APPENDIX E

NFCSC DOCUMENT COVER SHEET[1]

Name/Title of Deliverable/Milestone/Revision No. Workshop to Plan R&D Support of Fuel/Basket Modification for Direct Disposal of Future DPCs (M3SF-20SN010305052

Work Package Title and Number Technical and Programmatic Solutions for Direct Disposal of DPCs - SNL (SF-21SN01030505)

Work Package WBS Number WBS 1.08.01.03.05

Responsible Work Package Manager Ernest Hardin
(Name/Signature)

Date Submitted December 23, 2020

Quality Rigor Level for Deliverable/Milestone[2]	☐ QRL-1 ☐ Nuclear Data	☐ QRL-2	☐ QRL-3	☒ QRL-4 Lab QA Program[3]

This deliverable was prepared in accordance with Sandia National Laboratories
(Participant/National Laboratory Name)

QA program which meets the requirements of

☒ DOE Order 414.1 ☐ NQA-1 ☐ Other

This Deliverable was subjected to:

☒ Technical Review ☐ Peer Review

Technical Review (TR)	**Peer Review (PR)**
Review Documentation Provided	**Review Documentation Provided**
☐ Signed TR Report or,	☐ Signed PR Report or,
☐ Signed TR Concurrence Sheet or,	☐ Signed PR Concurrence Sheet or,
☒ Signature of TR Reviewer(s) below	☐ Signature of PR Reviewer(s) below

Name and Signature of Reviewers

Laura Price/SNL (see other sheet)

Sam Durbin/SNL

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Laura Price/SNL Laura L. P

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Workshop to Plan R&D Support of Fuel/Basket Modification for Direct Disposal of Future DPCs

Spent Fuel and Waste Disposition

Prepared for
US Department of Energy
Spent Fuel and Waste Science and Technology

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Work Package: SF-21SN01030505 Technical and Programmatic Solutions for Direct Disposal of DPCs - SNL WBS: 1.08.01.03.05	Sandia approval (Tracking # 1244777) of this report is for internal use only, and the resulting copy (Rev. 0) was submitted to PICS/NE in satisfaction of the deliverable, and to DOE for management review before publication. The cover sheet(s) attached to the beginning of this document represent the status at the time of deliverable submittal.
Final version: M3SF-21SN010305052 Rev. 1 (February 2021)	Following DOE review, Rev. 1 was prepared with a title change consistent with work planning documents, and submitted for formal Review & Approval at Sandia (technical reviews were not repeated for Rev. 1). The resulting file (SAND2021-1361 R) was then forwarded for publication.

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This report does not take into account contractual limitations or obligations under the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (Standard Contract) (10 CFR Part 961). For example, under the provisions of the Standard Contract, spent nuclear fuel in multi-assembly canisters is not an acceptable waste form, absent a mutually agreed to contract amendment.

To the extent discussions or recommendations in this report conflict with the provisions of the Standard Contract, the Standard Contract governs the obligations of the parties, and this report in no manner supersedes, overrides, or amends the Standard Contract.

This report reflects technical work which could support future decision making by DOE. No inferences should be drawn from this report regarding future actions by DOE, which are limited both by the terms of the Standard Contract and Congressional appropriations for the Department to fulfill its obligations under the Nuclear Waste Policy Act including licensing and construction of a spent nuclear fuel repository.

Abstract

By 2030 about half of all spent nuclear fuel (SNF) arising from the current fleet of commercial power plants will be in dual-purpose canisters (DPCs), which are designed for storage and transportation but not for disposal. As an alternative to complete repackaging of the fuel for disposal, considerable cost savings and lower worker dose could be realized by directly disposing of this SNF in DPCs. The principal technical consideration is criticality control in a geologic repository, because the DPCs are large and depend on neutron absorbing basket components for criticality control. Neutron absorbing materials are generally aluminum-based, and under disposal conditions can degrade after a few hundred years contact with ground water.

Simple modifications to the SNF assemblies or the DPC baskets could help to achieve direct disposal, and this is one of the approaches being studied to address the possibility of disposal criticality (SNL 2020a). Five fuel/basket modification concepts have been proposed (SNL 2020b) and a virtual workshop was conducted to solicit review and feedback on these concepts. The proposed solutions are: 1) zone loading of DPCs to limit reactivity, 2) replacing absorber plates with advanced neutron absorbing (ANA) material, 3) adding disposal control rods to pressurized water reactor (PWR) assemblies, 4) rechanneling boiling water reactor (BWR) assemblies with ANA material, and 5) basket insert plates (chevron inserts) made from ANA material.

The presentations from the workshop are provided in this report, and the workshop discussions are summarized. This information includes prioritization of the proposed fuel/basket modification solutions, and prioritization of the associated model development, validation testing, and quality assurance activities. Information documented in this report will help to steer research and development efforts at Sandia National Laboratories, Oak Ridge National Laboratory, and Idaho National Laboratory that support the U.S. Department of Energy, Office of Nuclear Energy, Spent Fuel and Waste Science and Technology program.

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Acronyms

ANA	Advanced Neutron Absorbing
BPRA	Burnable Poison Rod Assembly
BSS	Borated Stainless Steel
BWR	Boiling Water Reactor
CoC	Certificate of Compliance
DCRA	Disposal Control Rod Assembly
DOE	U.S. Department of Energy
DOE-NE	DOE Office of Nuclear Energy
DPC	Dual-Purpose Canister
EPRI	Electric Power Research Institute
ESCP	Extended Storage Collaboration Program
INL	Idaho National Laboratory
ISG	Interim Staff Guidance
MMC	Metal-Matrix Composite
MTU	Metric Tons Uranium
NQA-1	Nuclear Quality Assurance – Level 1
ORNL	Oak Ridge National Laboratory
PWR	Pressurized Water Reactor
QA	Quality Assurance
QAL	Quality Assurance Level
R&D	Research & Development
RCCA	Rod Cluster Control Assembly
SAM	Structurally Amorphous Metal
SFWST	Spent Fuel and Waste Science & Technology
SNF	Spent Nuclear Fuel
SNL	Sandia National Laboratories
WABA	Wet Annular Burnable Absorber

Workshop to Plan R&D Support of Fuel/Basket Modification for Direct Disposal of Future DPCs

1. Introduction

1.1 Purpose and Scope

A virtual workshop and discussions among consultants and investigators were conducted in October and November of 2020, to follow up on previous studies that proposed options for direct disposal of commercial spent nuclear fuel (SNF) in dual-purpose canisters (DPCs) to be loaded in the future (SNL 2020a,b). This report describes the workshop and the conclusions reached by investigators from Sandia National Laboratories (SNL) and Oak Ridge National Laboratory (ORNL) regarding the priority of these options, and the testing, modeling, and other activities needed to support them.

Motivation for direct disposal of DPCs is found in projections of SNF arising from nuclear power plants, and for loading of this SNF into DPCs (Figure 1). By 2030, approximately half of all the SNF that is projected to ever arise from the current fleet of power reactors will be in dry storage, mostly in DPCs. This means that a strategy for fuel and/or DPC basket modification to achieve direct disposability could affect half the SNF inventory (i.e., the SNF not yet loaded into DPCs) if implemented by that time. Note that other strategies (injectable fillers; disposal criticality analysis) are being investigated for direct disposal of all DPCs including those already loaded as well as those to be loaded in the future (SNL 2020a,c).

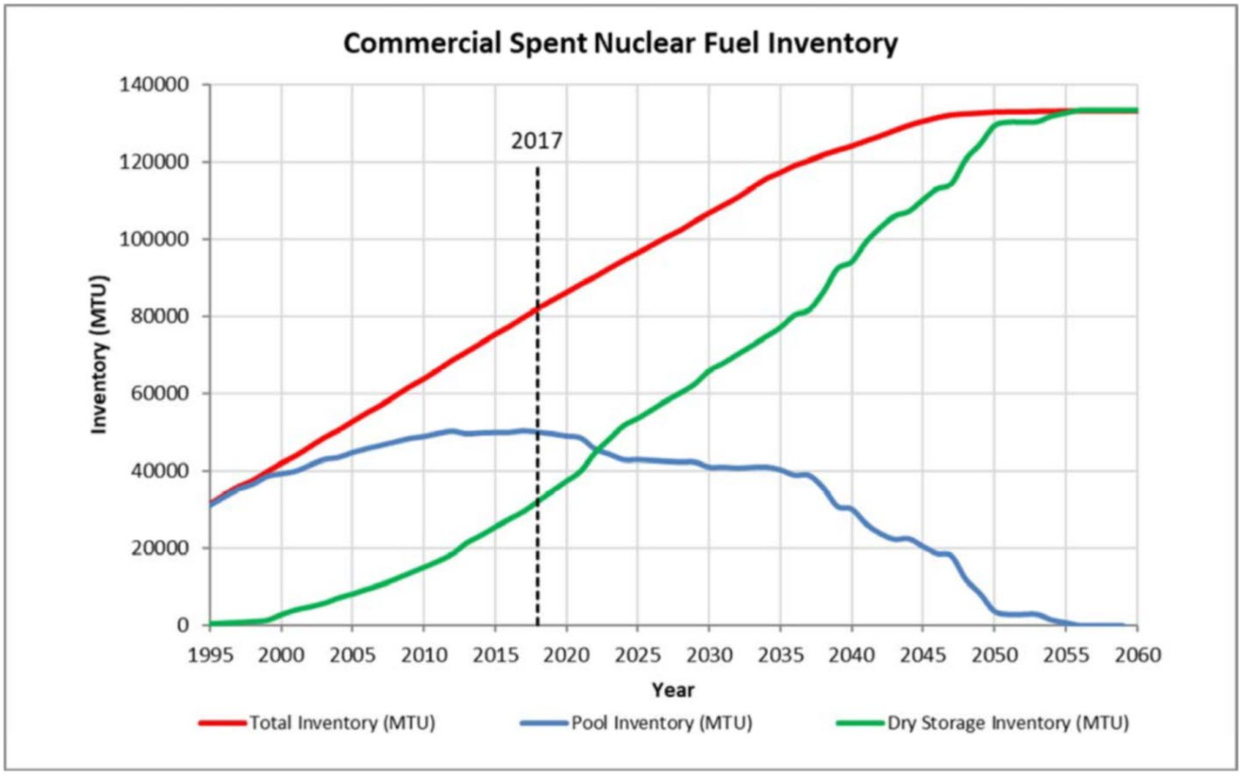

Figure 1. Projected inventory of commercial SNF, and the portion loaded into DPCs, for the current reactor fleet including SNF from decommissioned units (from Gunter 2020).

The goal of the workshop and review activity was to convene experts who could provide industry experience to guide the U.S. Department of Energy (DOE) research and development (R&D) program for

DPC fuel/basket modification. Waste management R&D at national labs such as SNL, ORNL, and Idaho National Laboratory (INL) is intended to generate technical innovation, and to identify and mitigate technical challenges, while not competing directly with the private sector. The technical information developed by these studies can inform future decision making by the Department of Energy, Office of Nuclear Energy.

The value of R&D was questioned in the workshop, since a decision to proceed with any of the fuel/basket modification solutions would be made by DPC vendors in response to their utility customers. However, because the feasibility of modifications depends on when they are implemented, time is of the essence. To implement changes in DPC loading by as soon as 2030, long-lead activities such as corrosion testing and advanced model development will need to be undertaken. This principle is taken into account in formulating the recommendations as discussed in Section 7.

1.2 Workshop Organization

Workshop participants included technical staff from SNL, ORNL and INL, plus a few consultants, current and former employees of utility companies, and a current employee of the Electric Power Research Institute (EPRI) (Appendix A). The consultants included SNF management specialists and geologic disposal licensing experts. A virtual workshop was conducted in four sessions (October 27, 29 and November 5, 13). An agenda was prepared in advance (Appendix B), scheduling two sessions of presentations and two sessions of interactive discussion with the expert panel. The presentations are provided as Appendix C.

1.3 Background

The DOE Office of Nuclear Energy (DOE-NE) Spent Fuel and Waste Science & Technology (SFWST) R&D campaign has investigated the technical feasibility of direct disposal of commercial SNF in DPCs since 2013. The study has addressed four technical elements: safety of workers and the public, engineering feasibility, thermal management, and postclosure criticality control (Hardin et al. 2015). The general finding is that direct disposal of loaded DPCs without modifications, is technically feasible at least for some DPCs, in a range of potential repository host media. Preventing postclosure criticality in DPCs that breach and flood with ground water is considered the major technical challenge. Neutron absorbing materials used in DPCs are based on aluminum, which readily corrodes on exposure to ground water causing dispersal of the B_4C absorber and loss of configuration.

By modifying current DPC loading practices with either additional neutron absorber materials or strategic loading of DPC's to limit overall reactivity, it is possible to significantly decrease the likelihood of criticality for a range of different disposal host media.

Zone loading of DPCs is an attractive solution that would not involve hardware modification to fuel or DPC baskets. Zone loading R&D is described and prioritized in this report, addressing concerns with the reactivity of fuel assemblies and with the regulatory acceptability of DPC loading criteria based on reactivity (which may conflict with other criteria such as those based on peak cladding temperature and worker dose). Also, to be most effective a zone loading approach would have to be simple enough to eliminate the need for reactivity analysis for each DPC loaded.

Adding additional neutron absorber hardware to DPCs when they are loaded, could increase the overall weight of loaded DPCs, which could exceed technical specifications for some systems, and could exceed hook load limits for overhead cranes used at spent fuel pools (SNL 2020b). Hardware solutions that have been identified as promising include disposal control rods (DCRs) in pressurized water reactor (PWR) guide tubes, rechanneling of boiling water reactor (BWR) assemblies using advanced neutron absorbing (ANA) material, and extra absorber plates (e.g., chevron inserts) made of ANA material. Analyses are underway to evaluate how many assemblies would need to be modified, at which locations in DPC baskets.

This report addresses technical, operational, and regulatory challenges associated with each proposed solution and identifies how R&D could lead to successful implementation.

Discussion of Postclosure Internal Criticality

Reactivity of commercial SNF in a flooded DPC declines by roughly 10% in the first few hundred years after discharge, due to radioactive decay and isotopic ingrowth (Wagner and Parks 2003). It then climbs to another maximum at approximately 25,000 yr, after which it steadily declines due to decay of ^{239}Pu. Without flooding, all DPCs remain subcritical.

To simulate reactivity of a DPC that is exposed to ground water, with degradation of neutron absorbing components, two stylized configurations have been used: 1) the loss-of-absorber case (absorber plates replaced by water); and 2) the basket degradation case (basket removed entirely and fuel assemblies moved together as close as possible, with grid spacers remaining intact). These are stylized, and the intermediate configurations possible during degradation from the intact state are part of the scope of R&D discussed in this report.

Extensive corrosive degradation of aluminum or stainless steel in DPCs would produce voluminous corrosion products, such as oxides or oxyhydroxides of Al and Fe. These products displace water, but they are hydrous so that moderation is retained. The configuration of corrosion products and the effect on DPC reactivity have not been previously analyzed but are also part of the scope of R&D discussed in this report.

Analysis has determined that flooding by chloride brine, such as could occur in a geologic repository in salt, suppresses reactivity because natural ^{35}Cl absorbs thermal neutrons (Clarity et al. 2019). The effect depends on fuel enrichment and burnup, and dissolved chlorine concentration. With typical fuel enrichment (up to approximately 4.5%) and burnup of at least 20 GW-d/MTU (relatively low for the current inventory), subcriticality is maintained for chloride concentration of approximately 2 molal or greater. This relationship is expected to hold for future SNF discharges, except possibly for isolated circumstances such as final core loads from decommissioned reactors, which may have low burnup. Fluids in prospective repository host rocks are generally much less concentrated (e.g., seawater at 0.5 molal), except for salt formations.

1.4 Objectives for Fuel/Basket Modification R&D

The overall objective is to support development and licensing of solutions to facilitate direct disposal of future DPCs. It is not a financial or legal review, although cost could be important to the engineering feasibility of solutions discussed. This review will help steer and prioritize the R&D program in the fuel/basket modification area by using existing expertise, recognizing that implementation will ultimately fall to an implementing organization.

1.5 General Discussion of Fuel/Basket Modification

The following topics are generally applicable to R&D that addresses any of the solutions discussed in this report.

Quality Assurance

Technical work at the national labs and their contractors is done under a quality assurance (QA) program compliant with DOE Order 414.1. If the work (data, software, models) could reasonably be used as significant support for technical conclusions in licensing, then it should be done under an appropriate QA program. R&D is conducted by the labs under the DOE Spent Fuel and Waste Science & Technology program, using the Nuclear Fuel Cycle and Supply Chain (NFCSC) QA program (SNL 2018). This program is graded and allows for a QA Level 1 (QAL-1) designation with requirements and controls consistent with nuclear quality assurance as implemented by industry (ASME 2019). These controls may take extra effort, but the investment is necessary and any additional costs can be examined once the controls are established.

QA activities will support all technical products to the level designated, but particular challenges for QAL-1 where it is implemented, will be software qualification, data qualification, and model validation:

- Software qualification will be needed for codes that perform reactivity calculations, and fuel/basket degradation modeling. These codes have already been developed, with histories of many versions.

In accordance with the standards used by the respective code developers, they have documentation, configuration management, test suites, expansive user groups, and other requirements for NQA-1 qualification. Many of the codes that make up the software packages can be considered commercial-off-the-shelf software.

- Data consist of nuclear properties and transport data used for reactivity and depletion modeling, DPC mechanical/structural properties and configurations for degradation modeling, and corrosion data for neutron absorber materials. Qualified data may come from many sources not limited to analysis and testing activities of the R&D program. However, data developed by the R&D program should be developed under an appropriate QA program so that needed quality can be determined (NRC 1988).
- Models for reactivity and depletion, and for fuel/basket degradation, will be needed to develop the approaches to postclosure criticality control identified here. Approaches involving specific hardware will use fuel/basket degradation modeling studies to determine configurations for reactivity analysis. All approaches considered will rely on reactivity modeling, including zone loading and those involving specific hardware. Absorber corrosion data will likely be formulated as a predictive model, which at this point in planning seems likely to be a data-driven spreadsheet product. Model validation can be accomplished in various ways (SKI/CNWRA 1999) but it will need to be done before any applicant can commit to the technical approaches developed.

As noted by the expert panel, the DOE-NE SFWST program has not done any NQA-1 compliant work since the Yucca Mountain Project was suspended in 2010. Most of the reactivity and depletion modeling code developed at ORNL, and the supporting data, does not currently comply with any version of NQA-1.

Operational Efficiency

To help ensure that fuel/basket modification will be acceptable to utility companies and their operators, operational efficiency must be addressed. Solutions that significantly slow SNF management operations may not be acceptable, or may be acceptable only in the final unloading of fuel pools after decommissioning. Besides efficiency of fuel/basket modification under normal conditions, vulnerability to failure or delay from off-normal conditions is important. One contributing cause for off-normal conditions, that is considered in this report, could be distortion of fuel assembly components that occurs in-reactor.

Analysis Required for Implementation

All of the solutions proposed would depend on reactivity analysis but it is hoped that zone loading and other solutions could be demonstrated effective for all possible fuel loading arrangements. Zone loading or any other solution might be accomplished with detailed analysis of each DPC before loading with identified fuel assemblies. However, the time and effort for such analysis could prove to be impractical, so a more generic approach (e.g., burnup vs. enrichment loading curves for zone loading, and similar fuel reactivity limits for other solutions) could be more acceptable.

2. Zone Loading

2.1 Presentation and Description of Option

The presentation on reactivity analysis by Kaushik Banerjee of ORNL, which included zone loading analysis, is included in Appendix C.

This solution represents the prospect that loading maps could be developed for DPCs to reduce the reactivity of the DPCs for flooded and degraded conditions, to subcritical levels. Zone loading for disposal criticality control is a compelling idea because it would not require new hardware, or DPC basket redesign, or major procedural changes. Technical feasibility depends closely on whether enough low-reactivity assemblies are available in each fuel pool to occupy the inner positions in DPC baskets. Zone loading to decrease reactivity is further complicated by potential conflict with loading specifications already in the certificates of compliance (CoCs) for DPC systems. Loading specifications have been established for most DPCs to limit peak cladding temperature during dewatering operations (hotter assemblies in outer positions), and worker dose (e.g., limits on heat generation/gamma flux from assemblies in outer positions, and loading of activated-metal control hardware in inner positions).

Zone loading for disposal was analyzed originally by EPRI (2008), with results that suggested that reduction in reactivity would be minimal. While zone loading of future DPCs is still being investigated by the disposal R&D program, a previous misload analysis showed that a useful range of k_{eff} could be achieved by rearranging assemblies within as-loaded DPCs (Clarity et al. 2019). This implies that an even greater and more useful range of k_{eff} could be achieved by selecting assemblies from the entire fuel pool, as each DPC is loaded.

2.2 Workshop Discussion

Feasibility of Zone Loading

Reactivity of spent fuel assemblies in commercial light-water reactors is determined by burnup and the initial state of ^{235}U enrichment. Higher burnup assemblies (for a given initial enrichment) have lower reactivity. Higher burnup depletes ^{235}U, but produces small amounts of fissile Pu isotopes, and produces certain fission products that lower reactivity by absorbing neutrons. The net result is that fuel assembly reactivity decreases during reactor operation, motivating eventual replacement. For a given enrichment a range of burnup is possible depending on how the fuel is loaded in the reactor and how the reactor is operated.

The availability of low-reactivity assemblies could limit the effectiveness of zone loading. Since the introduction of DPCs about 25 yr ago, tolerance for hotter fuel assemblies in DPCs has improved due to basket design. Analyses should be conducted to determine if there are enough low reactivity assemblies to sufficiently reduce k_{eff} for degraded DPC configurations. Many sites have already performed DPC loading campaigns and the early loadings used much of the older, less reactive fuel.

The objective should be to develop a loading map approach for reactivity that does not also violate loading specifications in DPC CoCs. As of now it is not known if this is technically feasible but it would greatly accelerate zone loading as a solution for disposal criticality control. If practical, reactivity loading criteria should also be generic so that individual canister reactivity analysis is not required.

As observed in the briefing (Appendix C) approximately 60% of existing DPCs are subcritical without modification, in degraded disposal conditions. If future loaded DPCs follow this trend, then zone loading would be applied for the remaining 40%. Scarcity of low-reactivity assemblies would be evident if zone loading changes the remaining fuel inventory in such a way that more DPCs eventually require zone loading.

Zone loading would be focused on PWR fuel, since PWR DPCs tend to have a greater degraded reactivity than BWR DPCs, as observed in the sample of as-loaded reactivity analyses presented.

A zone loading approach would supplement the current method (implemented in software) that is used to devise loading maps. Neutron transport simulation for every DPC would likely not be required if the approach could be implemented using separate loading curves (burnup vs. enrichment) for different zones within the DPC. The strategy for loading based on thermal criteria uses a ranking approach, and a similar approach might be used for reactivity. Fuel pools may have different regions segregated by enrichment and burnup categories, so that assemblies for zones within a DPC could simply be chosen from different regions of a pool.

The utility loading algorithm (DPC loading maps) could be adapted to include reactivity, allowing loading of low-reactivity assemblies in internal locations. If none of the thermal or dose based limits were violated, zone loading for reactivity also might be done without further licensing. Alternatively, this may not be realistic if reactivity limits cannot be achieved without violating thermal and dose loading criteria. R&D activities should address differences between loading to meet thermal, worker dose, and reactivity criteria. It was noted that the NRC is invested in the CoC specifications that limit peak cladding temperature, and how they have been implemented in DPC loading maps and implemented in vendor software.

Some relaxation of NRC requirements on cladding temperature, particularly for assemblies located in internal basket positions, could be needed for zone loading. Note that recent work by the Storage & Transportation R&D program (high-burnup storage demonstration) showed that thermal models are over-estimating heat output and temperatures. Even with larger thermal margins the NRC staff might be unwilling to relax the margins represented in current loading requirements. Discussions have been held with NRC staff about raising Interim Staff Guidance (ISG) 11, Rev. 3 cladding temperature limits, and more information on this may be available in 2021.

Depletion analysis used in the as-loaded reactivity analysis is conservative (i.e., relating enrichment and burnup, to final nuclide inventory). The degree of conservatism could translate to $\Delta k_{eff} \sim 0.05$. To extract this additional reactivity margin, reactor simulations would need to be run to validate the amount of depletion and nuclides remaining in the fuel.

Note that if a reactor shuts down part-way through a fueling cycle, and it is the final shutdown, then the last assemblies taken out of the core will be more reactive than previous core discharges.

Focusing a zone loading approach on disposition of the fuel pool inventory after plants are decommissioned, including the final core, could be a good place to start. This is because a known inventory can be more readily optimized, especially when it includes a partly burned final core. A regulatory review would evaluate whether constraints such as CoCs for dry storage and transportation systems would limit how zone loading is implemented during decommissioning.

Burnup Credit Analysis

The PWR burnup credit approach is qualified for use in regulatory analysis as described in ISG-8, but for BWR burnup credit much work remains. It is fundamentally simpler to perform burnup analysis for PWR fuel than for BWR fuel due to moderator voiding as the coolant water traverses axially along the fuel and boils. This complicates the simulation of load-following and other transients.

At present, burnup credit is analyzed in a more rigorous manner for storage and transport than for disposal. If reactor operation follows higher enrichment and burnup trends, future PWR and BWR discharges may have fuel characteristics that exceed the applicable ranges of nuclear data currently used in burnup analysis.

Misload Analysis

The misload analysis discussed in the modeling presentation involved hypothetical shuffling of assemblies only within as-loaded DPCs, wherein many DPCs were found to have excessive reactivity ($0.98 < k_{eff} < 1.01$) but shuffling could swing Δk_{eff} by +/- 0.05. This is a lower bound on the impact that might be obtained for future DPCs by selecting low-reactivity assemblies from the fuel pool. Accordingly, it is reasonable to conjecture that zone loading could lower reactivity for a substantial portion of future DPCs.

Misload analyses are required for licensing, but the assumed probabilities are typically conservative. Remote cameras and other means are used to verify correct assembly picking and insertion, but human error is considered to be important by the regulator. At shutdown sites certain types of human error could decrease in frequency, as there are progressively fewer fuel assemblies for management.

2.3 Testing and Validation Needs

Zone Loading Feasibility Analysis

The best starting point for analysis would be one or more power plant sites undergoing decommissioning, because the fuel inventory is static. If the entire site inventory cannot be loaded in low-reactivity configurations, then zone loading may be technically infeasible. Analysis for other sites including active plants can then proceed with an informed perspective.

Depletion and Burnup Credit Analysis

Evaluate how depletion is calculated for disposal reactivity analyses, and reduce conservatism where possible (lowering k_{eff}). Develop and document a qualified approach to BWR fuel burnup credit analysis. Each of these analytical steps could have a significant effect on reactivity analysis for degraded DPCs.

Data and Software Qualification

Future licensing of zone loading would require model validation and data qualification. As identified in Section 7, these activities involve more intensive effort and should be deferred pending resolution of scoping studies of zone loading.

3. Replace Absorber Plates

Current DPCs with stainless steel basket structures have absorber plates of aluminum-based metal-matrix composite (MMC). MMC replaced Boral® sandwich material approximately 5 yr ago, so there is also a population of DPCs with Boral® plates. The absorber in each case is granular B_4C ceramic, which is thought to be dislodged when corrosion occurs. These absorber plate basket designs can be readily modified by replacing the plates with corrosion resistant ANA material, if the required absorption can be achieved and the plate thickness is similar (2 to 3 mm).

An increasing sector of the current DPC market consists of MMC baskets that serve all three functions using one material: structural, neutron absorption, and heat dissipation. These baskets have no absorber plates (other than MMC basket plates) and cannot be readily modified by replacing plates with corrosion resistant material.

Borated aluminum and borated stainless steel (BSS) were used for absorber plates in earlier basket designs, most of them associated with bolted casks. Absorber plates of power-metallurgy grade borated stainless were selected for the Yucca Mountain (YM) triple-use disposable canister specification (DOE 2008a). A plate thickness of 11 mm was selected for corrosion allowance, in dilute corrosion environments thought to prevail after the repository thermal period. These thick plates would not be readily installed in any current DPC design, without system redesign. One possible remedy would be to use enriched ^{10}B, and therefore less boron, which improves corrosion resistance and could allow thinner plates.

The ANA material proposed for replacing DPC absorber plates is Alloy 22 (Ni-Cr-Mo based) doped with 2% w/w Gd metal, which has a strong thermal neutron absorption cross section. As discussed in the workshop, there are differences in neutron absorption by Gd vs. B. Since Gd is a stronger thermal absorber, any loss of moderator density or incorporation of particulates (e.g., Fe corrosion products) could reduce the absorption efficiency compared to B. This has been investigated previously with reactivity modeling and will be included in future studies by ORNL of ANA control hardware concepts.

INL is currently testing samples of BSS and ANA material previously acquired by the YM project. More samples will be needed to develop data suitably comprehensive for licensing of fuel/basket modification solutions. Hundreds of kilograms of additional material will be needed for corrosion testing and prototype fabrication.

Other options include advanced corrosion resistant coatings which have yet to be investigated. The following discussion of neutron absorber corrosion testing, and novel absorber materials, is also applicable to the discussions of PWR disposal control rods (Section 4), BWR fuel rechanneling (Section 5), and basket insert plates (Section 6).

3.1 Presentation and Description of Option

The presentation on corrosion testing, from Josh Jarrell and Tedd Lister of INL is included in Appendix C.

General corrosion occurs in a relatively uniform manner, while localized corrosion is a non-uniform attack. Localized corrosion comes in a broad variety of forms (e.g., pitting, crevice corrosion, stress corrosion cracking) depending on the material and environment. Electrochemical testing is an accepted method for characterizing corrosion rates for highly corrosion resistance materials (for which exposure testing would take an inordinately long time). It can characterize conditions that allow general and localized corrosion.

INL has recently started testing neutron absorber materials using electrochemical testing. ANA material has unique corrosion properties due to a secondary Ni-gadolinide phase (Ni_5Gd) which forms isolated inclusions that are corroded more readily than the Ni-Cr-Mo matrix (i.e., Alloy 22). Corrosion testing in the past has suggested rapid localized corrosion, but this is thought to have been caused by the gadolinide inclusions. Extended testing to exhaust the inclusions and leave only Alloy 22 matrix exposed to solution, were not performed previously and are a focus of the current testing program. Artificial seawater was selected as representing the most concentrated waters in clay/shale or crystalline geologic settings that might be considered for a repository. Two other conditions are also being used to connect with literature studies and previous testing for the YM project: 0.028 M NaCl and 0.1 M HCl. Initial testing is being performed at 30°C to represent conditions when a waste package breaches after a few thousand years in the repository. Plans call for future testing at 60°C which could reveal further differences between the types of materials tested. As discussed below, the initial program includes testing of BSS and several ANA compositions, with 316 stainless steel as a witness material. There are some remaining questions about localized corrosion of BSS, particularly in more concentrated solutions at elevated temperature.

For successful application in DPC absorber plates, and in other solutions described by this report, the general corrosion rate, or effective rate of surface retreat, must be less than 100 nm/yr for a range of disposal environments. This rate is small enough that exposure testing (maintaining samples in solution without applying electric current or potentials) would take years for each batch of samples, and introduce other error sources such as stability of the corrosion environment, production of colloids, etc.

INL has been procuring and sourcing sample materials including powders for thermal spray coatings, and coupons prepared by additive manufacture.

Preliminary Results From INL Testing

General corrosion rates for all materials tested rank from 0.1 M HCl >> 0.028 M NaCl > artificial seawater. No great difference in corrosion rates between BSS and ANA material (although Ni-Cr-Mo-Gd was the only material among those tested that clearly exhibited stability in all three test environments). Rates less than 100 nm/yr are common in the results obtained. General corrosion in seawater does not appear to be of primary concern. As anticipated, corrosion resistance of 316L stainless steel in seawater is better than that of 304L.

Future Testing

After complete analysis of recent tests, selections will be made for testing at higher temperature. Testing of new materials including alloys and spray coatings, will begin. For coatings, test fixtures are available that expose only the coating to corrosion and not the substrate (typically stainless steel).

Corrosion Modeling

The presentation on corrosion process and material degradation rates, from Pat Brady of SNL, is included in Appendix C.

Modeling of degradation rates was based on general corrosion rates measured and/or compiled by the YM project. The purpose of modeling was to simulate degradation of materials at temperature, in a DPC undergoing pseudo-steady criticality that generates significant thermal power. Modeling cases included an oxidizing, unsaturated case (alluvium) with a time-average temperature of 50°C, and a reducing, saturated case (shale) with a time-average temperature of 250°C. Note that only unheated or ambient temperature results (30°C) would be applicable to a DPC that floods after a few thousand years, with criticality prevented by fuel/basket modifications.

DPCs were idealized by assuming 316L stainless steel as the material of basket and canister construction, and Zr-alloys for fuel assembly components (except for nozzles). For irradiated Zr-alloys the corrosion rate was doubled. The results indicate that at 250°C, most DPC components could completely corrode in a few hundreds to a few thousand years. However at ambient temperature (e.g., 30°C) the rates would be 10 to 100 times slower. For example, 316L stainless steel basket components would be degraded in 7,111 yr at 50°C, 2,813 yr at 100°C, and 505 yr at 250°C.

These results are based on reaction-path kinetics and don't include mass transfer limitations. Over time, as corrosion products accumulate it is likely that the corrosion rates will slow significantly.

Steel corrosion is important because it produces hydrogen, which tends to lower the redox potential and slow or stop oxidative corrosion reactions. With sufficient hydrogen accumulation from stainless steel corrosion, dissolution of UO_2 and leaching of certain fission products from the fuel (with neutron absorption properties) slows by several orders of magnitude. From the modeling, hydrogen is likely to accumulate in breached DPCs in a clay/shale repository, but not in unsaturated alluvium. Oxidative products are generated by alpha radiolysis of the fuel, and can be catalytically recombined with hydrogen at metallic grains that form within the UO_2 fuel matrix.

3.2 Workshop Discussion

From YM project licensing experience, the NRC accepted electrochemical testing. The current testing approach at INL is based on the work done at INL for the YM project, for a range of corrosion environments. Extensive long-term exposure testing was also done by Lawrence Livermore National Laboratory, but stability of test conditions and reproducibility of test results were problematic. Whatever testing is performed on ANA materials, consideration should be given to how data are selected for licensing. This was critical for YM corrosion testing, causing NRC to initiate an investigation into corrosion data selection.

The question of how electrochemical tests could be scaled to represent longer term corrosion°C was discussed. Mechanistic models of corrosion (chemical species, chemical heterogeneity, redox, mass transport) are few and were not relied on for YM licensing (although modeling advances can be anticipated). As a practical matter any material that exhibits localized corrosion in electrochemical tests, in relevant corrosion environments, should be avoided.

A testing program for ANA materials could take 5 to 10 yr, which might not provide effective support to a fuel/basket modification option that needs to be licensed and implemented by 2030. Accordingly, the corrosion testing program needs to focus effort on promising materials and needs to be expedited. It would be a challenge to scale up the program, requiring more facilities, technicians, etc. One possible remedy would be an industrial partner or collaborating with EPRI. Attracting an industrial partner would involve narrowing the range of materials considered, which could be beneficial. Currently, there is no actual market for corrosion resistant ANA materials and industrial partners are likely to be cautious.

A collaboration with EPRI could be effective to address funding support and to get more investigators involved. The Extended Storage Collaboration Program (ESCP) group could be a good starting point. In the past, EPRI studied Boral® under the leadership of H. Akkurt/EPRI. A multi-year study of ANA materials would be similar. Ultimately the vendor and utility industries need to be engaged, and an EPRI collaboration could serve that purpose. Cost sharing might be possible, perhaps as in-kind contributions. Cooperation with Haynes International and other vendors of special alloys and metals, is definitely needed and can be achieved.

A suggestion was made to relax the seawater composition for testing, to a 50% dilution of standard artificial seawater. This would be more benign, and probably representative for many potential clay/shale repository settings (there was no similar discussion of crystalline settings). However, seawater represents prevalent oceanic and terrestrial ground water compositions and has been used as a benchmark for corrosion performance for many materials, for many years. For clay/shale media that were deposited in seawater, or crystalline rock media that underlie salt water, seawater is a natural choice for testing conditions.

Applicability of Absorber Plate Replacement

For a salt repository degradation of fuel components, canisters, baskets, and ANA materials would be accelerated. However, reactivity analysis has shown that flooding by chloride brine would make all DPCs subcritical even with neutron absorbers removed. Accordingly, no more work is needed on postclosure criticality of commercial SNF in a salt repository.

For unsaturated settings similar to Yucca Mountain, the YM project Safety Analysis Report (DOE 2008b) and the associated review by NRC staff (NRC 2014) should suffice to determine absorber materials and corrosion environments. It is mainly for potential clay/shale and crystalline repository settings that corrosion resistant ANA materials are needed.

Al-based MMC baskets are approaching half of all current DPC deliveries, although they are still a small fraction of the total DPC fleet. Not all of these will be Holtec DPCs made with Metamic® or Metamic-HT®; other vendors are bringing MMC baskets to market because of their advantages in fabrication and heat rejection. In these MMC baskets there are no absorber plates that could be replaced, but corrosion resistant ANA material could be added using other hardware solutions (Sections 4, 5 and 6).

Long-term goals of the electrochemical testing program should include evaluating the relationship between localized corrosion and general corrosion (i.e., can testing readily discriminate conditions for onset of general corrosion from localized corrosion).

The time frame for fuel and basket degradation is thousands of years, and highly temperature dependent. It also depends on the chemical boundary conditions, and access of reactants (e.g., ground water and air) to active corrosion fronts. Degradation rates have been worked out based on kinetic measurements, analogous systems, etc., and found to be hundreds to a few thousand years at 250°C, and an order of magnitude longer at 100°C, for DPC-based waste packages undergoing sustained heat-generating criticality event(s). At lower temperatures (e.g., roughly 30°C for waste packages breached at 5,000 to 30,000 yr, without criticality) corrosion would be much slower. Hence, it is possible or even likely that slow corrosion of stainless steel basket plates, and the canister itself, would allow these to perform their structural functions well beyond the 25,000-yr peak of postclosure reactivity.

The contents of DPCs will eventually weather to corrosion products consisting mostly of secondary Fe-oxides or -oxyhydroxides. Due to volume changes the waste package void space will eventually fill with these products. Moderator density and mechanical degradation will be affected.

Poison plates are a costly, if not the costliest part of DPC/basket systems. Cost could be a barrier to replacing MMC with ANA material if it is relatively expensive. A general R&D approach leading to lower ANA material cost at the production scale is therefore warranted. Also note that MMC replaced Boral because of dewatering concerns, so the ANA material would need to perform as well as MMC in dewatering.

Less heat rejection by ANA plates could be a technical hurdle for replacing MMC, since heat rejection by absorber plates is credited in thermal analysis of DPCs. Heat rejection is determined by modeling, so the effect from ANA material could be studied numerically.

The cover sheet construction for attaching MMC absorber plates to stainless steel baskets, is applicable to ANA plates. Absorber plates are held by thin sheets of stainless steel, and welded around the edges. The welds are discontinuous to allow water egress, described as “stitch welds.”

Residual stresses caused by welding will not be an issue for fuel/basket modification because welding will not be used, except in one or two situations that can be mitigated by thermal annealing. Alternatively, a solid-phase welding technique could be used, such as friction-stir welding, that produces less heat and affects a smaller volume of material (less residual stress).

A glass-like structural amorphous metal (SAM) material can be sprayed on, either as absorber material or to protect other absorber material from corrosion. This was reported by LLNL a few years ago, and is described in the current corrosion testing plan (Blink 2019). The Lincoln Electric company has a material patent, and sells spray powders with the previously reported SAM composition.

Validation of corrosion models can follow the approaches used for the YM SAR. Generally these will be simple, discrete statistical models based on test data.

3.3 Testing and Validation Needs

Corrosion Testing

The first priority for this option is corrosion testing of ANA materials to verify general corrosion at 100 nm/yr or less, for a range of corrosion environments including artificial seawater, intended to represent ground waters at potential clay/shale or crystalline rock repository sites. In addition, testing should evaluate whether localized corrosion could occur (materials that resist localized corrosion are preferred for long-term repository service). Replacement absorber plates would be used with stainless steel DPC baskets, so testing should also consider performance of ANA materials in close contact with stainless steel.

Thermal Performance

Heat rejection of DPC baskets with aluminum-MMC plates replaced by ANA plates, should be investigated to assess the reduction of heat rejection capacity for dry storage. The metric for heat rejection is the maximum thermal power, and its distribution throughout the basket (i.e., fuel loading), to achieve maximum cladding temperature of 400°C or other limit consistent with ISG-11 (NRC 2003). This can be done with sufficient accuracy for scoping purposes by simulation rather than physical testing. A configuration based on an actual DPC basket design is preferred for modeling since thermal modeling has already been done for licensing of the DPC for storage and transportation. A comparison of model results with the licensing basis will improve confidence in the model results with ANA.

Prototype Fabrication

Prototype absorber plate fabrication can be done to verify that no difficulties arise with rolling and cutting. Such difficulties are not expected since the material closely resembles Alloy 22. However, the distribution of the gadolinide phase after rolling to required thickness, including areal absorber density both before and after pickling to dissolve the gadolinide inclusions exposed to solution, should be verified.

Fuel/Basket Degradation Modeling

The fuel/basket degradation model (discussed in Section 4) could be important to show how the corrosion resistant ANA plates shift as the basket structure degrades. Such shifting seems unlikely because: 1) stainless steel baskets may continue to provide structural support beyond 25,000 yr if general corrosion is slow; and 2) plates will be sandwiched between fuel assemblies and corrosion products where they are unlikely to shift away from their positions between assemblies.

4. PWR Disposal Control Rods

4.1 Presentation and Description of Option

PWR disposal control rods (DCRs) would be designed to fit in the guide tubes of different types of fuel assemblies. In selected high-reactivity PWR fuel assemblies, DCRs would be inserted into most or all of the 24 guide tubes, making disposal control rod assemblies (DCRAs).

DCRs would likely be full-length rods to avoid uncertainty as to their positions. They would fit easily into guide tubes including those tubes with reduced diameter dashpot features at the lower ends. Guide tubes are generally made from corrosion resistant Zr-alloy, which resists corrosion similar to irradiated fuel rods. This means that DCR position and mechanical integrity could be controlled by the guide tubes, and that neutron absorption performance might not rely to a great extent on corrosion resistance of the DCRs.

The DCRs could readily be designed with some corrosion resistance, for example they could be designed around Zircaloy tubing, welded at the ends, and filled with low-solubility absorber such as low-porosity pellets of B_4C. Other possible designs include solid rods of corrosion resistant borated stainless steel or ANA material (Ni-Cr-Mo-Gd).

The reactivity control function would be immediate for intact DPCs starting when they are loaded, and it would persist in the repository as the DPCs are breached and flooded, and the basket and fuel assembly components begin to degrade. As fuel rods shift and settle, the DCRs would move with them, maintaining the neutron absorption function. Preliminary results from the fuel/basket degradation model (Itasca/SNL 2020) show that DCRs will move with the fuel as the structure collapses. Further development and validation of the fuel/basket degradation model is needed to support hardware options including absorber plates, PWR DCRs, BWR fuel rechanneling, and insert plates. Hence, fuel/basket model development and validation is addressed in Sections 3, 4, 5 and 6.

Preliminary Reactivity Analysis

The presentation on reactivity modeling by Kaushik Banerjee of ORNL is included in Appendix C.

Reactivity analyses are used to understand the importance of differences in DPC design and degradation, and fuel assembly characteristics (enrichment, burnup). For PWR DCRs the preliminary results presented in the workshop show adequate reduction in k_{eff} for as-loaded DPCs if the central nine assemblies in an MPC-37 basket contain pure B_4C in each guide tube. This result is similar to the DCR case analyzed by EPRI (2008).

Possible refinements include evaluating exclusion of DCRs in some guide tubes that are already occupied by reactor control hardware such as burnable poison rod assemblies (BPRAs), wet-annular burnable absorbers (WABAs), or reactor rod cluster control assembly rods (RCCA rods). Reactor control hardware could conceivably be stuck due to distortion of guide tubes. If reactivity reduction can be achieved without a DCR in every guide tube, then there is more flexibility on where in the basket assemblies with stuck hardware could be loaded. Other refinements include different absorber materials and configurations for DCRs.

Moderator displacement credit for discarded reactor control hardware could also be taken. This could be more effective than reported previously (EPRI 2008) because for a given DPC, technical specifications often require loading irradiated hardware in central positions where reactivity tends to be elevated (so moderator displacement would be applied where it is needed most to reduce reactivity).

Fuel/Basket Degradation Modeling

The presentation on fuel/basket degradation modeling by Branko Damjanac and Varun of Itasca, is included in Appendix C.

The fuel/basket model represents each fuel rod by a prismatic arrangement of elements. Spacer grids are generalized without representing each metal piece; grids are deformable and allow axial rod slip. Modeling of spacer grids is a challenge as discussed below. The basket is an egg-crate structure with the properties of aluminum to represent MMC. Stainless steel channels support the basket inside the DPC shell.

To reduce calculation effort degradation is studied using a slice of the fuel/basket array, called a 2.5D model. Models of a full 32-PWR basket and fuel assemblies have also been produced. With the 2.5D models it is possible to show how fuel assemblies adjust to complete loss of basket strength and become supported by the spacer grids. Some voiding occurs between assemblies, especially with degradation of the channel supports that hold the basket.

The order of failure of the different components controls the kinematics of fuel/basket collapse. Basket plates may fail rapidly (as with MMC) or much more slowly (stainless steel). Spacer grid failure increases fuel rod bending and may cause fuel rod breakage. Eventually with failure of basket plates and spacer grids, the fuel collapses. Corrosion and mechanical lifetimes for components are uncertain so that modeling cases will be limited to general cases representing trends.

One key timing question is whether the basket structure lasts well beyond 25,000 yr, which simplifies the simulation and increases confidence in predicted configurations. With 14 basket plates in a 32-PWR egg-crate type DPC basket, each nearly 5 m long, some heterogeneity of corrosive degradation is expected. Thus, if basket collapse occurs in the period of regulatory concern (>25,000 yr) it will not occur uniformly. Long-term corrosion resistance of the basket simplifies the interpretation of basket collapse.

Important conclusions from the presentation include: 1) need to validate the mechanical responses of basket structures and spacer grids as they degrade from corrosion; and 2) need to know whether stainless steel basket components and spacer grids (Zr-alloy) will maintain their structural functions beyond 25,000 yr.

4.2 Workshop Discussion

Disposal Control Rod Implementation

Disposal control rods would be installed into fuel assemblies in the pool, or in the DPC during the loading process. A small fraction of fuel assemblies would be loaded with DCRs (as few as nine in a 32-PWR DPC) so that there could be flexibility as to which were selected to occupy the central positions (based on preliminary analysis).

By comparison, rod clusters (RCCAs) can be reused for 12 to 15 yr in-reactor, and can readily be moved between assemblies. Only the oldest RCCAs find their way into DPCs. Many spent assemblies have open guide tubes so that shuffling of control hardware to make room for DCRs should not be problematic. That said, RCCAs require fixturing to move between assemblies, and can become stuck. One reason this can happen is due to “growth” of guide tubes due to irradiation. RCCA tips were known to stick lower in the guide tubes (which are tapered to provide cushioning of rapid insertions). However, this problem has been resolved by redesign of the control rods.

As for thimble plugs (which block open guide tubes to prevent coolant bypass during reactor operation), different sizes are used in different types of fuel. Whereas Westinghouse uses thimble plugs, Dominion reactors have not used them for 20 yr. Once removed, thimble plugs could be simply dropped into a collection vessel at the bottom of the pool, or they might be reinstalled after insertion of DCRs to prevent movement.

One problem with moving RCCAs out of the internal positions to make room for DCRAs is that many DPC loading maps limit RCCAs to internal positions for shielding of emissions from irradiated metal. Moving RCCAs to outer positions would require re-licensing of the loading maps (see comments about NRC staff licensing priorities).

For damaged fuel, preliminary reactivity analyses have shown that using the outer corner positions is effective, while DCRAs are placed only in internal positions. It would be advantageous to know the degree of fuel damage in “damaged fuel” cans, i.e., whether damage is limited to pinhole leaks or more gross failures. Whereas the GC-859 criteria require only a single check in a box for damaged fuel, another bit of information on the degree of damage to the assembly would be helpful. If the damaged assembly is still basically intact, then burnup credit could be taken in DPC reactivity analyses (damaged fuel is currently assumed to be fresh fuel). So far in the utility industry only shutdown sites have loaded damaged fuel cans in DPCs.

Gd absorbs thermal neutrons more strongly than B, thus any influence that hardens the spectrum such as moderator depletion by formation of corrosion products, could reduce absorption by Gd more than occurs with ^{10}B absorber. The effectiveness of Gd or B, or mixtures, for hardware solutions (Sections 4, 5, and 6) will be tested by reactivity modeling.

Fuel/Basket Degradation Model for PWR Disposal Control Rods

The fuel/basket degradation model could be used for licensing, in the context of repository regulations such as 10 CFR Part 63, if model and parameter uncertainties are properly handled. For PWR DCRs the model would be applied in analysis of features, events, and processes to show that the likelihood of an internal criticality event is less than 10^{-4} per 10,000-yr repository.

Postclosure internal criticality is a process likely to require analysis for longer than 10,000 yr in a repository performance assessment, meaning that the analysis used to include/exclude criticality in the licensing case would need to extend beyond the peak reactivity at about 25,000 yr. If stainless steel baskets do not fail from general corrosion in the >25,000-yr timeframe, then fuel configuration will be similar to the initial configuration. This could also be true if DPC baskets and canister shells were changed to more corrosion resistant materials such as duplex stainless steels, or even type 316 stainless which corrodes more slowly than type 304 in environments resembling seawater.

It was pointed out that spacer grids tend to shift in the reactor and possibly during handling, so that grids for different assemblies might not line up as shown in the models.

Laboratory testing could help in validating the degradation models used to represent degraded configurations of DPCs with DCRAs. Separate effects testing could focus on distortion of guide tubes, and the potential for DCRs refusal at insertion. Validation testing is needed for undamaged spacer grids, then grids that are degraded in some manner representing corrosion damage.

Heat transfer calculations could be useful to confirm effects from DCRAs on conduction and convection at maximum thermal conditions after loading.

Testing in Support of Fuel/Basket Degradation Modeling

For modeling of fuel/basket degradation, the testing program should at some point include Zircaloy. Testing concepts should address the fabrication steps used for cladding tubing and spacer grids (e.g., cold work, annealing, exposure to reactor conditions, etc.). Zircaloy corrodes very slowly at ambient temperature so testing would focus on validation of a mechanical model, that could then be used to predict the cumulative effects from slow spacer degradation.

According to the investigators, spacer grids are key to degradation modeling in addition to basket plates. Test data if available would be used to develop a load-deformation-failure function for the model. A detailed model of spacer grid components would be developed and used to design a spacer grid deformation test. Further validation could be achieved by modifying the grid structure, for example by breaking connections, or by heating the grid to change the metal properties, or by degrading the grid by exposure to radiation and/or autoclave conditions.

It was noted that spacer grids do break in-reactor occasionally, where the edge of the grid impacts core baffles. Loss of the springs or tabs that retain fuel rods also occurs (broken tabs are collected in the coolant strainers). To complicate matters there are different grid designs, and materials vary (Zircaloy-4, Inconel, M5, Zirlo). The SNF inventory should be surveyed to select spacer grids for testing that represent the largest population of fuel assemblies.

For disposal conditions it is likely that the rod springs and dimples, in which stresses are greatest, could be the first spacer grid features to degrade. This would loosen the fuel rods, a result that is not currently described in the degradation model. The remaining features of grids are under less stress (e.g., thicker outer walls) so corrosion could be slower.

Spacer grids leftover from other tests are available for testing. Also, fuel vendors make “grid strips” or partial grid assemblies that could be obtained for testing at lower cost than full grids.

4.3 Testing and Validation Needs

PWR Disposal Control Rod Design and Prototyping

Develop requirements for PWR DCRs, and perform a design selection study to choose materials and a configuration. Support the requirements development and design selection study with reactivity analyses that address the range of fuel characteristics to be accommodated, the number and loading positions of DCRs that are needed, and whether Gd or ^{10}B (or a mixture) is the preferred absorber. The design study should consider different types of PWR DPCs so that the solution is universal and does not require neutronic calculations for each DPC. To the extent that data for as-loaded DPCs and fuel pool inventory are available, determine the extent to which RCCAs and other reactor control hardware need to be shuffled to make room for DCRAs.

This activity is the highest priority for the PWR DCR solution because it is technically feasible and seems closest to implementation because:

- DCRs can be produced at low cost relative to other hardware solutions (SNL 2020b).
- Suitable absorbers such as solid B_4C are readily available (testing of ANA material is not needed).
- By analogy to reactor control rods, DCRs will control reactivity for any combination of fuel assemblies, so that analysis of each loaded DPC would not be required.
- Guide tubes are robust and corrosion resistant.
- Licensing could be straightforward if implementation does not require revising other DPC requirements such as loading map criteria.

Also, among as-loaded DPCs that have been analyzed for reactivity in degraded states, PWR DPCs are generally more reactive than BWR DPCs, so that a readily implemented PWR-specific solution has high potential utility for disposal criticality control.

Two additional technical issues that should be addressed are: 1) the neutronic configurations that occur with fuel/basket degradation in different types of DPCs; and 2) verification of available PWR assemblies with open guide tubes (otherwise a separate waste stream will result consisting of disused reactor control hardware).

Fuel/Basket Degradation Model Validation Testing

The fuel/basket degradation model can be improved by developing and validating detailed mechanical response models for degraded spacer grids and degraded stainless steel basket plate connections. A detailed load-deformation-failure model for spacer grid components will be developed and used to design a spacer grid deformation test. Further validation will be approached by modifying the grid structure as discussed in Section 4.2.

Basket plate corrosion, and degradation of plate connections, can be studied using a scale model with a material such as aluminum that corrodes rapidly at autoclave conditions. In addition, testing of stress-corrosion cracking (SCC) including heat-affected zones around welds between basket components, which are unmitigated during fabrication, is needed if these processes will impact basket degradation.

Fuel/Basket Model Development

The fuel/basket degradation model will be extended to represent different types of PWR basket construction, including stainless steel egg-crate designs, and stainless steel tube-and-plate designs. A modeling project using validated model components, in conjunction with the modeling project described in Section 5.3, will then provide degraded configurations for reactivity analysis (Stage II as described by Itasca/SNL 2020).

Another purpose for generating a set of degraded configurations for analysis, is to evaluate the stylized configurations that have been used to represent degradation (Section 1.3). The evaluation should focus on similar configurations simulated mechanistically, and on the potential reactivity of intermediate states of degradation (before the stylized end configuration is reached).

5. BWR Fuel Rechanneling

5.1 Presentation and Description of Option

Each BWR fuel assembly is enclosed in a thin metal shroud or channel, to guide coolant flow upward and prevent coolant bypass between adjacent assemblies. The channel fits around the assembly and is fixed by a single bolted clip at the top of the assembly. Channels are typically made from Zr-alloy for neutron transparency, and the rechanneling solution would replace certain channels with ANA material. The rechanneling operation could be performed in a dedicated station in the fuel pool. Disused Zr-alloy channels would be collected and compacted as a separate waste stream (low-level or greater-than-Class C waste).

The number of rechanneled assemblies would be less than half of the total loaded in a DPC, if placed in central locations in a checkerboard pattern. The net change of weight for rechanneling would be relatively small, and comparable to PWR DCRs on a per-DPC basis, depending on the channel thickness (density of Zircaloy is 6,560 kg/m^3 compared to 8,690 kg/m^3 for Alloy 22)(SNL 2020b).

5.2 Workshop Discussion

Warping of fuel channels can occur during reactor operation due to "growth" from irradiation, which then can impede BWR control blade movement. In this case, during outages the plant operators will rechannel those affected assemblies that are needed for another fueling cycle. For disposal, rechanneling offers the benefits of compatibility with existing DPC basket designs, and being a routine enough operation that is already employed at reactor sites.

Only alternating BWR assemblies would need rechanneling, in a checkerboard array that would position absorber material between every two adjacent assemblies. As discussed in Section 2, as-loaded BWR DPCs are typically subcritical for the degradation cases used in the analysis, which would further limit the extent of rechanneling needed (but also require reactivity analysis of each DPC prior to loading).

Work on channel distortion (Garzarolli et al. 2011) showed that channels tend to bow toward the blades due to neutron "shadowing." Bowing by as much as 6 mm can be tolerated without significantly impeding blade movement in-reactor. Distorted BWR channels may get stuck and not come off during rechanneling. Apparently, channels do not often become stuck within the limits of distortion used to protect blade movement, because this has not been reported. Operational knowledge is needed to evaluate how often channels have been stuck in the past, and how likely it is in the future. Since fewer than 50% of BWR assemblies in a DPC would require re-channeling for disposal criticality control, there would be opportunities to swap out stuck assemblies.

The Atrium series of BWR assemblies have a "water cross" that is welded to the channel and would impede channel removal. Rechanneling such assemblies would require significantly more complete disassembly, including removal of the fuel sub-assemblies. It was noted that few, if any Atrium-type assemblies have been sold by Westinghouse in the U.S.

Ultimately, BWR fuel designs at different sites will require different rechanneling designs for disposal criticality control.

Channels fabricated from ANA material would require some welding to form the walls of the box. Preliminary work on welding of Ni-Cr-Mo-Gd alloys was done 10 to 20 yr ago and could be restarted. Results from a Ni-Cr-Mo-Gd welding study showed depletion of Gd in welds, but channels don't require uniform absorber distribution at the corners where welding would be used. It would be easiest to show that welding can be effective structurally if there is not requirement for Gd in the welds (allowing use of Alloy 22 welding wire, or "buttering" with pure Ni, etc.).

Neutronic models used for predicting BWR rechanneling performance require validation, and the ensuing discussion focused on the need for better modeling of BWR burnup credit. The UNF-ST&DRDS software and neutron transport/depletion software used at ORNL for DPCs, meets ORNL requirements and could likely meet NQA-1 standards as well because of its genesis and documentation. However, it was pointed that the workhorse SCALE software is not NQA-1 qualified, nor is all of the supporting nuclear data, or the GC-859 data used to represent DPCs. ORNL is reported to be working on qualification of nuclear and other data needed for depletion and reactivity calculations. Note that 10CFR961 does not stipulate that fuel data are qualified.

As pointed out in Section 4, any influence that hardens the spectrum such as moderator depletion by formation of corrosion products, could reduce absorption by Gd (^{155}Gd and ^{157}Gd) more than with ^{10}B. The effectiveness of Gd or B, or mixtures, in hardware solutions (Sections 4, 5 and 6) will be tested by reactivity modeling.

5.3 Testing and Validation Needs

Corrosion Testing

Unlike PWR DCRs, rechanneling requires development of a new, corrosion resistant ANA material. Such a material may presently exist, such as some form of borated stainless steel, but corrosion resistance for a range of disposal environments has not been established. Therefore, the first priority for this potential solution is the corrosion testing program described in Section 3.

Fuel/Basket Model Development

The next priority is advancement of fuel/basket degradation modeling to confirm that corrosion resistant BWR channels move with the fuel after degradation of spacer grids and/or basket plates. The model for BWR fuel/basket components will require the same validation testing approach described in Section 4. The model will be extended to represent different types of BWR basket construction, including stainless steel egg-crate designs, and stainless steel tube-and-plate designs. A modeling project using validated model components, in conjunction with the modeling project described in Section 4.3, should then provide degraded configurations for reactivity analysis (Stage II as described by Itasca/SNL 2020).

Rechanneling Design and Prototyping

Analysis of dimensions and tolerances for fuel assemblies and DPC baskets is needed to validate the channel thickness available for replacement channels (and the minimum areal density and maximum general corrosion rate).

6. Basket Insert Plates

6.1 Presentation and Description of Option

The basket insert option (chevron inserts) is described in Appendix C and SNL (2020b).

Chevron inserts were developed to supplement neutron absorption in spent fuel pool racks with degrading Boroflex® absorber material. The inserts are typically made from aluminum-MMC or borated aluminum alloy and may be anodized for corrosion protection. Aluminum is not suitable for disposal criticality control applications because it readily corrodes on contact with ground water, so inserts made from ANA material are considered here. Each chevron insert would cover two sides of the fuel rack cell or fuel assembly, with the folded shape helping to center and anchor it.

Insert plates could take other configurations such as single flat plates or square tubes, but these have not been used in spent fuel racks. The chevron configuration allows greater thickness for corrosion allowance than square tubes, by using the available clearance on only one side. Single flat plates might be inserted after loading each fuel assembly but could readily hang up on spacer grids or other features of the fuel.

Chevron inserts for fuel pool racks are made of aluminum and are not suitable for disposal applications. For DPCs they would be made from ANA material that is shown to have sufficiently slow general corrosion, ductility and other properties favorable to fabrication, and sufficient areal absorber density. Insert plates would be designed to maintain the minimum areal absorber density beyond 25,000 yr exposure to ground water. The available thickness is up to about 3 to 4 mm, so the corrosion rate must be <<100 nm/yr. Preliminary corrosion testing indicates that the Ni-Cr-Mo-Gd ANA composition could provide this performance at least in more benign environments.

Rough calculations show that chevron inserts could add as much as 3,000 lb to the weight of a loaded DPC in its transfer cask, for hoisting from the fuel pool (SNL 2020b). One option is to pump water out of the DPC during the lift (with shield lid in place), which could lower the overall weight by approximately 10,000 lb.

Chevron inserts could be used in any DPC, either PWR or BWR, with enough clearance between fuel assemblies and basket cells. For example, an insert that is 3 mm thick might be used if there is 6 mm or more clearance between fuel assemblies and basket cells in the x- and y-directions, if there are no other circumstances such as distortion that would make fuel insertion difficult.

In this study, chevron inserts are envisioned as a way to provide disposal criticality control where other solutions are not workable for any reason, and particularly for retrofitting baskets made from aluminum-MMC material.

6.2 Workshop Discussion

Operational Challenges with Chevron Inserts for Spent Fuel Pool Racks

Inserts have been used to retrofit fuel racks to make up for loss of absorber due to degrading Boroflex® or Boral® (which can blister). Two main designs are used: 1) the NETCO Snap-In deforms as it is placed in the rack before the fuel assembly, locking in place; and 2) Holtec has another design that is placed in the rack after the fuel is inserted and hangs on the top of the assembly (SNL 2020b). Inserts continue to be used in fuel racks today for mitigation of absorber degradation. Chevron inserts are available in different thicknesses needed to accommodate local conditions, particularly variations in rack designs and the available clearance, which can be reduced by absorber degradation. According to one panelist, there were some operational challenges with the Snap-In inserts that would occasionally not snap in place correctly causing clearance issues.

The R&D program will pursue ANA material and its corrosion resistance and other properties, to determine what thickness would be required, for feasibility evaluation. BSS would probably need to be enriched in ^{10}B if natural B does not provide sufficient poison loading at the allowable insert thickness.

It was noted that the additional surface area of the inserts could increase dewatering time which could be problematic for hotter waste packages.

Hook Load Considerations

The weight of inserts was discussed as a possible barrier to implementation in fuel pool facilities that are operating at or near hook load limits for fuel pool cranes. The oldest plants have the least hook load margin, and such measures as removable shielding and water jackets (filled only after hoisting from the pool) have been used. Pumping water out of the DPC (i.e., 5 to 6 cubic meters) while it is still in the pool, could reduce hook load by 10,000 lb. but has not been done or is developmental. It is necessary to know exactly how many inserts would be needed to determine if the additional weight would be of concern.

6.3 Testing and Validation Needs

Corrosion Testing

BSS and ANA materials should be tested to provide assurance that they can provide reactivity control beyond 25,000 yr exposure to the disposal environment.

Reactivity Analysis

Reactivity analysis is needed to determine the minimum absorber areal density, and how many inserts would be needed in a DPC (without analyzing each DPC before loading).

Review of Dimensional Clearance Data and Hook Load Limits

Once the composition, required thickness, number, and placement of inserts is better known, an investigation is needed of available clearance between fuel assemblies and DPC baskets, and the hook load limits that could be problematic at certain plants.

Prototype Fabrication

If sufficient clearance is available, then the next step is to design and fabricate a chevron insert prototype, as a demonstration of workability. If welding is used, then a neutron absorbtion scan would be done to verify the absorber distribution within and near welds.

Fuel/basket Degradation Model Analysis

The fuel/basket degradation model will be modified to include chevron inserts. Corrosion resistant inserts could help maintain geometric configuration as the basket degrades, or the basket and spacer grids degrade. They also increase weight which could adversely affect assemblies at the bottom of the waste package.

7. Recommendations

This section is based on direct input from the workshop, and interpretation of those discussions by the authors.

7.1 Prioritization of Solutions

1. **Zone Loading** – Highest priority because it requires no foreseeable modification to any DPC, while relying on the same methods for reactivity analysis and fuel/basket degradation that would be needed for implementation of every other option. Zone loading could require re-analysis and licensing of changes to DPC loading criteria that limit peak cladding temperature and worker dose.
2. **Replace Absorber Plates** – Higher priority because it is a simple modification to DPC baskets made from stainless steel, which at present are the majority of DPCs. It would be implemented during DPC fabrication and would not change fuel pool operations. Replacing absorber plates would require ANA material, accordingly, corrosion testing is identified as a high priority activity in Section 7.2. ANA material is needed for three of the four hardware options proposed in this report.
3. **PWR Disposal Control Rods** – Higher priority because it could be implemented for nearly any PWR DPC, and as-loaded PWR DPCs have been shown to have higher degraded reactivity than BWR DPCs. Could be implemented with any type of DPC including those with aluminum-MMC baskets, and requires fuel pool operations. Fitment issues would be limited to sliding DCRs into guide tubes, and displacing reactor control hardware into other locations. Requires reconciliation with existing technical specifications on DPC loading maps (cladding temperature and worker dose), and locations for irradiated control hardware.
4. **BWR Rechanneling** – This is the only hardware modification possible for BWR fuel assemblies if they are reactive enough to require mitigation, and basket modifications (absorber plates, insert plates) are not available. Requires ANA material, fuel pool operations, and may be subject to dimensional clearance and assembly distortion issues.
5. **Basket Insert Plates** – Chevron inserts are the most promising variant, and have been implemented extensively for mitigation of fuel pool racks. Would require modification to fuel pool operations, especially if assemblies do not fit into modified DPC basket cells. Requires ANA material and will be subject to dimensional clearance and assembly distortion issues. Could be most useful for retrofitting of aluminum-MMC baskets.

7.2 Prioritization of R&D Activities

Activities can support more than one fuel/basket modification option, and are prioritized separately below. Suggestions on QA are included in the list. All activities will be subject to QA grading, and in addition, the indicated suggestions should be considered. For example, a notation of QAL-1 indicates that some aspect of the work scope is likely to be used for licensing. The default is no notation of this type, and indicates graded QA will be used.

7.2.1 Corrosion Testing

Needed for three out of the four proposed hardware solutions.

- ANA material selection and corrosion testing (QAL-1).
- Material selection for prototype disposal criticality control solutions.
- Verification of selected ANA material properties including heat transfer properties, thermal expansion, and yield strength.

- Scoping model of DPC basket heat rejection after replacing aluminum-MMC absorber plates with ANA material (stainless steel baskets).
- Fabrication process demonstration (rolling, bending, welding, annealing) and verification of areal absorber density and corrosion performance of worked samples. Testing concepts are further explored in Section 3.3, and in ORNL (2020).

7.2.2 Reactivity Analysis for Scoping Evaluation of Fuel/Basket Modification Options

Reactivity analysis supports all of the solutions proposed in this report. It is an ongoing, iterative effort with immediate activities (zone loading, preliminary degraded configurations), and longer-term activities to evaluate degraded configurations (Section 7.2.5). Eventual qualification of data and software is addressed in Section 7.2.7.

7.2.3 Testing to Support Fuel/Basket Degradation Modeling (with modeling support)

Predictive degradation modeling is needed to some extent for each of the proposed solutions, and validation is a major challenge that needs to be addressed before extensive predictive modeling.

- Develop a load-deformation-failure model for spacer grids and basket structures.
- Using the model, design a validation test series. Additional testing concepts are explored by ORNL (2020).
- Procure representative BWR and/or PWR spacer grids, and verify test predictions.
- Design and construct scaled basket structures, and verify test predictions (QAL-1).
- Perform tests on intact and progressively degraded test structures (QAL-1).
- Compare to model predictions for model validation.

7.2.4 PWR Disposal Control Rod Design and Prototyping

PWR DCRs are promising for the reasons given in Section 7.1.

- Perform k_{eff} analysis with idealized DCRs to estimate the required number, location, and neutronic properties.
- Review PWR assembly types, and develop disposal control rod requirements.
- Design and fabricate prototype disposal control rods.
- Test DCR properties and insertion characteristics (e.g., in deformed guide tubes). Concepts for “separate effects” tests as explored by ORNL (2020) could be useful here.
- Demonstrate DCR insertion in mock-up PWR fuel assemblies underwater, to demonstrate fixturing and estimate time and other resources needed for implementation.

7.2.5 Fuel/Basket Model Development and Prediction Project

Eventually, degradations model predictions will be needed for selected fuel/basket modification solutions, even if only to support the two stylized degradation cases (Section 1.3).

- Incorporate validation test results.
- Extend model to stainless steel egg-crate baskets, and tube-and-plate baskets.
- Extend model to BWR DPCs.
- Generate degraded configurations for reactivity analysis.
- Reactivity analysis of degraded configurations (see QA discussion in Section 7.2.7).

7.2.6 BWR Fuel Re-channeling and Insert Plate Prototyping

The following activities are deferred pending testing and selection of suitable ANA materials (QA requirements are to-be-determined).

- Perform k_{eff} analysis with idealized hardware to estimate the required number, location, and neutronic properties.
- Develop requirements, based on review of BWR and PWR assembly types, DPC basket dimensions, and ANA material characteristics (required thickness).
- Design and fabricate prototype hardware. Select whether plates are inserted in DPC baskets before or after immersion, or attached to fuel assemblies before insertion.
- Test fit of hardware solutions (channel-to-assembly; modified assembly-to-basket cells).
- Demonstrate rechanneling and plate insertion underwater, to demonstrate fixturing and estimate time and other resources needed for implementation.

7.2.7 Reactivity Model Quality Assurance

The following activities are deferred pending resolution of which disposal criticality control solutions will be selected for further development. Until the need is clear, deferral is warranted, and scope should be limited to planning of the QA effort, because: 1) reactivity modeling system components were developed under ORNL requirements; 2) some components may already be qualified; 3) some qualification efforts are currently underway for other users; 4) the zone loading solution, which relies entirely on reactivity modeling, is developmental and still undergoing feasibility analysis; and 5) disposal criticality control solutions will be selected (or not selected) in the future, and the cost for qualification and validation of reactivity modeling system components should be commensurate with the intended use. QA requirements are to-be-determined.

- Qualification of propagation and depletion codes.
- Qualification of nuclear data used by the codes.
- Validation of burnup credit models.
- Qualification, if determined to be necessary, of as-loaded DPC configurations and fuel characteristics (e.g., GC-859).
- Review and qualification, if necessary, of configurations for reactivity analysis of selected fuel/basket modification(s).
- Run models for fuel/basket applications.

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Appendix A – Workshop Participants

Kaushik Banerjee (ORNL)
Don Beckman (Consultant)
Bruce Bevard (ORNL)
Pat Brady (SNL)
Geoffrey Carter (retired vendor)
Danielle Castley (Becq)
Stylianos Chatzidakis (ORNL)
Justin B. Clarity (ORNL)
Bob Clark (DOE)
Kevin Connolly (ORNL)
Branko Damjanac (Itasca)
Sam Durbin (SNL)
Geoff Freeze (SNL)
Jason Furtney (Itasca)
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Tim Gunter (DOE)
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Bob Hall (ORNL)
Ernest Hardin (SNL)
Josh J. Jarrell (INL)
Tedd Lister (INL)
Jorge (George) Monroe-Rammsy (DOE)
Rose Montgomery (ORNL)
Raymond Paulsen (retired utility)
Zorica Radakovic (Itasca)Brian Wakeman (retired utility)
Keith Waldrop (EPRI)
Brad Williamson (Dominion)

Appendix B – Workshop Agenda

When:
(all times 1 pm Eastern, virtual meetings to last 3 hours)

Oct 27 & 29	Information briefings (SNL, ORNL presentations)
Nov 5	Discussion with experts (Q&A)
Nov 13	Expert recommendations, other business

Virtual format to be set up by ORNL (Kevin Connolly, ORNL; contact info below)

(Encourage Q&A during presentations)

Day 1: Introduction and briefings

1300 Introduction and discussion of modification options (Hardin, SNL)
- Objectives of this activity (R&D steering, support development and licensing of solutions for future DPCs and generic repository applications)
- Not a financial or legal review, although cost could be important to engineering feasibility of solutions discussed
- Participants
- Review of F&B modification options report

1345 Q&A

1400 Reactivity analysis of as-loaded DPCs (Banerjee, ORNL)
- Methods (neutronics, stylized degradation cases)
- Scope (analyses applicable to generic repositories, including salt repositories)
- Disposal of as-loaded DPCs without modification (results, trends, misload analyses)
- Recent analysis of DPC control rods, etc. F&B modification options
- Plans for future analyses

1445 Q&A

1500 Modeling of fuel/basket degradation (Damjanac/Varun, Itasca)
- Objectives for modeling (kinematics, trends, seismic response, method development)
- Basket degradation model description
- Tracking the relocation of control features during F&B degradation
- Overview of results
- Information needs and recommended future analyses

1545 Q&A

1600 Adjourn

Day 2: Continuation of briefings

1300 Neutron absorber material testing (Jarrell/Lister, INL)
- History and material descriptions (borated stainless and Ni-Cr-Mo-Gd)
- Absorber corrosion lifetime requirements
- Corrosion environments (fresh, seawater, dilute HCl; not brine or unsat.)
- Questions to be addressed in addition to general corrosion rates (phase behaviors, applicability of AMs or SAMs, etc.)
- Preliminary and historical results
- Ongoing test program

1345 Q&A
1400 Modeling corrosion lifetime of DPC materials (Brady, SNL)
  - Geochemical modeling approach
  - Assumptions and boundary conditions (thermochemical data, redox, mixing, open/closed, temp. dependence, kinetics)
  - Similar models and regulatory reviews
  - Results for thermal and post-thermal repository conditions, without criticality
1445 Q&A
1500 SNL/ORNL testing capabilities (Durbin/Howard)
  - Recent testing of fuel/basket components
  - Capabilities
  - SNL, ORNL and other labs
1545 Q&A

Days 3 and 4: Discussion of approaches, strengths/vulnerabilities, and testing ideas.

Questions to be asked of experts. The following may not be answerable from the information provided, but expert opinions would be useful, and any discussion of other questions that should be raised.

I. General questions
  a) Could the degradation modeling approach be developed sufficiently for licensing? What are the perceived strengths and weaknesses?
  b) Could a licensing case for reliance on ANA materials be supported adequately by the testing program described?
  c) What types of additional testing is needed to establish corrosion rates for fuel/basket materials, and to validate models of fuel/basket degradation mechanics?
  d) What are the most promising approaches for achieving generic disposability of PWR and BWR fuel in future DPCs?

II. PWR disposal control rods
  a) What operational problems could arise during installation of PWR control rods (DCRAs)?
  b) Would it be practical to shuffle control hardware around to make room for disposal control rods, particularly in reactive assemblies where they may be needed?
  c) Could thermal or especially radiation constraints on DPC loading maps be relaxed in lieu of reactivity constraints, in a strategy for placement of DCRAs?
  d) Could corrosive degradation and mechanics models be relied on for licensing, i.e., to extend reactivity predictions after mechanical degradation of basket plates or spacer grids?
  e) Is there flexibility in PWR SNF assembly configurations and inventory to allow a generic modeling approach, or would can-by-can reactivity analysis be needed?
  f) How could damaged fuel be accommodated in a DCRA concept?
  g) Are the implementation costs, including labor estimates from the options report realistic?
  h) What further model development and additional testing activities could provide support to the PWR DCRA solution?

III. BWR fuel rechanneling
  a) What operational problems could arise during BWR fuel rechanneling?
  b) Could the old channels be disposed of as LLW?
  c) Could thermal or especially radiation constraints on DPC loading maps be relaxed in lieu of reactivity constraints, in a strategy for placement of DCRAs?

  d) Could corrosive degradation and mechanics models be relied on for licensing, i.e., to extend reactivity predictions after mechanical degradation of basket plates or spacer grids?
  e) Is it likely that a generic approach could be developed that does not require can-by-can reactivity analysis, or new criteria for loading maps?
  f) How could damaged fuel be accommodated in a DCRA concept?
  g) Are the implementation costs, including labor estimates from the options report realistic?
  h) What further model development and additional testing activities could provide support to the BWR rechanneling solution?

IV. Chevron inserts
  a) Would an insert strategy be effective as an addition to DPCs with aluminum-based baskets?
  b) What technical problems could arise in testing, licensing, and implementation?
  c) Would basket redesign be required or is there
  d) Assuming there are fuel pool facilities operating at their hook load limits when hoisting loaded DPCs, are there practical solutions that could accommodate the additional weight of inserts?
  e) Are the implementation costs, including labor estimates from the options report realistic?
  f) What further model development and additional testing activities could provide support to the chevron insert solution for PWR and BWR DPCs?

V. Zone loading
  a) Could there be sufficient low-reactivity fuel assemblies available in pools (e.g., during 2030-2060) to load a significant number of DPCs for disposal criticality control?
  b) Can additional can-by-can reactivity analysis be accommodated in SNF operations, or should other, more generic solutions be sought?
  c) Could thermal or especially radiation constraints on loading maps be relaxed in lieu of reactivity constraints for zone loading?

VI. Replacement absorber plates
  a) What technical problems could arise in the testing, licensing, and implementation of replacement absorber plates (for Boral and B-Al absorber plate DPC designs)?

Other Q&A
Wrap-up/final recommendations

Appendix C – Workshop Presentations

Listed in order of their presentation (see agenda, Appendix B). Movie links are not provided, only static first-page images are shown.

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Fuel/Basket Modification for Direct Disposal of Future DPCs – Workshop Introduction

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U.S. DEPARTMENT OF ENERGY NNSA

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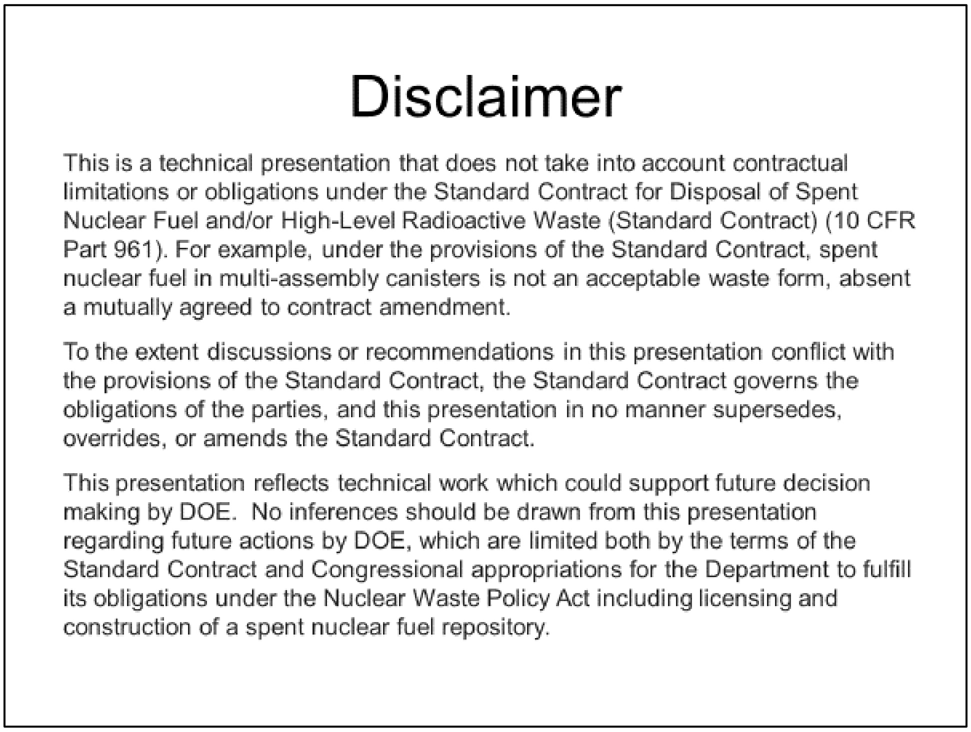


Disclaimer

This is a technical presentation that does not take into account contractual limitations or obligations under the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (Standard Contract) (10 CFR Part 961). For example, under the provisions of the Standard Contract, spent nuclear fuel in multi-assembly canisters is not an acceptable waste form, absent a mutually agreed to contract amendment.

To the extent discussions or recommendations in this presentation conflict with the provisions of the Standard Contract, the Standard Contract governs the obligations of the parties, and this presentation in no manner supersedes, overrides, or amends the Standard Contract.

This presentation reflects technical work which could support future decision making by DOE. No inferences should be drawn from this presentation regarding future actions by DOE, which are limited both by the terms of the Standard Contract and Congressional appropriations for the Department to fulfill its obligations under the Nuclear Waste Policy Act including licensing and construction of a spent nuclear fuel repository.

Additional Disclaimer

Outline

Introductory Briefing to the Fuel/Basket Modification Expert Panel

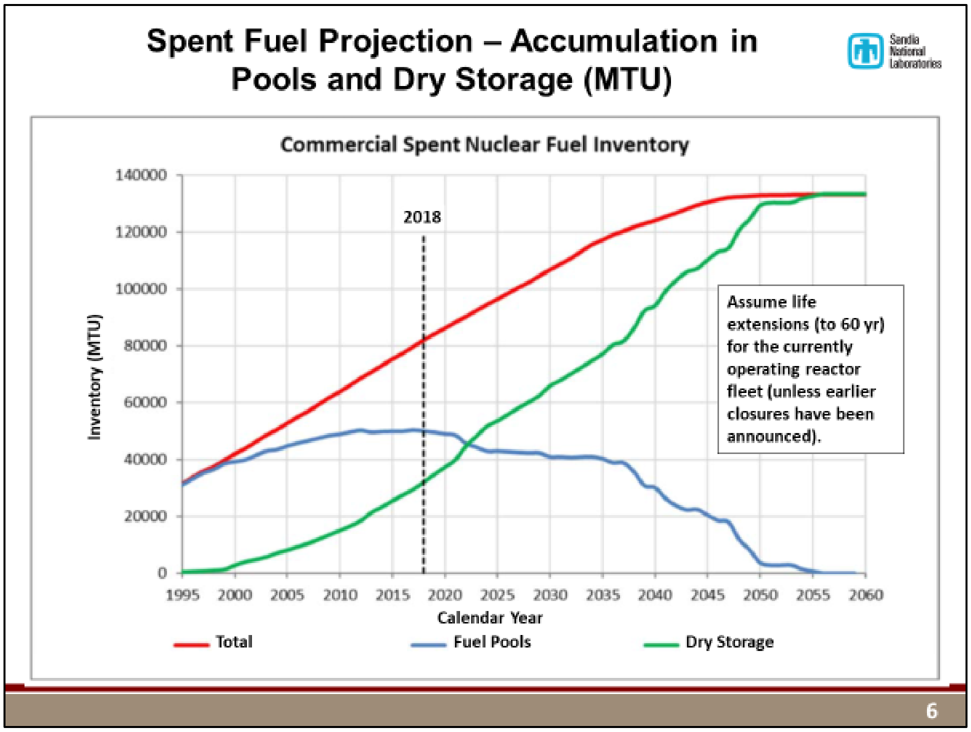
- **Objective**
- **DPC projection**
- **Fuel/basket modification options**
- **Estimated ROM costs**
- **R&D activities**
- **Possible future R&D activities**
- **Format for workshop**

Workshop Objectives

- **R&D Steering**
- **Informal Technical Review**
- **Solutions to DPC Direct Disposal:**

  Identify effective R&D activities to facilitate future implementation of fuel/basket modification(s) as a strategy to make commercial SNF directly disposable in DPCs (of existing or similar designs).

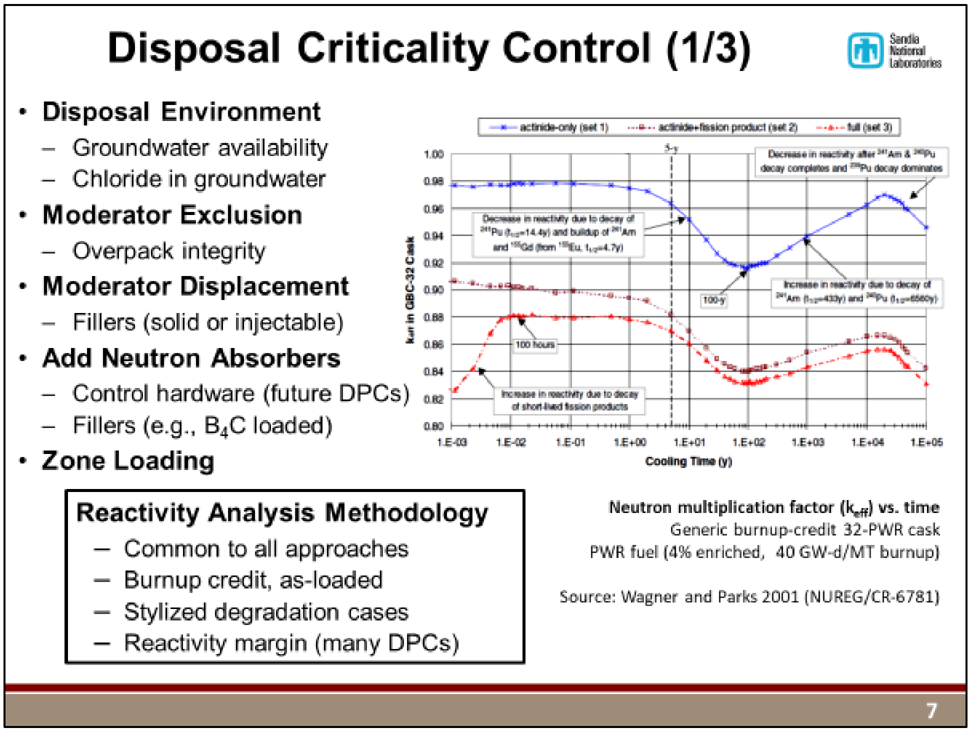
- **Recommend Multiple, Redundant Technical Approaches for R&D if Practical**
- **Generic Repository (non-site specific)**



Spent Fuel Projection – Accumulation in Pools and Dry Storage (MTU)

Commercial Spent Nuclear Fuel Inventory

Assume life extensions (to 60 yr) for the currently operating reactor fleet (unless earlier closures have been announced).



Disposal Criticality Control (1/3)

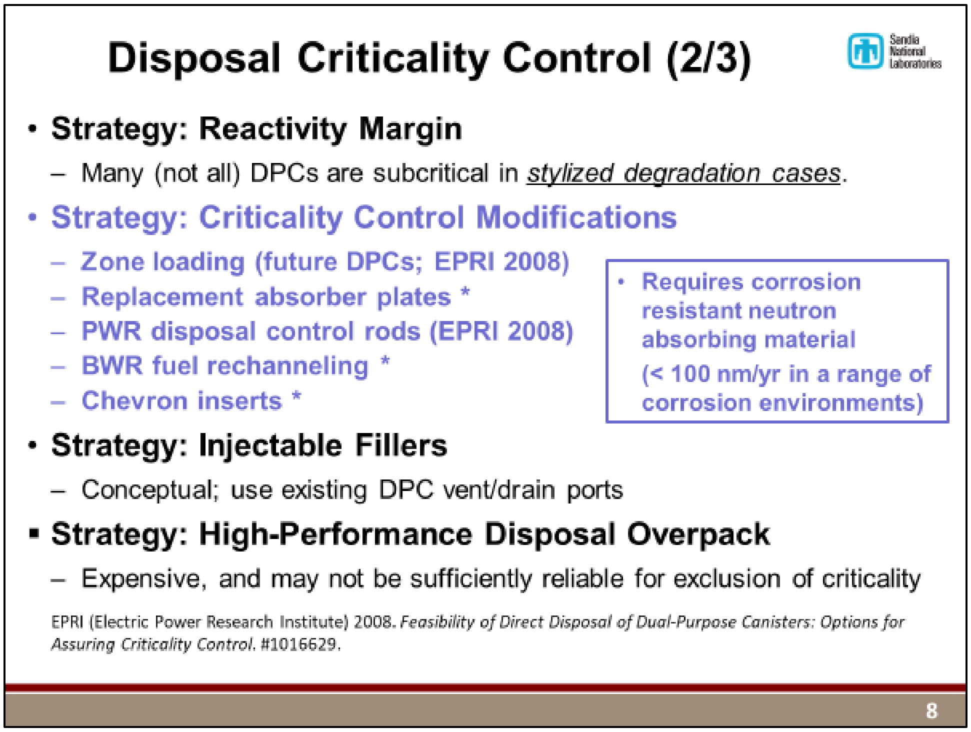
- **Disposal Environment**
  - Groundwater availability
  - Chloride in groundwater
- **Moderator Exclusion**
  - Overpack integrity
- **Moderator Displacement**
  - Fillers (solid or injectable)
- **Add Neutron Absorbers**
  - Control hardware (future DPCs)
  - Fillers (e.g., B_4C loaded)
- **Zone Loading**

Neutron multiplication factor (k_{eff}) vs. time
Generic burnup-credit 32-PWR cask
PWR fuel (4% enriched, 40 GW-d/MT burnup)

Source: Wagner and Parks 2001 (NUREG/CR-6781)

Reactivity Analysis Methodology

- Common to all approaches
- Burnup credit, as-loaded
- Stylized degradation cases
- Reactivity margin (many DPCs)



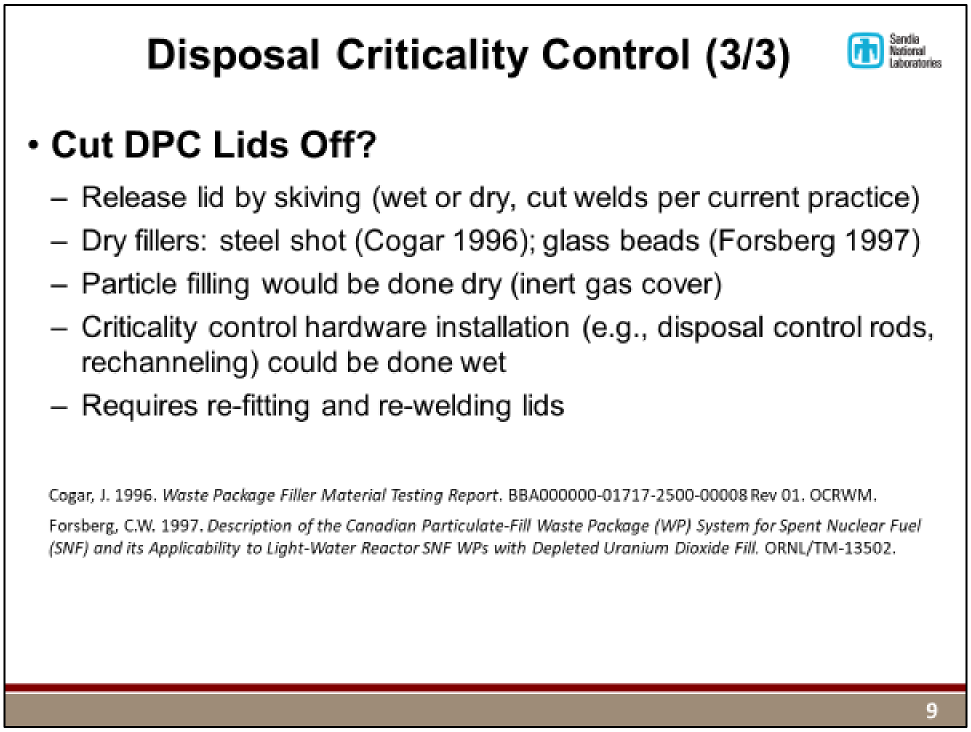
Disposal Criticality Control (2/3)

- **Strategy: Reactivity Margin**
  - Many (not all) DPCs are subcritical in *stylized degradation cases*.
- **Strategy: Criticality Control Modifications**
  - **Zone loading (future DPCs; EPRI 2008)**
  - **Replacement absorber plates ***
  - **PWR disposal control rods (EPRI 2008)**
  - **BWR fuel rechanneling ***
  - **Chevron inserts ***

- **Requires corrosion resistant neutron absorbing material (< 100 nm/yr in a range of corrosion environments)**

- **Strategy: Injectable Fillers**
  - Conceptual; use existing DPC vent/drain ports
- **Strategy: High-Performance Disposal Overpack**
  - Expensive, and may not be sufficiently reliable for exclusion of criticality

EPRI (Electric Power Research Institute) 2008. *Feasibility of Direct Disposal of Dual-Purpose Canisters: Options for Assuring Criticality Control.* #1016629.

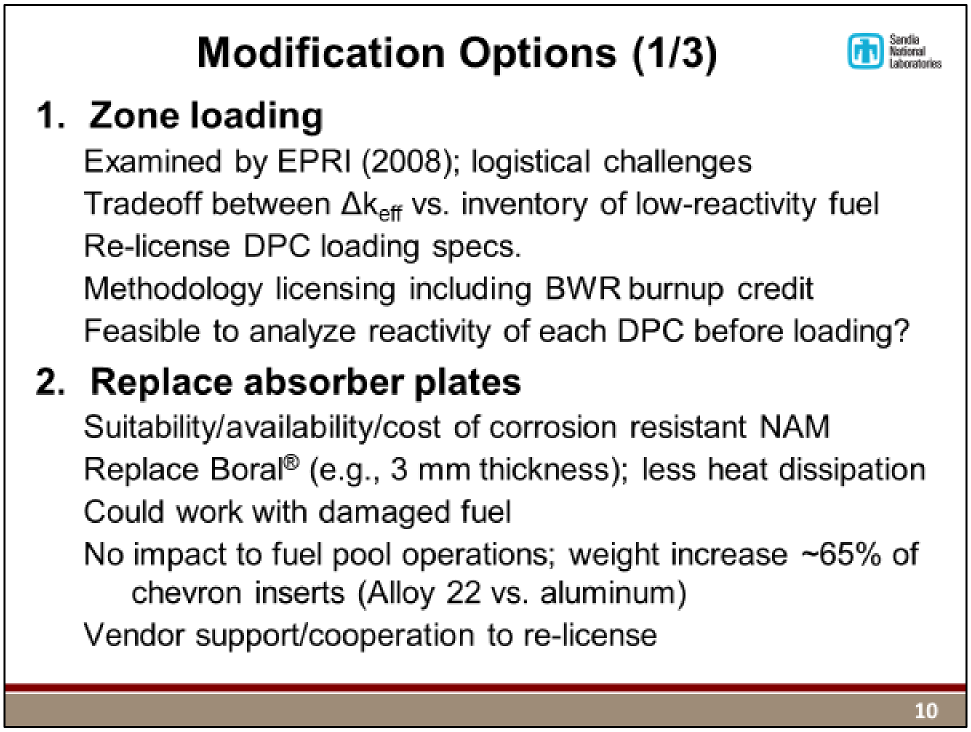


Disposal Criticality Control (3/3)

- **Cut DPC Lids Off?**
  - Release lid by skiving (wet or dry, cut welds per current practice)
  - Dry fillers: steel shot (Cogar 1996); glass beads (Forsberg 1997)
  - Particle filling would be done dry (inert gas cover)
  - Criticality control hardware installation (e.g., disposal control rods, rechanneling) could be done wet
  - Requires re-fitting and re-welding lids

Cogar, J. 1996. *Waste Package Filler Material Testing Report*. BBA000000-01717-2500-00008 Rev 01. OCRWM.

Forsberg, C.W. 1997. *Description of the Canadian Particulate-Fill Waste Package (WP) System for Spent Nuclear Fuel (SNF) and its Applicability to Light-Water Reactor SNF WPs with Depleted Uranium Dioxide Fill.* ORNL/TM-13502.



Modification Options (1/3)

1. Zone loading

Examined by EPRI (2008); logistical challenges

Tradeoff between Δk_{eff} vs. inventory of low-reactivity fuel

Re-license DPC loading specs.

Methodology licensing including BWR burnup credit

Feasible to analyze reactivity of each DPC before loading?

2. Replace absorber plates

Suitability/availability/cost of corrosion resistant NAM

Replace Boral® (e.g., 3 mm thickness); less heat dissipation

Could work with damaged fuel

No impact to fuel pool operations; weight increase ~65% of chevron inserts (Alloy 22 vs. aluminum)

Vendor support/cooperation to re-license

Modification Options (2/3)

3. PWR disposal control rods

Simple materials and manufacture (does not require ANAM)

Fuel pool operations; some added weight (~1,000 lb)

Re-license DPC loading specs; e.g., moving irradiated hardware outward or high-burnup assemblies inward

Control hardware shuffling feasible?

Single loading map for a wide range of fuel characteristics?

4. BWR fuel rechanneling

Suitability/availability/cost of corrosion resistant NAM

Fuel pool operations; small weight difference

Multiple BWR fuel types; possible US patent or fuel design licensing complications

Single loading map for a wide range of fuel characteristics?

Modification Options (3/3)

5. Chevron inserts

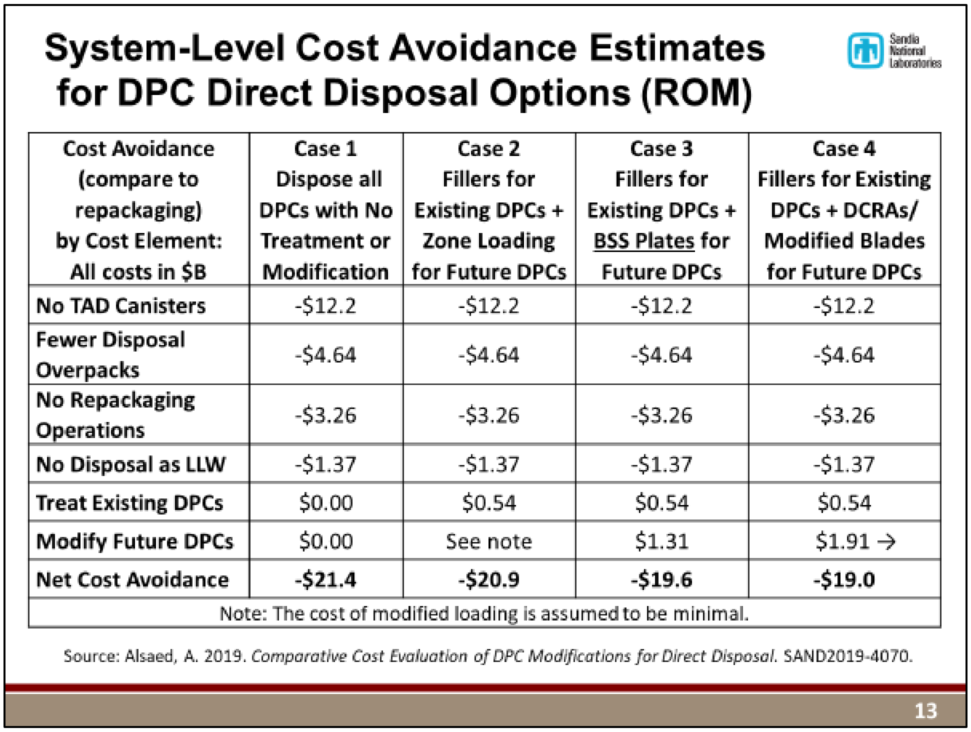
Basket preparation away from fuel pool

Potential retrofit to Al-MMC baskets

Dimensional clearance could vary by basket type and manufacture

Possible US patent complications

Heavy (e.g., adds approx. 3,000 lb/DPC)

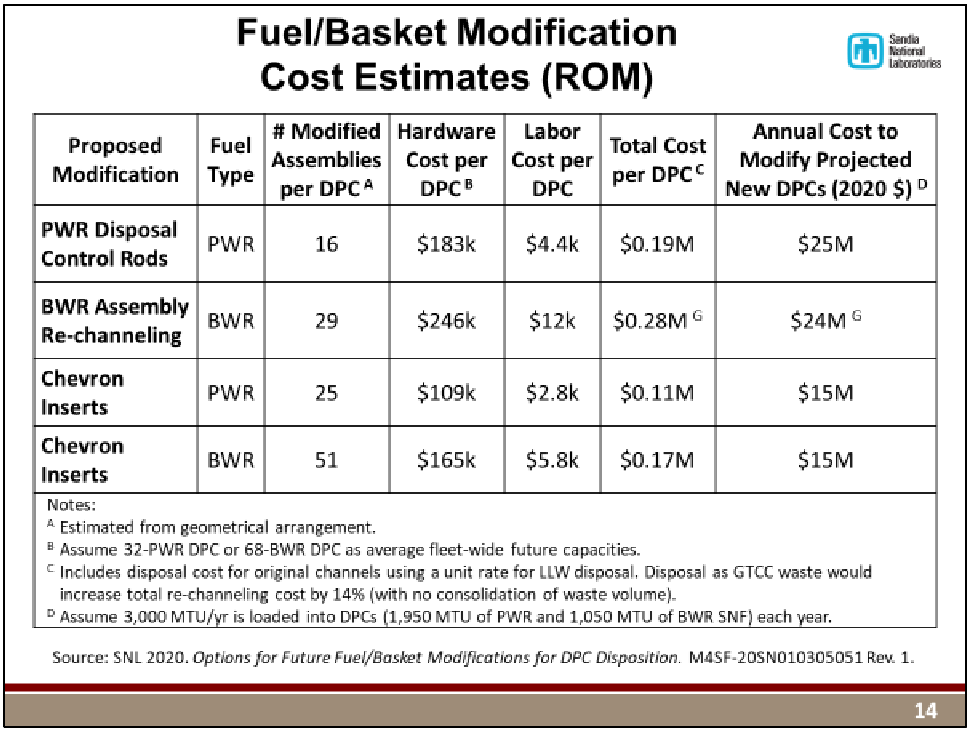


System-Level Cost Avoidance Estimates for DPC Direct Disposal Options (ROM)

Cost Avoidance (compare to repackaging) by Cost Element: All costs in $B	Case 1 Dispose all DPCs with No Treatment or Modification	Case 2 Fillers for Existing DPCs + Zone Loading for Future DPCs	Case 3 Fillers for Existing DPCs + BSS Plates for Future DPCs	Case 4 Fillers for Existing DPCs + DCRAs/ Modified Blades for Future DPCs
No TAD Canisters	-$12.2	-$12.2	-$12.2	-$12.2
Fewer Disposal Overpacks	-$4.64	-$4.64	-$4.64	-$4.64
No Repackaging Operations	-$3.26	-$3.26	-$3.26	-$3.26
No Disposal as LLW	-$1.37	-$1.37	-$1.37	-$1.37
Treat Existing DPCs	$0.00	$0.54	$0.54	$0.54
Modify Future DPCs	$0.00	See note	$1.31	$1.91 →
Net Cost Avoidance	**-$21.4**	**-$20.9**	**-$19.6**	**-$19.0**

Note: The cost of modified loading is assumed to be minimal.

Source: Alsaed, A. 2019. *Comparative Cost Evaluation of DPC Modifications for Direct Disposal.* SAND2019-4070.



Fuel/Basket Modification Cost Estimates (ROM)

Proposed Modification	Fuel Type	# Modified Assemblies per DPC[A]	Hardware Cost per DPC[B]	Labor Cost per DPC	Total Cost per DPC[C]	Annual Cost to Modify Projected New DPCs (2020 $)[D]
PWR Disposal Control Rods	PWR	16	$183k	$4.4k	$0.19M	$25M
BWR Assembly Re-channeling	BWR	29	$246k	$12k	$0.28M[G]	$24M[G]
Chevron Inserts	PWR	25	$109k	$2.8k	$0.11M	$15M
Chevron Inserts	BWR	51	$165k	$5.8k	$0.17M	$15M

Notes:

[A] Estimated from geometrical arrangement.

[B] Assume 32-PWR DPC or 68-BWR DPC as average fleet-wide future capacities.

[C] Includes disposal cost for original channels using a unit rate for LLW disposal. Disposal as GTCC waste would increase total re-channeling cost by 14% (with no consolidation of waste volume).

[D] Assume 3,000 MTU/yr is loaded into DPCs (1,950 MTU of PWR and 1,050 MTU of BWR SNF) each year.

Source: SNL 2020. *Options for Future Fuel/Basket Modifications for DPC Disposition.* M4SF-20SN010305051 Rev. 1.

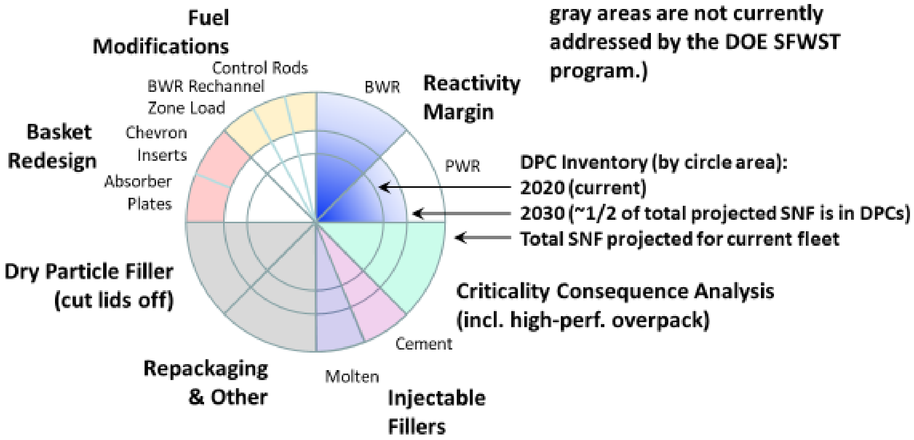
DPC Direct Disposal R&D Program Summary – FY20

Schematic of Technical Approaches Overlaid Over Commercial SNF Inventory

Goal for DPC disposition:

Expand one or more solutions to provide *radial* (not circumferential) coverage of the full inventory circle.

(White areas cannot be expanded; gray areas are not currently addressed by the DOE SFWST program.)



Fuel Modifications
Control Rods
BWR Rechannel
Zone Load

Basket Redesign
Chevron Inserts
Absorber Plates

Reactivity Margin
BWR
PWR

DPC Inventory (by circle area):
2020 (current)
2030 (~1/2 of total projected SNF is in DPCs)
Total SNF projected for current fleet

Criticality Consequence Analysis (incl. high-perf. overpack)

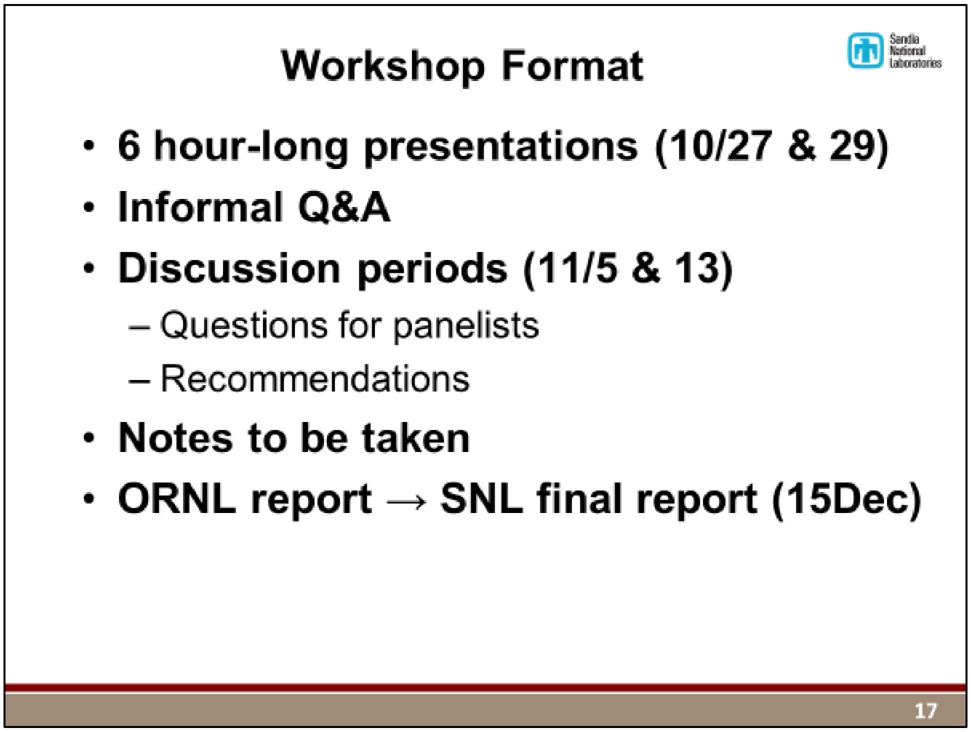
Dry Particle Filler (cut lids off)

Repackaging & Other

Injectable Fillers
Molten
Cement

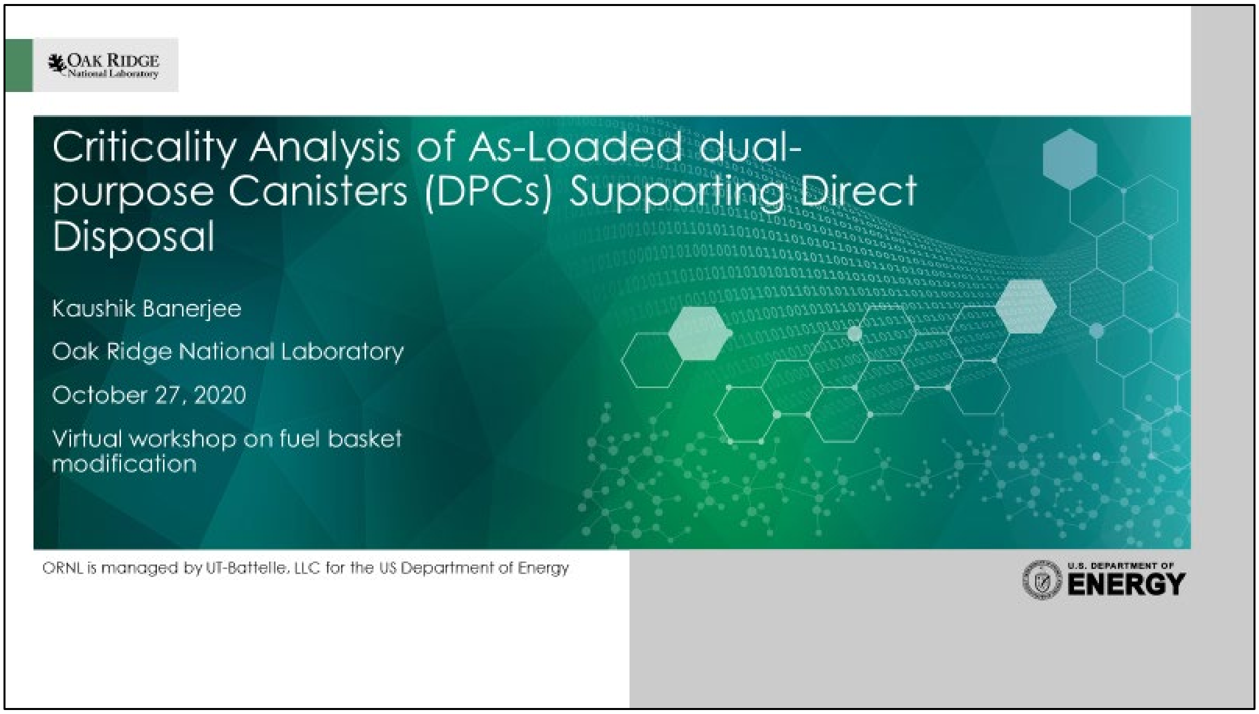
Possible Future R&D Activities

- **Degradation model development**
  - Various DPC basket designs and materials
  - Full-canister model domains
  - Spatial variability
  - Seismic shaking
- **Model calibration/validation test data**
- **BWR burnup approach development**
- **Enhanced stylized degradation cases**
- **Further NAM testing and development**
- **Prototype hardware fabrication and testing**
- **Logistical studies of zone loading**



Workshop Format

- 6 hour-long presentations (10/27 & 29)
- Informal Q&A
- Discussion periods (11/5 & 13)
  - Questions for panelists
  - Recommendations
- Notes to be taken
- ORNL report → SNL final report (15Dec)



Criticality Analysis of As-Loaded dual-purpose Canisters (DPCs) Supporting Direct Disposal

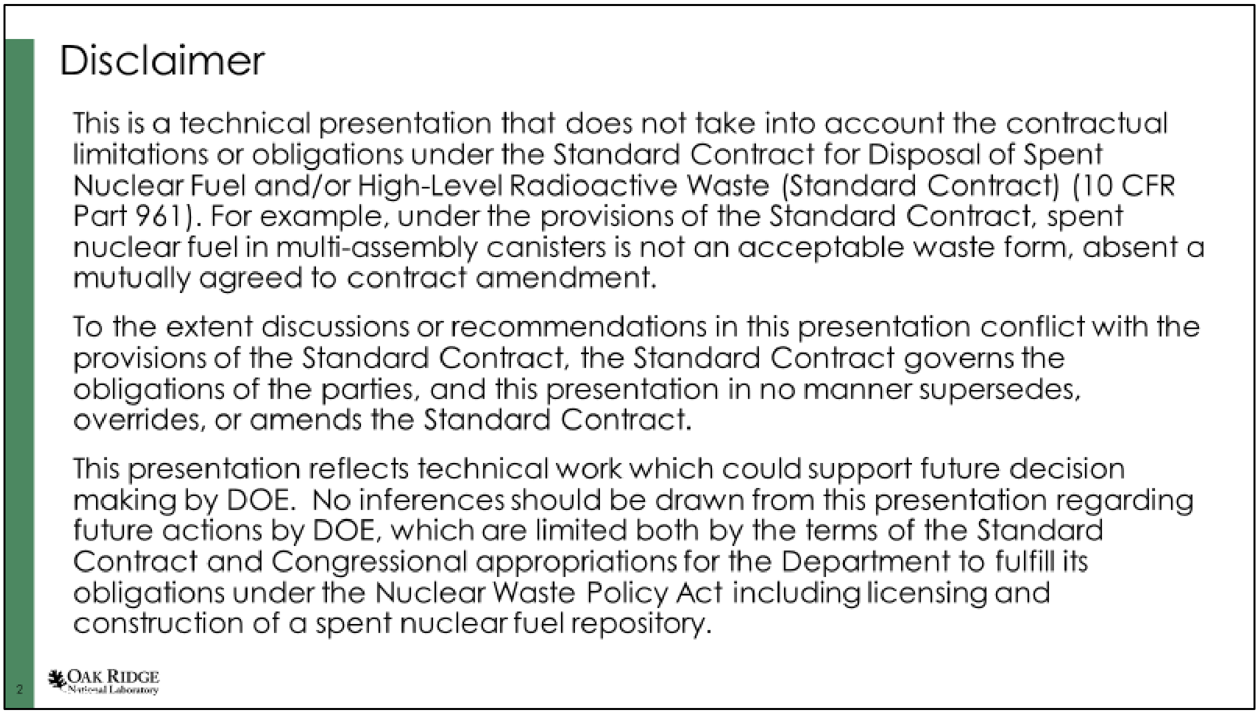
Kaushik Banerjee

Oak Ridge National Laboratory

October 27, 2020

Virtual workshop on fuel basket modification

ORNL is managed by UT-Battelle, LLC for the US Department of Energy



Disclaimer

This is a technical presentation that does not take into account the contractual limitations or obligations under the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (Standard Contract) (10 CFR Part 961). For example, under the provisions of the Standard Contract, spent nuclear fuel in multi-assembly canisters is not an acceptable waste form, absent a mutually agreed to contract amendment.

To the extent discussions or recommendations in this presentation conflict with the provisions of the Standard Contract, the Standard Contract governs the obligations of the parties, and this presentation in no manner supersedes, overrides, or amends the Standard Contract.

This presentation reflects technical work which could support future decision making by DOE. No inferences should be drawn from this presentation regarding future actions by DOE, which are limited both by the terms of the Standard Contract and Congressional appropriations for the Department to fulfill its obligations under the Nuclear Waste Policy Act including licensing and construction of a spent nuclear fuel repository.

Criticality analysis of DPCs is being performed to identify DPCs with criticality potential in a repository

- Majority of the spent nuclear fuel (SNF) is being stored in dual-purpose (storage and transportation) canisters (DPCs)
  - DPCs are not designed or loaded with disposal considerations
- Aluminum-based neutron absorbers typically used in DPCs are not expected to provide criticality control during a repository performance period (e.g., 10,000 years or more), specially in aqueous environment
  - Design-basis analysis (without basket neutron absorber credit) would incorrectly show that all loaded DPCs can achieve criticality when flooded in a repository
- As-loaded criticality analysis is being used to identify DPCs that can potentially achieve criticality in a repository when flooded

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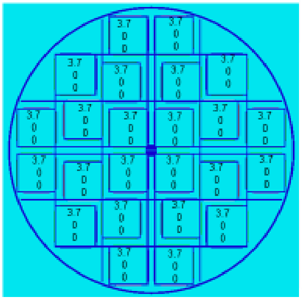
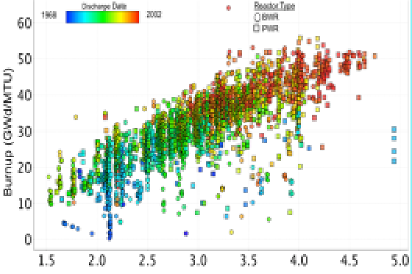
As-loaded criticality analysis (fully flooded) can be used to quantify uncredited margin

- Current design-basis approach uses bounding fuel characteristics (e.g., fuel type, initial enrichment, and discharge burnup) for spent nuclear fuel (SNF) storage and transportation systems certification process
- In practice, discharge SNFs available for loading are diverse (e.g., wide variation in SNF assembly burnup values)

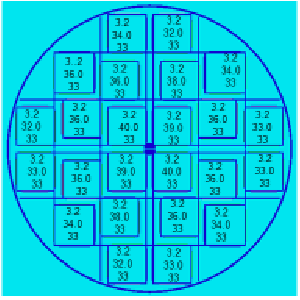
Design-basis k_{eff} = 0.90



Discharged inventory

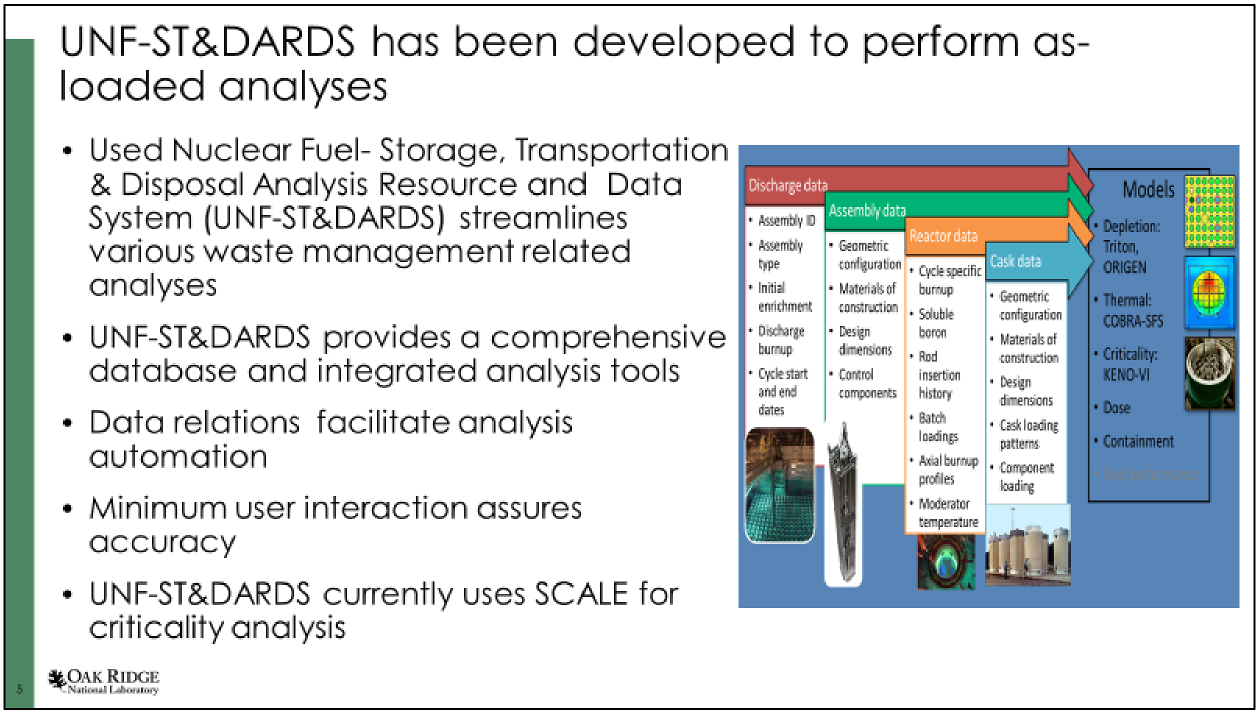


As-loaded k_{eff} = 0.66



Uncredited margin = 0.90-0.66 = 0.24 Δk_{eff}

X	Assembly average initial enrichment (wt %)
Y	Assembly average burnup (GWd/MTU)
Z	Cooling (years)



UNF-ST&DARDS has been developed to perform as-loaded analyses

- Used Nuclear Fuel- Storage, Transportation & Disposal Analysis Resource and Data System (UNF-ST&DARDS) streamlines various waste management related analyses
- UNF-ST&DARDS provides a comprehensive database and integrated analysis tools
- Data relations facilitate analysis automation
- Minimum user interaction assures accuracy
- UNF-ST&DARDS currently uses SCALE for criticality analysis

Discharge data
- Assembly ID
- Assembly type
- Initial enrichment
- Discharge burnup
- Cycle start and end dates

Assembly data
- Geometric configuration
- Materials of construction
- Design dimensions
- Control components

Reactor data
- Cycle specific burnup
- Soluble boron
- Rod insertion history
- Batch loadings
- Axial burnup profiles
- Moderator temperature

Cask data
- Geometric configuration
- Materials of construction
- Design dimensions
- Cask loading patterns
- Component loading

Models
- Depletion: Triton, ORIGEN
- Thermal: COBRA-SFS
- Criticality: KENO-VI
- Dose
- Containment
- Fuel performance

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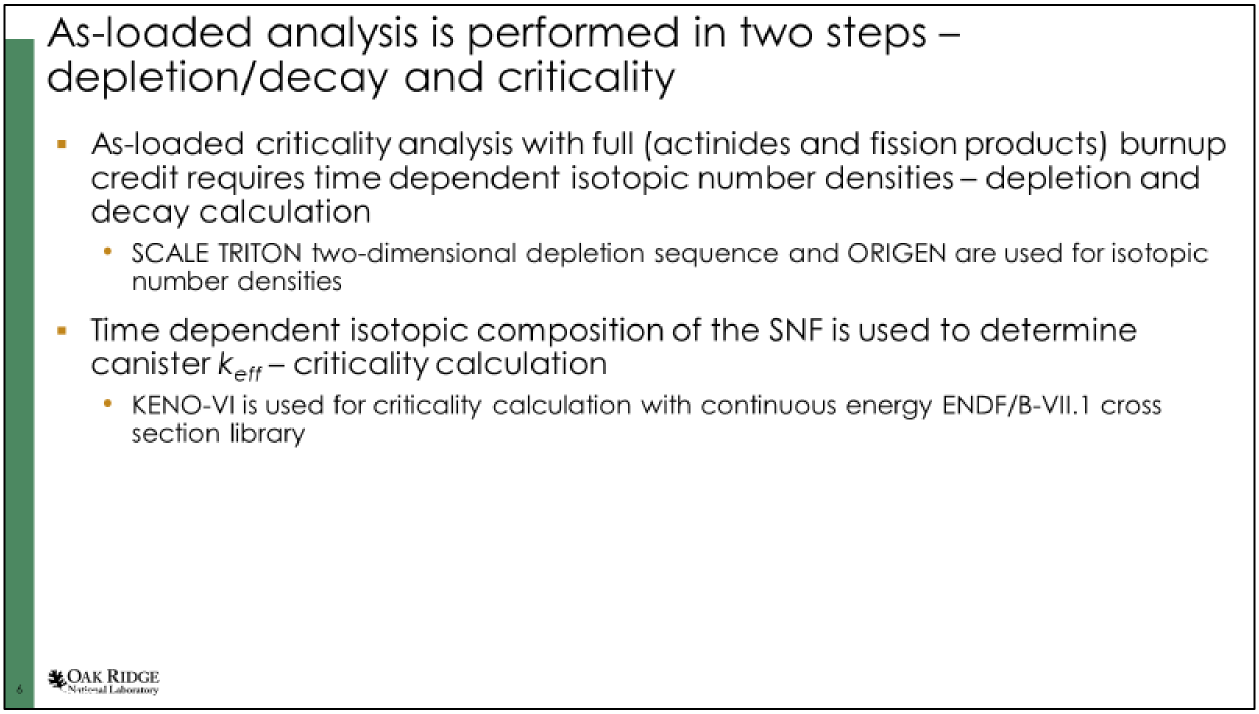

As-loaded analysis is performed in two steps – depletion/decay and criticality

- As-loaded criticality analysis with full (actinides and fission products) burnup credit requires time dependent isotopic number densities – depletion and decay calculation
  - SCALE TRITON two-dimensional depletion sequence and ORIGEN are used for isotopic number densities
- Time dependent isotopic composition of the SNF is used to determine canister k_{eff} – criticality calculation
  - KENO-VI is used for criticality calculation with continuous energy ENDF/B-VII.1 cross section library

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UNF-ST&DARDS as-loaded criticality analysis uses limiting burnup profiles based on burnup range

- Conservative depletion modeling techniques used
- PWR
  - High soluble boron concentration, low moderator density, burnable absorber throughout life of assembly in reactor
  - Bounding PWR burnup profiles from NUREG/CR-6801 "Recommendations for Addressing Axial Burnup in PWR Burnup Credit Analyses"
- BWR
  - Blade insertion throughout life, relatively high void fraction
  - Limiting BWR burnup profiles have been selected from Commercial Reactor Criticality (CRC) Data

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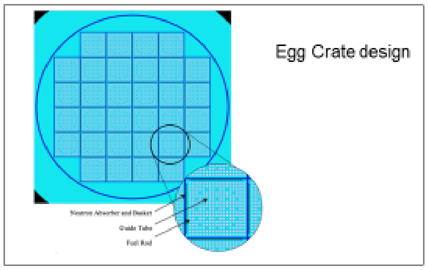
UNF-ST&DARDS as-loaded disposal analysis model includes postulated degradation

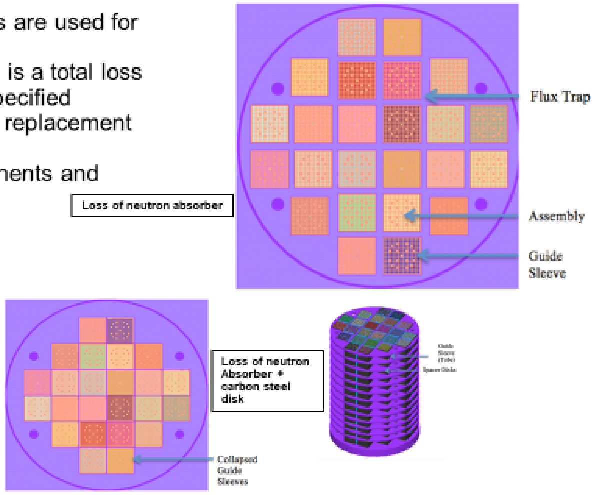
Two simplified, conservative degradation scenarios are used for disposal analysis

Loss of neutron absorber: In this scenario, there is a total loss of basket neutron absorber components from unspecified degradation and material transport processes with replacement by groundwater

Basket degradation: Loss of carbon steel components and neutron absorber panels



MPC-32 canister Storage/transportation model



Canister differentiator: Flux trap vs. egg crate designs

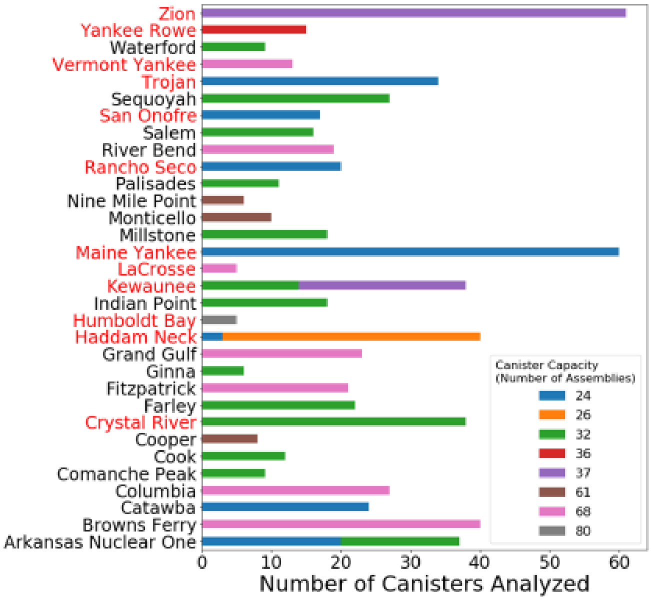
Models are verified by comparing with the safety analysis report

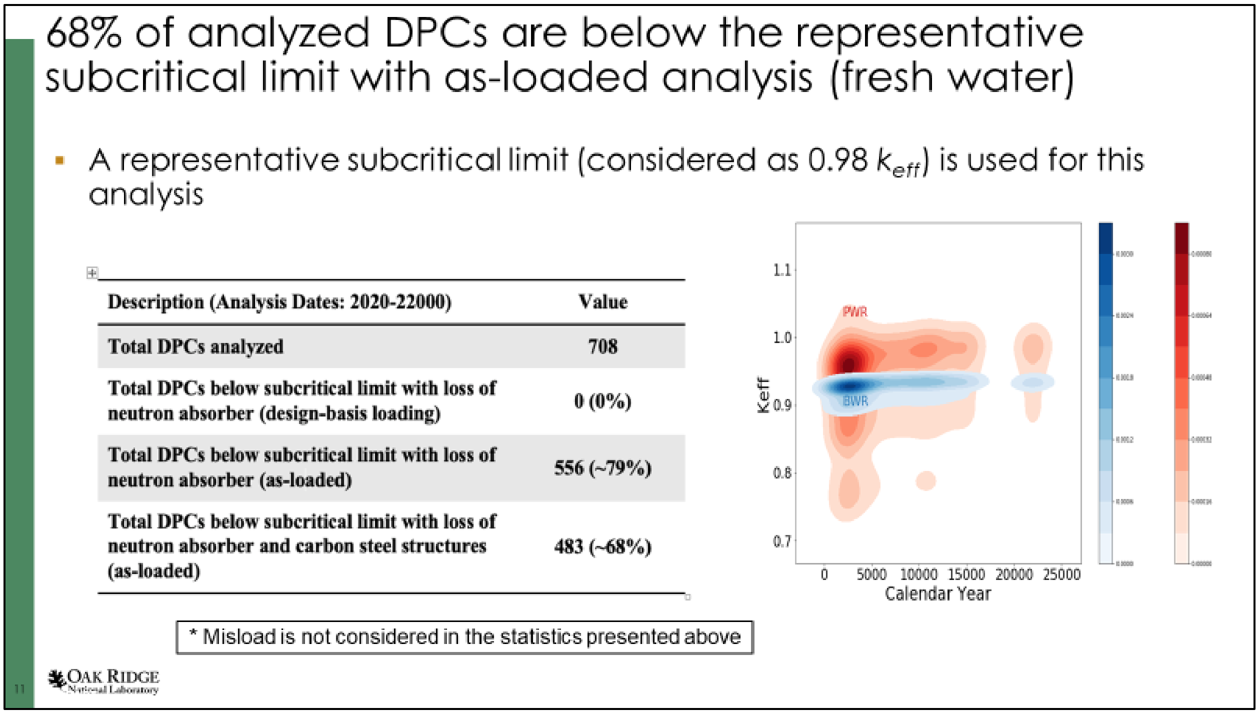
- UNF-ST&DARDS storage/transportation criticality models are run with design-basis fuel characteristics from safety analysis report and results are compared with safety analysis report to perform model verification and validation
  - Verified storage/transportation criticality models are modified to incorporate disposal scenarios

Canister Name	Flux Trap?	^{10}B Areal Density In Neutron Absorber (g/cm²)	Canister Construction	Contains Carbon Steel?	Reference k_{eff}	Calculated Reference k_{eff} (UNF-ST&DARDS)
TSC-24	Yes	0.0250	Tube and disk	No	0.9192	0.9187 ± 0.00017
TSC-37	No	0.0360	Egg crate	Yes	0.9189	0.9193 ± 0.00047
CY-MPC 26	Yes	0.0200	Tube and disk	No	0.9064	0.8991 ± 0.00029
CY-MPC 24	Yes	0.0200	Tube and disk	No	0.9197	0.9132 ± 0.00024
Yankee-MPC	Yes	0.0100	Tube and disk	No	0.8761	0.8767 ± 0.00045
MPC-24E/EF	Yes	0.0250	Egg crate	No	0.9187	0.9006 ± 0.00026
MPC-24	Yes	0.0267	Egg crate	No	0.9325	0.9302 ± 0.00022
MPC-32	No	0.0372	Egg crate	No	0.9123	0.9076 ± 0.00018
FO/FC-DSC	Yes	0.0216	Tube and disk	Yes	0.9316	0.9316 ± 0.00026
MPC-LACBWR	Yes	0.0200	Tube and disk	No	0.8420	0.8451 ± 0.00044
MPC-HB	No	0.0100	Egg crate	No	0.8318	0.8331 ± 0.00034
MPC-68	No	0.0372	Egg crate	No	0.9273	0.9274 ± 0.00026

As-loaded criticality analysis has been performed for 708 already loaded canisters at 32 sites

- Analyzed PWR DPCs include 24, 26, 32, 36, and 37-assembly capacity
- Analyzed BWR DPCs include 61, 68 and 80-assembly capacity
- Calculations performed for each DPC from canister in-service date to year 22,000



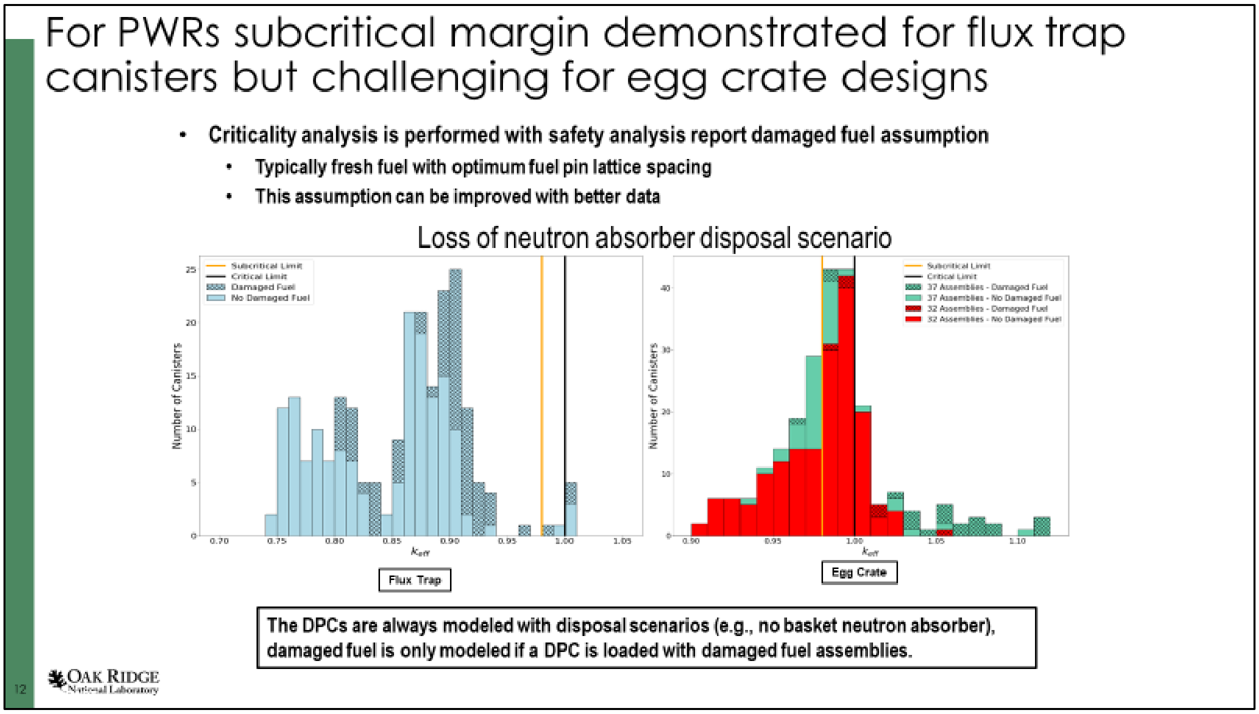


68% of analyzed DPCs are below the representative subcritical limit with as-loaded analysis (fresh water)

- A representative subcritical limit (considered as 0.98 k_{eff}) is used for this analysis

Description (Analysis Dates: 2020-22000)	Value
Total DPCs analyzed	708
Total DPCs below subcritical limit with loss of neutron absorber (design-basis loading)	0 (0%)
Total DPCs below subcritical limit with loss of neutron absorber (as-loaded)	556 (~79%)
Total DPCs below subcritical limit with loss of neutron absorber and carbon steel structures (as-loaded)	483 (~68%)

* Misload is not considered in the statistics presented above

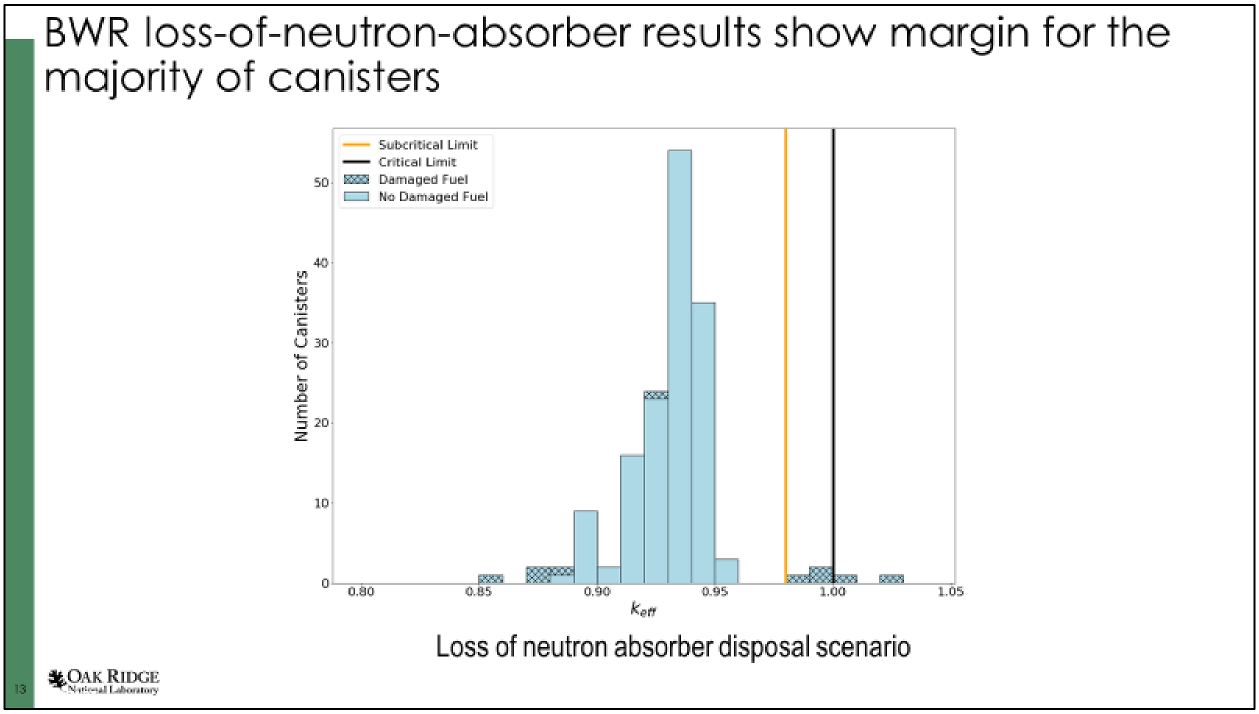


For PWRs subcritical margin demonstrated for flux trap canisters but challenging for egg crate designs

- Criticality analysis is performed with safety analysis report damaged fuel assumption
  - Typically fresh fuel with optimum fuel pin lattice spacing
  - This assumption can be improved with better data

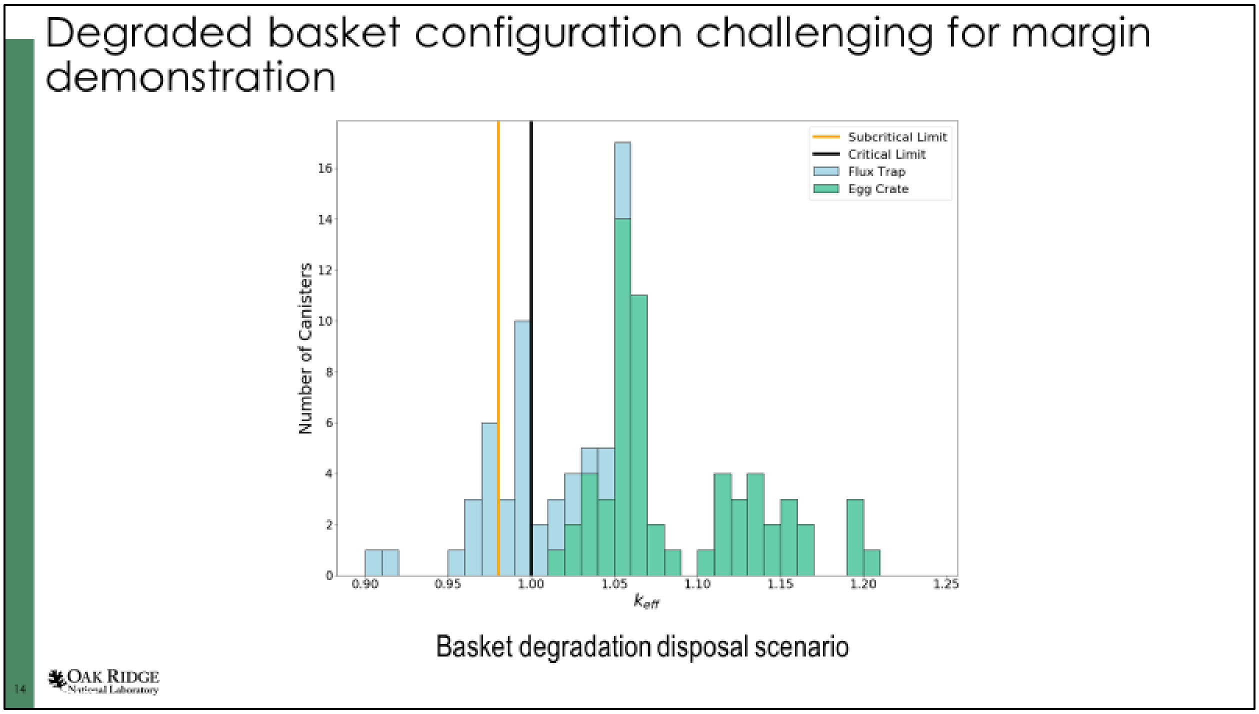
Loss of neutron absorber disposal scenario

The DPCs are always modeled with disposal scenarios (e.g., no basket neutron absorber), damaged fuel is only modeled if a DPC is loaded with damaged fuel assemblies.



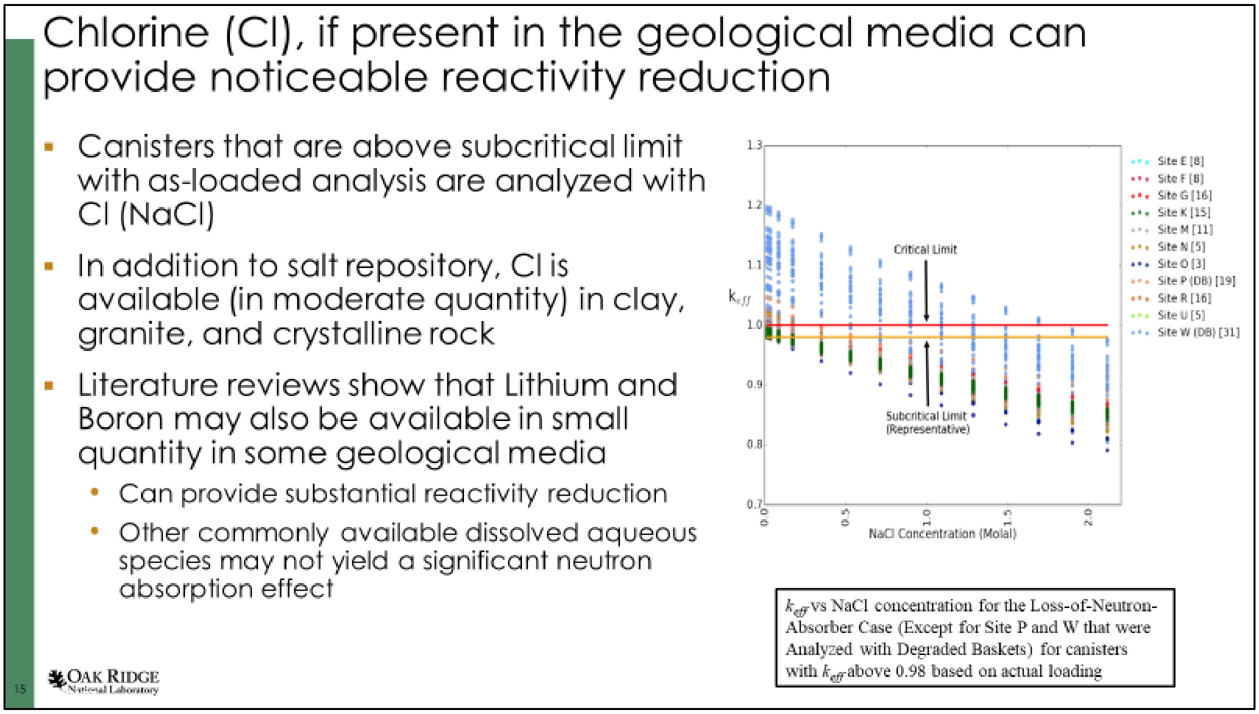
BWR loss-of-neutron-absorber results show margin for the majority of canisters

Loss of neutron absorber disposal scenario



Degraded basket configuration challenging for margin demonstration

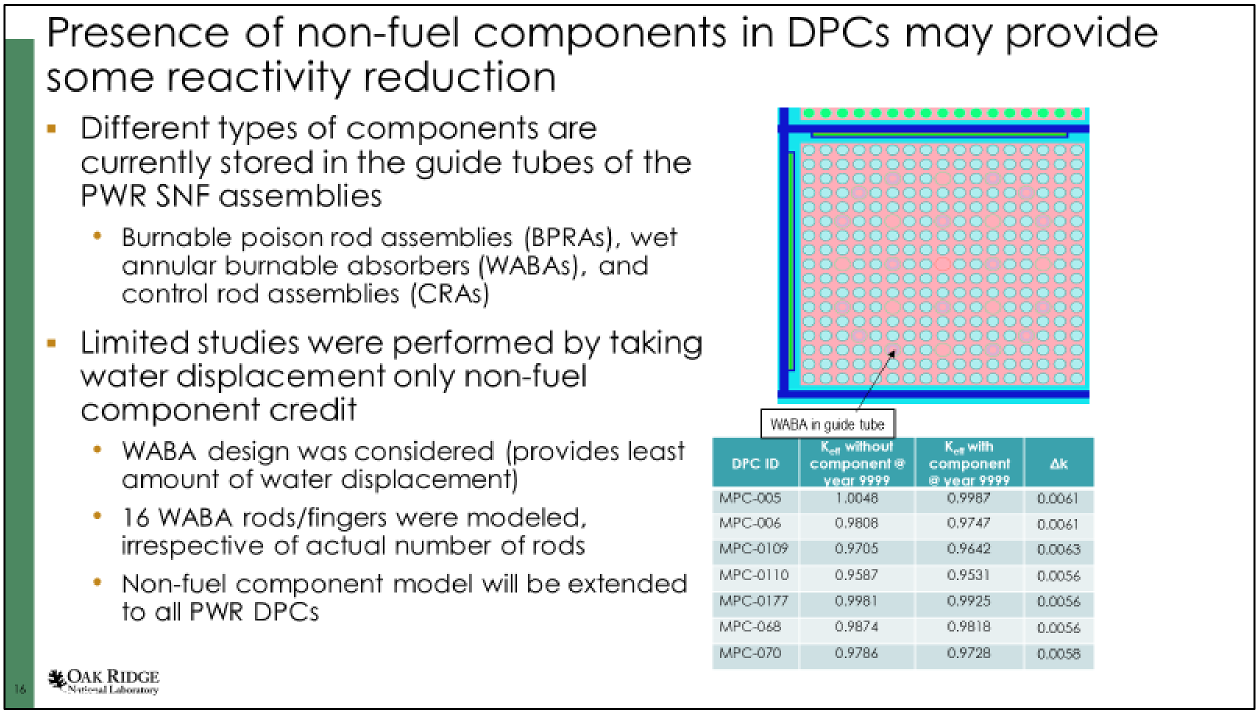
Basket degradation disposal scenario



Chlorine (Cl), if present in the geological media can provide noticeable reactivity reduction

- Canisters that are above subcritical limit with as-loaded analysis are analyzed with Cl (NaCl)
- In addition to salt repository, Cl is available (in moderate quantity) in clay, granite, and crystalline rock
- Literature reviews show that Lithium and Boron may also be available in small quantity in some geological media
  - Can provide substantial reactivity reduction
  - Other commonly available dissolved aqueous species may not yield a significant neutron absorption effect

k_{eff} vs NaCl concentration for the Loss-of-Neutron-Absorber Case (Except for Site P and W that were Analyzed with Degraded Baskets) for canisters with k_{eff} above 0.98 based on actual loading

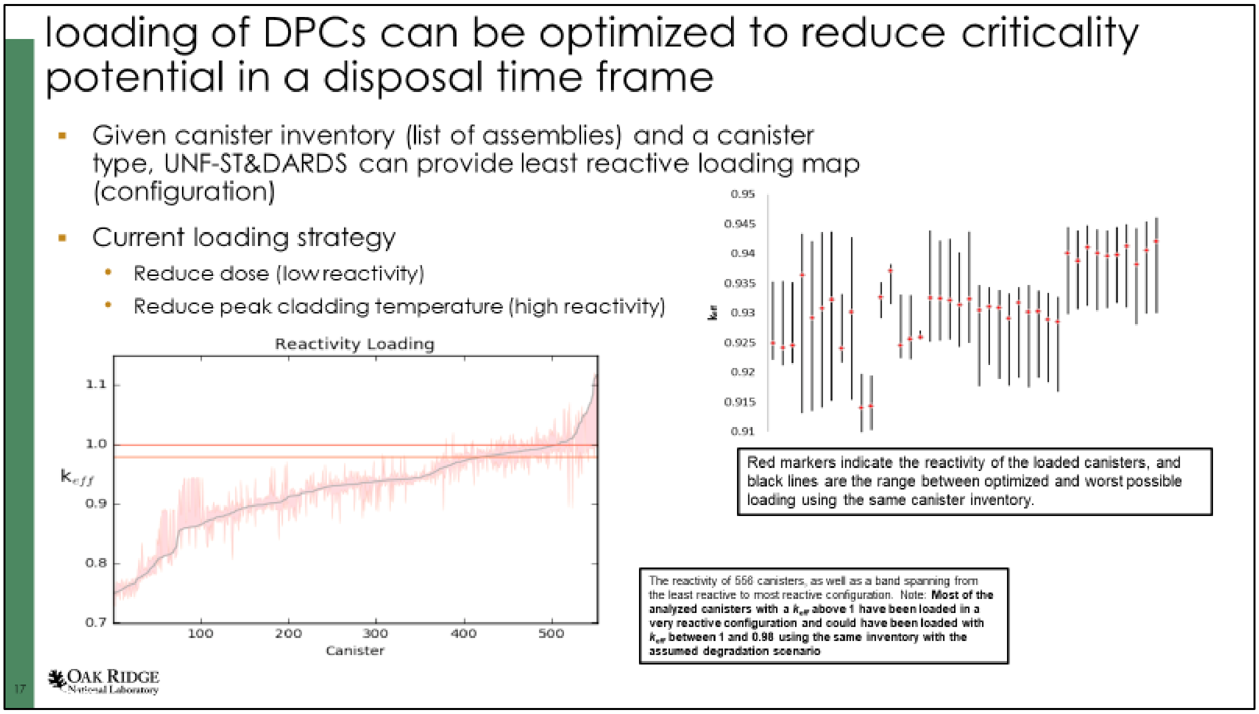


Presence of non-fuel components in DPCs may provide some reactivity reduction

- Different types of components are currently stored in the guide tubes of the PWR SNF assemblies
  - Burnable poison rod assemblies (BPRAs), wet annular burnable absorbers (WABAs), and control rod assemblies (CRAs)
- Limited studies were performed by taking water displacement only non-fuel component credit
  - WABA design was considered (provides least amount of water displacement)
  - 16 WABA rods/fingers were modeled, irrespective of actual number of rods
  - Non-fuel component model will be extended to all PWR DPCs

WABA in guide tube

DPC ID	K_{eff} without component @ year 9999	K_{eff} with component @ year 9999	Δk
MPC-005	1.0048	0.9987	0.0061
MPC-006	0.9808	0.9747	0.0061
MPC-0109	0.9705	0.9642	0.0063
MPC-0110	0.9587	0.9531	0.0056
MPC-0177	0.9981	0.9925	0.0056
MPC-068	0.9874	0.9818	0.0056
MPC-070	0.9786	0.9728	0.0058

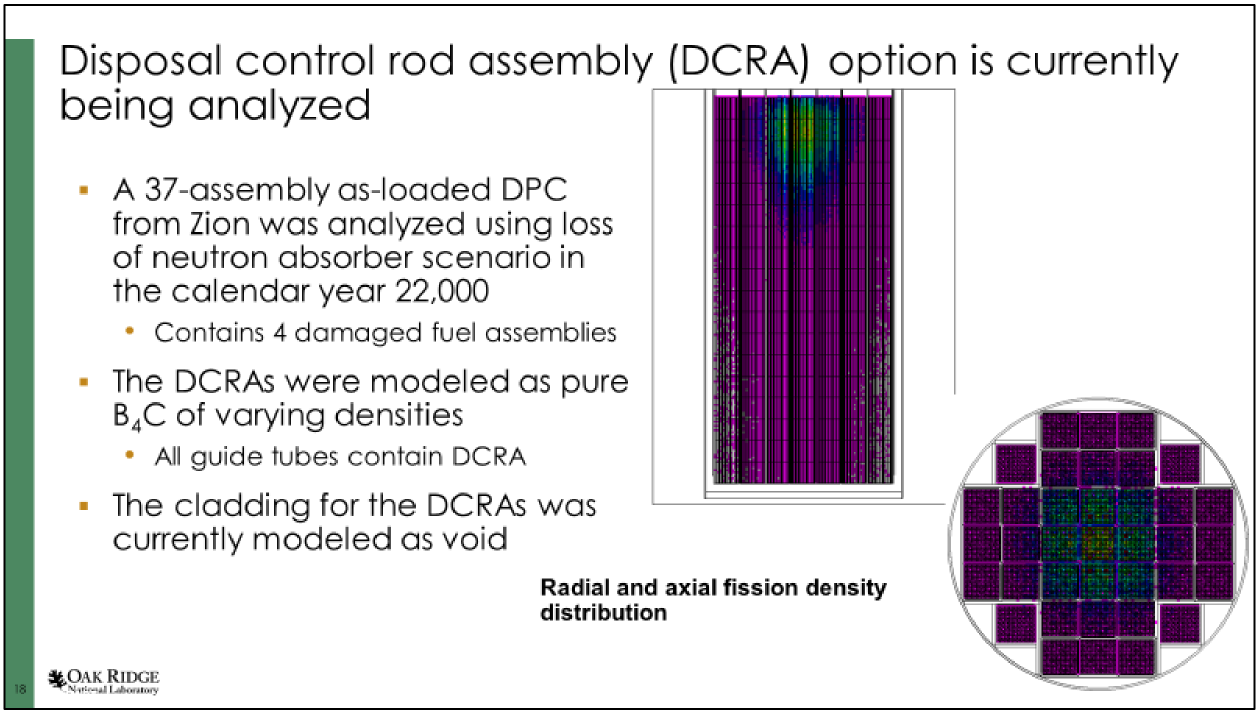


loading of DPCs can be optimized to reduce criticality potential in a disposal time frame

- Given canister inventory (list of assemblies) and a canister type, UNF-ST&DARDS can provide least reactive loading map (configuration)
- Current loading strategy
  - Reduce dose (low reactivity)
  - Reduce peak cladding temperature (high reactivity)

Red markers indicate the reactivity of the loaded canisters, and black lines are the range between optimized and worst possible loading using the same canister inventory.

The reactivity of 558 canisters, as well as a band spanning from the least reactive to most reactive configuration. Note: **Most of the analyzed canisters with a k_{eff} above 1 have been loaded in a very reactive configuration and could have been loaded with k_{eff} between 1 and 0.98 using the same inventory with the assumed degradation scenario**

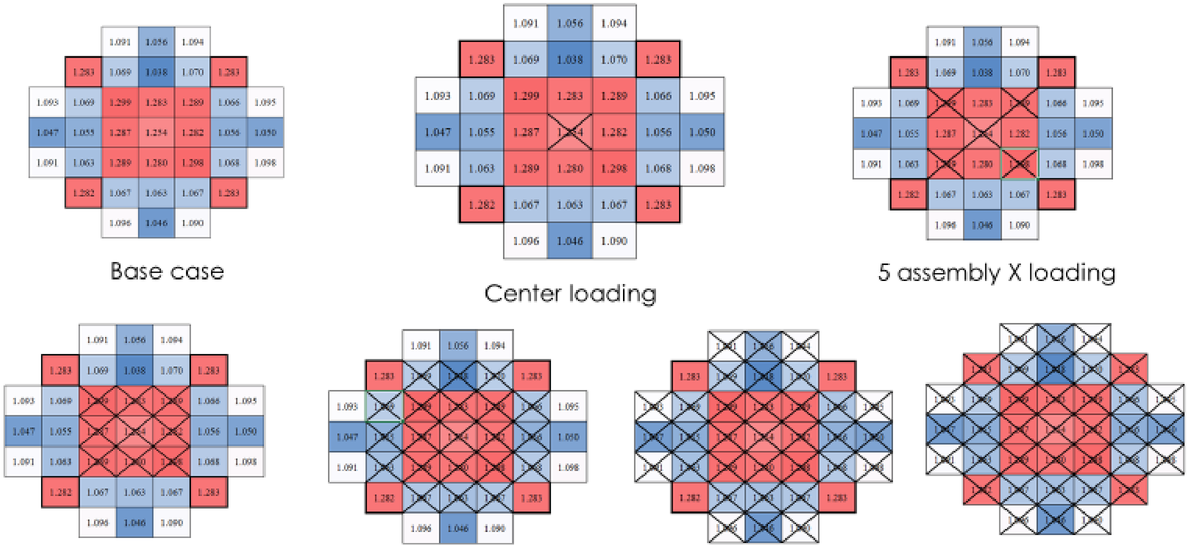


Disposal control rod assembly (DCRA) option is currently being analyzed

- A 37-assembly as-loaded DPC from Zion was analyzed using loss of neutron absorber scenario in the calendar year 22,000
  - Contains 4 damaged fuel assemblies
- The DCRAs were modeled as pure B_4C of varying densities
  - All guide tubes contain DCRA
- The cladding for the DCRAs was currently modeled as void

Radial and axial fission density distribution

Various DCRA loadings were analyzed



		1.091	1.056	1.094		
	1.283	1.069	1.038	1.070	1.283	
1.093	1.069	1.299	1.283	1.289	1.066	1.095
1.047	1.055	1.287	1.254	1.282	1.056	1.050
1.091	1.063	1.289	1.280	1.298	1.068	1.098
	1.282	1.067	1.063	1.067	1.283	
		1.096	1.046	1.090		

Base case

Center loading

5 assembly X loading

Center 9 assembly loading

Center 9 + 12 adjacent

All but damaged fuel

All

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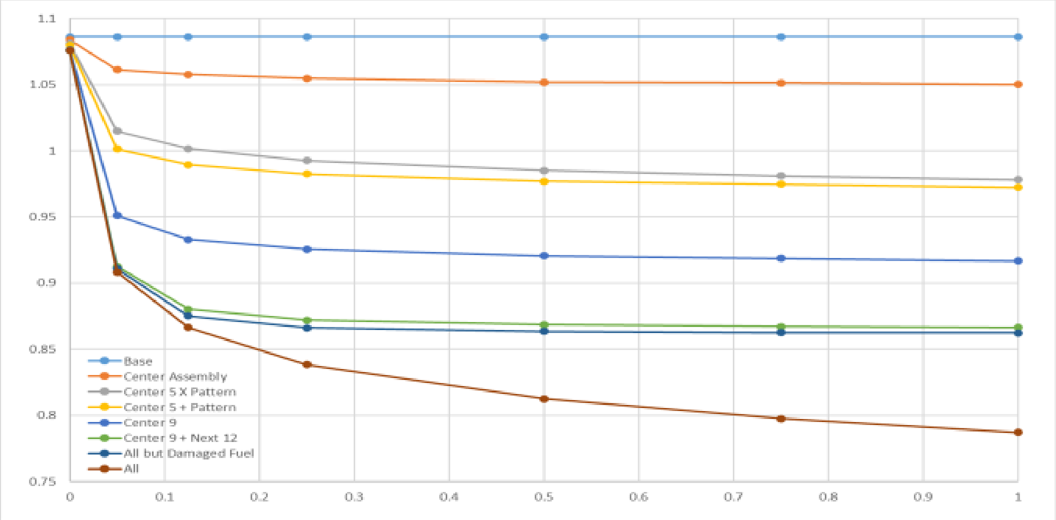
Initial result suggests at least 9 DCRAs will be needed to provide criticality control in a repository



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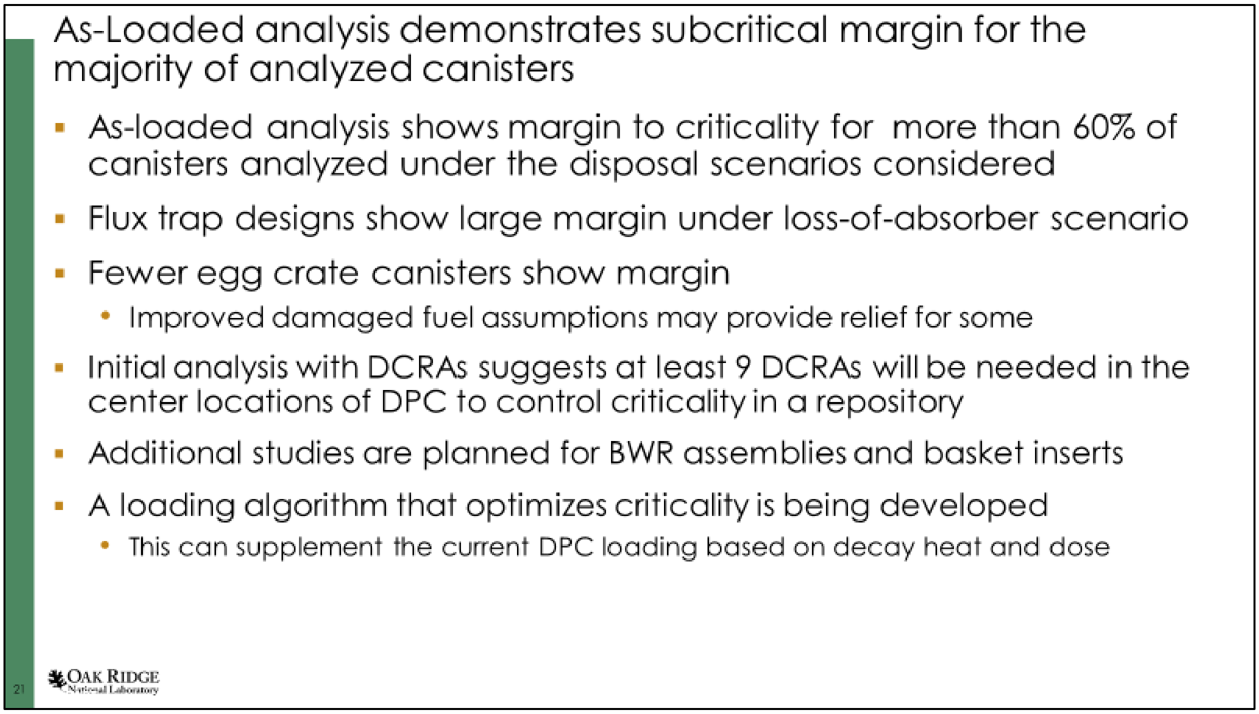

As-Loaded analysis demonstrates subcritical margin for the majority of analyzed canisters

- As-loaded analysis shows margin to criticality for more than 60% of canisters analyzed under the disposal scenarios considered
- Flux trap designs show large margin under loss-of-absorber scenario
- Fewer egg crate canisters show margin
  - Improved damaged fuel assumptions may provide relief for some
- Initial analysis with DCRAs suggests at least 9 DCRAs will be needed in the center locations of DPC to control criticality in a repository
- Additional studies are planned for BWR assemblies and basket inserts
- A loading algorithm that optimizes criticality is being developed
  - This can supplement the current DPC loading based on decay heat and dose

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Criticality Study: Modeling of Degradation of Dual-Purpose Canisters

Varun and Branko Damjanac

Disclaimer

This is a technical presentation that does not take into account contractual limitations or obligations under the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (Standard Contract) (10 CFR Part 961). For example, under the provisions of the Standard Contract, spent nuclear fuel in multi-assembly canisters is not an acceptable waste form, absent a mutually agreed to contract amendment.

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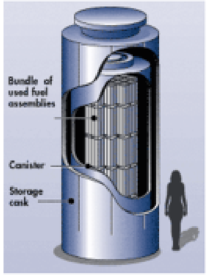
Background

- The Department of Energy (DOE) is investigating the feasibility of direct disposal of spent nuclear fuel (SNF) in existing dual-purpose canisters (DPCs) that have been designed and licensed for storage and transportation, but not for disposal.
- Previous work led by Sandia National Laboratories (SNL) has shown that for direct disposal to be technically feasible, the potential for nuclear criticality must be better understood.
- Over geological timescales, it is envisioned that the canister and canister overpack will be breached by initial cracks (fractures) due to stress corrosion cracking processes. A breach in the canister could allow groundwater to fill the canister. Fresh water is a neutron moderator. Thus, if the canister internals and fuel assemblies have been sufficiently degraded, a criticality event could occur.
- Itasca is modeling the effects of corrosion-induced degradation of structural components on evolution of configuration of DPC over time to assist SNL in the investigation of post-closure criticality in a geologic repository.

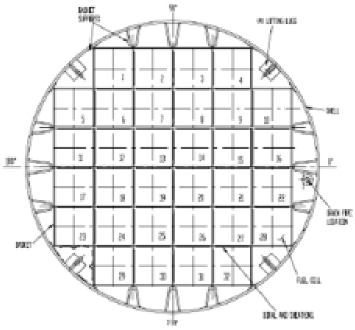
Canister and Basket



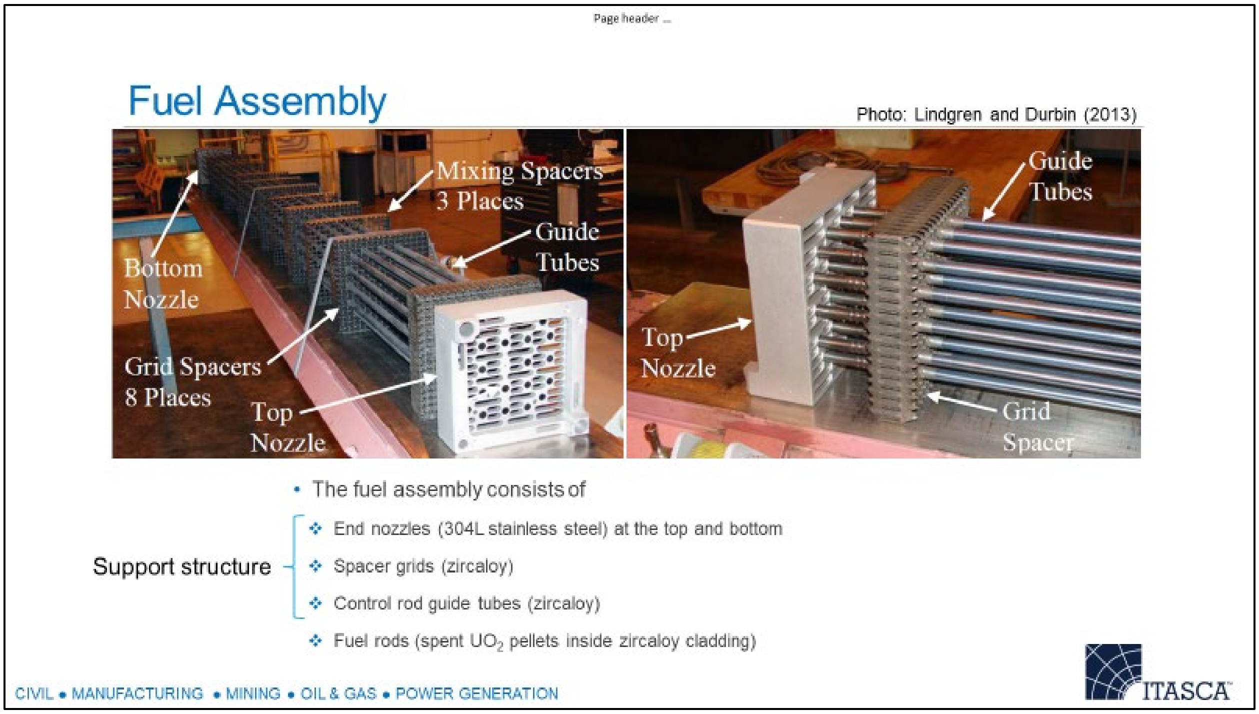
Canister with overpack and fuel assemblies

Photo: nrc.gov

- The system consists of a steel canister (cylindrical shell) inside a thicker overpack (steel).
- The canister has a rectilinear honeycomb basket in the middle used to hold the spent fuel assemblies. There are two basket configurations: Egg-crate and tube-and-plate.
  - Older designs use steel plates steel plates use thin plates of Boral® (aluminum-B4C composite) as neutron absorber that are fixed to the longitudinal structural plates by thin cover sheets of stainless steel.
  - For newer designs, the basket structure is made using aluminum-based Metamic-HT which also serves as the neutron absorber material and prevents the spent fuel from going critical.
- The configuration used for this study corresponds to MPC-32 basket (egg-crate) made of Metamic-HT and PWR fuel assembly with 17 x 17 fuel rods in each assembly.



Configuration used for this study showing MPC-32 basket in a canister

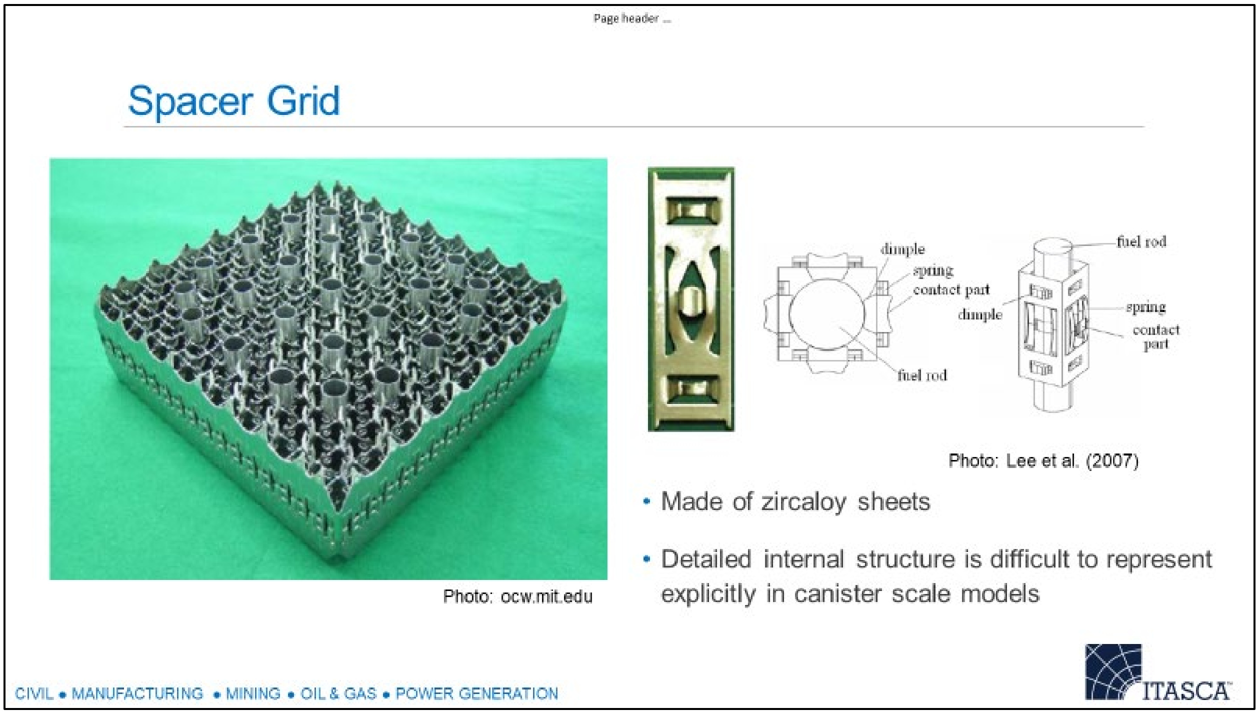


Fuel Assembly

Photo: Lindgren and Durbin (2013)

- The fuel assembly consists of
  - ❖ End nozzles (304L stainless steel) at the top and bottom
  - ❖ Spacer grids (zircaloy)
  - ❖ Control rod guide tubes (zircaloy)
  - ❖ Fuel rods (spent UO_2 pellets inside zircaloy cladding)

Support structure



Spacer Grid

Photo: ocw.mit.edu

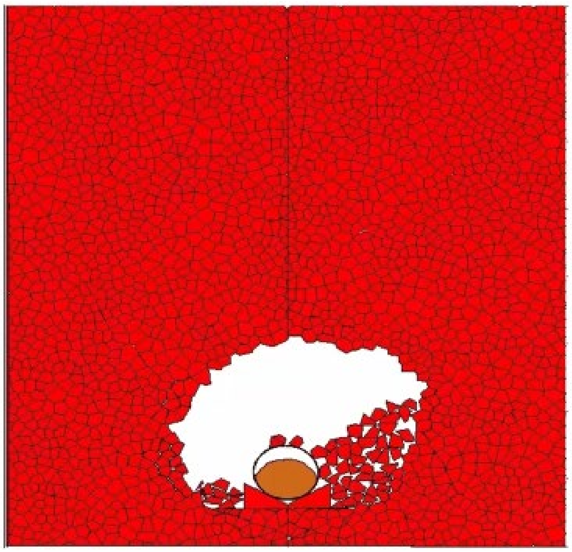
Photo: Lee et al. (2007)

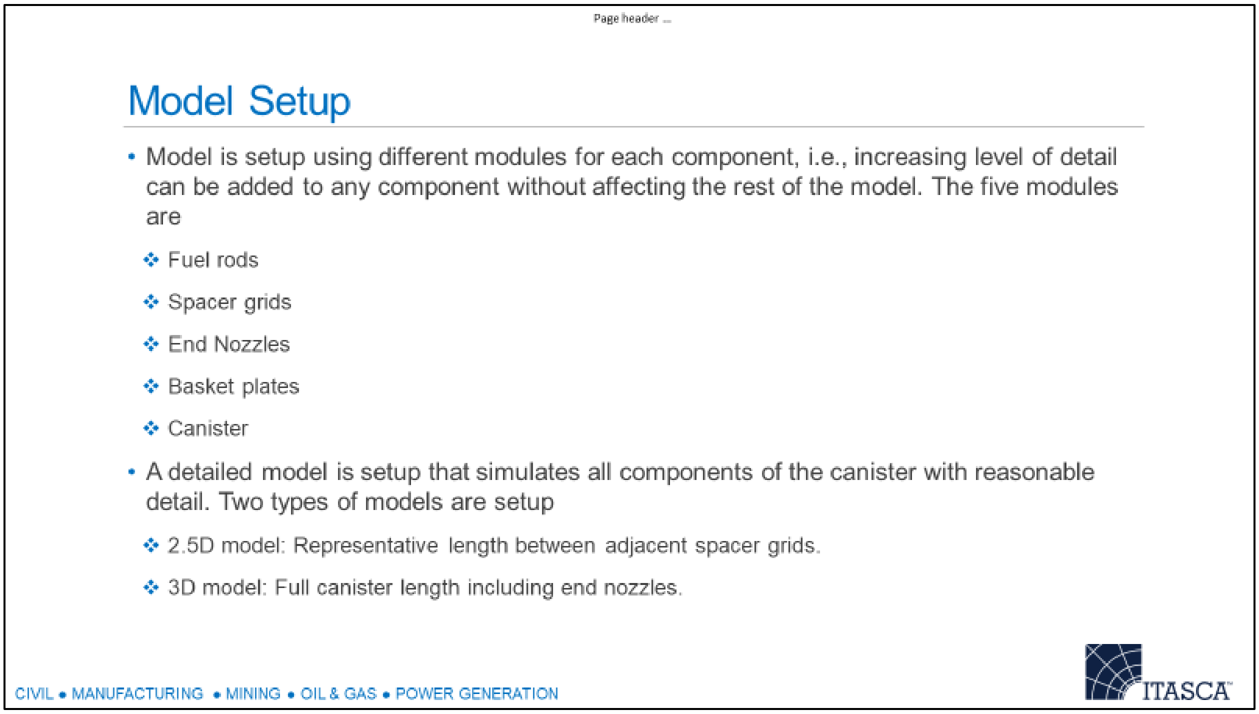
- Made of zircaloy sheets
- Detailed internal structure is difficult to represent explicitly in canister scale models

Modeling Approach

- The codes (*3DEC*, *PFC*) are based on Distinct Element Method (DEM)
  - ❖ Physics-based codes
  - ❖ Established mathematical models, numerically implemented using explicit finite-difference numerical scheme
  - ❖ Commercial codes used by engineers in different industries and researchers at universities and laboratories worldwide
- Previously qualified and used at Yucca Mountain project
  - ❖ Drift degradation analysis
  - ❖ Seismic consequences abstraction
  - ❖ Capping of the extreme ground motions
- The latest versions were used for this project (additional functionalities and faster execution)
  - ❖ Every released version of the code is carefully tested and verified by executing a suite of verification and examples problems

Nuclear Waste Disposal Earthquake





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Model Setup

- Model is setup using different modules for each component, i.e., increasing level of detail can be added to any component without affecting the rest of the model. The five modules are
  - Fuel rods
  - Spacer grids
  - End Nozzles
  - Basket plates
  - Canister
- A detailed model is setup that simulates all components of the canister with reasonable detail. Two types of models are setup
  - 2.5D model: Representative length between adjacent spacer grids.
  - 3D model: Full canister length including end nozzles.

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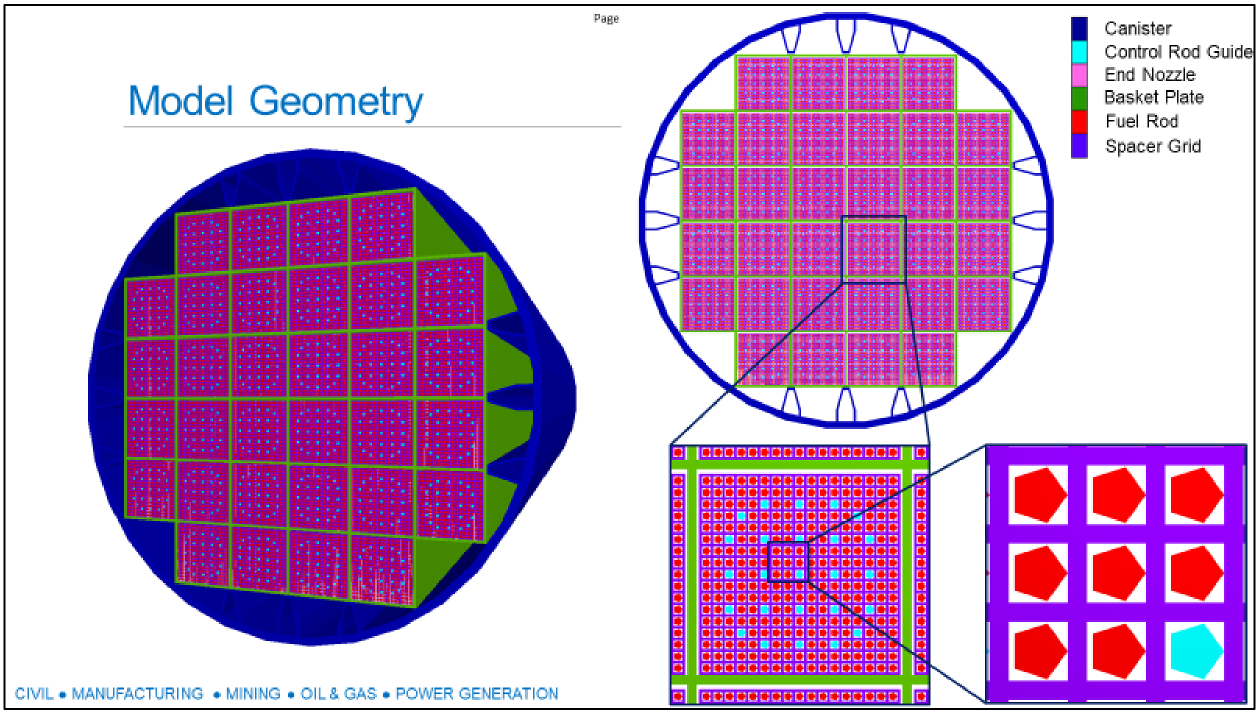

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Model Geometry

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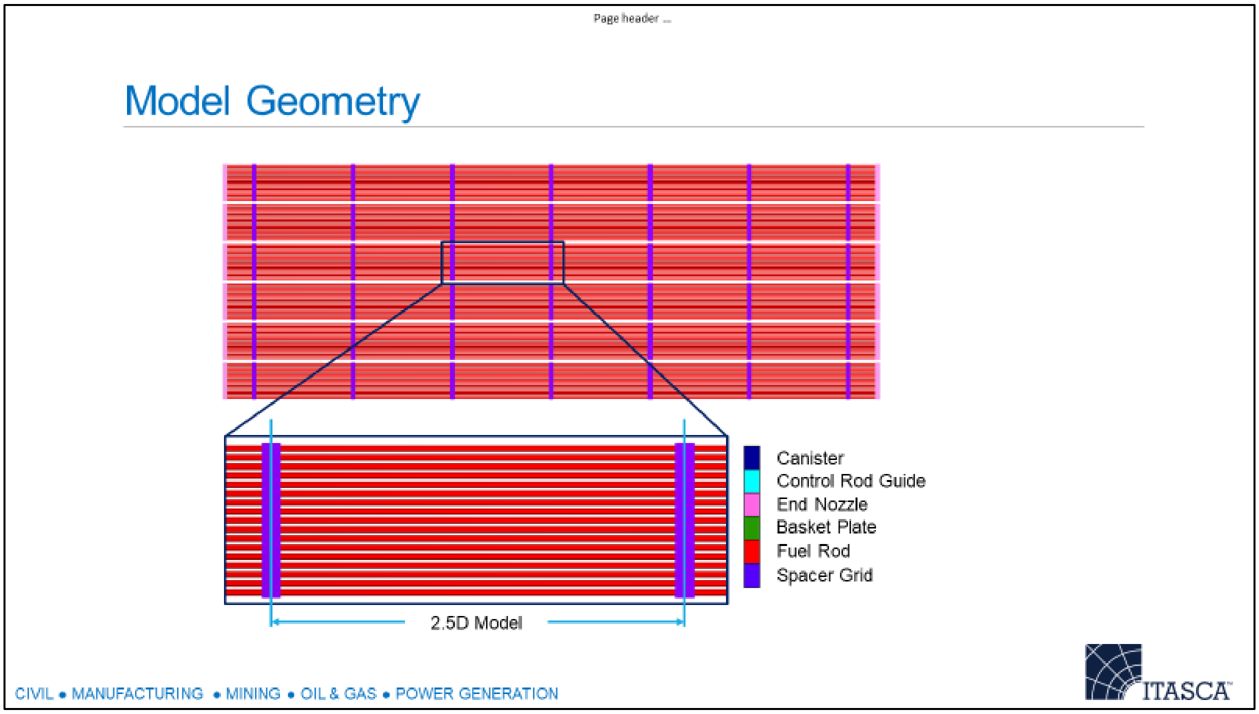
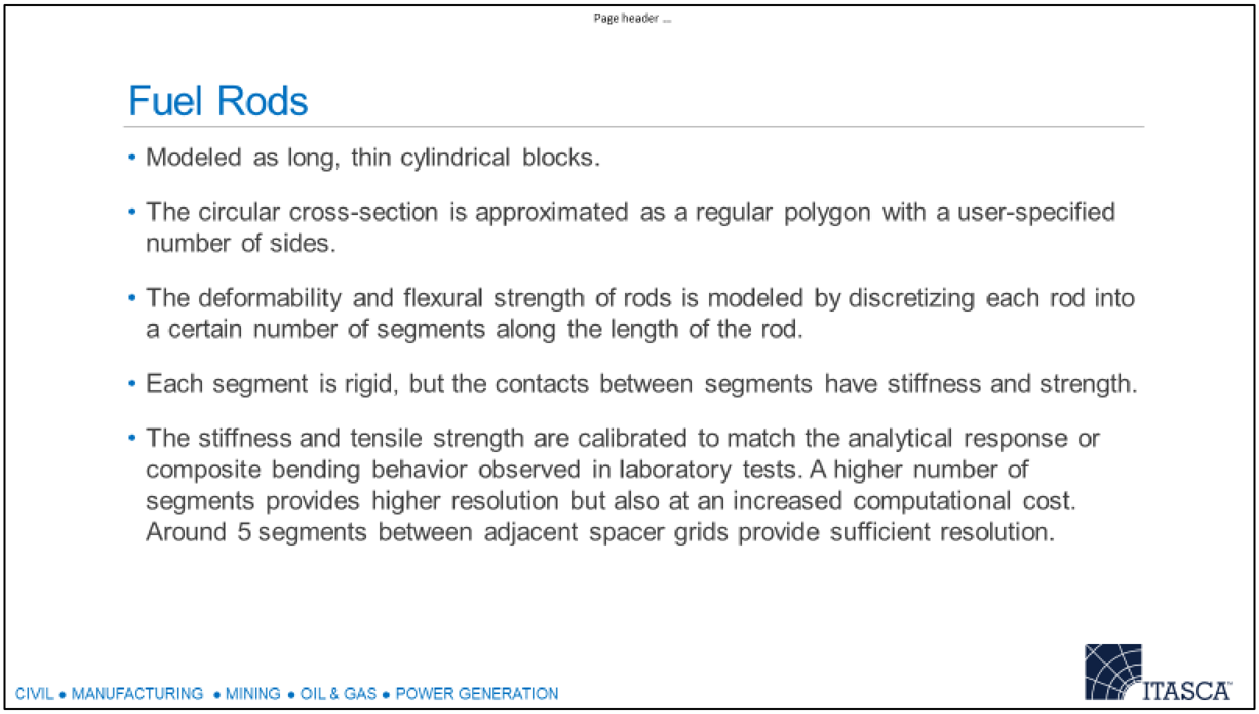
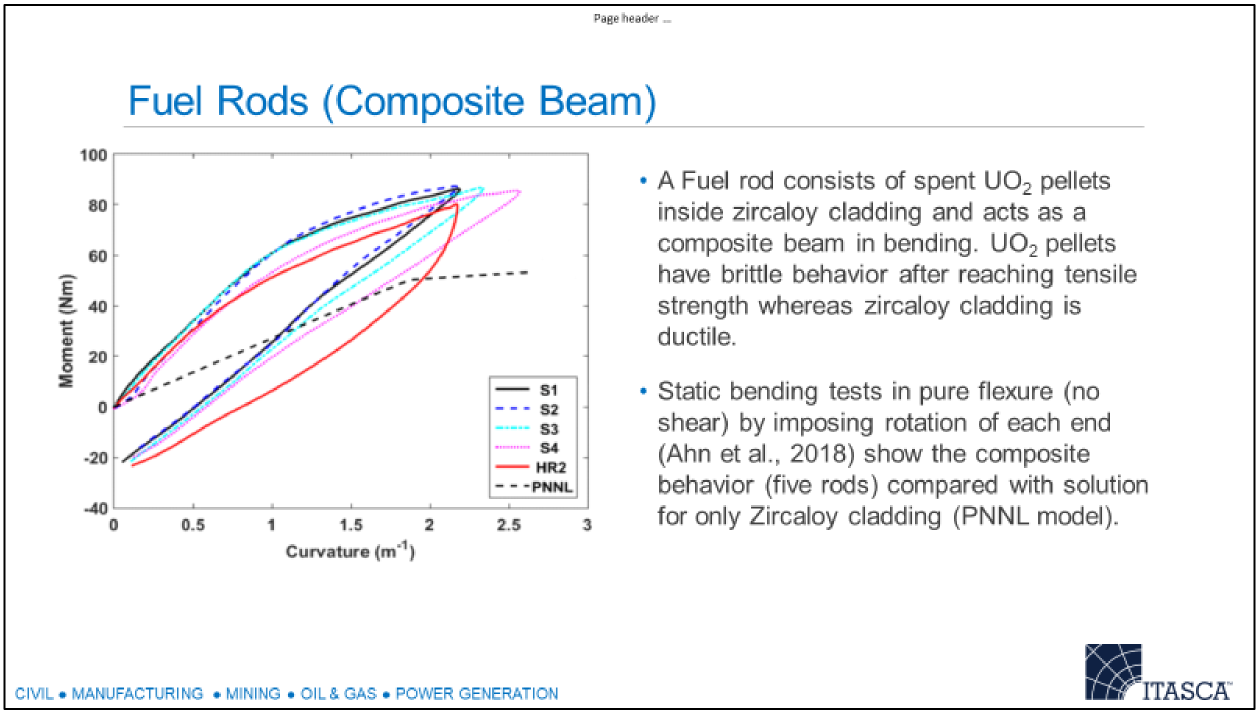


Model Geometry



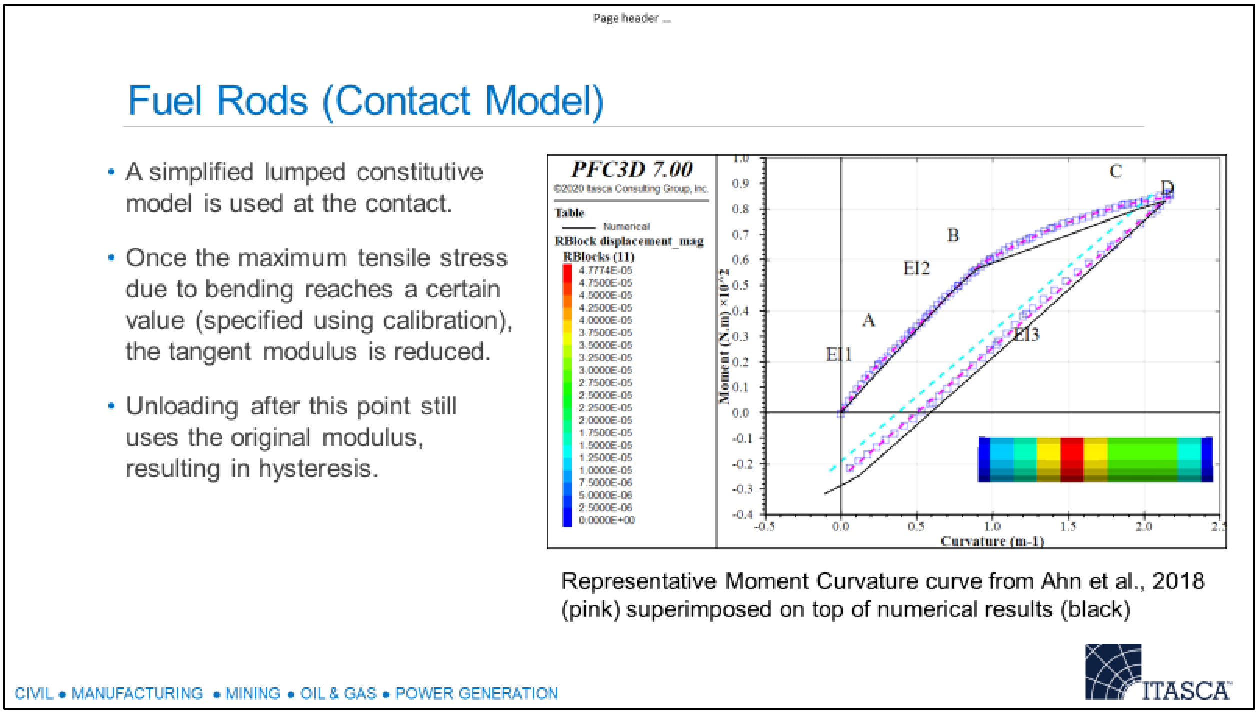
Fuel Rods

- Modeled as long, thin cylindrical blocks.
- The circular cross-section is approximated as a regular polygon with a user-specified number of sides.
- The deformability and flexural strength of rods is modeled by discretizing each rod into a certain number of segments along the length of the rod.
- Each segment is rigid, but the contacts between segments have stiffness and strength.
- The stiffness and tensile strength are calibrated to match the analytical response or composite bending behavior observed in laboratory tests. A higher number of segments provides higher resolution but also at an increased computational cost. Around 5 segments between adjacent spacer grids provide sufficient resolution.



Fuel Rods (Composite Beam)

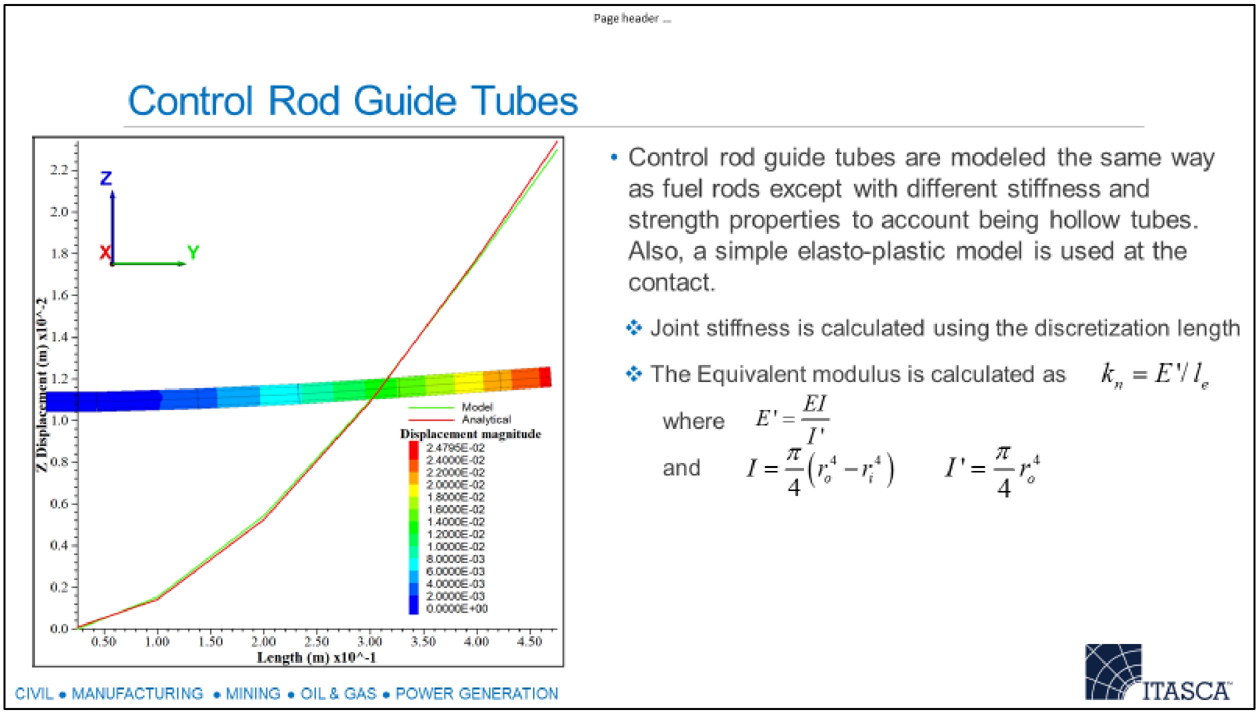
- A Fuel rod consists of spent UO_2 pellets inside zircaloy cladding and acts as a composite beam in bending. UO_2 pellets have brittle behavior after reaching tensile strength whereas zircaloy cladding is ductile.
- Static bending tests in pure flexure (no shear) by imposing rotation of each end (Ahn et al., 2018) show the composite behavior (five rods) compared with solution for only Zircaloy cladding (PNNL model).



Fuel Rods (Contact Model)

- A simplified lumped constitutive model is used at the contact.
- Once the maximum tensile stress due to bending reaches a certain value (specified using calibration), the tangent modulus is reduced.
- Unloading after this point still uses the original modulus, resulting in hysteresis.

Representative Moment Curvature curve from Ahn et al., 2018 (pink) superimposed on top of numerical results (black)

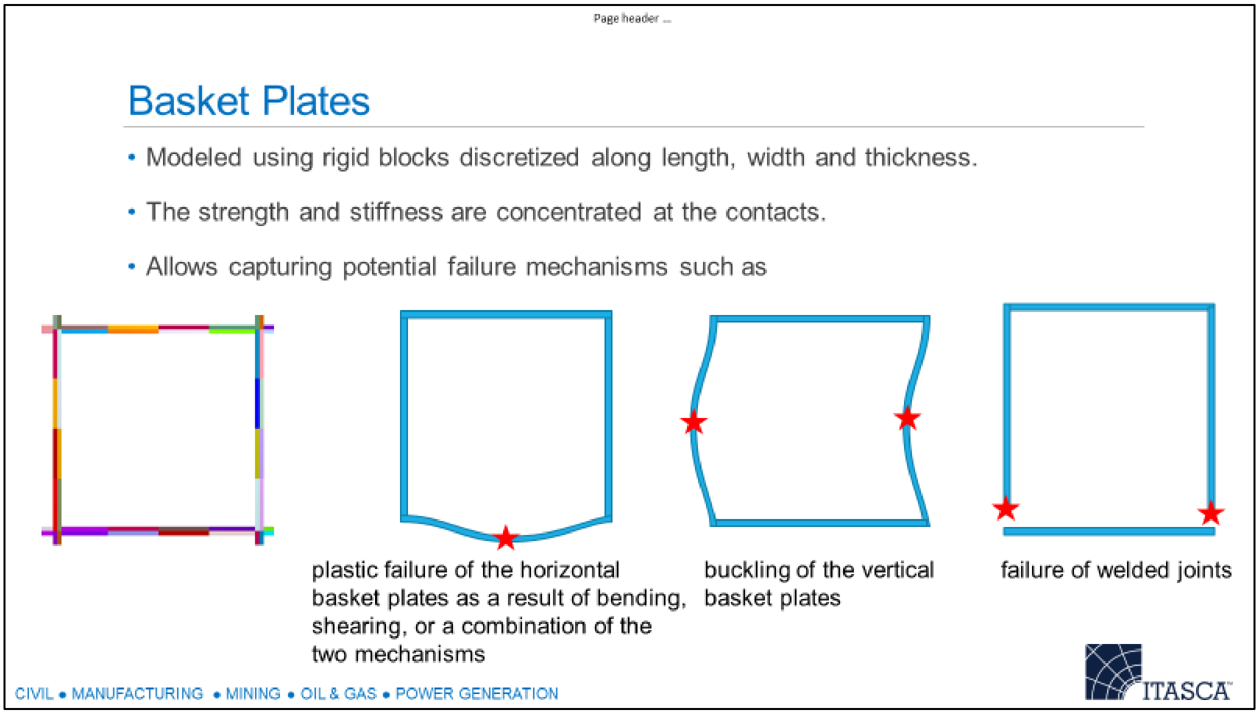


Control Rod Guide Tubes

- Control rod guide tubes are modeled the same way as fuel rods except with different stiffness and strength properties to account being hollow tubes. Also, a simple elasto-plastic model is used at the contact.
  - ❖ Joint stiffness is calculated using the discretization length
  - ❖ The Equivalent modulus is calculated as $k_n = E'/l_e$

    where $E' = \frac{EI}{I'}$

    and $I = \frac{\pi}{4}\left(r_o^4 - r_i^4\right)$ $I' = \frac{\pi}{4} r_o^4$



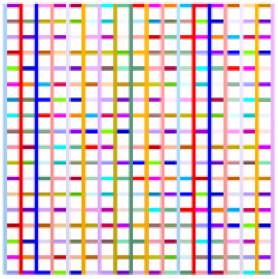
Basket Plates

- Modeled using rigid blocks discretized along length, width and thickness.
- The strength and stiffness are concentrated at the contacts.
- Allows capturing potential failure mechanisms such as

plastic failure of the horizontal basket plates as a result of bending, shearing, or a combination of the two mechanisms

buckling of the vertical basket plates

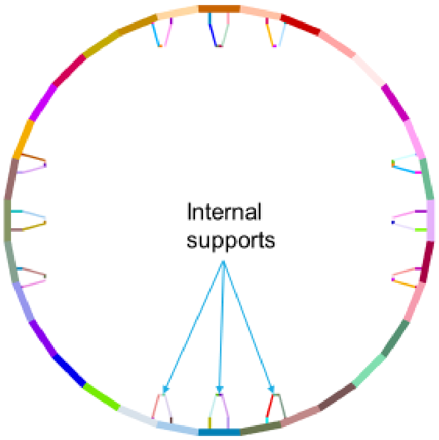
failure of welded joints



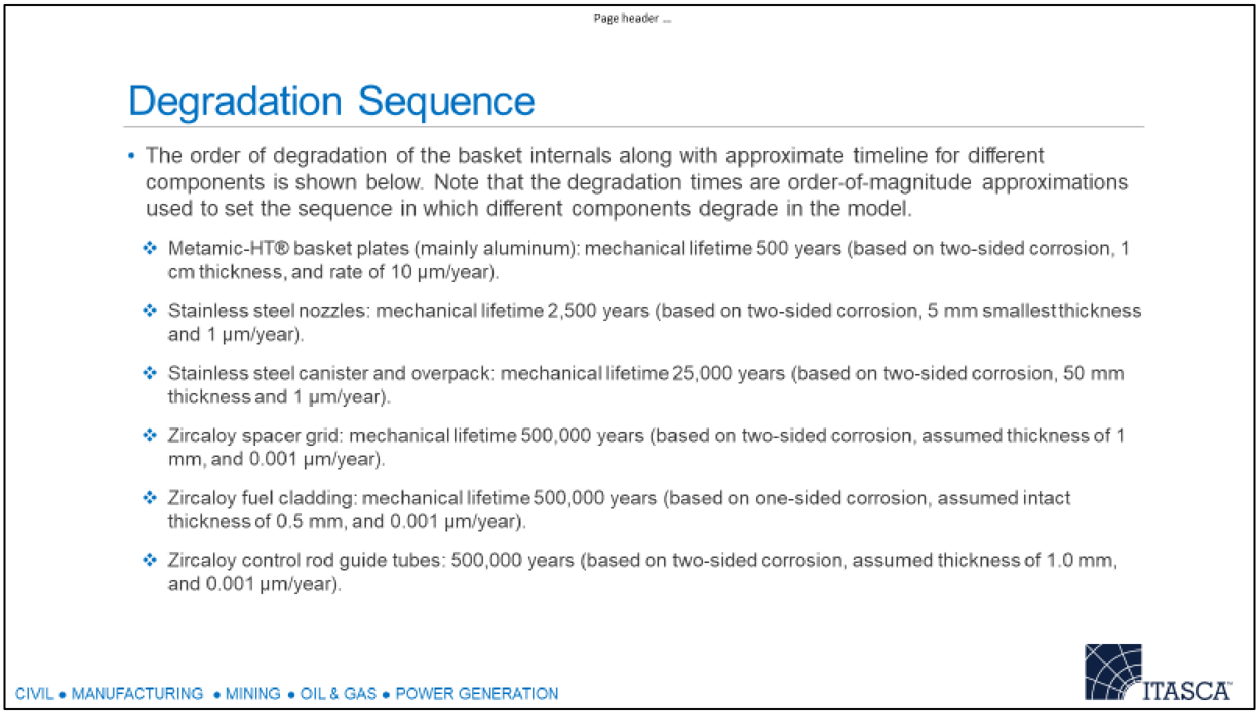
Spacer Grid and End Nozzles

- End Nozzles: 304L Stainless Steel   Spacer Grids: Zircaloy – 4
- Detailed internal structure is difficult to represent explicitly.
- Both are represented as a rectilinear array of blocks.
- Control rod guide tubes are rigidly attached to the spacer grids and end nozzles but the fuel rods are able to slide in and out. The resistance to sliding is based on the normal force and the friction angle specified.
- Thickness of plates modeled is larger than the actual thickness such that the boundary condition that the rods have no free room available to move in the plane normal to their axis is simulated correctly. However, the density of the plates is reduced accordingly to match the mass of the spacer grid
- If needed, the clamping effect of spacer grid springs on fuel rods can be simulated by initializing a normal force at the fuel rod and spacer grid contact.

Canister and Internal Supports



- Canister is discretized along circumference and length.
- Supports are coarsely discretized as shown and along the length as well.
- Canister can fail for models where overpack is also modeled. Otherwise, canister is assumed to stay intact and acts as the model boundary.
- When overpack is modeled, overpack acts as the boundary.



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Degradation Sequence

- The order of degradation of the basket internals along with approximate timeline for different components is shown below. Note that the degradation times are order-of-magnitude approximations used to set the sequence in which different components degrade in the model.
  - Metamic-HT® basket plates (mainly aluminum): mechanical lifetime 500 years (based on two-sided corrosion, 1 cm thickness, and rate of 10 µm/year).
  - Stainless steel nozzles: mechanical lifetime 2,500 years (based on two-sided corrosion, 5 mm smallest thickness and 1 µm/year).
  - Stainless steel canister and overpack: mechanical lifetime 25,000 years (based on two-sided corrosion, 50 mm thickness and 1 µm/year).
  - Zircaloy spacer grid: mechanical lifetime 500,000 years (based on two-sided corrosion, assumed thickness of 1 mm, and 0.001 µm/year).
  - Zircaloy fuel cladding: mechanical lifetime 500,000 years (based on one-sided corrosion, assumed intact thickness of 0.5 mm, and 0.001 µm/year).
  - Zircaloy control rod guide tubes: 500,000 years (based on two-sided corrosion, assumed thickness of 1.0 mm, and 0.001 µm/year).

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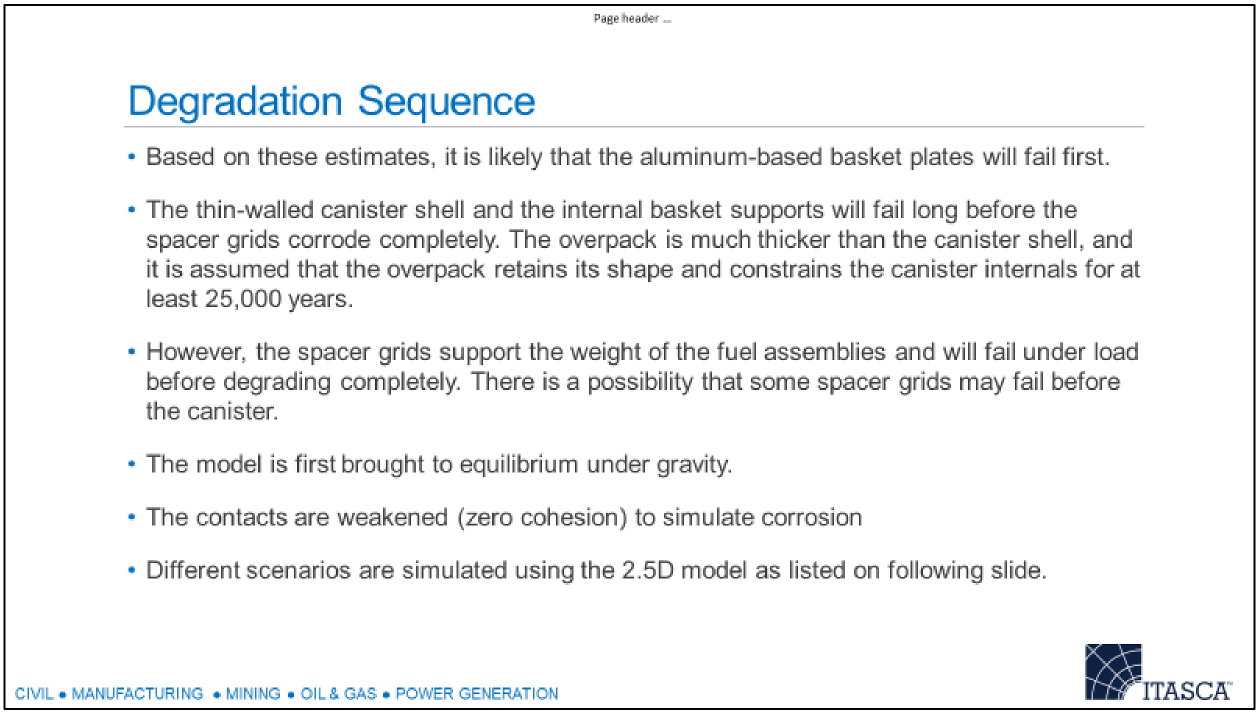

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Degradation Sequence

- Based on these estimates, it is likely that the aluminum-based basket plates will fail first.
- The thin-walled canister shell and the internal basket supports will fail long before the spacer grids corrode completely. The overpack is much thicker than the canister shell, and it is assumed that the overpack retains its shape and constrains the canister internals for at least 25,000 years.
- However, the spacer grids support the weight of the fuel assemblies and will fail under load before degrading completely. There is a possibility that some spacer grids may fail before the canister.
- The model is first brought to equilibrium under gravity.
- The contacts are weakened (zero cohesion) to simulate corrosion
- Different scenarios are simulated using the 2.5D model as listed on following slide.

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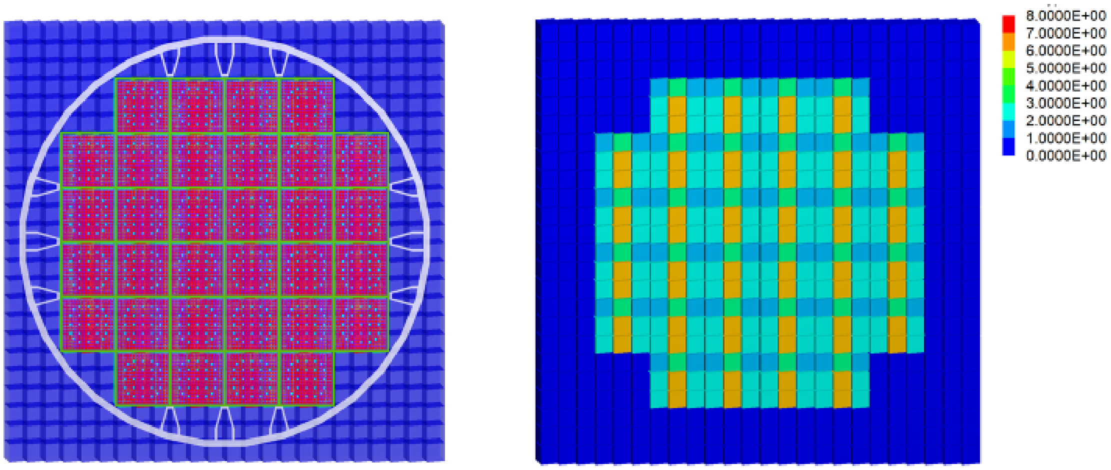
Number of guide tubes per grid cell



A rectilinear grid (user specified size) can be used to track the number of control rods in each grid cell

---

Cases using 2.5D model

- Sequence 1:

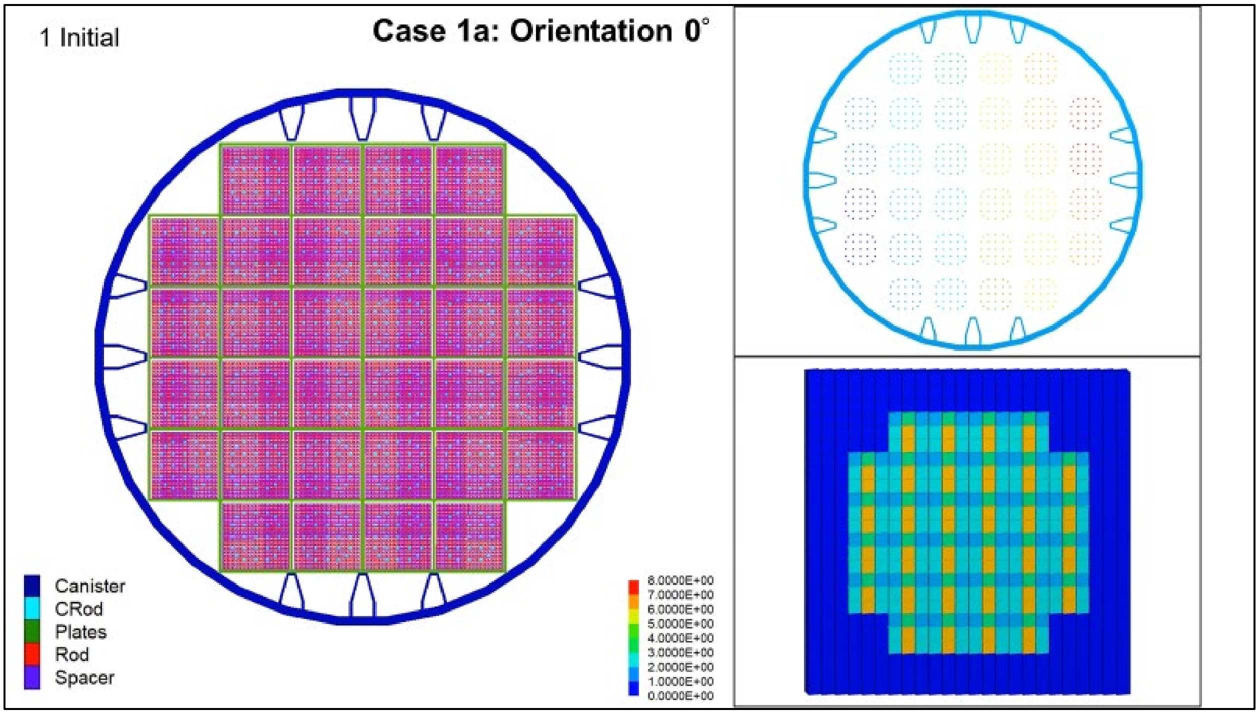
  Plates → Spacer Grids
  - 0° orientation

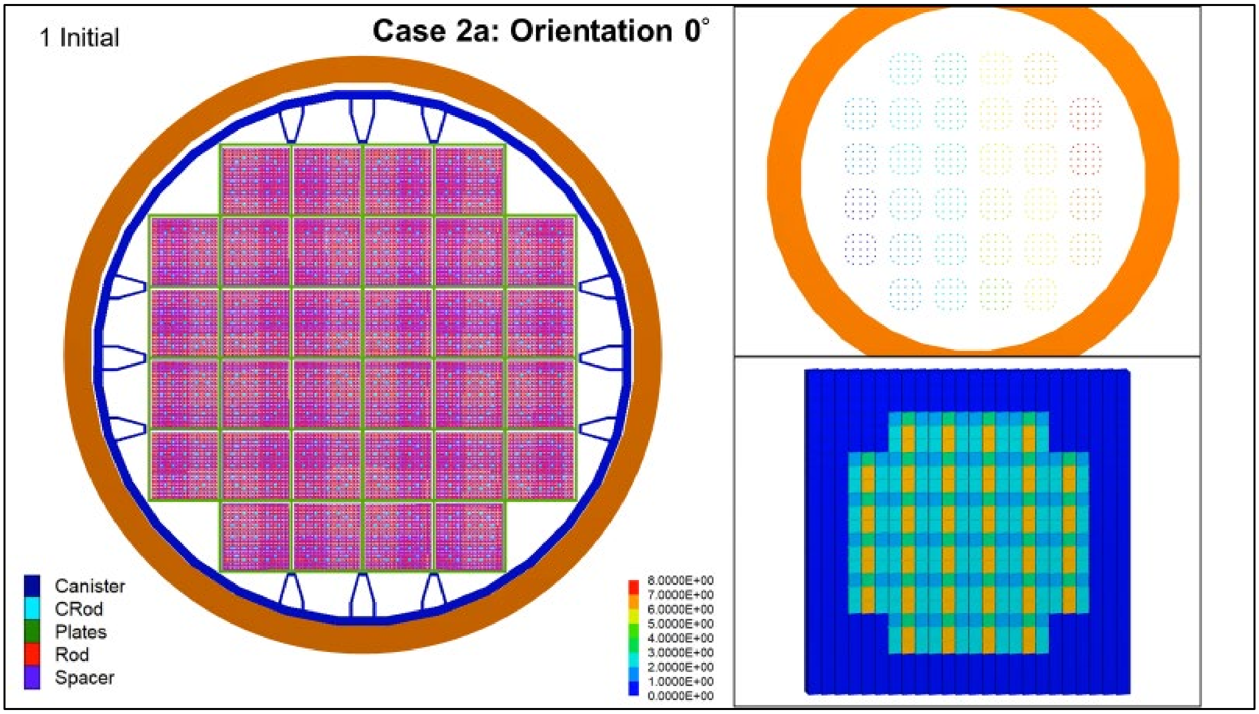
- Sequence 2:

  Plates → Internal supports → Canister → Spacer Grids
  - 2a: 0° orientation
  - 2b: 30° orientation
  - 2c: 45° orientation

- Sequence 3:

  Plates corrode sequentially from bottom to top
  - 3a: 0° orientation


1 Initial
Case 1a: Orientation 0°
Canister
CRod
Plates
Rod
Spacer
8.0000E+00
7.0000E+00
6.0000E+00
5.0000E+00
4.0000E+00
3.0000E+00
2.0000E+00
1.0000E+00
0.0000E+00


1 Initial
Case 2a: Orientation 0°
Canister
CRod
Plates
Rod
Spacer
8.0000E+00
7.0000E+00
6.0000E+00
5.0000E+00
4.0000E+00
3.0000E+00
2.0000E+00
1.0000E+00
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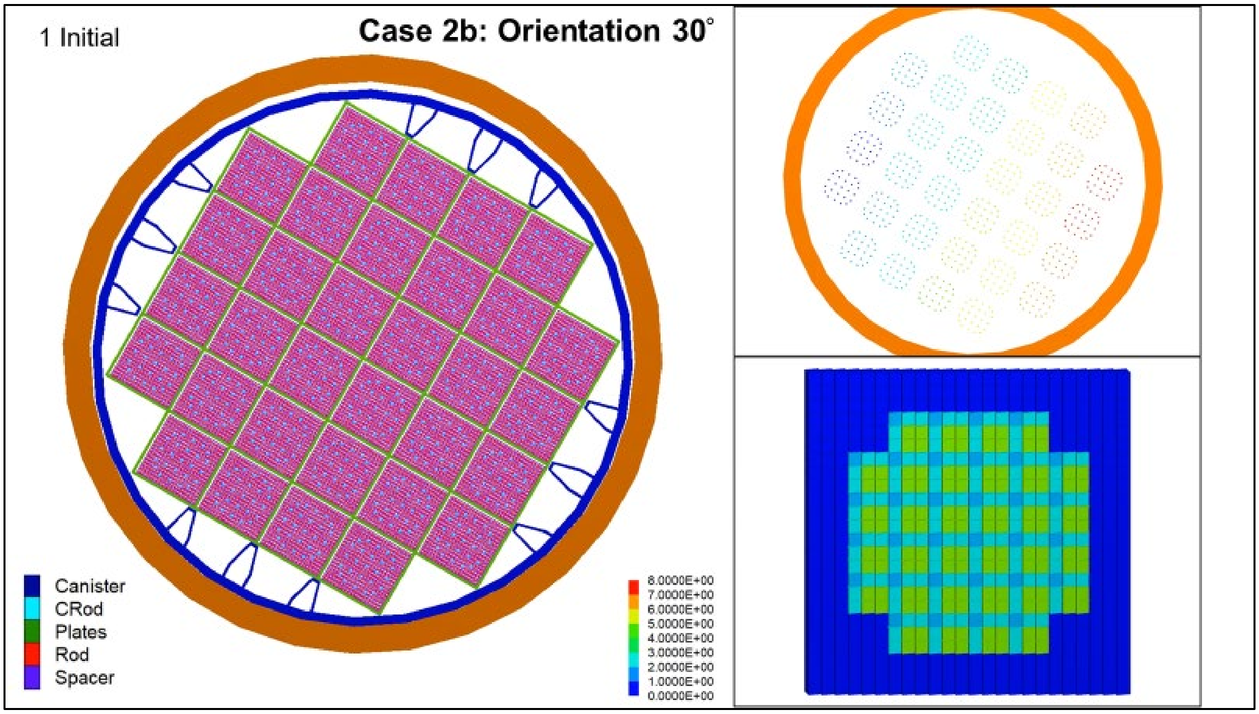
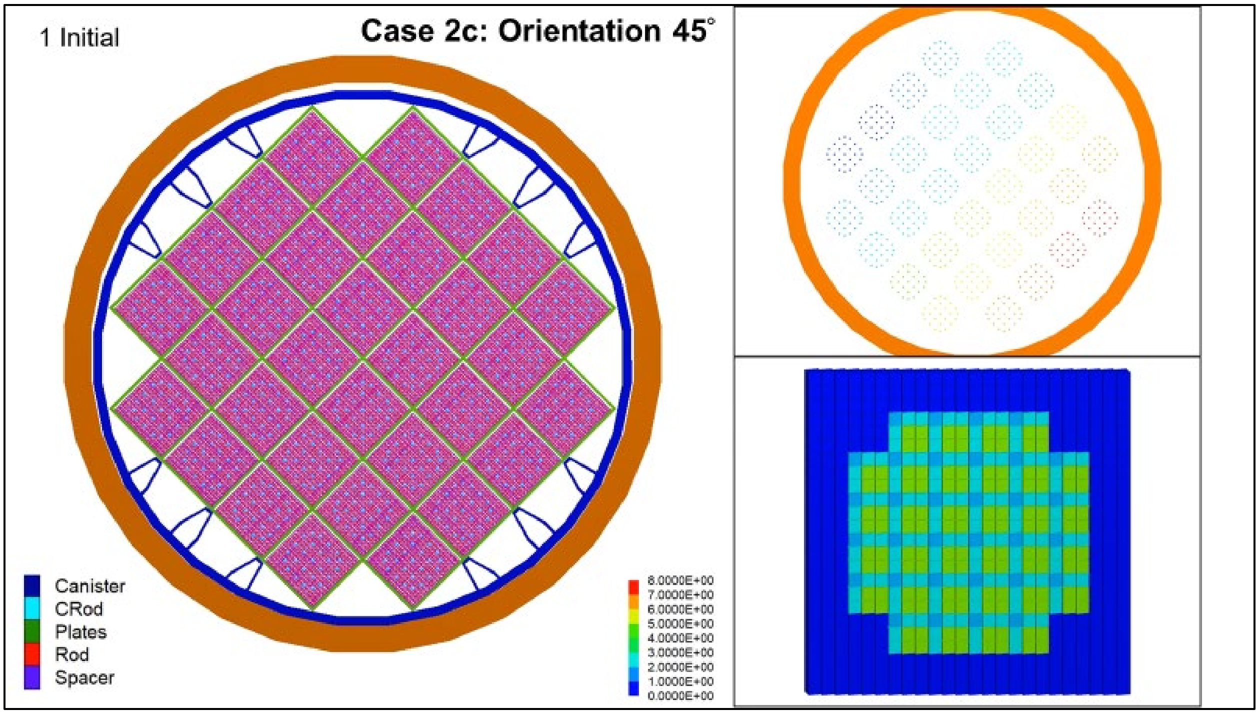

1 Initial
Case 2b: Orientation 30°
Canister
CRod
Plates
Rod
Spacer
8.0000E+00
7.0000E+00
6.0000E+00
5.0000E+00
4.0000E+00
3.0000E+00
2.0000E+00
1.0000E+00
0.0000E+00


1 Initial
Case 2c: Orientation 45°
Canister
CRod
Plates
Rod
Spacer
8.0000E+00
7.0000E+00
6.0000E+00
5.0000E+00
4.0000E+00
3.0000E+00
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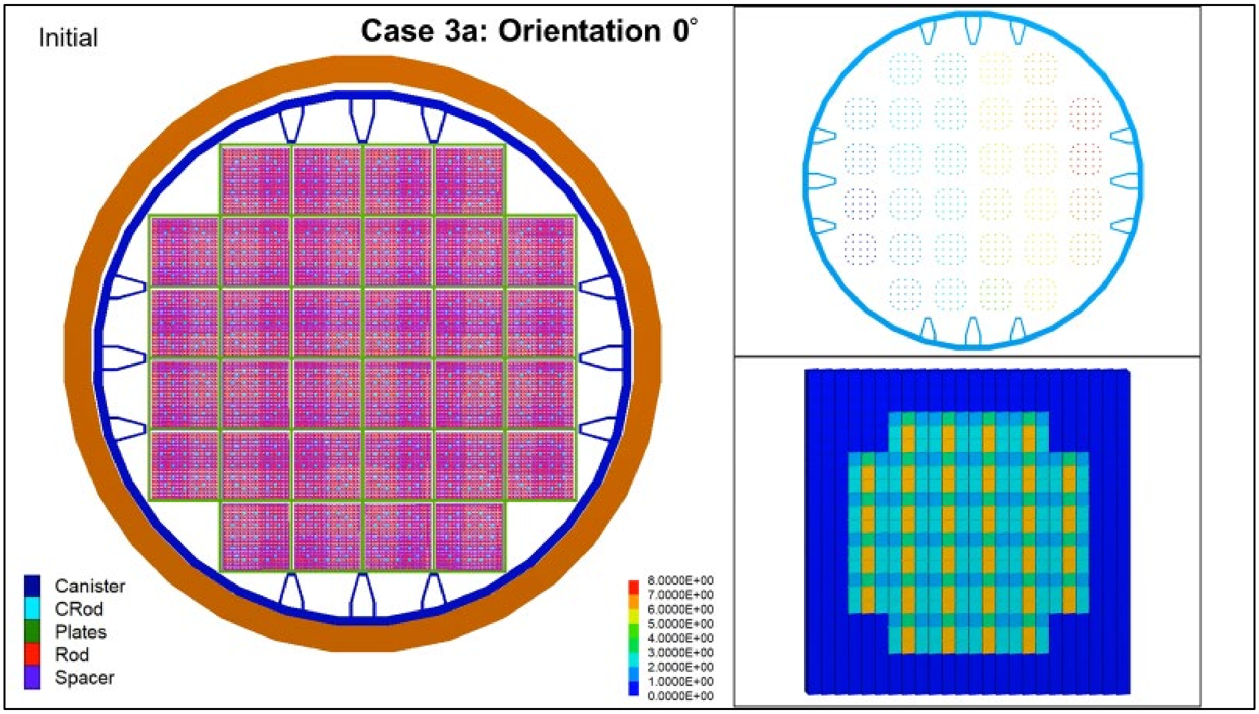
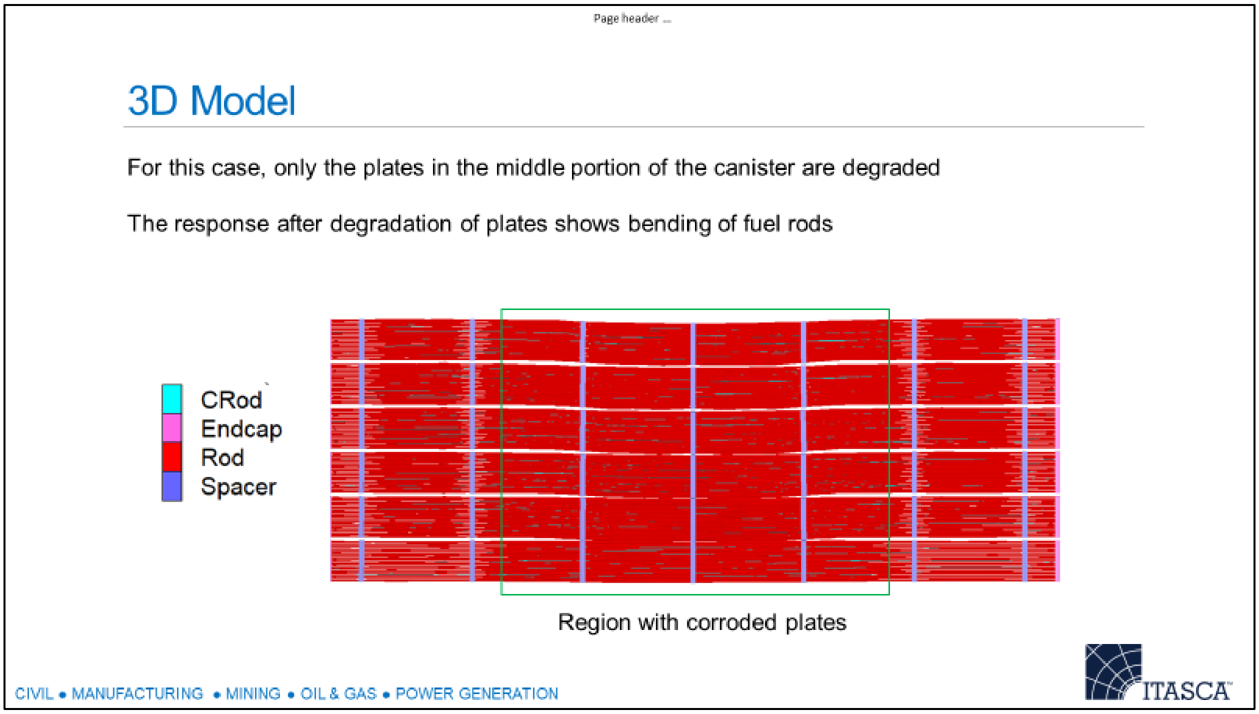


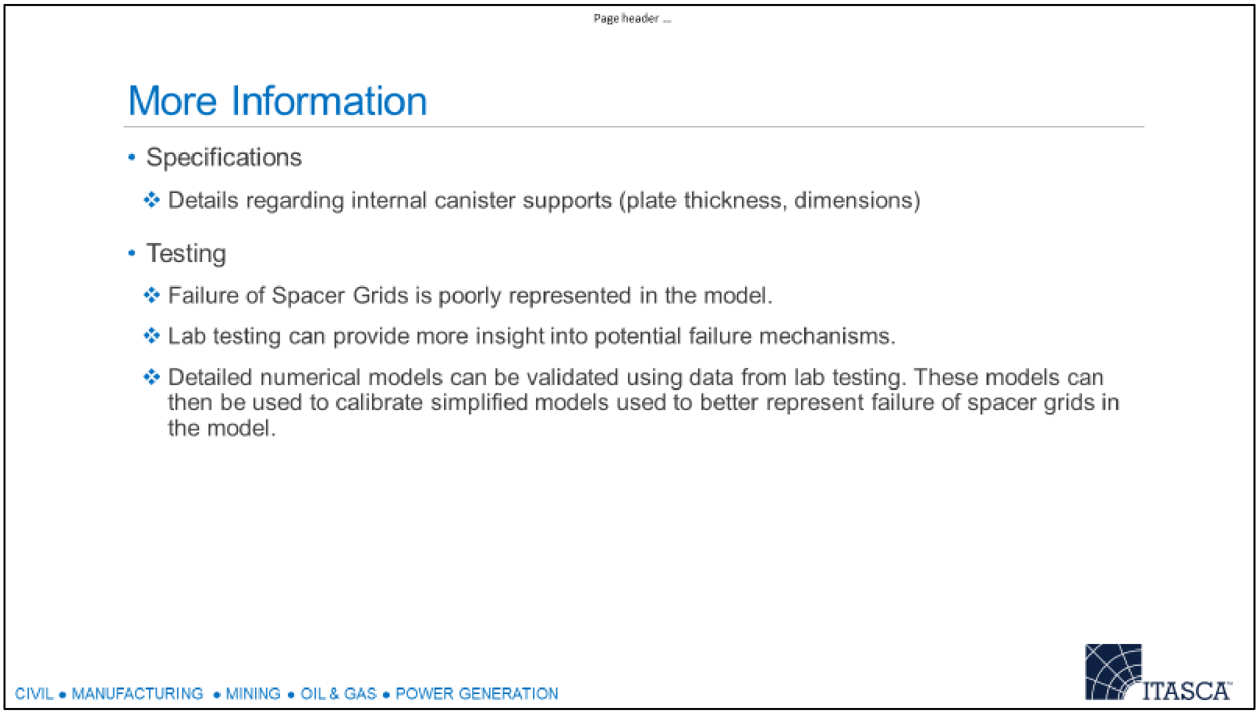


3D Model

For this case, only the plates in the middle portion of the canister are degraded

The response after degradation of plates shows bending of fuel rods

Region with corroded plates



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More Information

- Specifications
  - ❖ Details regarding internal canister supports (plate thickness, dimensions)
- Testing
  - ❖ Failure of Spacer Grids is poorly represented in the model.
  - ❖ Lab testing can provide more insight into potential failure mechanisms.
  - ❖ Detailed numerical models can be validated using data from lab testing. These models can then be used to calibrate simplified models used to better represent failure of spacer grids in the model.

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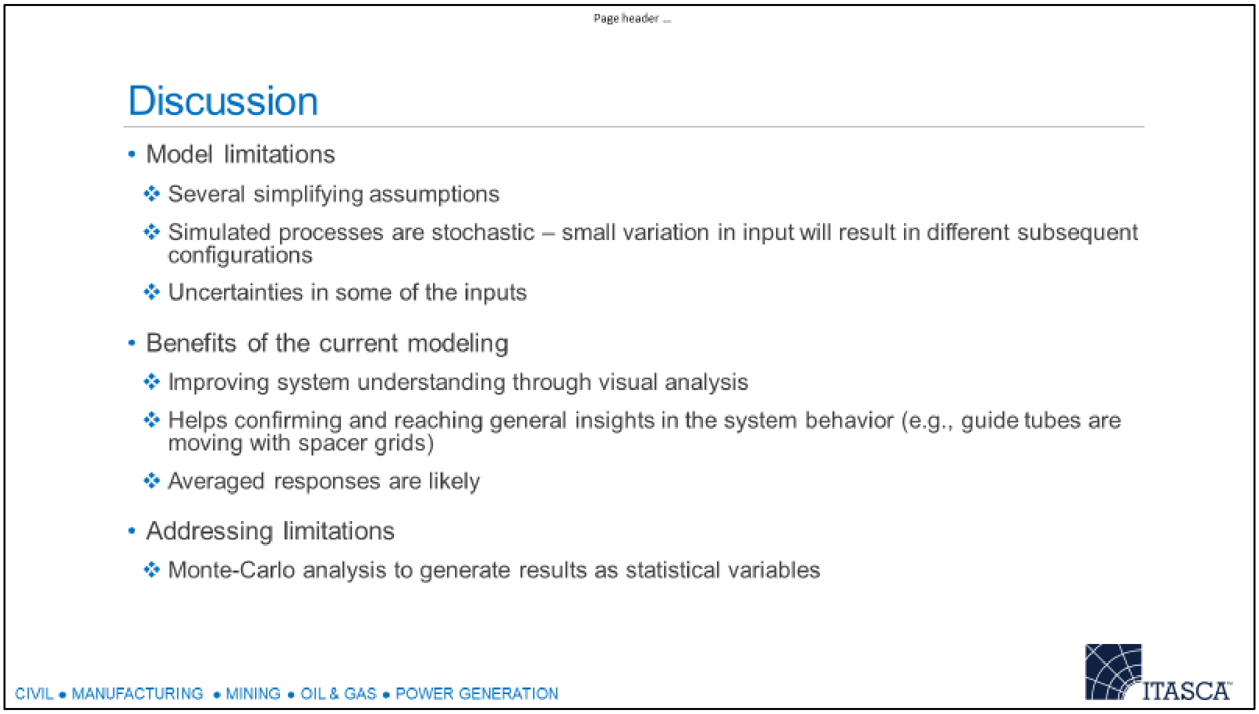

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Discussion

- Model limitations
  - ❖ Several simplifying assumptions
  - ❖ Simulated processes are stochastic – small variation in input will result in different subsequent configurations
  - ❖ Uncertainties in some of the inputs
- Benefits of the current modeling
  - ❖ Improving system understanding through visual analysis
  - ❖ Helps confirming and reaching general insights in the system behavior (e.g., guide tubes are moving with spacer grids)
  - ❖ Averaged responses are likely
- Addressing limitations
  - ❖ Monte-Carlo analysis to generate results as statistical variables

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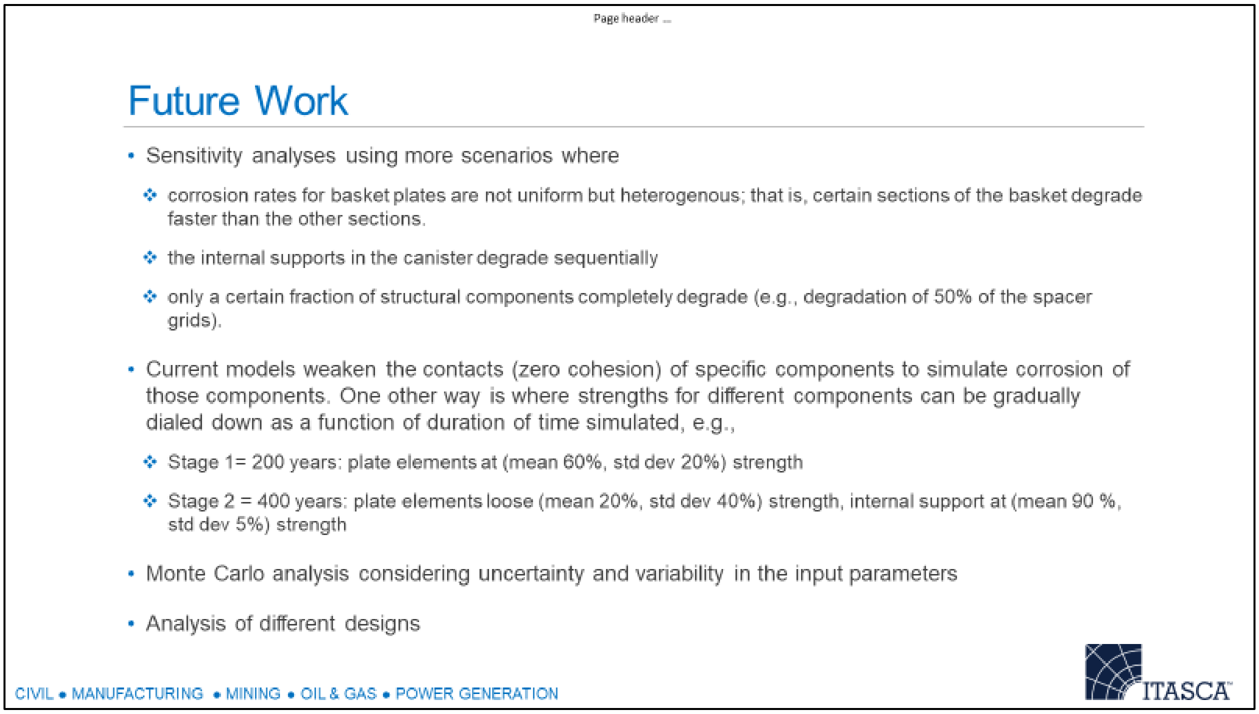

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Future Work

- Sensitivity analyses using more scenarios where
  - ❖ corrosion rates for basket plates are not uniform but heterogenous; that is, certain sections of the basket degrade faster than the other sections.
  - ❖ the internal supports in the canister degrade sequentially
  - ❖ only a certain fraction of structural components completely degrade (e.g., degradation of 50% of the spacer grids).
- Current models weaken the contacts (zero cohesion) of specific components to simulate corrosion of those components. One other way is where strengths for different components can be gradually dialed down as a function of duration of time simulated, e.g.,
  - ❖ Stage 1= 200 years: plate elements at (mean 60%, std dev 20%) strength
  - ❖ Stage 2 = 400 years: plate elements loose (mean 20%, std dev 40%) strength, internal support at (mean 90 %, std dev 5%) strength
- Monte Carlo analysis considering uncertainty and variability in the input parameters
- Analysis of different designs

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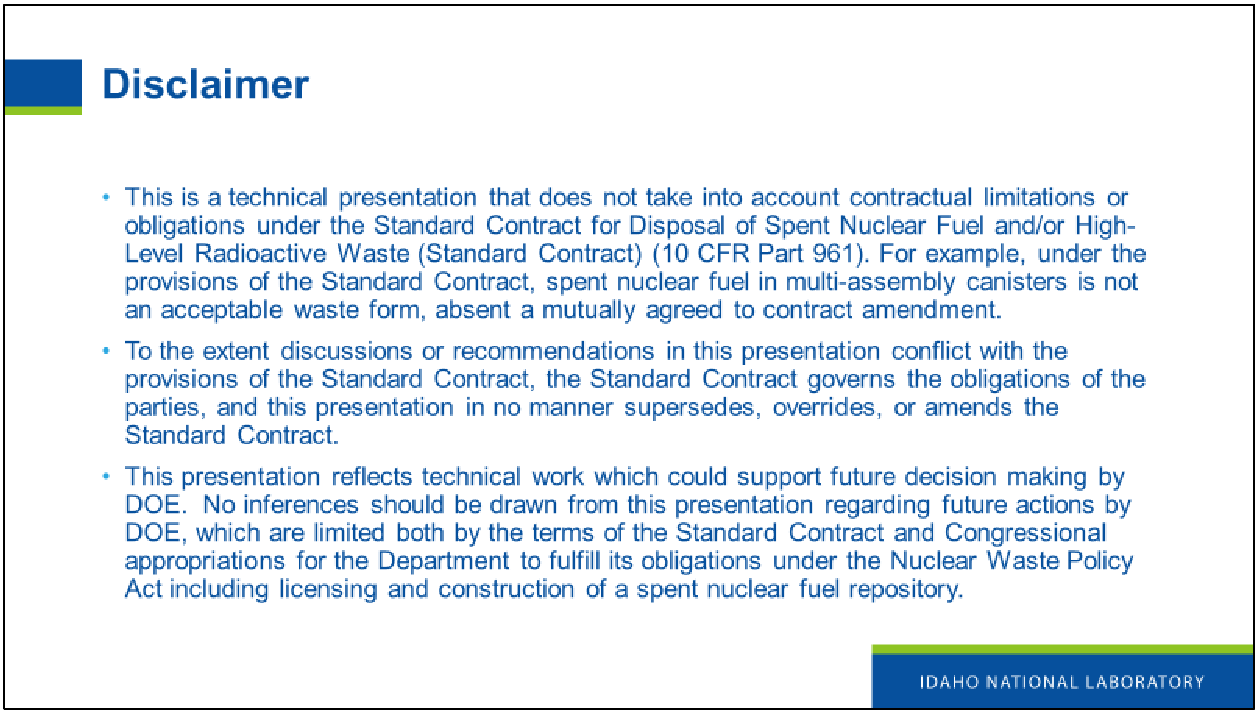
October 27, 2020

Josh Jarrell, Tedd Lister, Luis Diaz and Ron Mizia

Neutron Absorbing Alloy Corrosion Testing

Preliminary results and future work

Idaho National Laboratory



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Background on Neutron Absorbing Materials for Long-Term Storage

- Long-term storage introduces the need for maintaining sub-critical conditions in spent nuclear fuel packages over long time periods where package breach is possible
- Neutron absorber material (NAM) testing was performed to assess corrosion resistant materials
  - National Spent Nuclear Fuel Program (NSNFP) developed a Ni-Cr-Mo-Gd alloy (also called the Advanced Neutron Absorbing Alloy or ANA)
  - YMP examined borated stainless steels (BSS) and later ANA
- INL tested ANA and BSS materials
  - NSNFP supported ANA development and testing
  - YMP supported NQA-1 level testing program
- While BSS was selected for the YMP commercial SNF design, there are questions about the susceptibility to localized corrosion (Chromium tied up by boron)
- ANA has unique corrosion properties due to a secondary phase
  - Low Cr content and thus poorly performing from a testing standpoint
  - Performance appears to improve as secondary phase is dissolved

Common Modes of Corrosion

General vs localized corrosion

General corrosion occurs in a relatively uniform manner while localized corrosion is a non-uniform attack

- General corrosion can be assigned a corrosion rate (mm per year: mmpy) which allow selection of material and environment
- Localized corrosion cannot be assigned a rate and **presence usually precludes selection**

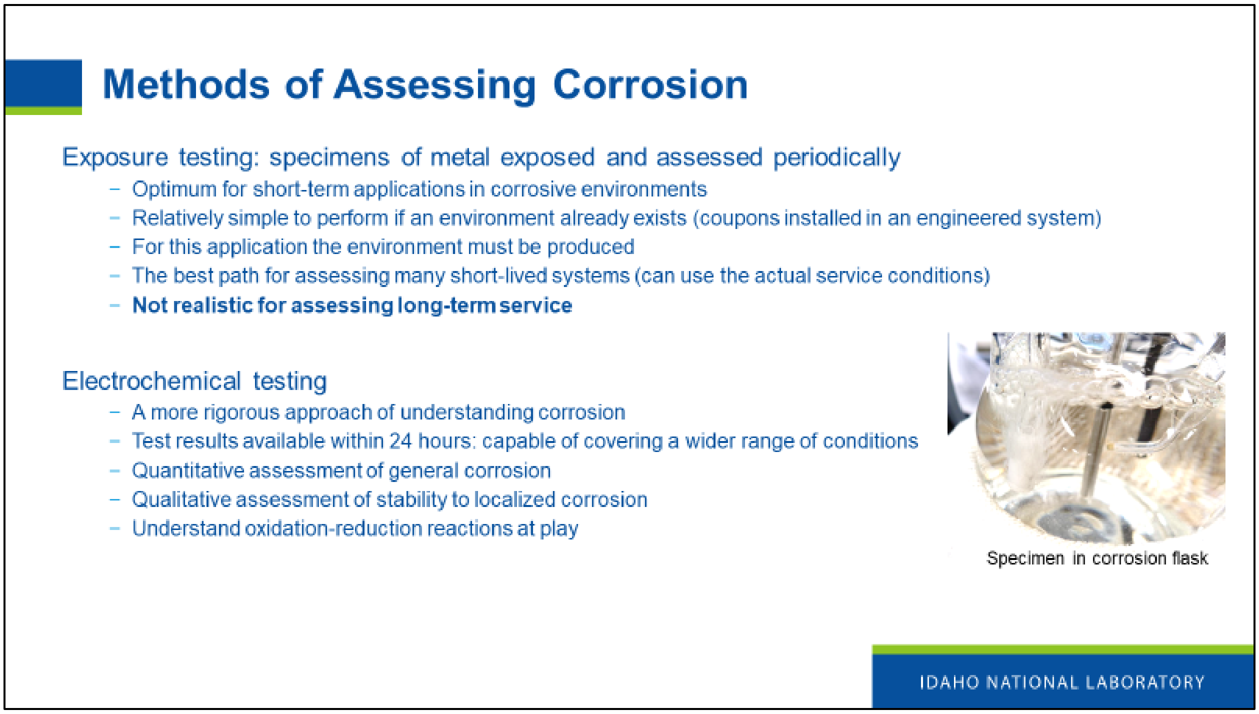
Localized corrosion comes in a broad variety of forms depending on the material and environment

- Pitting corrosion is the most common form
- Crevice corrosion occurs at occluded environments where local chemistry influences the environment (often a pH drop as metals start to dissolve)

Example of (mostly) uniform corrosion

Example of pitting corrosion at a weld

Crevice corrosion at a flange



Methods of Assessing Corrosion

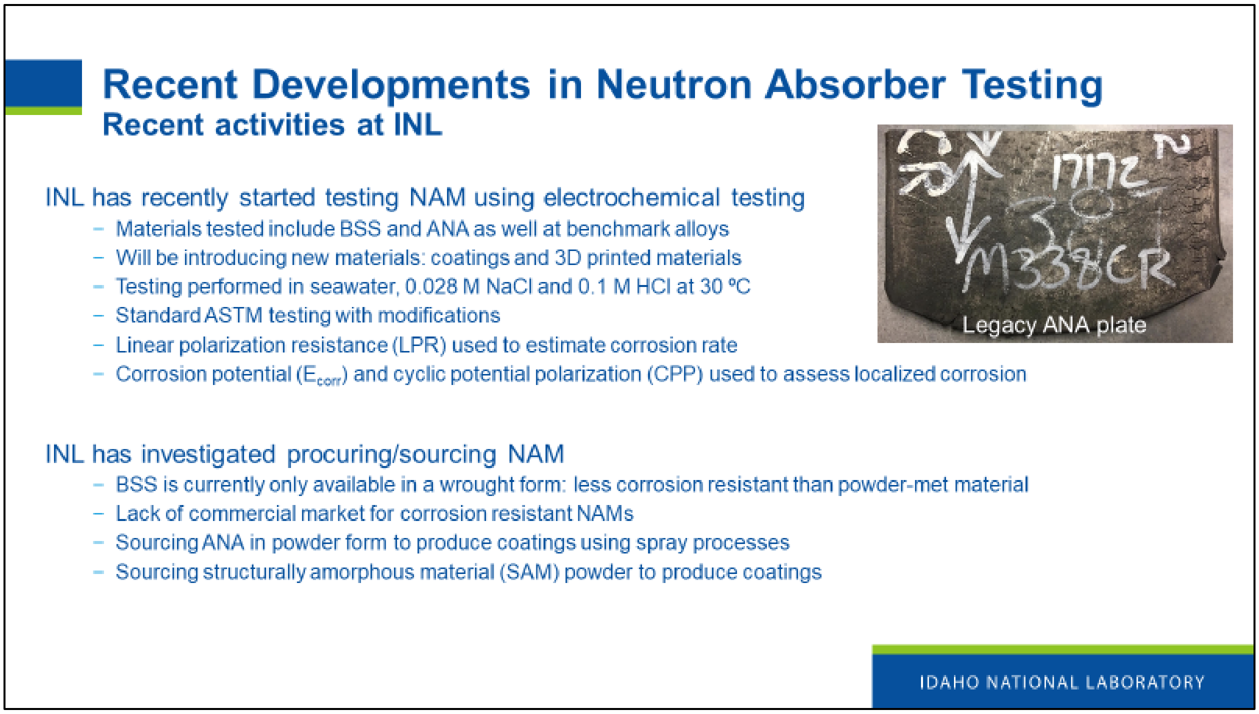
Exposure testing: specimens of metal exposed and assessed periodically

- Optimum for short-term applications in corrosive environments
- Relatively simple to perform if an environment already exists (coupons installed in an engineered system)
- For this application the environment must be produced
- The best path for assessing many short-lived systems (can use the actual service conditions)
- **Not realistic for assessing long-term service**

Electrochemical testing

- A more rigorous approach of understanding corrosion
- Test results available within 24 hours: capable of covering a wider range of conditions
- Quantitative assessment of general corrosion
- Qualitative assessment of stability to localized corrosion
- Understand oxidation-reduction reactions at play

Specimen in corrosion flask



Recent Developments in Neutron Absorber Testing

Recent activities at INL

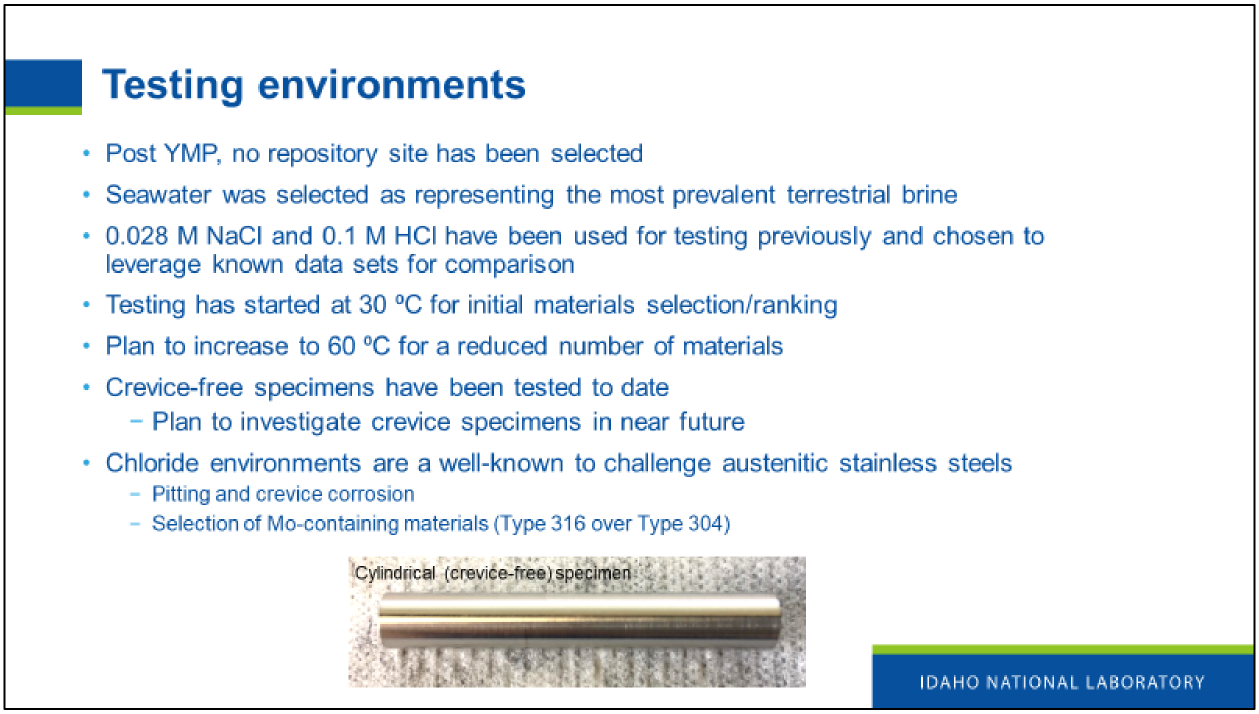
INL has recently started testing NAM using electrochemical testing

- Materials tested include BSS and ANA as well at benchmark alloys
- Will be introducing new materials: coatings and 3D printed materials
- Testing performed in seawater, 0.028 M NaCl and 0.1 M HCl at 30 °C
- Standard ASTM testing with modifications
- Linear polarization resistance (LPR) used to estimate corrosion rate
- Corrosion potential (E_{corr}) and cyclic potential polarization (CPP) used to assess localized corrosion

Legacy ANA plate

INL has investigated procuring/sourcing NAM

- BSS is currently only available in a wrought form: less corrosion resistant than powder-met material
- Lack of commercial market for corrosion resistant NAMs
- Sourcing ANA in powder form to produce coatings using spray processes
- Sourcing structurally amorphous material (SAM) powder to produce coatings



Testing environments

- Post YMP, no repository site has been selected
- Seawater was selected as representing the most prevalent terrestrial brine
- 0.028 M NaCl and 0.1 M HCl have been used for testing previously and chosen to leverage known data sets for comparison
- Testing has started at 30 ºC for initial materials selection/ranking
- Plan to increase to 60 ºC for a reduced number of materials
- Crevice-free specimens have been tested to date
  - Plan to investigate crevice specimens in near future
- Chloride environments are a well-known to challenge austenitic stainless steels
  - Pitting and crevice corrosion
  - Selection of Mo-containing materials (Type 316 over Type 304)

Cylindrical (crevice-free) specimen

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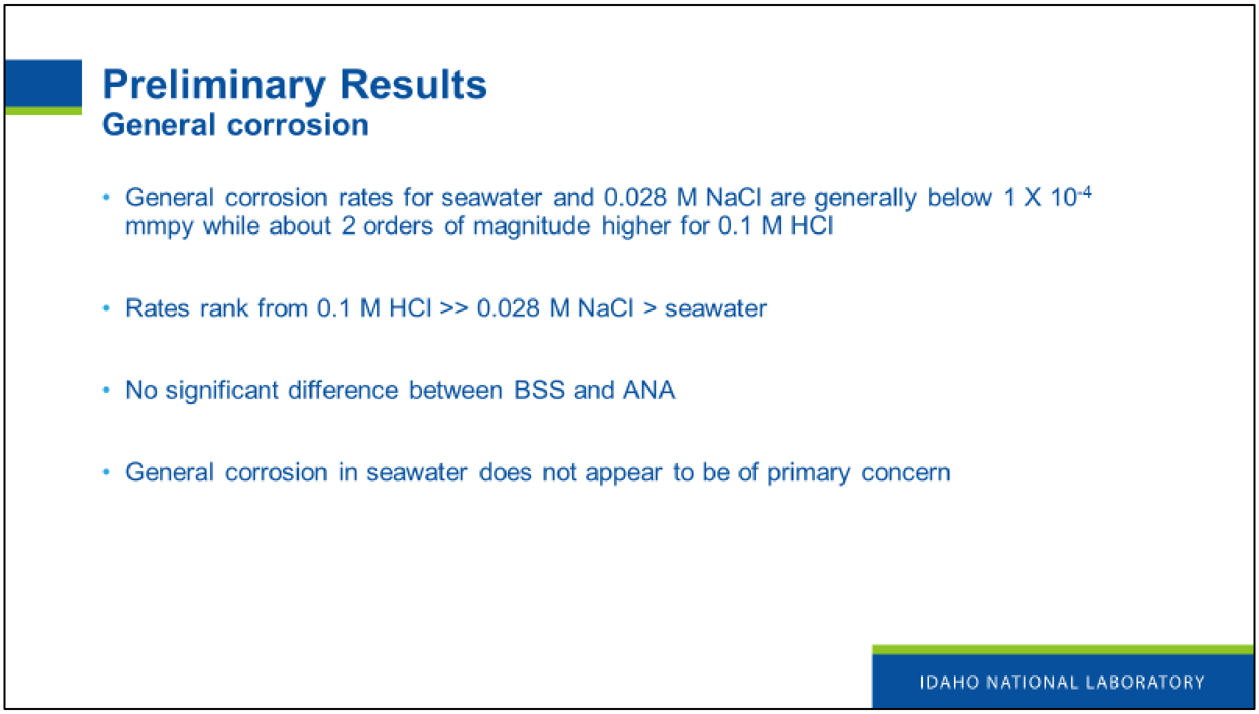

Preliminary Results

General corrosion

- General corrosion rates for seawater and 0.028 M NaCl are generally below 1 X 10^{-4} mmpy while about 2 orders of magnitude higher for 0.1 M HCl
- Rates rank from 0.1 M HCl >> 0.028 M NaCl > seawater
- No significant difference between BSS and ANA
- General corrosion in seawater does not appear to be of primary concern

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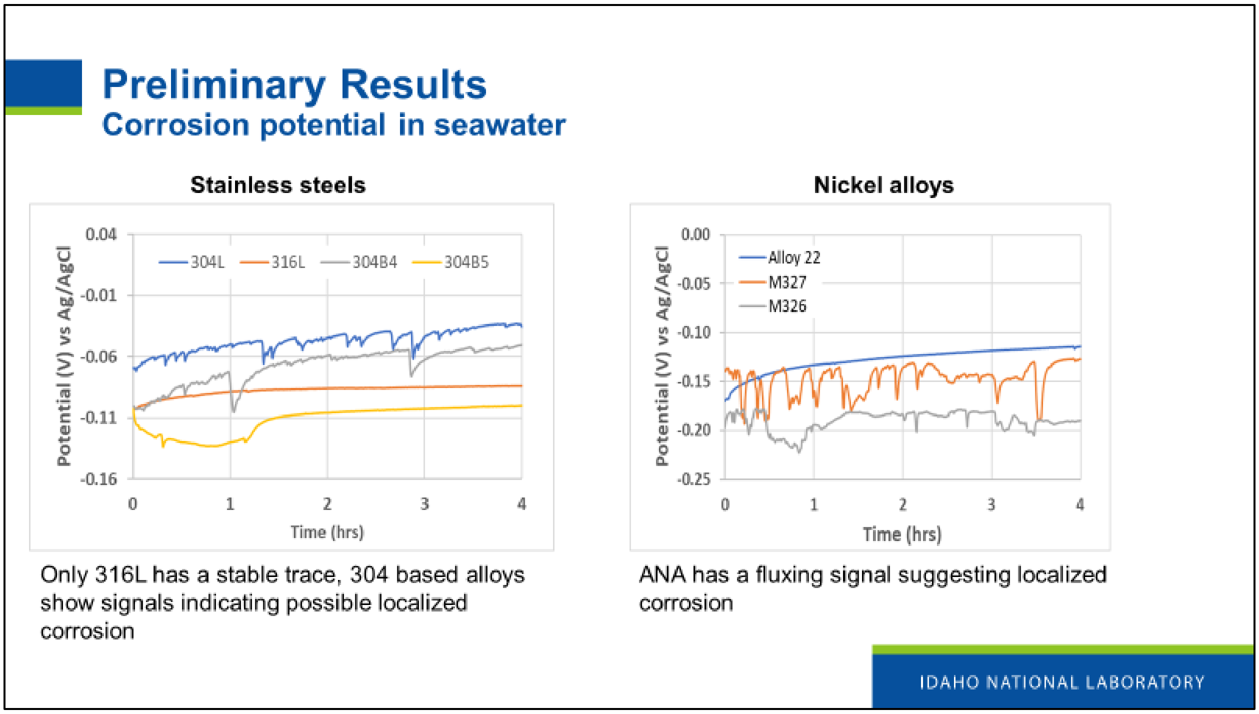

Preliminary Results

Corrosion potential in seawater

Stainless steels

Only 316L has a stable trace, 304 based alloys show signals indicating possible localized corrosion

Nickel alloys

ANA has a fluxing signal suggesting localized corrosion

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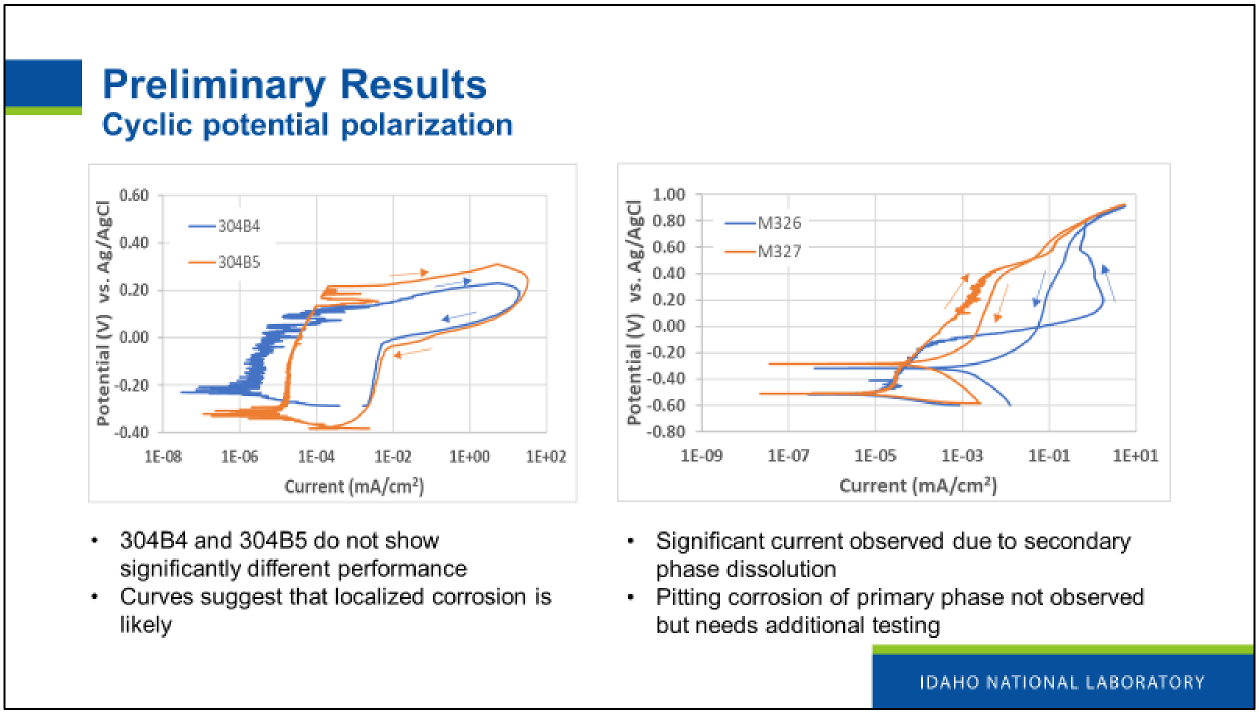

Preliminary Results

Cyclic potential polarization

- 304B4 and 304B5 do not show significantly different performance
- Curves suggest that localized corrosion is likely

- Significant current observed due to secondary phase dissolution
- Pitting corrosion of primary phase not observed but needs additional testing

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Future Testing

- Complete analysis of recently completed testing campaign and perform additional tests to complete analysis
  - ANA primary/secondary phase testing
  - Additional 316-based NAMs

- Perform testing for NAM alloys and coatings not available for first campaign
  - ORNL-provided 3D printed specimens
  - ANA powder-based specimens
  - SAM specimens
- Make selections (with consensus) to carry forward to crevice and higher temperature tests

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Conclusions

- NAM material testing has started using new environments (i.e., seawater)

- Initial NAM materials were the same material investigated in previous work

- Additional materials and coating will be tested in future work

- BSS, based on Type 304SS, appears susceptible to localized corrosion

- ANA will require additional work to assess the stability of the primary phase

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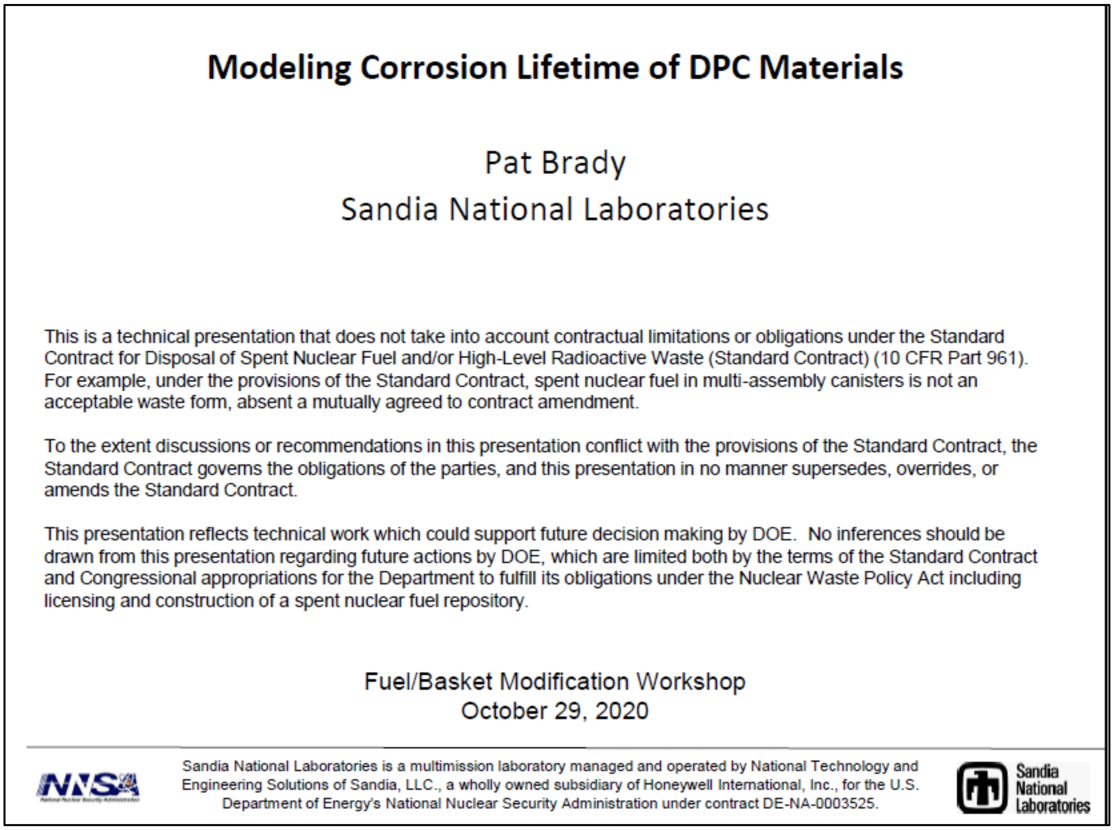

Modeling Corrosion Lifetime of DPC Materials

Pat Brady
Sandia National Laboratories

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Fuel/Basket Modification Workshop
October 29, 2020

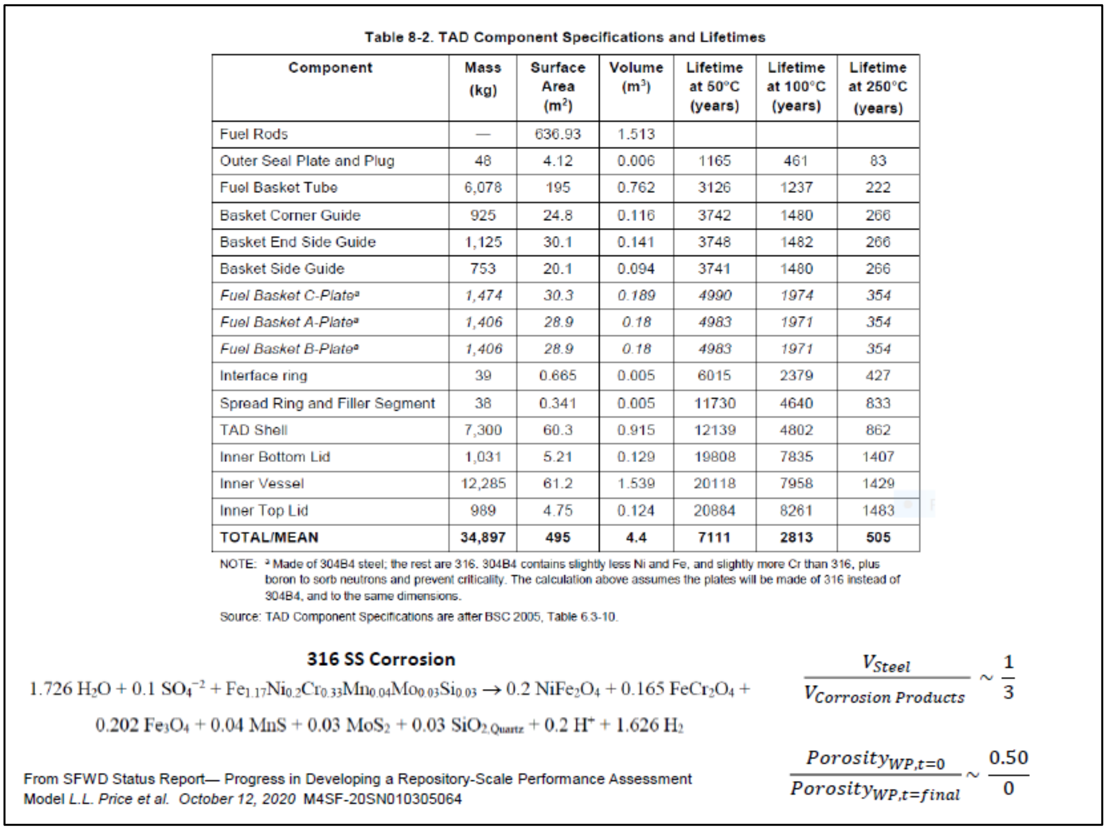


Table 8-2. TAD Component Specifications and Lifetimes

Component	Mass (kg)	Surface Area (m^2)	Volume (m^3)	Lifetime at 50°C (years)	Lifetime at 100°C (years)	Lifetime at 250°C (years)
Fuel Rods	—	636.93	1.513			
Outer Seal Plate and Plug	48	4.12	0.006	1165	461	83
Fuel Basket Tube	6,078	195	0.762	3126	1237	222
Basket Corner Guide	925	24.8	0.116	3742	1480	266
Basket End Side Guide	1,125	30.1	0.141	3748	1482	266
Basket Side Guide	753	20.1	0.094	3741	1480	266
Fuel Basket C-Plate[a]	*1,474*	*30.3*	*0.189*	*4990*	*1974*	*354*
Fuel Basket A-Plate[a]	*1,406*	*28.9*	*0.18*	*4983*	*1971*	*354*
Fuel Basket B-Plate[a]	*1,406*	*28.9*	*0.18*	*4983*	*1971*	*354*
Interface ring	39	0.665	0.005	6015	2379	427
Spread Ring and Filler Segment	38	0.341	0.005	11730	4640	833
TAD Shell	7,300	60.3	0.915	12139	4802	862
Inner Bottom Lid	1,031	5.21	0.129	19808	7835	1407
Inner Vessel	12,285	61.2	1.539	20118	7958	1429
Inner Top Lid	989	4.75	0.124	20884	8261	1483
TOTAL/MEAN	**34,897**	**495**	**4.4**	**7111**	**2813**	**505**

NOTE: [a] Made of 304B4 steel; the rest are 316. 304B4 contains slightly less Ni and Fe, and slightly more Cr than 316, plus boron to sorb neutrons and prevent criticality. The calculation above assumes the plates will be made of 316 instead of 304B4, and to the same dimensions.

Source: TAD Component Specifications are after BSC 2005, Table 6.3-10.

316 SS Corrosion

$$1.726\ H_2O + 0.1\ SO_4^{-2} + Fe_{1.17}Ni_{0.2}Cr_{0.33}Mn_{0.04}Mo_{0.03}Si_{0.03} \rightarrow 0.2\ NiFe_2O_4 + 0.165\ FeCr_2O_4 + 0.202\ Fe_3O_4 + 0.04\ MnS + 0.03\ MoS_2 + 0.03\ SiO_{2,Quartz} + 0.2\ H^+ + 1.626\ H_2$$

$$\frac{V_{Steel}}{V_{Corrosion\ Products}} \sim \frac{1}{3}$$

$$\frac{Porosity_{WP,t=0}}{Porosity_{WP,t=final}} \sim \frac{0.50}{0}$$

From SFWD Status Report— Progress in Developing a Repository-Scale Performance Assessment Model *L.L. Price et al. October 12, 2020* M4SF-20SN010305064

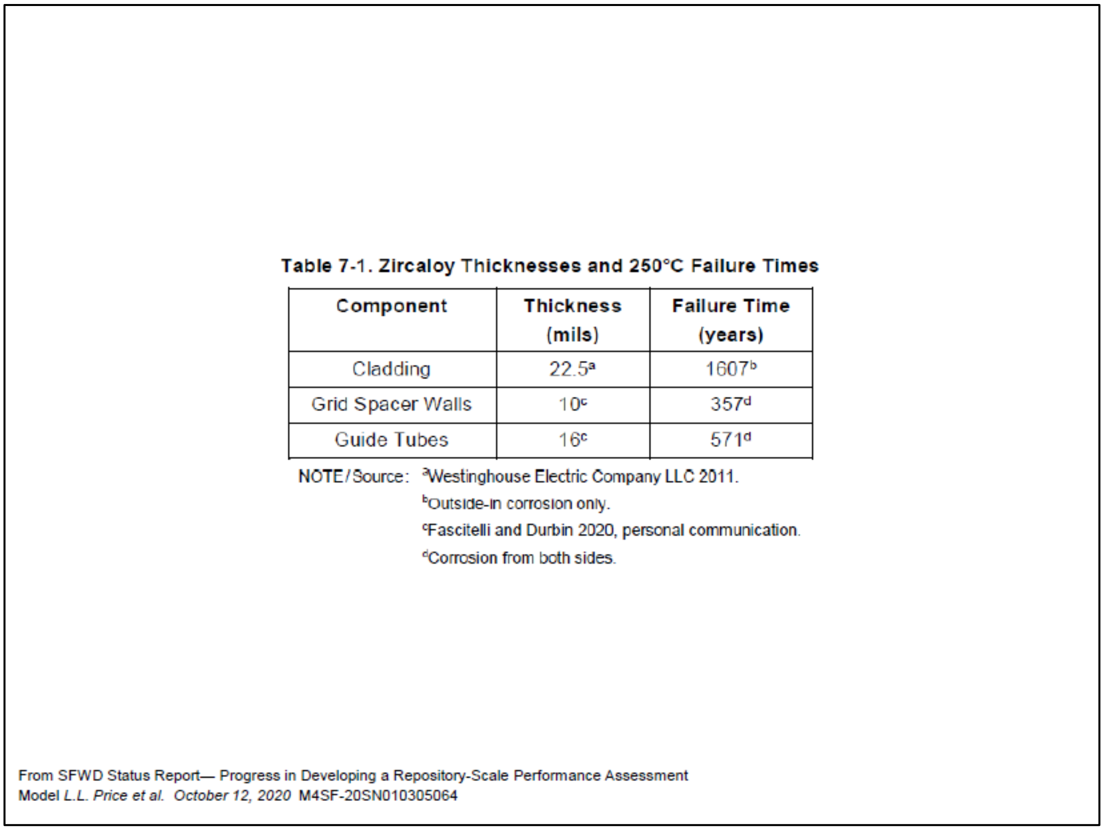
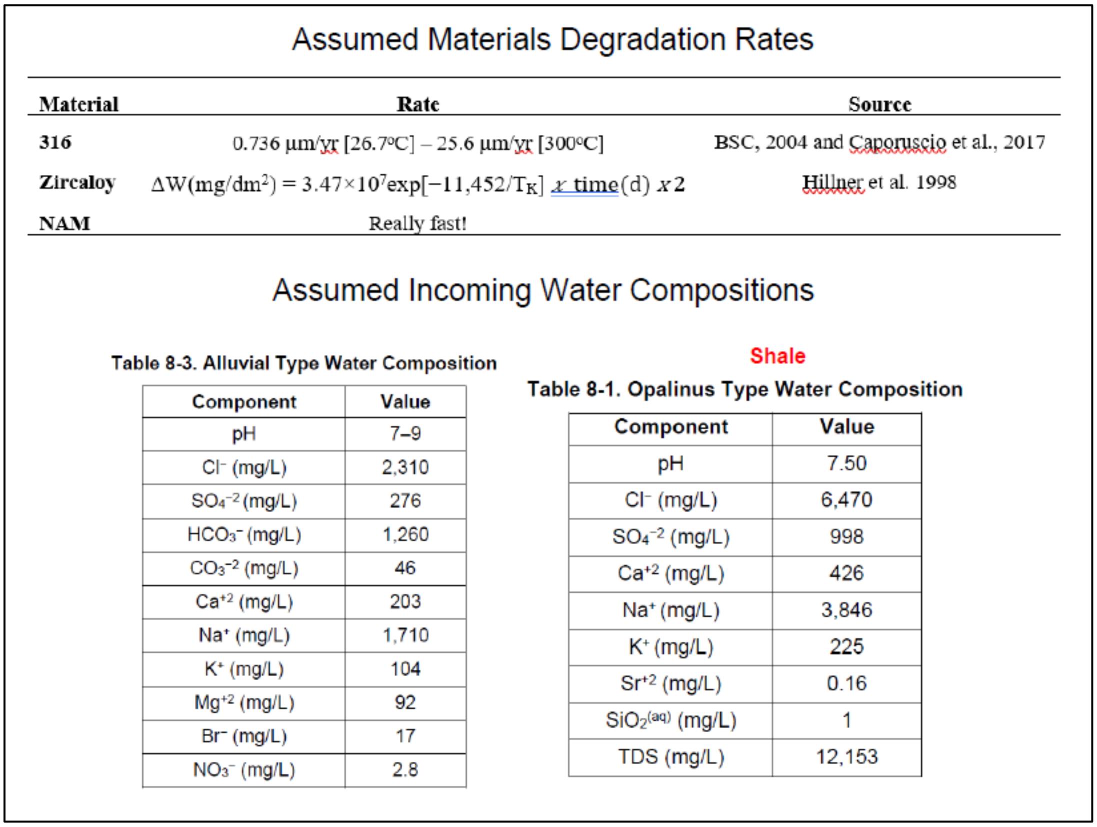


Table 7-1. Zircaloy Thicknesses and 250°C Failure Times

Component	Thickness (mils)	Failure Time (years)
Cladding	22.5[a]	1607[b]
Grid Spacer Walls	10[c]	357[d]
Guide Tubes	16[c]	571[d]

NOTE/Source: [a]Westinghouse Electric Company LLC 2011.
[b]Outside-in corrosion only.
[c]Fascitelli and Durbin 2020, personal communication.
[d]Corrosion from both sides.

From SFWD Status Report— Progress in Developing a Repository-Scale Performance Assessment Model *L.L. Price et al. October 12, 2020* M4SF-20SN010305064



Assumed Materials Degradation Rates

Material	Rate	Source
316	0.736 μm/yr [26.7°C] – 25.6 μm/yr [300°C]	BSC, 2004 and Caporuscio et al., 2017
Zircaloy	$\Delta W(mg/dm^2) = 3.47\times10^7 \exp[-11{,}452/T_K]$ *x* time(d) *x* 2	Hillner et al. 1998
NAM	Really fast!	

Assumed Incoming Water Compositions

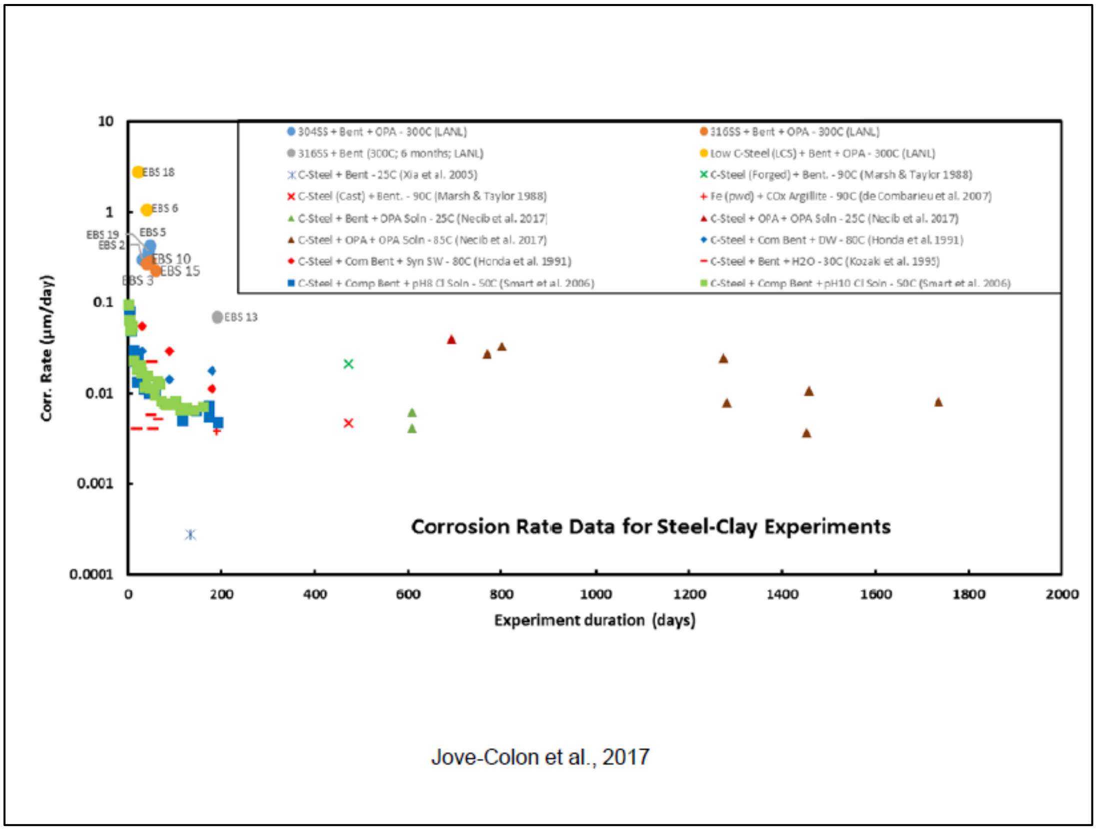
Table 8-3. Alluvial Type Water Composition

Component	Value
pH	7–9
Cl^- (mg/L)	2,310
SO_4^{-2} (mg/L)	276
HCO_3^- (mg/L)	1,260
CO_3^{-2} (mg/L)	46
Ca^{+2} (mg/L)	203
Na^+ (mg/L)	1,710
K^+ (mg/L)	104
Mg^{+2} (mg/L)	92
Br^- (mg/L)	17
NO_3^- (mg/L)	2.8

Shale

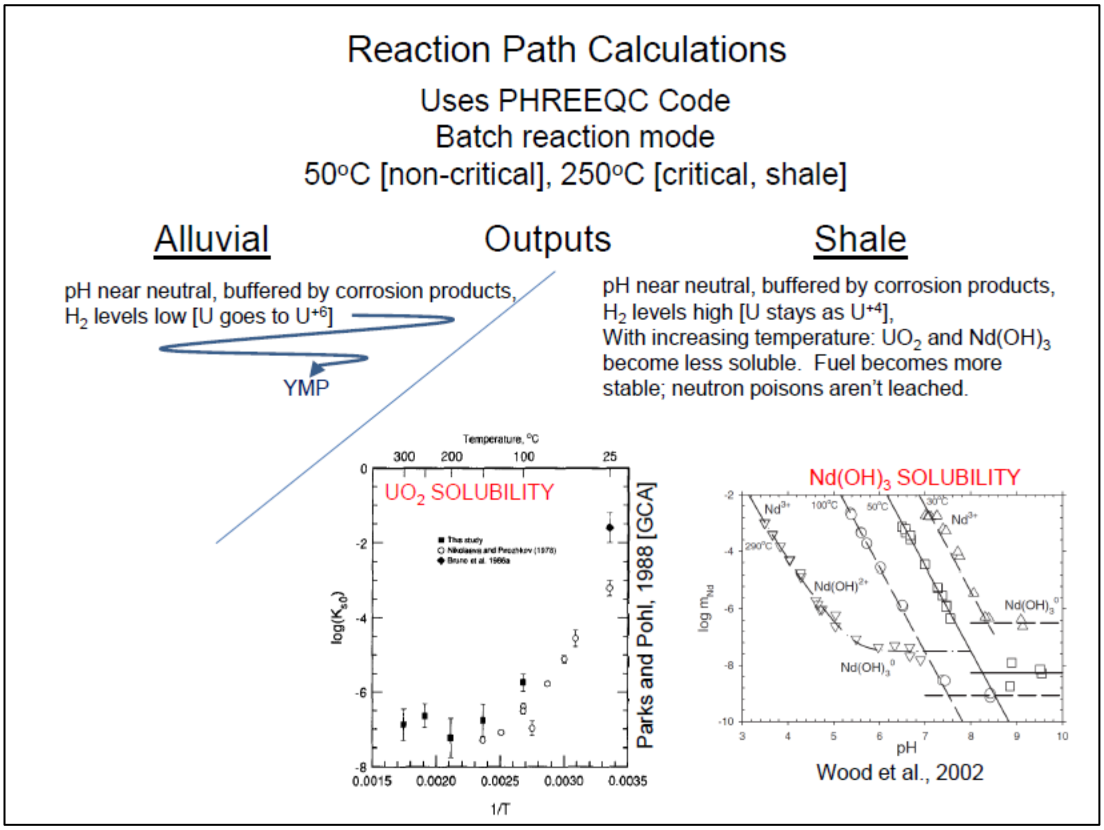
Table 8-1. Opalinus Type Water Composition

Component	Value
pH	7.50
Cl^- (mg/L)	6,470
SO_4^{-2} (mg/L)	998
Ca^{+2} (mg/L)	426
Na^+ (mg/L)	3,846
K^+ (mg/L)	225
Sr^{+2} (mg/L)	0.16
$SiO_2^{(aq)}$ (mg/L)	1
TDS (mg/L)	12,153



Corrosion Rate Data for Steel-Clay Experiments

Jove-Colon et al., 2017



Reaction Path Calculations

Uses PHREEQC Code
Batch reaction mode
50°C [non-critical], 250°C [critical, shale]

Alluvial

pH near neutral, buffered by corrosion products, H_2 levels low [U goes to U^{+6}]

YMP

Outputs

Shale

pH near neutral, buffered by corrosion products, H_2 levels high [U stays as U^{+4}], With increasing temperature: UO_2 and $Nd(OH)_3$ become less soluble. Fuel becomes more stable; neutron poisons aren't leached.

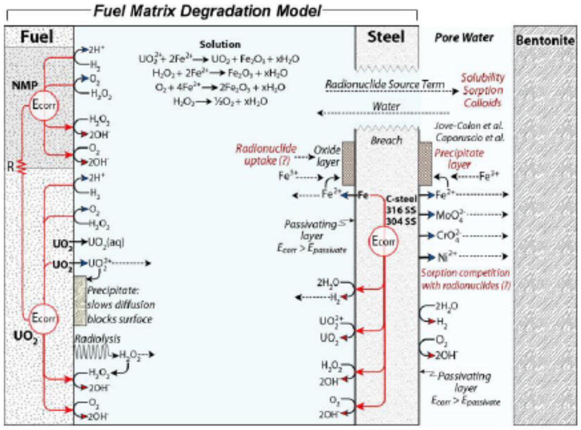
UO_2 SOLUBILITY

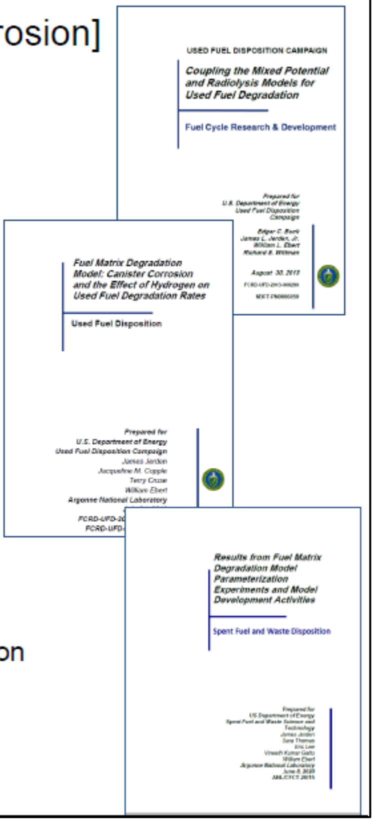
Parks and Pohl, 1988 [GCA]

$Nd(OH)_3$ SOLUBILITY

Wood et al., 2002

FMDM Model for Fuel Degradation [and corrosion]
Jerden, Ebert, et al.





USED FUEL DISPOSITION CAMPAIGN

Coupling the Mixed Potential and Radiolysis Models for Used Fuel Degradation

Fuel Cycle Research & Development

Prepared for
U.S. Department of Energy
Used Fuel Disposition
Campaign
Edgar C. Buck
James L. Jerden, Jr.
William L. Ebert
Richard S. Wittman

August 30, 2013

Fuel Matrix Degradation Model: Canister Corrosion and the Effect of Hydrogen on Used Fuel Degradation Rates

Used Fuel Disposition

Prepared for
U.S. Department of Energy
Used Fuel Disposition Campaign
James Jerden
Jacqueline M. Copple
Terry Cruse
William Ebert
Argonne National Laboratory

Results from Fuel Matrix Degradation Model Parameterization Experiments and Model Development Activities

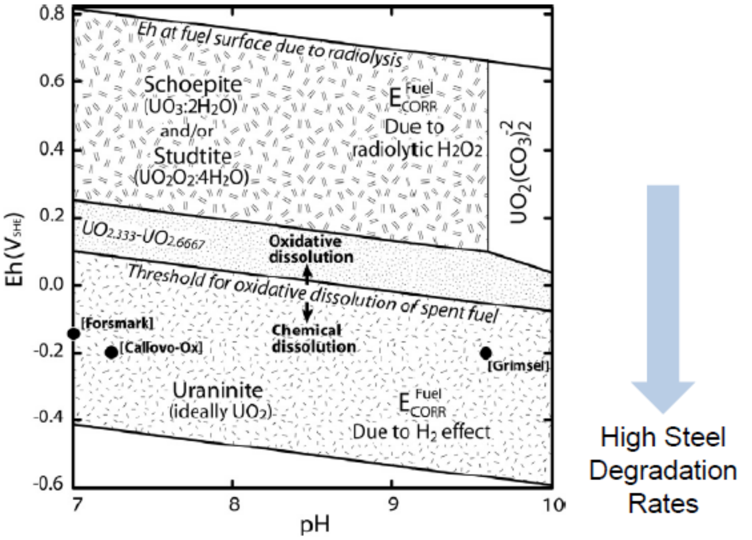
Spent Fuel and Waste Disposition

Prepared for
US Department of Energy
Spent Fuel and Waste Science and
Technology
James Jerden
Sara Thomas
Eric Lee
Vineeth Kumar Gattu
William Ebert
Argonne National Laboratory
June 8, 2020

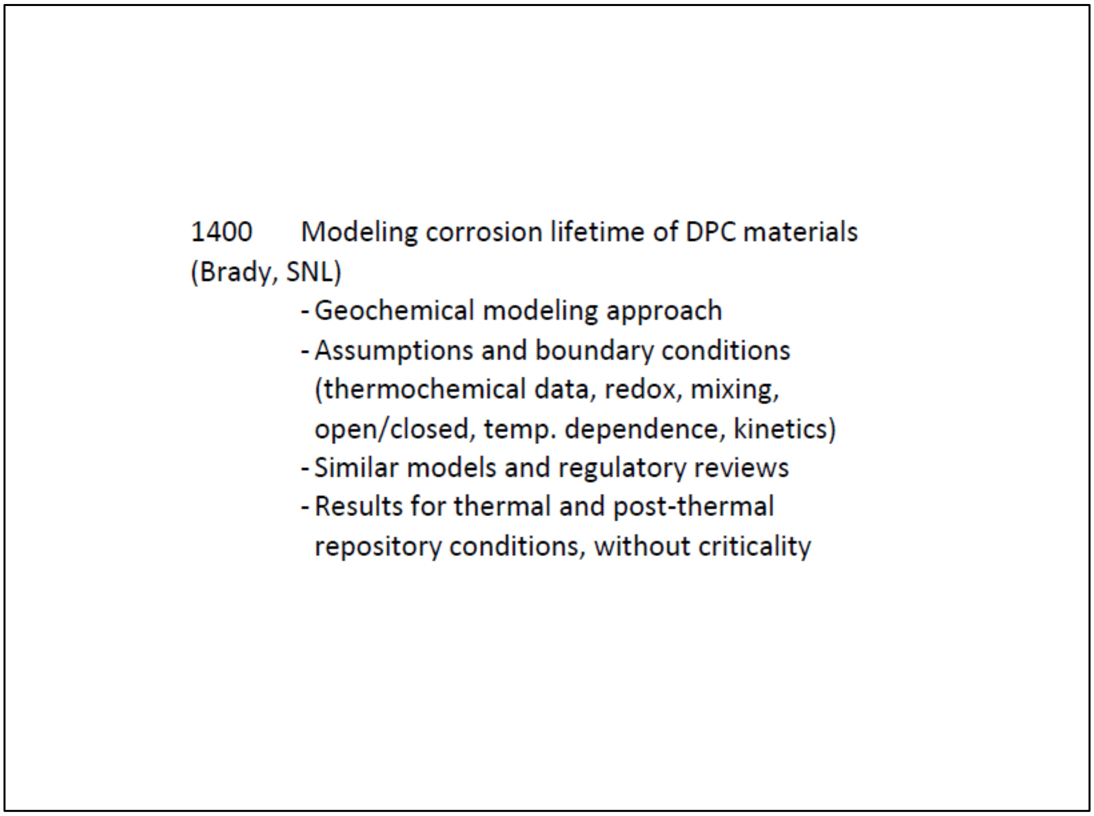
THE SHORT VERSION

Ambient O_2 levels set by H_2O_2 - H_2 reaction
- Radiolysis produces H_2O_2 and H_2
- Steel corrosion produces H_2

H_2 sharply limits fuel degradation



From Jerden et al., 2015



1400 Modeling corrosion lifetime of DPC materials (Brady, SNL)

- Geochemical modeling approach
- Assumptions and boundary conditions (thermochemical data, redox, mixing, open/closed, temp. dependence, kinetics)
- Similar models and regulatory reviews
- Results for thermal and post-thermal repository conditions, without criticality

Disclaimer

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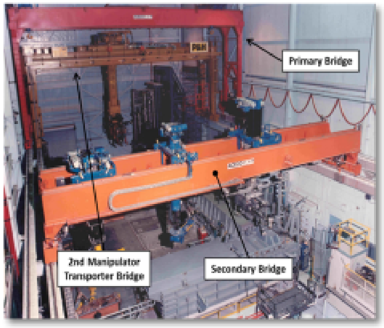
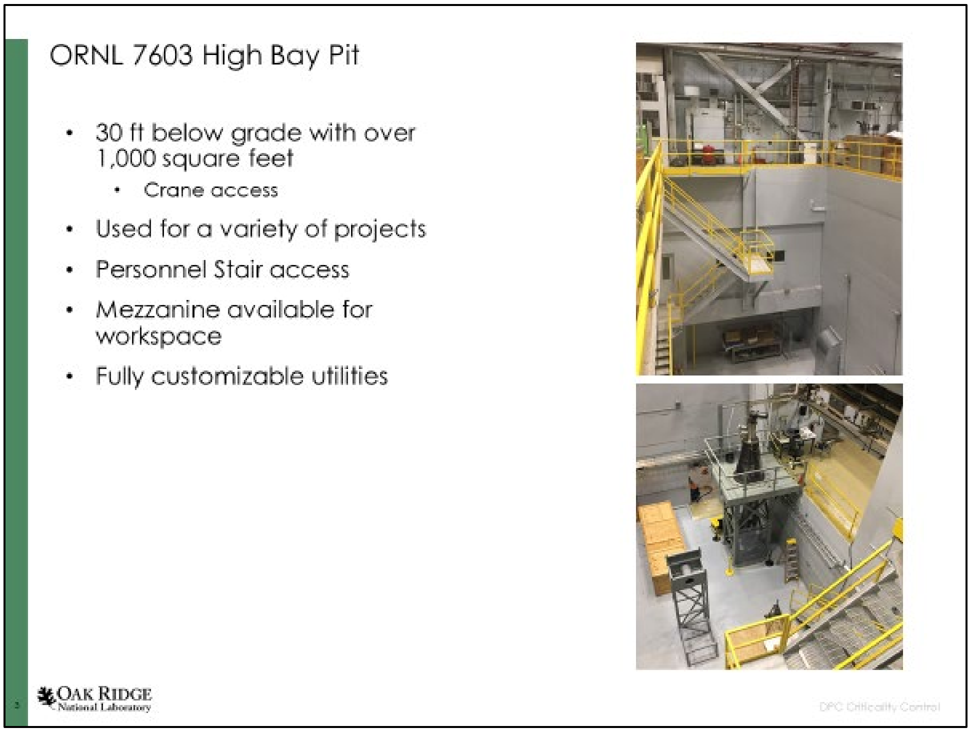
ORNL 7603 High Bay Facility – Enabling Science of All Sizes

Lab Space Manager: Adam J. Carroll

- Unmatched large-scale experimental accommodations for ORNL
  - Over 7,800 square feet
  - 50ft high ceilings
  - 30ft pit with over 1,000 square feet
  - Two 10-ton cranes on a 20-ton bridge
- Unique Testing Capabilities
  - PAR bridge mounted power arm
  - Two hot cell window workstations
  - Customizable electrical, vacuum, and compressed air utilities
- Small-scale experimental capabilities
  - Additional lab spaces within the 7600 complex include fume hood and wet chemistry utilities





ORNL 7603 High Bay Pit

- 30 ft below grade with over 1,000 square feet
  - Crane access
- Used for a variety of projects
- Personnel Stair access
- Mezzanine available for workspace
- Fully customizable utilities

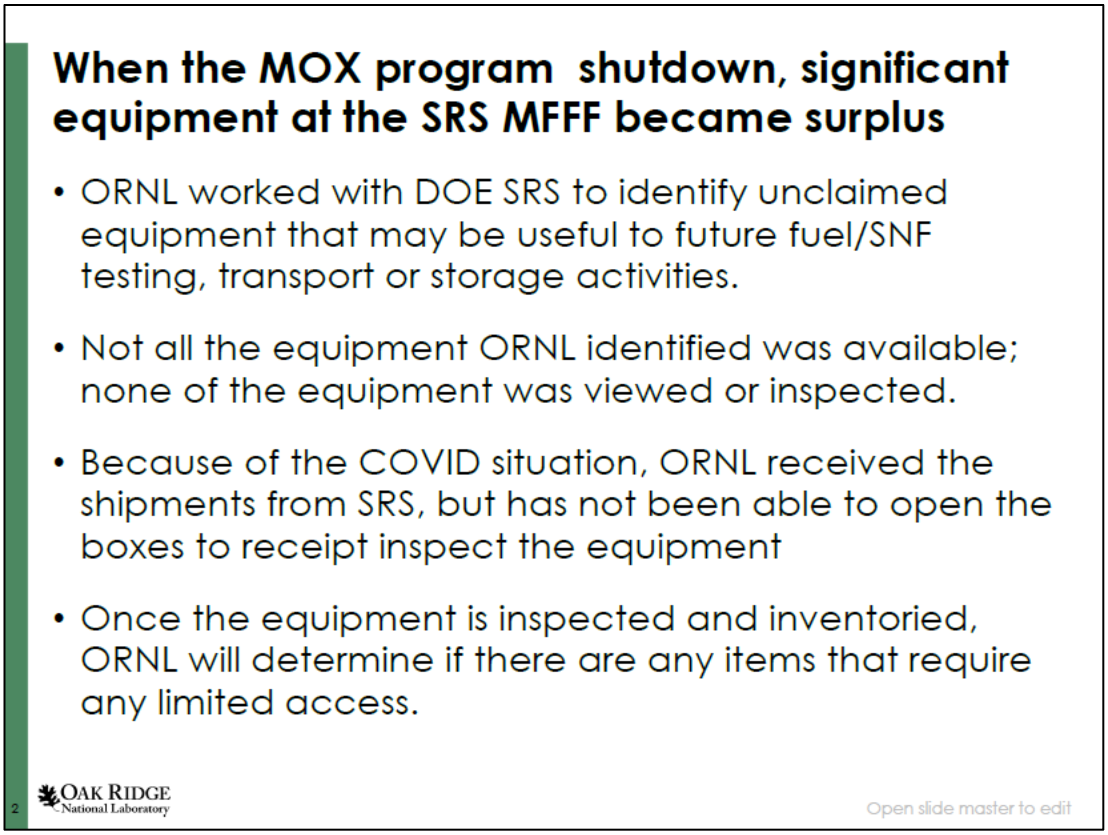
MOX Surplus Equipment at ORNL

Bruce Bevard

bevardbb@ornl.gov

October 29, 2020

ORNL is managed by UT-Battelle, LLC
for the US Department of Energy



When the MOX program shutdown, significant equipment at the SRS MFFF became surplus

- ORNL worked with DOE SRS to identify unclaimed equipment that may be useful to future fuel/SNF testing, transport or storage activities.
- Not all the equipment ORNL identified was available; none of the equipment was viewed or inspected.
- Because of the COVID situation, ORNL received the shipments from SRS, but has not been able to open the boxes to receipt inspect the equipment
- Once the equipment is inspected and inventoried, ORNL will determine if there are any items that require any limited access.

OAK RIDGE
National Laboratory

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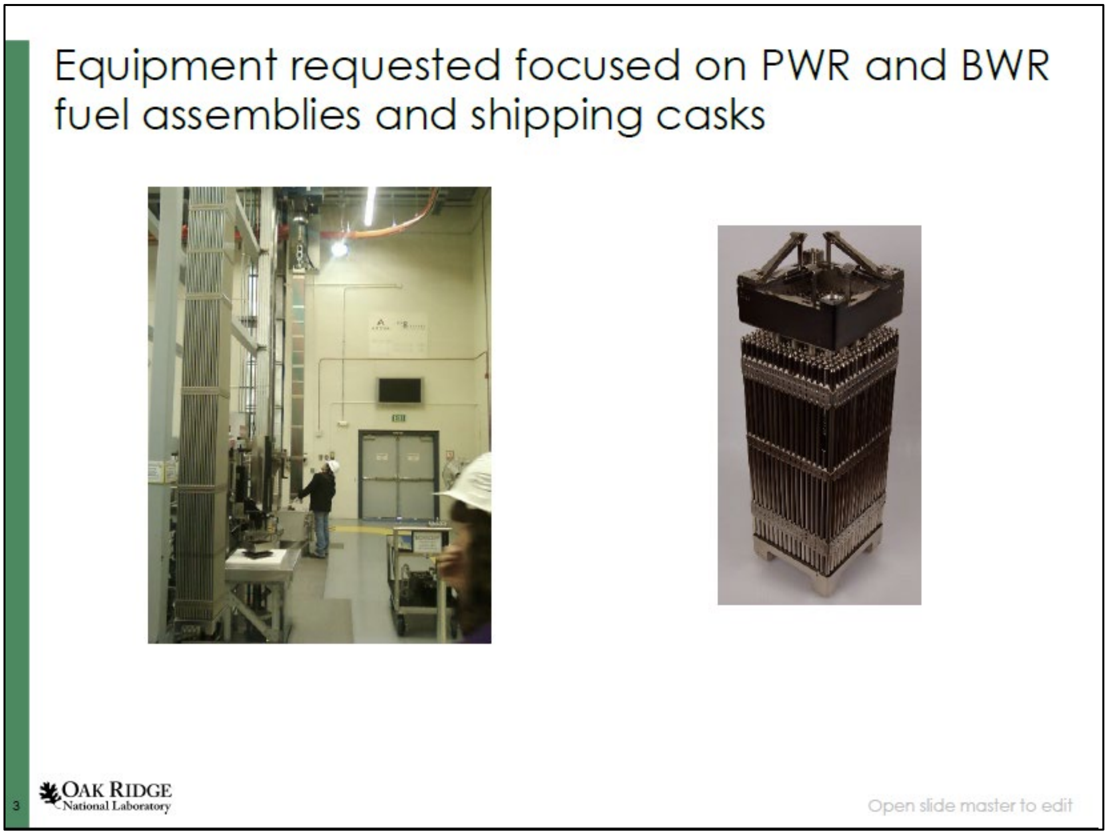
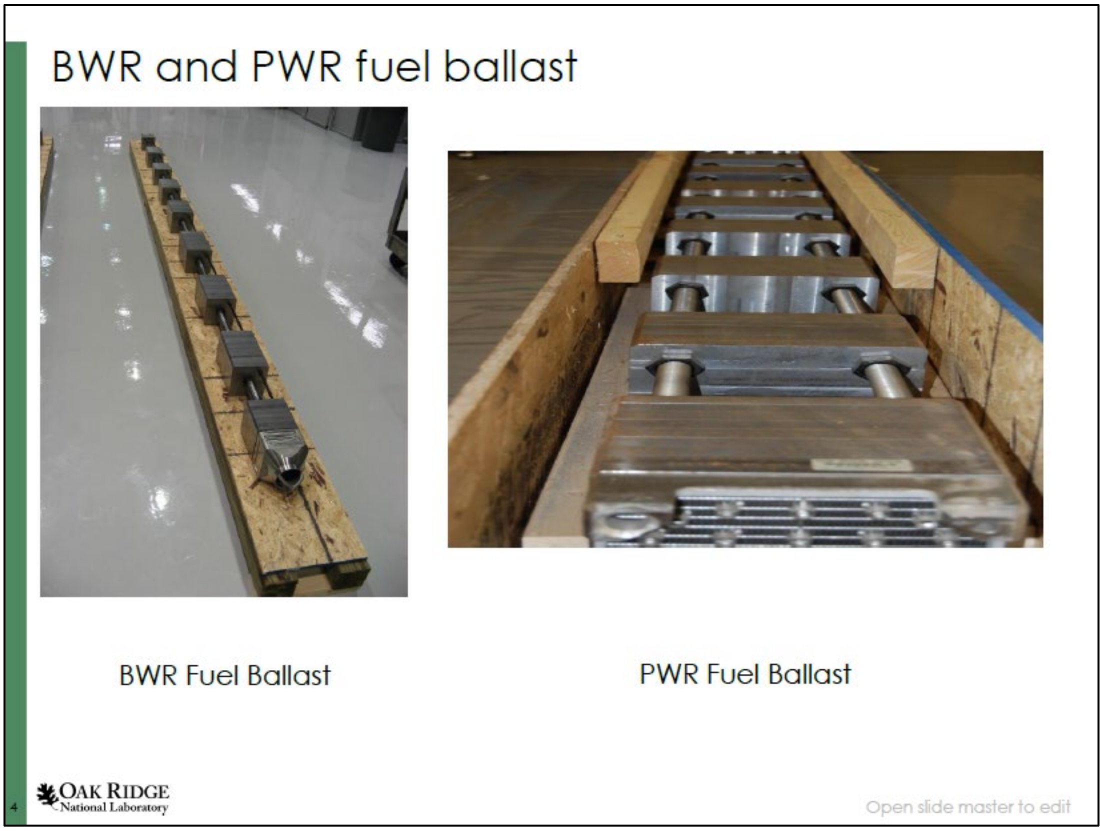


Equipment requested focused on PWR and BWR fuel assemblies and shipping casks

OAK RIDGE National Laboratory



BWR and PWR fuel ballast

BWR Fuel Ballast

PWR Fuel Ballast

OAK RIDGE National Laboratory

BWR and PWR MOX Fresh Fuel Packages

Upper and lower Impact Limiters

MFFF Cask Assembly

7 OAK RIDGE National Laboratory

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How everything looks at ORNL right now!

8 OAK RIDGE National Laboratory

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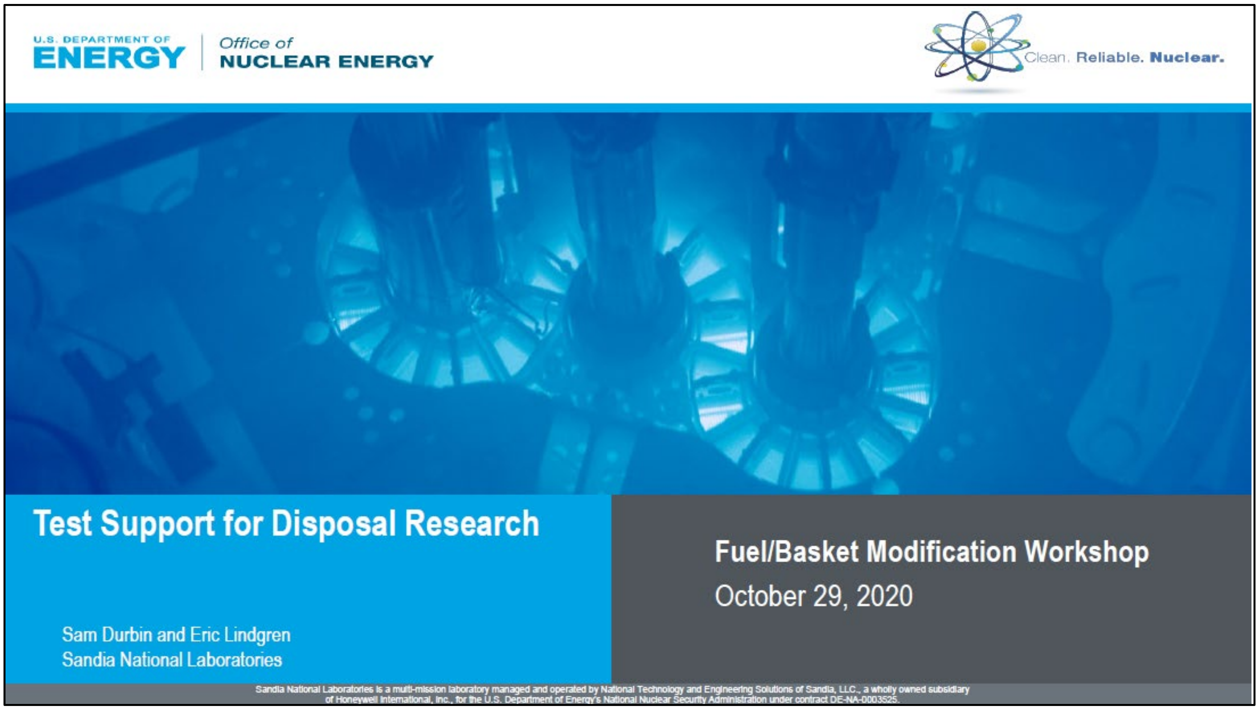

U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Clean. Reliable. Nuclear.

Test Support for Disposal Research

Sam Durbin and Eric Lindgren
Sandia National Laboratories

Fuel/Basket Modification Workshop
October 29, 2020

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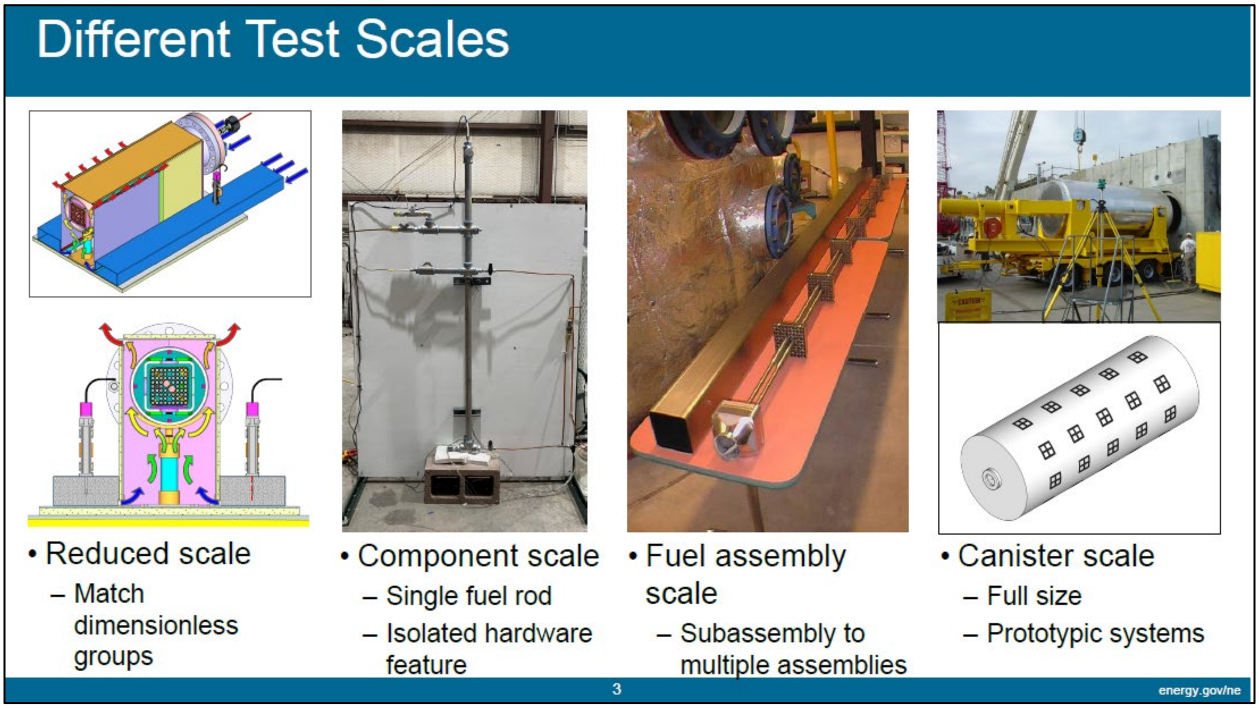
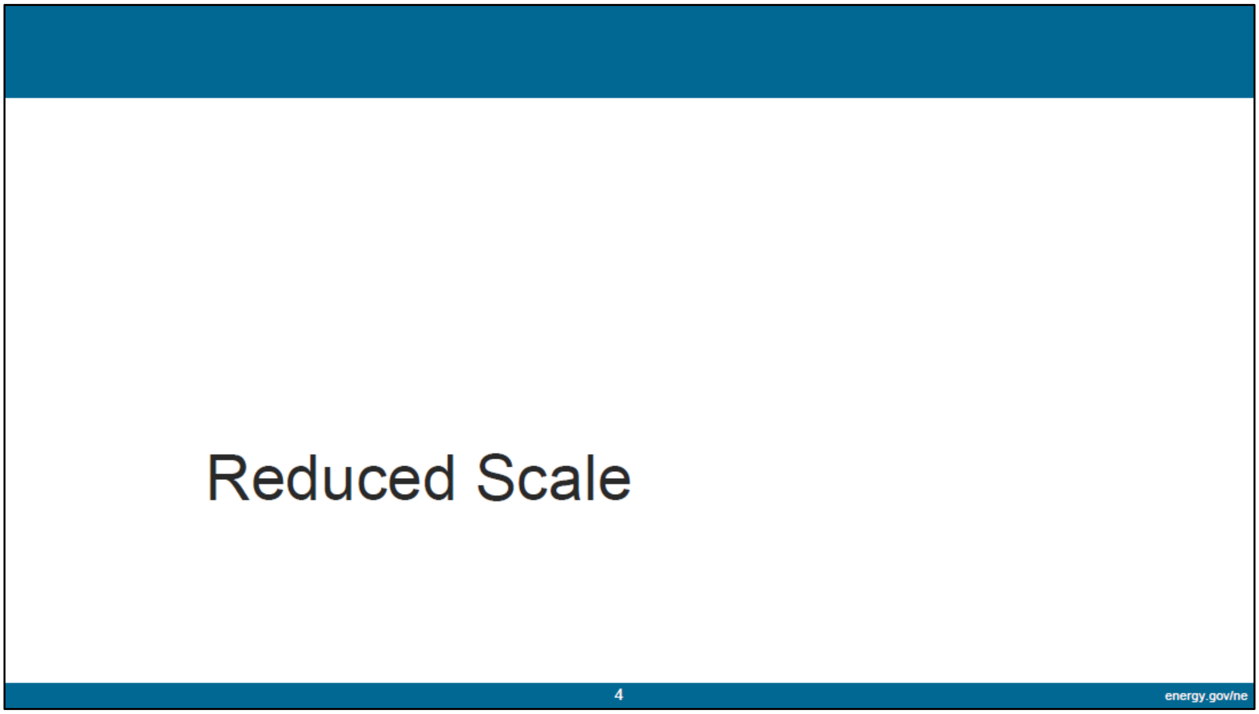
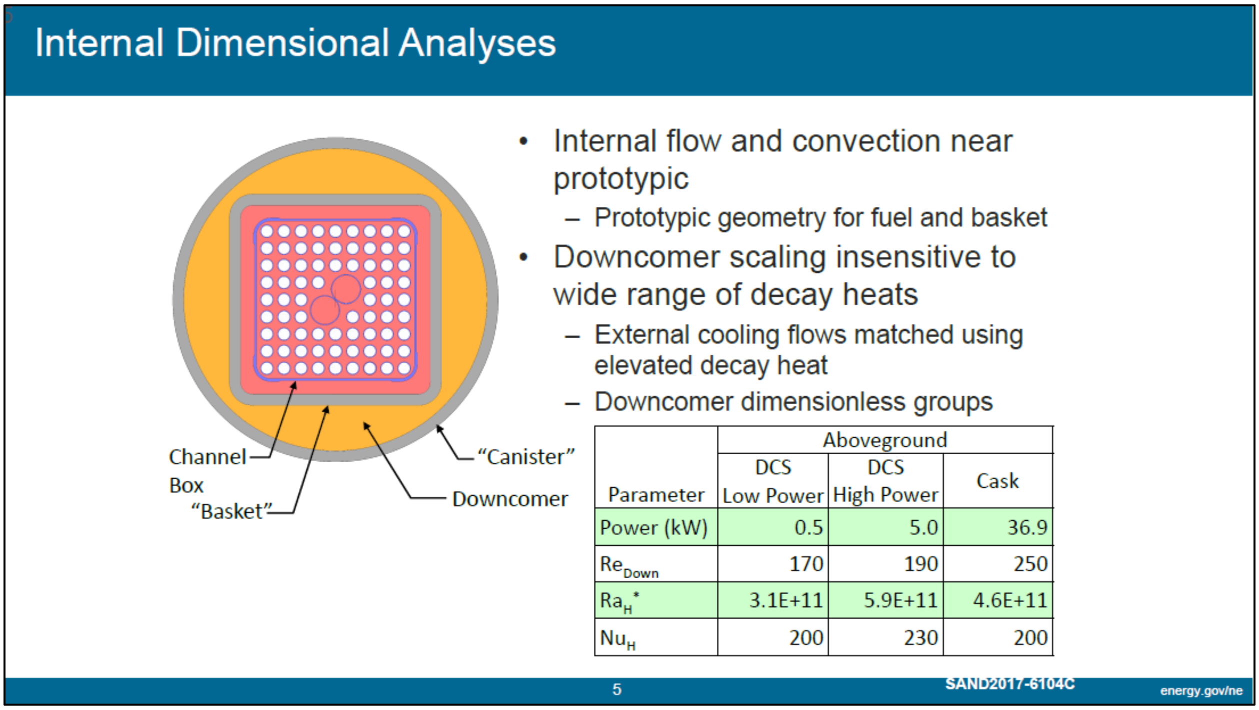


Different Test Scales

- Reduced scale
  - Match dimensionless groups
- Component scale
  - Single fuel rod
  - Isolated hardware feature
- Fuel assembly scale
  - Subassembly to multiple assemblies
- Canister scale
  - Full size
  - Prototypic systems



Reduced Scale

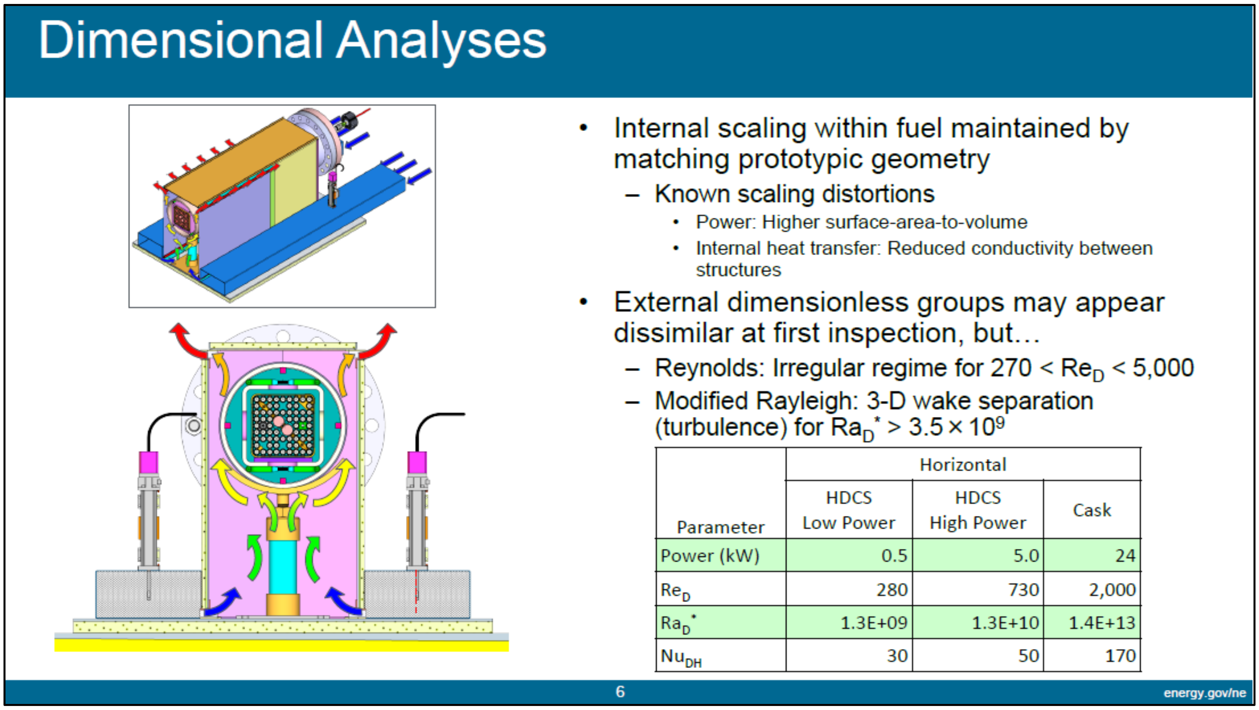


Internal Dimensional Analyses

- Internal flow and convection near prototypic
  - Prototypic geometry for fuel and basket
- Downcomer scaling insensitive to wide range of decay heats
  - External cooling flows matched using elevated decay heat
  - Downcomer dimensionless groups

	Aboveground		
Parameter	DCS Low Power	DCS High Power	Cask
Power (kW)	0.5	5.0	36.9
Re_{Down}	170	190	250
Ra_H^*	3.1E+11	5.9E+11	4.6E+11
Nu_H	200	230	200

SAND2017-6104C



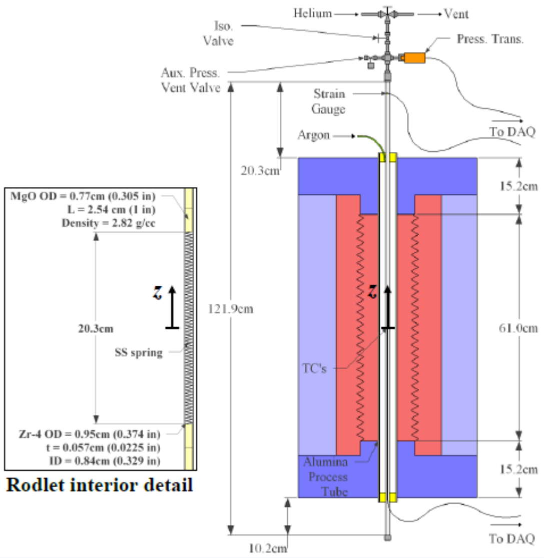
Dimensional Analyses

- Internal scaling within fuel maintained by matching prototypic geometry
  - Known scaling distortions
    - Power: Higher surface-area-to-volume
    - Internal heat transfer: Reduced conductivity between structures
- External dimensionless groups may appear dissimilar at first inspection, but…
  - Reynolds: Irregular regime for $270 < Re_D < 5{,}000$
  - Modified Rayleigh: 3-D wake separation (turbulence) for $Ra_D^* > 3.5 \times 10^9$

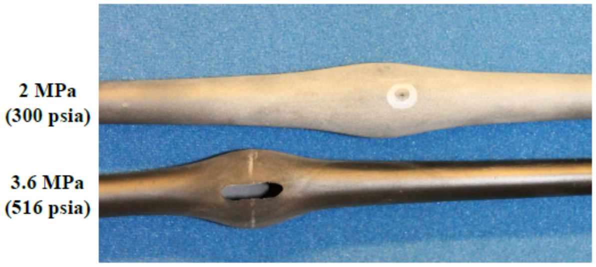
	Horizontal		
Parameter	HDCS Low Power	HDCS High Power	Cask
Power (kW)	0.5	5.0	24
Re_D	280	730	2,000
Ra_D^*	1.3E+09	1.3E+10	1.4E+13
Nu_{DH}	30	50	170

Component Scale

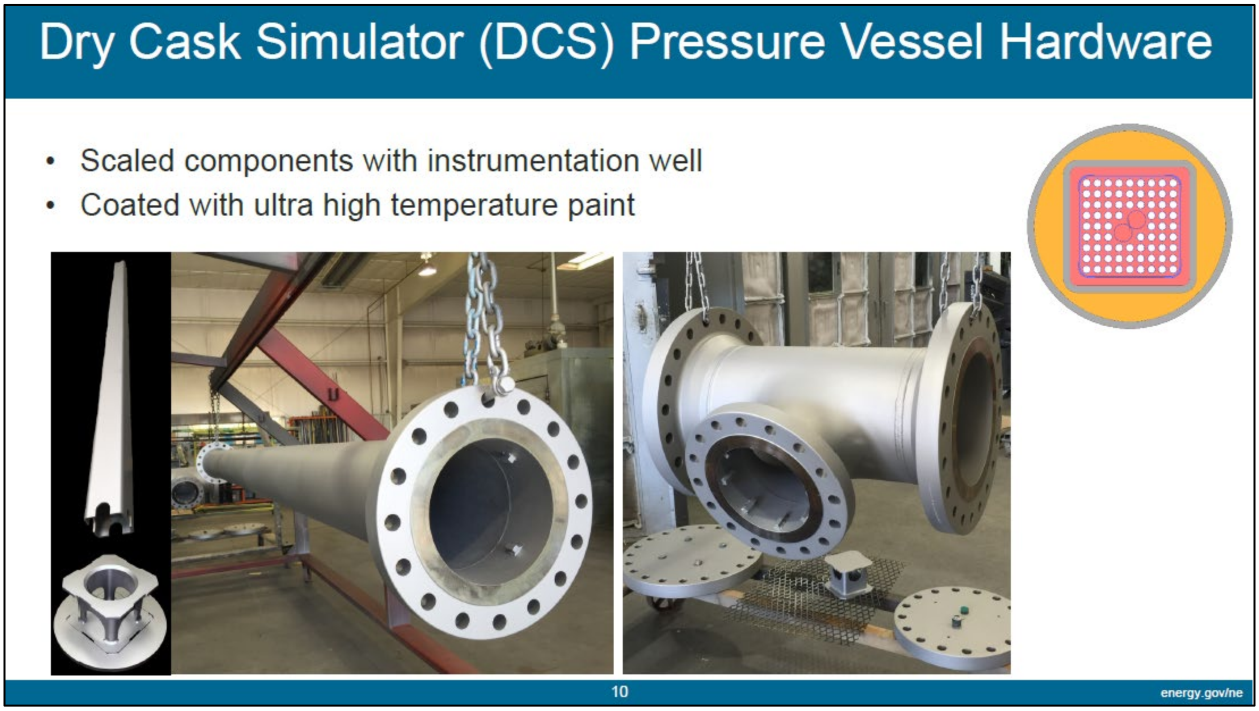
Rod Ballooning Tests



- Electric tube furnace
  - Heated length 61 cm
  - Furnace length 91 cm
- Zr-4 rodlet loaded in alumina process tube
  - Pressurized to 2 – 6.9 MPa (300 – 1000 psi) w/ He
  - Filled with MgO and SS plenum

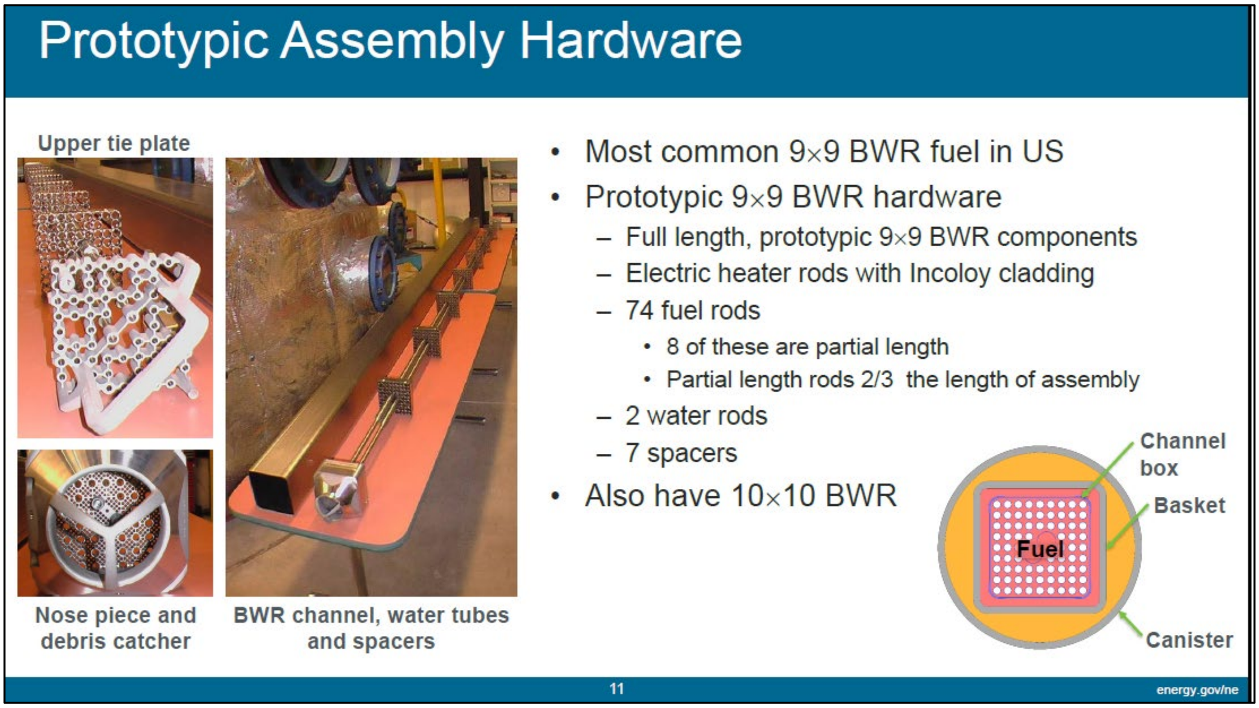


Assembly Scale



Dry Cask Simulator (DCS) Pressure Vessel Hardware

- Scaled components with instrumentation well
- Coated with ultra high temperature paint



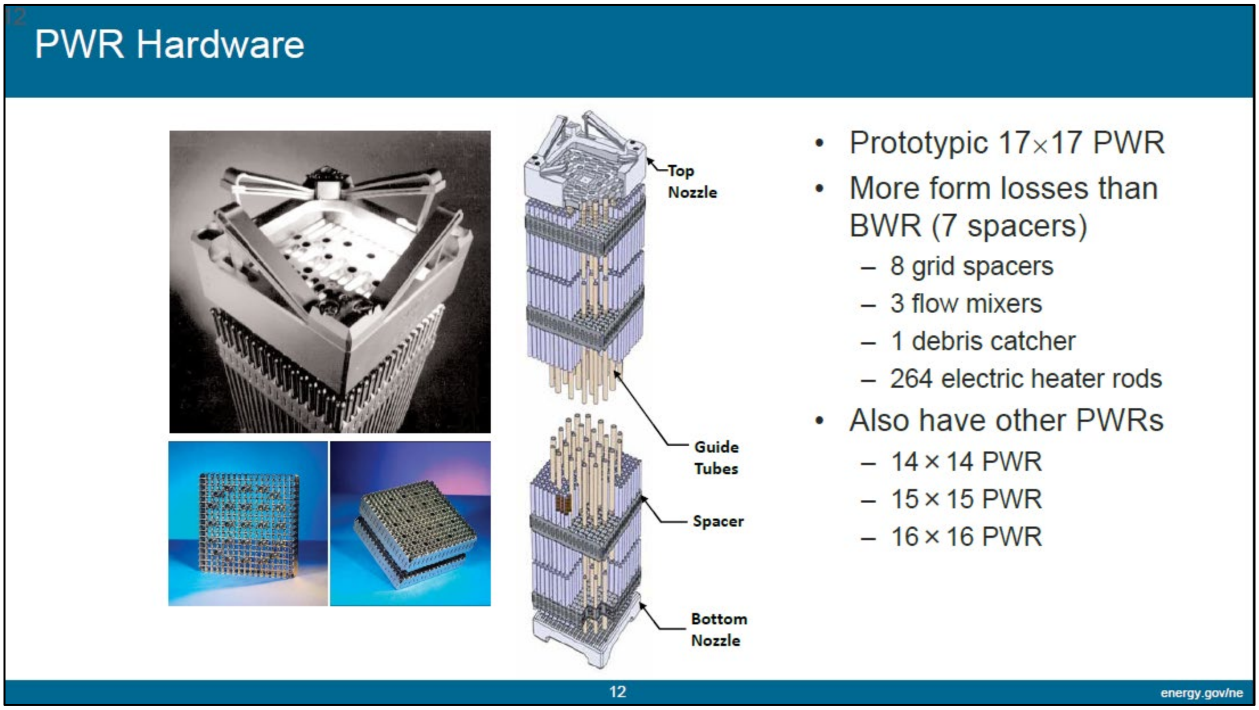
Prototypic Assembly Hardware

Upper tie plate

Nose piece and debris catcher

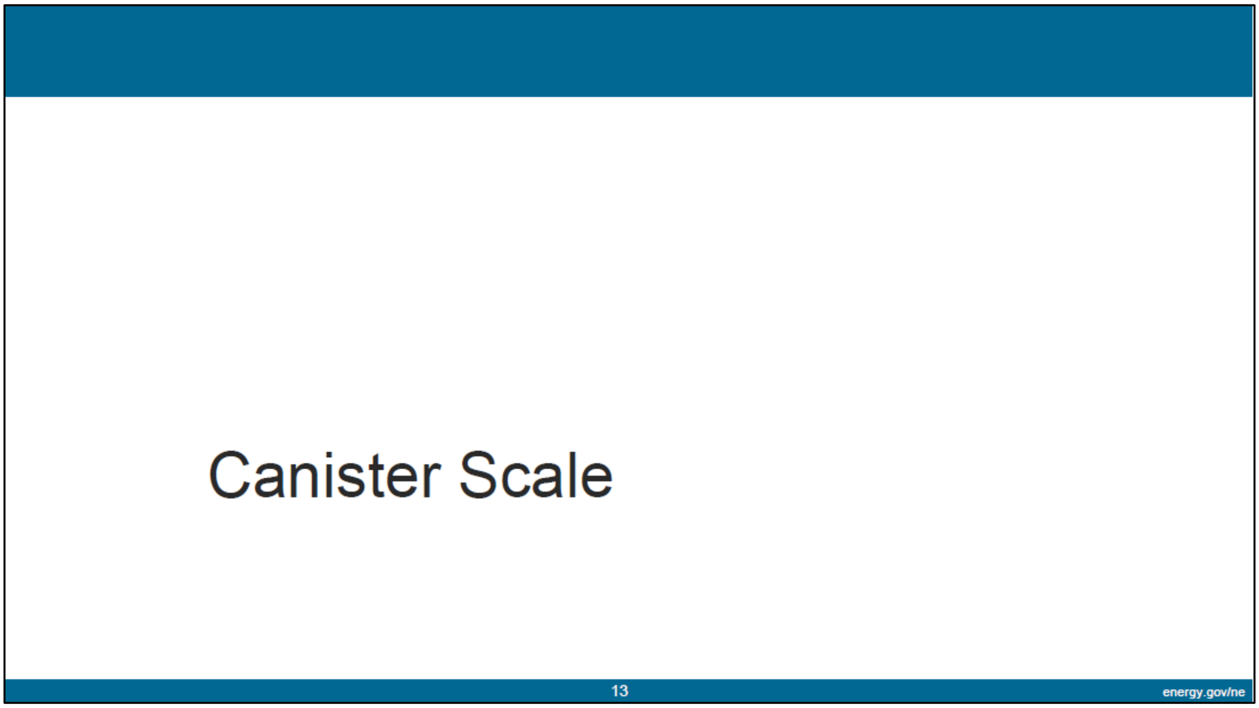
BWR channel, water tubes and spacers

- Most common 9×9 BWR fuel in US
- Prototypic 9×9 BWR hardware
  - Full length, prototypic 9×9 BWR components
  - Electric heater rods with Incoloy cladding
  - 74 fuel rods
    - 8 of these are partial length
    - Partial length rods 2/3 the length of assembly
  - 2 water rods
  - 7 spacers
- Also have 10×10 BWR

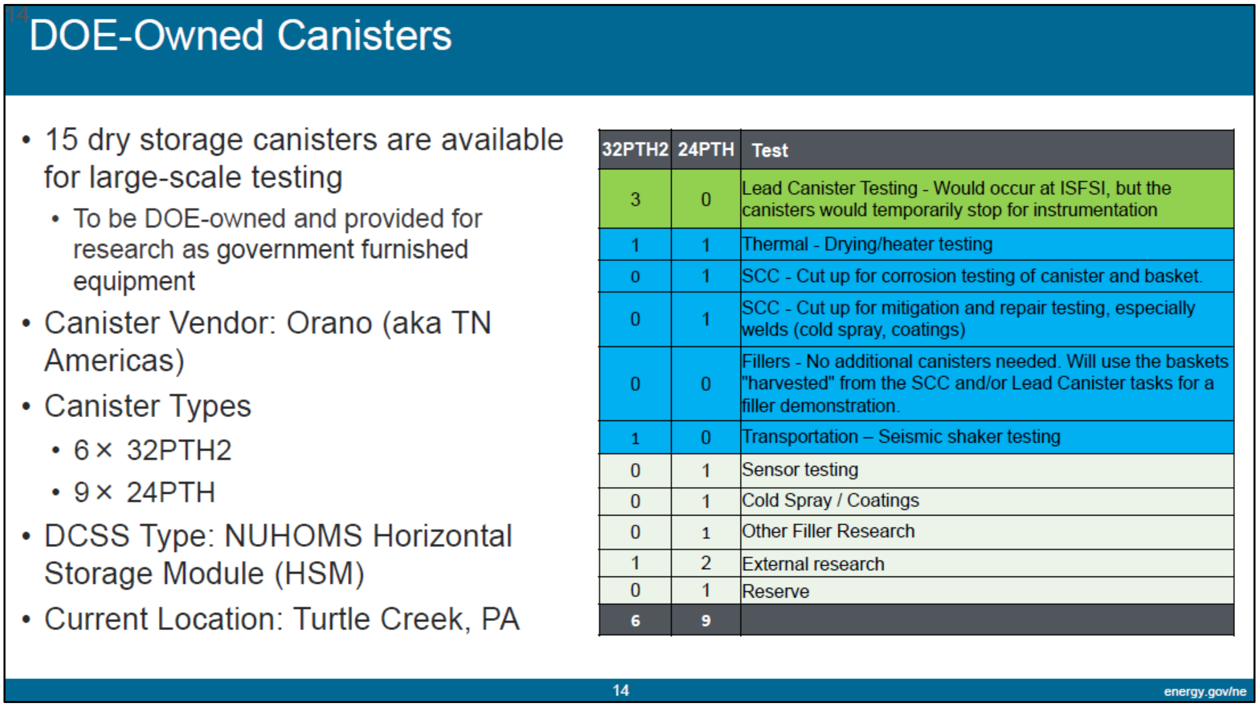


PWR Hardware

- Prototypic 17×17 PWR
- More form losses than BWR (7 spacers)
  - 8 grid spacers
  - 3 flow mixers
  - 1 debris catcher
  - 264 electric heater rods
- Also have other PWRs
  - 14 × 14 PWR
  - 15 × 15 PWR
  - 16 × 16 PWR



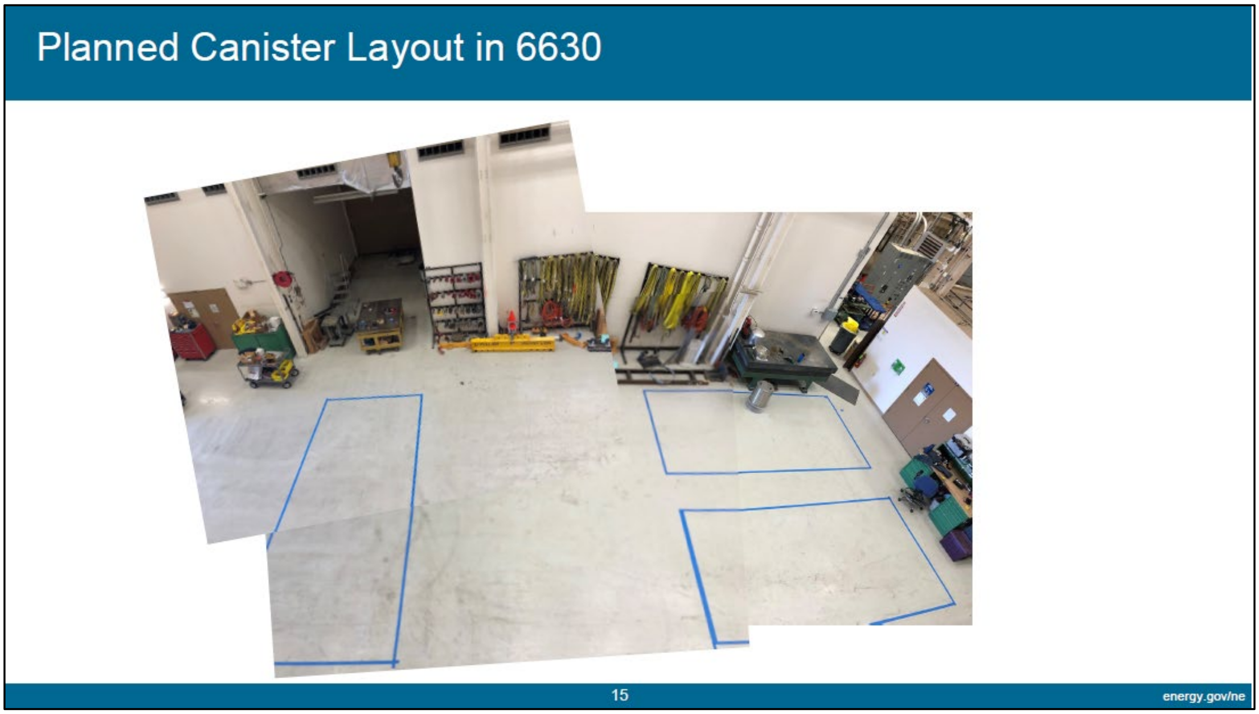
Canister Scale



DOE-Owned Canisters

- 15 dry storage canisters are available for large-scale testing
  - To be DOE-owned and provided for research as government furnished equipment
- Canister Vendor: Orano (aka TN Americas)
- Canister Types
  - 6 × 32PTH2
  - 9 × 24PTH
- DCSS Type: NUHOMS Horizontal Storage Module (HSM)
- Current Location: Turtle Creek, PA

32PTH2	24PTH	Test
3	0	Lead Canister Testing - Would occur at ISFSI, but the canisters would temporarily stop for instrumentation
1	1	Thermal - Drying/heater testing
0	1	SCC - Cut up for corrosion testing of canister and basket.
0	1	SCC - Cut up for mitigation and repair testing, especially welds (cold spray, coatings)
0	0	Fillers - No additional canisters needed. Will use the baskets "harvested" from the SCC and/or Lead Canister tasks for a filler demonstration.
1	0	Transportation – Seismic shaker testing
0	1	Sensor testing
0	1	Cold Spray / Coatings
0	1	Other Filler Research
1	2	External research
0	1	Reserve
6	**9**	



Planned Canister Layout in 6630

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