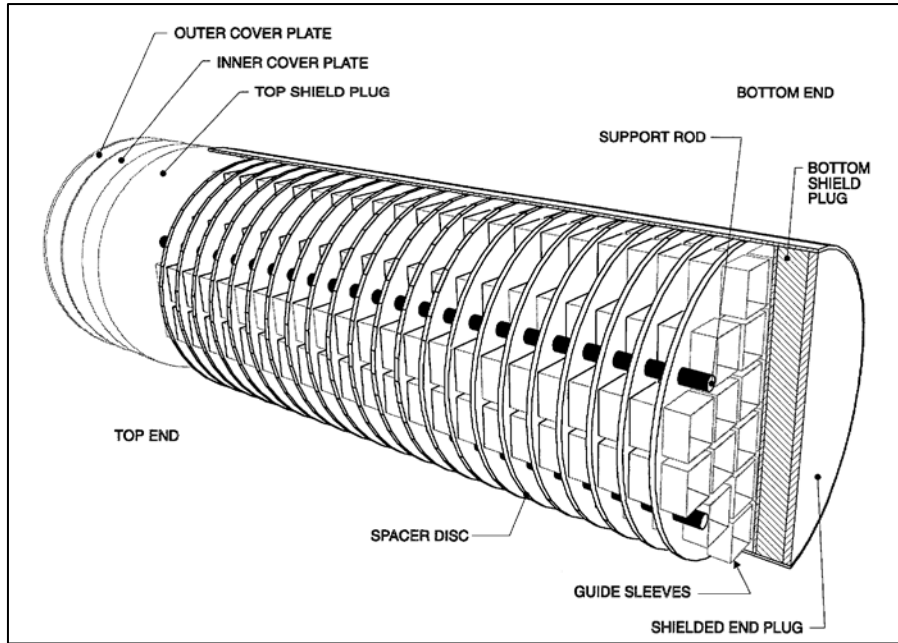
Fig. 1. Schematic cutaway of the FO/FC-DSC manufactured by Transnuclear, an example of tube-and-disk basket design
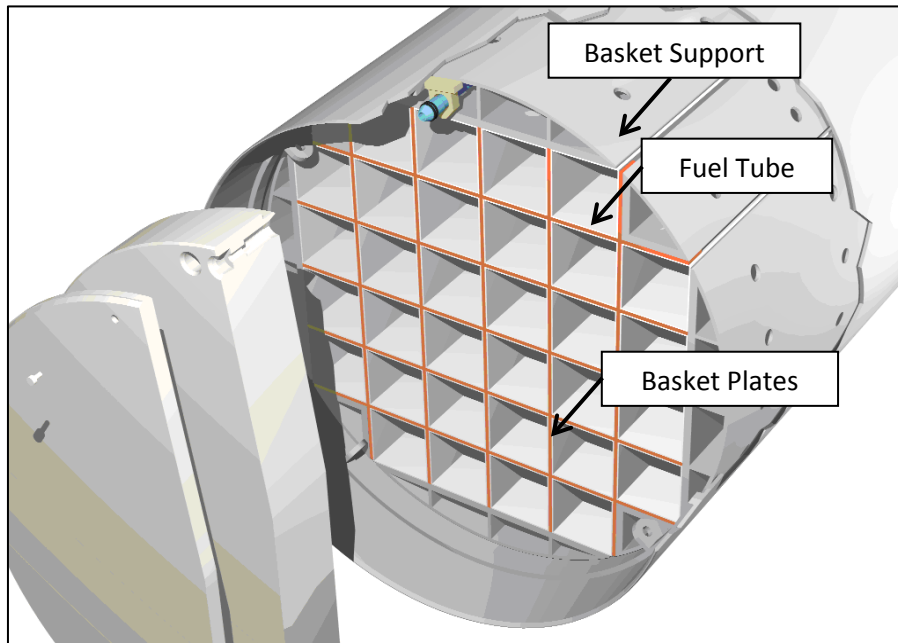
Fig. 2. Schematic cutaway of the DSC-32PTH manufactured by Transnuclear, an example of egg-crate basket design

For this evaluation the existing canister inventory, PWR and BWR assembly counts, and other data were obtained from an industry newsletter publication [Ref. 1]. The materials of construction for each canister were extracted from licensing documents [Ref. 2 through 11].

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, and emplacement in the repository. They would ensure waste containment during repository operations, and possibly after repository closure. The postclosure containment function of the disposal overpack would be determined from a safety strategy developed for each disposal concept or host geologic medium under consideration. Many possible disposal concepts were identified for this evaluation [Ref. 12] and the ones selected for presentation of the final results would be implemented in rock salt, hard rock (i.e., crystalline), and argillaceous sedimentary rock:

Salt Concept – 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 backfilled with crushed salt (e.g., from excavating the next drift). This concept is similar to an option developed in the German program [Ref. 13] and to a concept developed for heat-generating high-level waste glass [Ref. 14]. Waste packages of any size (including 32-PWR size or larger) could be used with heat output limited to approximately 10 kW at emplacement [Ref. 12]). The fuel basket would be designed to meet preclosure structural and criticality control requirements. Any liquid water present in the repository would be chloride brine. All repository openings would be backfilled at closure. Repository panels would be isolated by plugs, and shafts would be sealed.

Hard Rock Unsaturated, Unbackfilled, In-Drift Concept – A repository constructed and operated in competent hard rock (e.g., igneous intrusive or extrusive, or metamorphic) using in-drift emplacement and forced ventilation for ~50 years. Disposal overpacks would be made from materials that resist corrosion in chemically oxidizing conditions [Ref. 15, 16]. 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 [Ref. 12, 17, 18].

Hard Rock Saturated, Backfilled, In-Drift Concept – A repository constructed and operated in competent, hard rock in a saturated (or unsaturated) hydrologic setting. This concept would also use in-drift emplacement with forced ventilation for ~50 years. Disposal overpacks would be designed to perform in the disposal environment (i.e., oxidizing or reducing conditions, or both). A low permeability backfill would be installed around the packages, prior to closure, to condition the waste package corrosion environment and limit groundwater flow. Backfill could be installed remotely, or directly if waste packages are self-shielding. The disposal overpack would be corrosion resistant, and could consist of two separate layers to reduce the possibility of breach from defects in manufacture or placement. Repository panels would be isolated by plugs, and shafts would be sealed [Ref. 12].

Argillaceous Rock, Saturated, Backfilled, In-Drift 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 consistent with construction, maintenance, and ventilation requirements to decrease the thermal resistance of a backfill layer. Emplacement, access, and service drifts would be backfilled at closure, with a low-permeability engineered material [Ref. 12, 17]. Backfill would be installed either remotely, or directly if waste packages are self-shielding. Backfill functions would include low permeability and mechanical support after roof collapse to limit the extent of damage in the host formation. The disposal overpack would be corrosion resistant, and could consist of two separate layers to reduce the possibility of breach from defects in manufacture or placement. Repository panels would be isolated by plugs, and shafts would be sealed [Ref. 12]. Postclosure performance would be similar to a reference concept for Opalinus clay that uses in-drift emplacement [Ref. 19, 20, 21].

This set of concepts is not exhaustive, but it covers a range of behaviors potentially important to DPC direct disposal including thermal response, postclosure nuclear criticality, and long-term opening stability. Other factors such as ground support, waste package transport and emplacement, and shaft vs. ramp access, are also important and may depend more on site-specific characteristics and in some instances, local experience and preference.

The remainder of this paper describes how these disposal concepts could be used with DPCs (and storage-only canisters) to achieve: 1) safety of workers and the public; 2) engineering feasibility; 3) thermal management; and 4) criticality control after permanent closure of a repository.

SAFETY OF WORKERS AND THE PUBLIC

Handling and packaging of large DPCs in surface facilities at the repository or at upstream installations, are within the state of available technology and current practice. The operations needed to transfer each DPC to a suitable disposal overpack are similar to those used for DPC loading, storage and transportation. Moreover, 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 options are needed for standardized or universal equipment to handle the wide variety of DPC systems, there appear to be no significant technical questions concerning worker or public safety associated with repository operations until the waste is transported underground.

This evaluation was generic, elucidating technical issues without site-specific information, consistent with the current strategic plan for spent fuel management in the U.S. 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, and for which transport properties are insensitive to the expected temperature history [Ref. 12]. Containment functions would be assigned to the disposal overpack, and published data show that suitable materials exist for most possible disposal environments [Ref. 22]. Further analysis of postclosure waste isolation is hindered without site-specific characterization data that support performance assessment simulations meaningful to comparison of DPC direct disposal with alternatives [Ref. 12]. Performance of a repository for packaged DPCs would be very similar to 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.

ENGINEERING FEASIBILITY

Earlier studies have shown that DPC-based waste packages would be only slightly larger and heavier than those proposed for a repository in volcanic tuff [Ref. 12]. Engineered solutions are available for transporting and emplacing these packages underground, although some solutions could be the largest of their kind. For example, heavy shaft hoists have been designed and tested, and could be constructed for tens of millions of dollars [Ref. 17, 23] which would be a small fraction of overall disposal cost [Ref. 17]. Such first-of-a-kind systems for waste package transport and emplacement would be based on conservative design, with modern monitoring systems to limit off-normal conditions.

Developments in excavation and construction over the past 20 years suggest that repository development costs could be managed and that openings could be stable for 50 years with little or no maintenance even in sedimentary rock [Ref. 22]. Repository tunneling and construction costs on the order of $10k per meter are achievable and represent a small fraction of overall disposal cost even for repository layouts involving hundreds of kilometers.

The cost of DPC direct disposal in various geologic settings has been estimated for comparison to options involving a change from loading DPCs to loading standardized multi-purpose canisters (MPCs), or re-packaging DPCs for disposal. In general DPC direct disposal would cost less than re-packaging, and

larger canisters (such as DPCs) cost less than much smaller ones. The various DPC, MPC and re-packaging scenarios differ by tens of billions of dollars in packaging and disposal costs [Ref. 12].

A challenge for disposal overpacks (into which DPCs would be sealed for disposal) is to further reduce the probability of failures caused by human error in material preparation, fabrication, etc. The "early failure" probability used in the criticality FEP analysis for a repository in volcanic tuff [Ref. 18] predicted that roughly 1 in 10,000 waste packages would be breached, allowing flooding. Reducing this probability, for example by using independent corrosion-resistant overpack layers, could be important for reducing the likelihood of waste package flooding leading to criticality of SNF in DPCs (see discussion below).

THERMAL MANAGEMENT

A disposal solution using larger packages is attractive for the U.S. which currently faces the disposal of more than twice as much SNF as any other nation, but the disposal concept must be capable of dissipating greater thermal power from each package. More thermal management flexibility is obtained with host rock that has both high thermal conductivity and tolerance for higher peak temperatures. This is illustrated in Figure 3 which shows estimated power limits for 32-PWR size packages at repository closure, that meet peak temperature targets for salt and hard rock (200°C limits), and backfill that could be used with sedimentary or hard rock (assumed 100, 150 and 200°C limits). For the salt repository and the hard rock unsaturated unbackfilled concepts, a host rock temperature limit of 200°C could be readily met by managing fuel age and burnup, with repository closure at fuel age much less than 150 years from reactor discharge. Use of backfill poses the most restrictive power limits for both hard rock and sedimentary backfilled concepts.

Sedimentary media such as shales could pose additional thermal management challenges especially if they have low thermal conductivity. Significant aging (duration of decay storage plus repository ventilation) would be needed to accommodate higher burnup SNF in sedimentary rock. If backfill is used around DPC-based packages the 100°C target used in Figure 3 could be difficult to meet with 32-PWR size packages, and even a peak temperature of 200°C could require extended aging for high-burnup SNF.

Longer aging is always an option for cooling prior to emplacement or repository closure, although DPCs contain more SNF and therefore more intermediate half-life nuclides (e.g., Am-241) that take many hundreds of years to decay. This effect makes the heat output from DPCs emplaced in a repository more sustained compared to smaller packages, even if aging is used to match the power at emplacement. Also, the additional size of DPC-based packages would spread the heat flux over a larger contact area with the disposal environment outside, however, this effect has been shown to be relatively unimportant (compared to heat output) in limiting peak temperatures [Ref. 17]. Accordingly, the salt repository concept and the hard rock concepts discussed above (especially the hard rock unsaturated, unbackfilled concept) could be best suited for larger DPC-based waste packages with higher heat output.

POSTCLOSURE CRITICALITY CONTROL

Without flooding of waste packages with 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 potentially corrosion. Once flooded, the aluminum-based neutron absorber materials used in most DPCs would tend to degrade readily. Criticality control for DPC direct disposal thus involves analyzing reactivity without the original neutron absorbing components, possibly combined with structural degradation of the basket from corrosion (Figure 4). However, reactivity increase from DPC flooding and associated material degradation can be offset by: 1) 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; and 2) reactivity reduction effects from dissolved solids in ground water

that could flood the waste packages.

For flooding with fresh water, with loss of neutron absorbers, many (but not all) DPCs have been shown to be subcritical using uncredited margin. Significantly fewer are subcritical if the fuel basket also degrades (Figure 5). Thus, the materials of basket construction could be important if they fully corrode, along with the neutron absorbers, during the performance period.

Stainless steel used in basket construction could corrode slowly enough (e.g., less than 0.1 μm yr^{-1} surface retreat rate) to maintain basket structural integrity throughout the postclosure performance period, especially in reducing conditions [Ref. 22]. Other materials such as aluminum, carbon steel, or Metamic® would corrode faster and could not be relied on to maintain the 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 (Figure 6). Some stainless steel structural components are thin, such as guide sleeves used in tube-and-spacer-disk baskets (Figure 1). 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.

The 2/3 estimate is an upper bound for DPCs that could be found subcritical using the loss-of-absorber case with uncredited margin, and possibly with saline ground water. Of the 179 DPCs analyzed for this study [Ref. 22] 23 were critical when flooded with fresh water, but all were subcritical when flooded with water slightly less saline than seawater. Analysis of more DPCs could show further reduction in the number of proportion of subcritical DPCs, because only ~10% of the existing DPC inventory has been analyzed so far and these are mostly early designs. Also, corrosion after flooding may significantly degrade thin basket structural components, and the corrosion rate could be higher in some disposal environments.
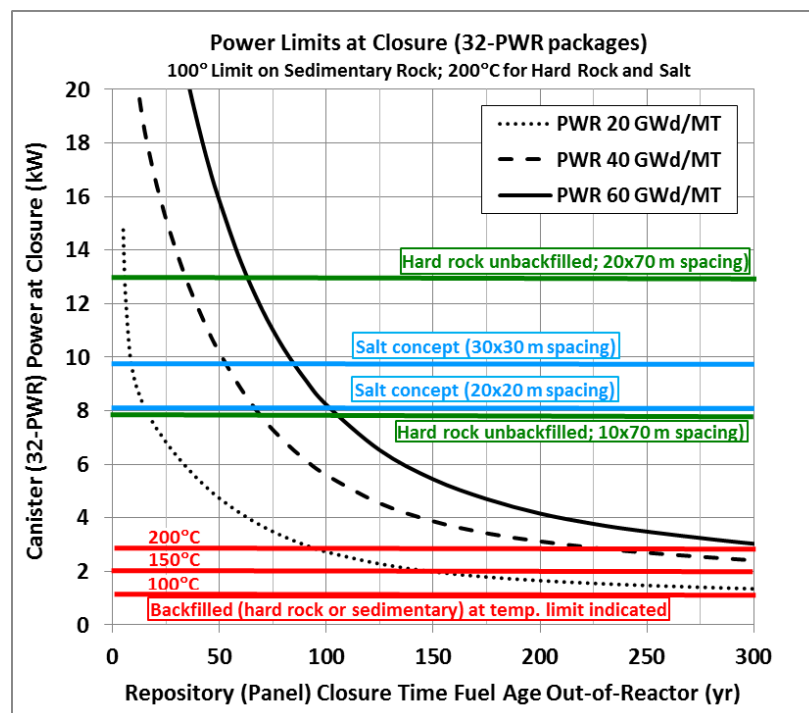

Fig. 3. Heat output limits for 32-PWR size waste packages at repository closure, for three values of burnup (20, 40 and 60 GW-d/MT) showing minimum aging times for different disposal concepts

a) normal MPC-32 configuration (neutron absorber
plates replaced by liquid for loss-of-absorber case);

b) basket degradation configuration (basket removal,
with zero spacing between fuel assemblies);

c) rod redistribution configuration used to evaluate
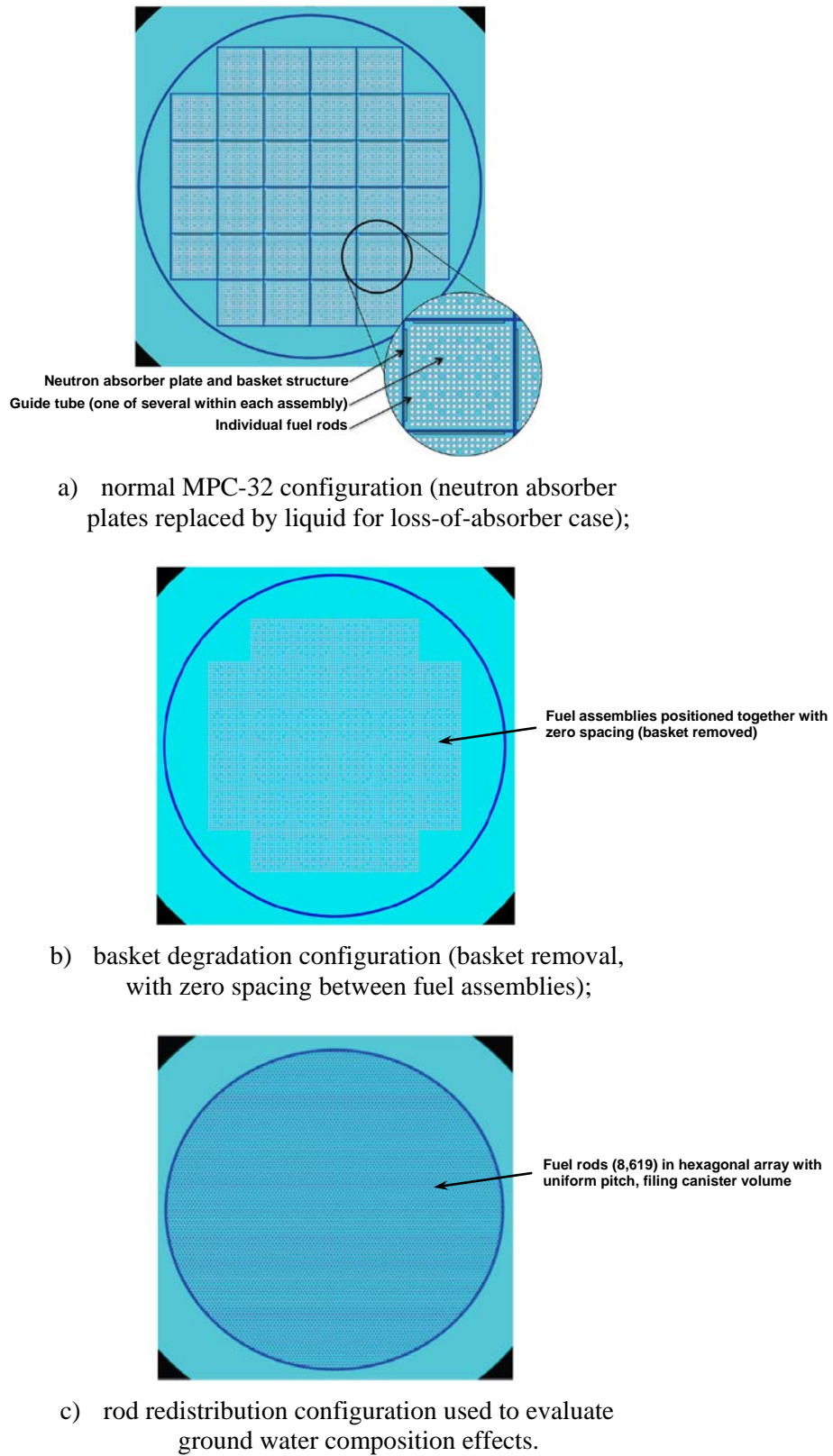ground water composition effects.

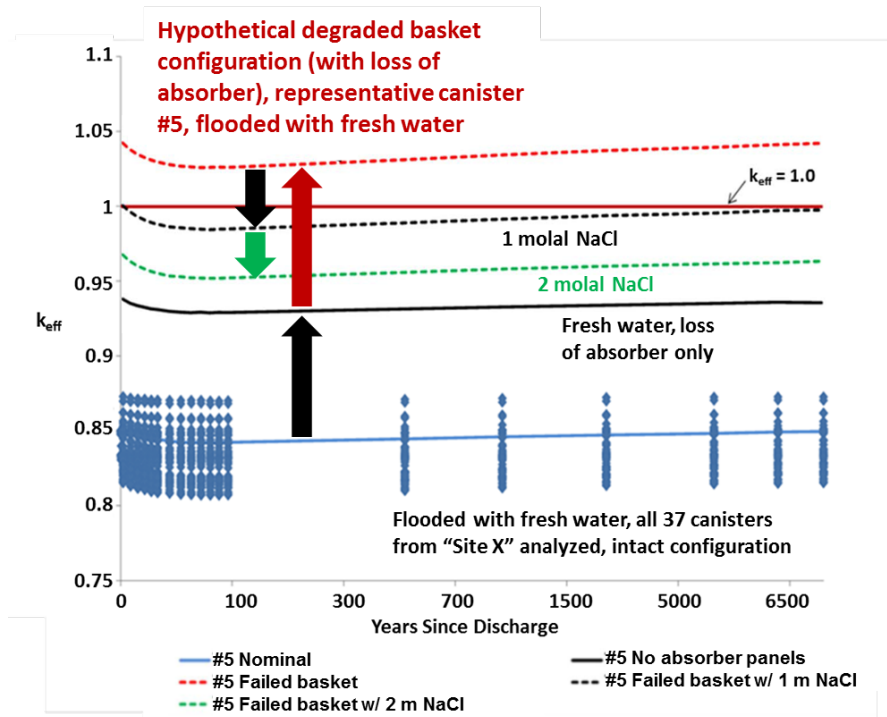Fig. 4. Degradation cases used in DPC postclosure criticality analysis

Fig. 5. Neutron multiplication factor scoping results modeled using SCALE (Ref. 25), for 37 DPCs from a site in the U.S. ("Site X") with analysis of one representative canister (#5) in degraded configurations.
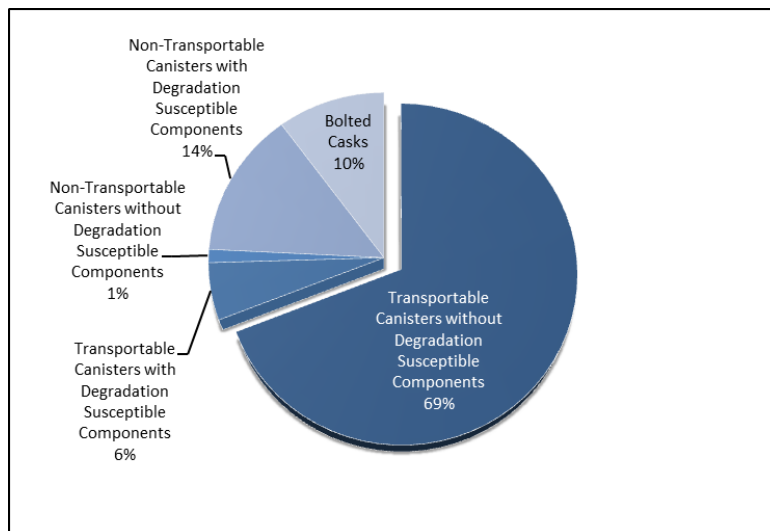

Fig. 6. Fractional representation of the total number of DPCs and bare fuel casks by canister type and material susceptibility [Ref. 22]

Criticality modeling has shown that even without neutron absorbers, virtually all DPCs would be subcritical if flooded with chloride brine, as would be prevalent in a salt repository. This result is represented by a hypothetical, conservative high-reactivity configuration whereby the fuel rods in a typical DPC are assumed to be distributed throughout the canister volume in a hexagonal array with uniform pitch

(Figure 4). This configuration is used to estimate a lower-bound chlorine concentration to maintain subcriticality in DPCs over the postclosure performance period.

Criticality analysis of the hypothetical rod-redistribution case flooded with sodium chloride brine of varying strength, are summarized in Figure 7. A saturated brine (158,000 ppm as calculated) could ensure that any fuel with 4% enrichment, or 5% fuel with at least moderate burnup, would be subcritical for the analyzed configuration. Similarly, many (but not all) DPCs would be subcritical if flooded with seawater, with loss-of-absorbers, analyzed using uncredited margin [Ref. 22]. 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.
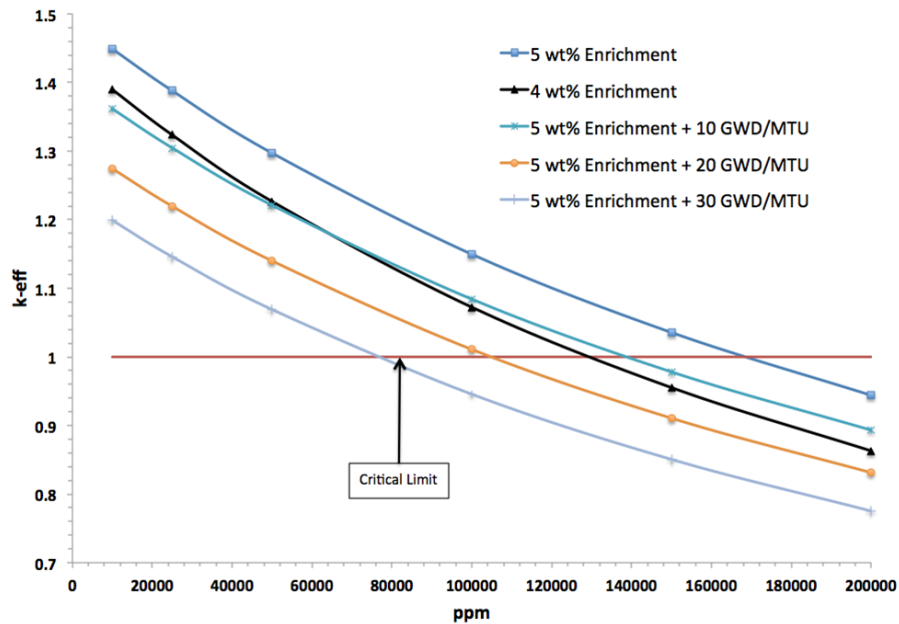
Note: Solubility limit for NaCl at 20°C corresponds to 158,000 ppm. Higher chlorine concentrations could be possible with naturally occurring divalent salts.

Fig. 7. Reactivity effect from chlorine concentration in flooding ground water, for hypothetical high-reactivity rod-redistribution case

In order to exclude postclosure criticality from performance assessment for a geologic repository, because of low probability, the probability that one or more packages would achieve criticality during the performance period would need to be less than 10^{-4} (per repository realization; based on 10CFR63). This would require that the impacts from disruptive events (e.g., seismic ground motion and faulting), and early overpack breach due to defective manufacture or damage in handling, are equally unlikely. Disruption by natural events is controlled by site-specific factors that cannot be addressed in a generic study, however, early overpack breach can be addressed. We note that excluding criticality on low probability is not the only approach, and that an alternative and allowable approach would analyze consequences from one or more criticality events.

For a recent repository performance assessment [Ref. 18] the probabilities for different types of waste package manufacturing defects were estimated and summed, and represented as complete failure to perform any containment function beginning at emplacement. The calculated probability for early failure

was on the order of 10^{-5} per waste package. If applied to disposal of thousands of waste packages containing SNF, in a saturated setting (where flooding is very likely for any breached package), the result could far exceed the probability screening threshold for criticality. Accordingly, the reliability of containment (probability of overpack breach due to manufacturing defects) is an important aspect of criticality control in saturated media. Improving the reliability from 10^{-5} to 10^{-8} per overpack, could allow screening of probability on low probability (at least for undisrupted conditions, or if damage from natural disruptive events were similarly unlikely). Such reliability could be achieved using multiple, dissimilar corrosion-resistant engineered barriers, for example, layers of nickel-based alloy and titanium in the overpack. Finally, it is important to recognize that criticality can be managed as a 10,000-year FEP, as discussed here, but the current regulation (10CFR63) is likely to be revised to reflect repository sites other than Yucca Mountain, and the 10,000-year specification could be changed. Extending to substantially longer postclosure performance periods could significantly limit options for DPC direct disposal (or even for disposal of purpose-designed canisters).

ADDITIONAL DISCUSSION

Logistical simulations using TSL-CALVIN [Ref. 22, 26] were done to better understand the relationship between the 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 (disposable) canisters at nuclear power plants. TSL-CALVIN models all steps in management of commercial SNF from discharge until delivery to a repository, and thermal decay, for SNF from all existing and shut down power plants. In the simulation cases current dry-storage canister loading practices were projected into the future, assigning dates to repository opening and transition to loading MPCs. Thermal constraints on disposal were imposed to represent disposal (particularly of DPCs) in different geologic settings.

Results show that the benefit from implementing a new MPC design, with respect to shortening the cooling time for all SNF including that in DPCs, is associated with the earliest possible repository start date. As time passes, more of the total SNF inventory will be in DPCs so the value of a transition to MPCs will decline (without re-packaging of fuel from DPCs into disposal canisters, which introduces other costs and complications). This result emphasizes the value of timely repository siting and implementation, and timely decision-making on transition to disposable MPCs at the power plants, as well as timely decision-making on DPC direct disposal.

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 drastically decreasing the required decay storage time, but increasing overall system cost by tens of billions of dollars. If the 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).

SUMMARY AND CONCLUSIONS

Following preliminary evaluations [Ref. 12, 22] technical analysis continues to show that direct disposal of a substantial fraction of existing DPCs, limited mainly by thermal management, uncredited criticality margin, materials of DPC basket construction, and the salinity of ground water in the disposal environment, could be part of the overall waste management system. Results described in this paper are summarized in Table 1. 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 likelihood of criticality if breach occurs.

Disposal in bedded or domal salt could be more readily achieved, particularly with respect to postclosure

criticality control, with the caveat that a first-of-a-kind heavy shaft hoist with roughly 3× the payload capacity of the largest existing hoist, would likely be needed. Site-specific salt rheology could also be important (for disposal of heat-generating SNF in packages of any size, not just DPCs) [Ref. 22, 23].

All of the results posted in Table 1 would benefit from repository site-specific information, especially thermal management and criticality control. These are objectives closely related to postclosure safety strategy, and sensitive to DPC size and characteristics. Note however that site characteristics favoring DPC direct disposal are generally too restrictive for MPCs or other purpose-designed disposal canisters that are smaller (e.g., 21-PWR size or smaller) and have long-lived neutron absorbers. Whereas advantages from switching to loading MPCs were shown to decline with time, a practical approach to disposal implementation would be to first implement the switch to MPCs, then acquire a site for MPC disposal, 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 repository siting and operation. If direct disposal was selected, most if not all DPCs (loaded before the switch to MPCs) would have cooled enough by that time for prompt disposal.

Table 1. 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)	< 100	< 110	150+	150+
Host Rock Temperature Tolerance (°C)	200	200	100	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 Ref. 18.
   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., > 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.

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