DEVELOPMENT AND EVALUATION OF CASK DEMONSTRATION PROGRAMS

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Background

The U.S. Nuclear Regulatory Commission (NRC) staff has developed a project plan for the Extended Storage and Transportation Regulatory Program Review (COMSECY–10–0007) to evaluate the adequacy of the existing regulatory framework for ensuring the safety and security of extended storage and transportation of spent nuclear fuel (SNF) beyond 120 years. The project plan includes participating in the Electric Power Research Institute's Extended Storage Collaboration Program (EPRI-ESCP) to demonstrate safety of extended SNF storage and future transportation after extended storage. Through the EPRI-ESCP, a high burnup SNF demonstration project has been proposed. The scope and type of the demonstration project has not yet been chosen. In preparation for this collaborative effort, NRC has tasked the Center for Nuclear Waste Regulatory Analyses to support developing and evaluating cask demonstration programs and assist an overall effort that provides independent observations.

Objectives

NRC, the U.S. Department of Energy (DOE), the U.S. Nuclear Waste Technical Review Board (NWTRB), and the EPRI-ESCP have led recent gap assessments focusing on long-term aging issues important to the performance of the structures, systems, and components of the dry cask storage systems. A number of technical issues and research and data needs have emerged from these assessments. Future demonstration project activities may use various configurations of dry storage cask systems and experiments. The goals for such a demonstration include (i) benchmarking the predictive models and empirical conclusions that will be developed from short-term laboratory testing for aging of dry storage cask system components and (ii) building confidence in the ability to predict the performance of these systems over extended time periods. Aging effects that can be missed in short-term studies may become apparent in the demonstration program. At present, no specific cask demonstration program has been developed, for example specific casks, SNF types, and test configurations have not been selected; consequently, this report evaluates potential cask demonstration program options that consider various types of casks, SNF types, and other parameters. These options are evaluated against one another to identify differences between potential program data obtained for each demonstration of extended storage and other program requirements, including activities that would be necessary for each option (e.g., transportation of SNF, opening cask to access SNF). Specifically, this effort will technically evaluate a range of potential cask demonstration options. However, the intent of this effort is only to provide a technical evaluation for a range of options and no recommendations of these options are provided in this report.

Cask Demonstration Options

A number of potential cask demonstration configurations, environments, and additional parameters have been considered. In the present report, these parameters are referred to as "elements and factors" and include aspects like the SNF-assembly type (i.e., pressurized water reactor and boiling water reactor), SNF cladding materials (Zircaloy-4, lined Zircaloy-2, Zirlo$^{\text{TM}}$, M5$^{®}$), cask system components, and environments (highly industrial, coastal/marine). Combinations of these elements and factors were used to develop the cask demonstration options, and the following considerations were viewed as the most important for selection of parameters:

(1) Obtaining collection of maximum data for technical issues EPRI-ESCP, NRC, DOE, and NWTRB identified as high and medium priority[1]

(2) Timeframe or urgency for collecting data

(3) Obtaining measurable data for selected high burnup SNF types and cladding [pressurized water reactor (PWR) and boiling water reactor (BWR) UO_2 SNF]

(4) Obtaining data from major dry cask system design variations (direct-load metal cask system, canister-based system in concrete overpack or module)

(5) Costs, feasibility, and regulatory and operational requirements (e.g., if the canister-based system is welded, because of the complicated welding procedure, it is not considered feasible to cut open the cask during demonstration to access SNF and other internal components, and weld it back on; however, opening the direct-load bolted cask is considered to be feasible because the procedure is less complicated)

To develop cask demonstration options, potential testing configurations (i.e., dry cask systems or experiments) were generalized into three classes. These classes were developed based upon the assumption that a cask demonstration program could use new dry cask storage systems or use systems that are already in use at a utility site. Because using new dry casks may be prohibitively complex and costly and the availability of already-in-use casks loaded with high burnup SNF may be limited, a cask demonstration program may consider separate assessments of the SNF and the cask system components. Therefore, an additional class is included as a hot cell demonstration program that would replicate a cask confinement environment. This is considered the most feasible approach for assessing the SNF; high burnup SNF could especially be assessed separately from a dry cask storage system.

Three general classes of demonstration testing configurations, coupled with examination of existing cask systems, are considered in this report:

Class 1—Use new cask storage system(s), with the following features:

- Installation of new cask(s) for the demonstration
- Selection of SNF assemblies from SNF pool
- Predemonstration examination
- Monitoring during demonstration
- Modifications of storage system for enhanced monitoring (would require license amendment to allow for confinement penetration)

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[1] Residual water from the cask drying process could affect degradation of cask system components, which will be addressed elsewhere. Nevertheless, residual water is referenced as an issue and mentioned when data to be obtained would support informing the knowledge base for this potential issue.

- Possible periodic removal of SNF and examination for direct-load metal cask

- Postdemonstration examination of SNF and system

- SNF access for canister-based systems would only be done at termination of demonstration program

Class 2—Utilize already-in-use casks at Independent Spent Fuel Storage Installation site(s) with two possible options

(1) Monitoring of selected cask(s)

  - Possibly obtaining an exemption to add penetrations to monitor cask interior; however, monitoring options may be less than those for Class 1

  - Possible periodic removal of SNF and examination for direct-load metal cask

  - For canister-based cask, SNF would not be removed until program termination

(2) Accessing a cask system to assess cask system component conditions

  - Only considering the cask system non-SNF components (postdemonstration examination of SNF and non-accessible components may be optional)

  - Monitoring of appropriate parameters related to cask system components if necessary (e.g., monitoring a cask at a lower temperature with a stainless steel canister in a coastal environment to assess stress corrosion cracking)

Class 3—Perform a hot cell demonstration

The hot cell demonstration is a full demonstration for SNF and potentially other materials exposed to the same normal environments inside the dry storage system. Inclusion of a hot cell demonstration allows for decoupling of the demonstration for SNF behavior from the demonstration of the cask system. Doing so would allow for more flexibility to maximize data collection and to use casks that have already been in storage for longer duration. The hot cell demonstration is supplementary to Class 1 or Class 2 where SNF removal during demonstration is not feasible and/or desirable.

The advantages of the hot cell demonstration follow:

- Does not require periodic opening of casks to examine SNF on a frequent basis and does not require *in-situ* monitoring of SNF and environmental parameters

- Does not require SNF/cask transport during demonstration

- Decouples from cask demonstration

- Provides continuous monitoring of environmental parameters and potential for *in-situ* SNF condition without requiring confinement penetration before demonstration, unlike the cask demonstration

- Complements data gathered from the cask demonstration

- Provides option for frequent nondestructive examination to detect any possible SNF breaches and destructive examination of fuel conditions such as swelling, cracking, interaction and spacing between fuel and cladding

- Provides potential for *in-situ* examination of SNF condition (e.g., laser profilometry with glass container vessel)

- Provides option to examine SNF if/when monitored conditions change (e.g., fission gas release to vessel, change in SNF dimensions, change in vessel pressure/atmosphere from presence of fission gas, hydrogen, or moisture)

- Provides option for comparison of measured SNF condition with any SNF examination from cask demonstration

- Provides option to alter demonstration conditions if desired (e.g., introduction of air, increased temperature, and additional water)

The cask demonstration options developed include the following

Options A–C: New cask storage systems

Option A—Multiple new casks with multiple SNF types and other conditions

Option B—Limited number (>1) of new casks with multiple SNF types and other conditions

Option C—Single new cask with limited SNF types and other conditions, depending on the priority to obtain data on the single cask; an alternative selection of Option C with a different type of cask is proposed as Option C–Alternate

Options A–C are progressively less complicated.

Options D–E: Already-in-use casks

Option D—Assess multiple, already-in-use casks with multiple SNF types

Option E—Assess single, already-in-use cask with one SNF type, depending on the priority to obtain data on the single cask; an alternative selection of Option E with a different type of cask is proposed as Option E–Alternate

Option E is less complicated than Option D.

Options F–G: Already-in-use casks and hot cell demonstration

Already-in-use casks will be monitored to assess external cask system components, but the SNF and internal cask component materials such as baskets and neutron absorbers will be assessed separately through the hot cell demonstration. The direct-load metal cask may be opened to examine the seals, gaskets, and bolts only.

> Option F—Assess multiple, already-in-use casks and a hot cell demonstration
>
> Option G—Assess a single, already-in-use cask and a hot cell demonstration, depending on the priority to obtain data on the single case; an alternative selection of Option G with a different type of cask is proposed as Option G–Alternate
>
> Option G is less complicated than Option F.

Table ES–1 summarizes the details of the developed cask demonstration options, including number of casks, the focus of each cask demonstration, and the overall pros and cons for each demonstration option. Table ES–2 summarizes all the activities associated with all demonstration options, and Table ES–3 summarizes the data to be obtained in all options to address technical issues NRC, DOE, NWTRB, and EPRI-ESCP identified recently.

Table ES–1. Summary of All Cask Demonstration Options, Casks, Focus of Demonstration, Pros, and Cons

Options	Casks	Focus of Demonstration	Pros	Cons	Report Section
Option A (multiple new casks)	Cask A1	Effects of marine environment on stainless steel canister degradation.	Most detailed and thorough demonstration with low and high burnup SNF, two major cask types in various environments, and a broad coverage of materials and components to ensure a broad coverage of representative data of interest.	Many activities and several storage sites are needed. License amendment may be needed to allow for confinement penetration. The costs, and regulatory and operational requirements are likely to be high.	3.2.1
	Cask A2	Effects of highly industrial-seasonal environment on stainless steel canister and concrete overpack degradation.			3.2.2
	Cask A3	Effects of marine environment on direct-load cask, bolts, and seals degradation and effects of extended storage on internal neutron absorber, SNF basket, and shielding materials degradation.			3.2.3
	Cask A4	Effects of highly industrial environment on direct-load bolted cask, bolts, and seals degradation and effects of extended storage on degradation of other materials supplementary to those in Cask A3.			3.2.4
	Cask A5	Degradation of high burnup PWR* SNF, including cladding such as Zirlo or M5, thermo-mechanical degradation of bolts and seals, radiation-induced polymeric materials degradation.			3.2.5
	Cask A6	Degradation of high burnup BWR† SNF, including lined Zircaloy-2 cladding, and other materials supplementary to those in Cask A5.			3.2.6
Option B (limited number of new casks)	Cask B1	Effects of marine environment on stainless steel canister degradation (similar to Cask A1).	Covered a range of data needs that is considered high and medium priority with fewer casks than those in Option A. The cost, and regulatory and operational requirements are lower compared to Option A.	The range of data to be obtained is not as broad as Option A. Some data have been traded off.	3.3.1
	Cask B2	Effects of highly industrial-seasonal environment on direct-load cask, bolts, and seals degradation and effects of extended storage on degradation of internal neutron absorber, SNF basket, and shielding materials degradation (similar to Cask A4).			3.3.2
	Cask B3	Degradation of high burnup SNF, cladding, thermo-mechanical degradation of bolts and seals, radiation-induced polymeric materials degradation (similar to Casks A5 and A6).			3.3.3

Table ES–1. Summary of All Cask Demonstration Options, Casks, Focus of Demonstration, Pros, and Cons (continued)

Options	Casks	Focus of Demonstration	Pros	Cons	Report Section
Option C (single new cask)	Cask C1	Effects of marine environment on direct-load bolted cask, bolts, seals, and degradation of high burnup SNF and cladding.	Only a single cask is used to obtain some data that are considered high and medium priority. The cost is the least compared to Options A and B.	It requires a mix of low and high burnup SNF in one cask. The regulatory requirements are likely to be high.	3.4.1
	Cask C1–Alternate	Effects of marine environment on stainless steel canister and degradation of high burnup SNF and cladding.			3.4.2
Option D (multiple already-in-use casks)	Cask D1	Effects of marine environment on stainless steel canister degradation.	Demonstration covers low and high burnup SNF, two major cask types in various environments, and a broad coverage of materials and components.	Predemonstration examination may not be as detailed as for Option A depending on the record in utility. Already-in-use casks with high burnup SNF may be limited. License amendment may be needed to allow for confinement penetration for internal monitoring.	3.5.1
	Cask D2	Effects of highly industrial environment on direct-load cask, bolts, and seals degradation.			3.5.2
	Cask D3	Degradation of high burnup PWR SNF, including cladding such as Zirlo or M5, thermo-mechanical degradation of bolts and seals, radiation-induced polymeric materials degradation.			3.5.3
	Cask D4	Degradation of high burnup BWR SNF, including lined Zircaloy-2 cladding, and other materials supplementary to those in Cask D3.			3.5.3

Table ES–1. Summary of All Cask Demonstration Options, Casks, Focus of Demonstration, Pros, and Cons (continued)

Options	Casks	Focus of Demonstration	Pros	Cons	Report Section
Option E (single already-in-use cask)	Cask E1	Effects of marine environment on stainless steel canister degradation.	Only a single cask is needed to obtain some data that are considered high and medium priority. It is more feasible for a utility.	Only limited data are obtained. License amendment may be needed to allow for confinement penetration for internal monitoring.	3.6.1
	Cask E1–Alternate	Effects of seasonal environment on direct-load bolted cask degradation and effects of extended storage on degradation of bolts, seals, and gaskets.			3.6.2
Option F (multiple already-in-use casks and hot cell demonstration)	Cask F1	Effects of marine environment on stainless steel canister degradation.	It covers a broad range of data. Hot cell demonstration provides continuous *in-situ* monitoring and potential for frequent examination of SNF and cladding independent of casks. No additional confinement penetration is needed.	It requires multiple sites and a hot cell dedicated for demonstration. The cost and operational requirements are likely to be high.	3.7.1
	Cask F2	Effects of highly industrial environment on direct-load bolted cask degradation and effects of extended storage on degradation of bolts, seals, gaskets.			3.7.2
	Cask F3	Effects of seasonal environment on direct-load bolted cask and concrete structure degradation.			3.7.3
	Hot cell demonstration	Degradation of high burnup SNF, cladding, and other cask component materials.			3.7.4

Table ES–1. Summary of All Cask Demonstration Options, Casks, Focus of Demonstration, Pros and Cons (continued)

Options	Casks	Focus of Demonstration	Pros	Cons	Report Section
Option G (single already-in-use cask and hot cell demonstration)	Cask G1	Effects of marine environment on stainless steel canister degradation.	Only single cask is needed to obtain some data that are considered high and medium priority. It is more feasible for a utility. Hot cell demo provides continuous *in-situ* monitoring and potential for frequent examination of SNF and cladding independent of cask. No additional confinement penetration is needed.	Only limited data are obtained. Requires dedicated hot cell for demonstration.	3.8.1
	Cask G1–Alternate	Effects of highly industrial environment on direct-load bolted cask degradation and effects of extended storage on items such as degradation of bolts, seals, and gaskets.			3.8.2
	Hot cell demonstration	Degradation of high burnup SNF, cladding, and other cask component materials.			3.7.4

*Pressurized water reactor
†Boiling water reactor

Table ES–2. Demonstration Activities for All Options A–G

Demonstration Activities	New Cask Storage Systems				Already-In-Use Casks			Already-In-Use Casks and Hot Cell Demonstration		
	Option				Option			Option		
	A	B	C	C-Alternate	D	E	E-Alternate	F	G	G-Alternate
Transportation of SNF to site for monitoring in hot cell								🟩	🟩	🟩
Predemonstration examination	🟩	🟩	🟩	🟩				🟩 *	🟩 *	🟩 *
Internal monitoring of SNF conditions	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 *	🟩 *	🟩 *
Exemption(s) required for penetrations for additional monitoring in cask environment	🟩	🟩	🟩	🟩	🟩	🟩	🟩			
External monitoring for components	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Opening of cask to access SNF during demonstration	🟩	🟩	🟩		🟩		🟩			
Opening of cask to access internal non-SNF components (e.g., baskets, neutron absorbers) during demonstration	🟩	🟩	🟩		🟩		🟩			
Postdemonstration examination	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Transportation of SNF for examination	🟩	🟩	🟩	🟩 †	🟩	🟩	🟩			

Shaded area denotes that activities will be assessed in the demonstration.

*For hot cell demonstration only

†Before and at the end of demonstration only

Table ES–3. Data To Be Obtained in All Options A–G To Address Technical Issues Identified in the Literature*

SNF, Cladding, and System Components		Degradation Under Extended Storage	New Cask Storage Systems				Already-In-Use Casks			Already-In-Use Casks and Hot Cell Demonstration		
			Option				Option			Option		
			A	B	C	C-Alternate	D	E	E-Alternate	F	G	G-Alternate
Cladding		Off-normal air oxidation†										
		Hydrogen embrittlement	🟩	🟩	🟩		🟩		🟩	🟩	🟩	🟩
		Delayed hydride cracking	🟩	🟩	🟩		🟩		🟩	🟩	🟩	🟩
		Annealing of radiation damage	🟩	🟩	🟩		🟩		🟩	🟩	🟩	🟩
		Low temperature creep	🟩	🟩	🟩		🟩		🟩	🟩	🟩	🟩
		Stress corrosion cracking	🟩	🟩	🟩		🟩		🟩	🟩	🟩	🟩
		Galvanic corrosion	🟩	🟩	🟩		🟩		🟩	🟩	🟩	🟩
		Propogation of existing flaws	🟩	🟩	🟩		🟩		🟩	🟩	🟩	🟩
SNF		Off-normal air oxidation										
		Fragmentation, restructuring–swelling, SNF oxidation under normal condition, rim structure degradation, fission gas release during accident, helium release	🟩	🟩	🟩		🟩		🟩	🟩	🟩	🟩
SNF Assembly Hardware		Wet corrosion and stress corrosion cracking, metal fatigue caused by temperature fluctuations	🟩	🟩	🟩		🟩		🟩	🟩	🟩	🟩
Canister-Based Storage System (Mostly dual-purpose canister system, welded canister in bolted overpack or concrete storage module)	Canister body and weld (stainless steel)	Atmospheric corrosion (pitting and crevice corrosion including marine environment), stress corrosion cracking near the marine or highly industrial environments, aqueous corrosion	🟩	🟩		🟩	🟩	🟩		🟩	🟩	
	Concrete and steel overpack or concrete vault-type overpack	Corrosion of embedded steel, concrete degradation because of freeze–thaw cycle	🟩	🟩		🟩	🟩	🟩		🟩	🟩	

Table ES–3. Data To Be Obtained in All Options A–G To Address Technical Issues Identified in the Literature* (continued)												
SNF, Cladding, and System Components		**Degradation Under Extended Storage**	**New Cask Storage Systems**				**Already-In-Use Casks**			**Already-In-Use Casks and Hot Cell Demonstration**		
			Option				**Option**			**Option**		
			A	**B**	**C**	**C-Alternate**	**D**	**E**	**E-Alternate**	**F**	**G**	**G-Alternate**
Direct-Load Metal Cask Storage System (Generally bolted, thick walled)	Steel cask (carbon steel, nodular cast iron, low-alloy steel)	Atmospheric corrosion (including marine environment), aqueous corrosion.	🟩	🟩	🟩		🟩		🟩	🟩		🟩
	Metallic seals and gaskets	Stress relaxation, crevice corrosion, microbial influenced corrosion, plastic deformation, creep, thermo-mechanical fatigue.	🟩	🟩	🟩		🟩		🟩	🟩		🟩
	Bolts	Corrosion, stress corrosion cracking, creep, thermo-mechanical fatigue, embrittlement.	🟩	🟩	🟩		🟩		🟩	🟩		🟩
SNF Basket (Stainless steel, aluminum, Inconel, carbon steel)		Loss of geometry due to creep, metal fatigue, general corrosion, galvanic corrosion, weld embrittlement.	🟩	🟩	🟩					🟩 ‡	🟩 ‡	🟩 ‡
Neutron Absorbers (Borated stainless steel; other metals; metal matrix composites, such as Boral^{TM}, Metamic^{TM})		Corrosion (blistering), thermal aging effects, creep, embrittlement and cracking.	🟩	🟩	🟩					🟩 ‡	🟩 ‡	🟩 ‡
Shielding Material (e.g., borated polymers)		Oxidation-induced mechanical property changes leading to slump within the overpack.	🟩	🟩	🟩		🟩		🟩	🟩 ‡	🟩 ‡	🟩 ‡

Table ES–3. Data To Be Obtained in All Options A–G To Address Technical Issues Identified in the Literature* (continued)

SNF, Cladding, and System Components	Degradation Under Extended Storage	New Cask Storage Systems				Already-In-Use Casks			Already-In-Use Casks and Hot Cell Demonstration		
Reinforced Concrete Pad	Corrosion of steel in reinforced concrete leading to concrete spallation and loss of structural function for cask and retrieval equipment foundation, freeze–thaw cycle, effect of elevated temperature.	🟩	🟩	🟩		🟩	🟩	🟩	🟩	🟩	🟩

Shaded area denotes that technical issues are covered in the demonstration.

*Based upon the following references:

- EPRI (Electric Power Research Institute). “Extended Storage Collaboration Program Progress Report and Review of Gap Analyses.” EPRI 1022914. Palo Alto, California: Electric Power Research Institute. 2011.
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- NWTRB (U.S. Nuclear Waste Technical Review Board). “Evaluation of the Technical Basis for Extended Dry Storage and Transportation of Used Nuclear Fuel.” Washington, DC: U.S. Nuclear Waste Technical Review Board. 2010.

†Off-normal oxidation means oxidation when air leaks through the cask storage system.

‡Could potentially be done with hot cell demonstration

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: All CNWRA-generated original data contained in this report meet the quality assurance requirements described in the Geosciences and Engineering Division Quality Assurance Manual. Sources for other data should be consulted for determining the level of quality for those data.

ANALYSES AND CODES: No scientific or engineering software was used in the analyses contained in this report.

1 INTRODUCTION

This section briefly describes background information on extended storage of spent nuclear fuel (SNF), historical and projected cask demonstration programs, and the objectives and scope of the work in this report.

1.1 Background

The U.S. Nuclear Regulatory Commission (NRC) staff has developed a project plan for the Extended Storage and Transportation Regulatory Program Review (COMSECY–10–0007) to evaluate the adequacy of the existing regulatory framework for ensuring the safety and security of extended storage and transportation of SNF beyond 120 years. The project plan includes participating in the Electric Power Research Institute-led Extended Storage Collaboration Program (EPRI-ESCP) to demonstrate safety of extended SNF storage and future transportation after extended storage. NRC intends to obtain support for independent observations and analysis of the demonstration program results. Through the EPRI-ESCP, a high burnup SNF demonstration project has been proposed. The scope and type of the demonstration project has not yet been chosen, and details may become available later. This report focuses on the development and evaluation of potential confirmatory cask demonstration programs including a series of progressively less complicated prototype cask demonstration options to determine what information can be garnered from each option.

1.2 Historical and Projected Cask Demonstration Programs in the United States and Other Countries

1.2.1 Electric Power Research Institute, the U.S. Nuclear Regulatory Commission, and the U.S. Department of Energy 15-Year Dry Cask Storage Characterization Project

To develop the technical basis for license renewal for SNF dry storage in the United States, the Electric Power Research Institute (EPRI), the U.S. Department of Energy (DOE), and NRC jointly funded a dry cask storage characterization project in 1999 to investigate the condition of a dry cask storage system in which SNF has been stored for approximately 15 years (Kimball and Billone, 2002). This demonstration project evaluated a Castor V/21 cask containing 21 pressurized water reactor (PWR) SNF rods with an average burnup of 35.7 GWd/MTU. Over the 15 year storage period, the cladding was exposed to temperatures ranging from an approximate maximum of 350 °C [662 °F] to 150 °C [302 °F]. The cladding was cold-worked/stress-relieved Zircaloy-4. Because the SNF had been originally stored as part of a different project with different goals, limited predemonstration characterization was conducted, including cask exterior surface inspection and temperature measurements, and helium backfill gas analysis. Postdemonstration performance evaluation focused on SNF rod dimensional changes, cladding oxidation and hydriding characteristics, fission gas release (FGR) measurements, and cladding mechanical properties (e.g., creep). Backfill gas was sampled and analyzed for composition including water content during demonstration, but the water content was below detection limit and no data was reported. Selected SNF rods were removed from one assembly and visually examined, followed by detailed nondestructive and destructive examination and testing. The examination and testing included profilometry scans; measurement of FGR, internal pressure, and void volume; metallographic examinations; microhardness and hydrogen content determinations; and creep testing. In addition, selected SNF assembly temperatures, as well as cask surface gamma and neutron dose rates, were measured.

The following conclusions can be drawn from this dry cask storage characterization project:

- No evidence of cask, shielding, or SNF rod degradation was observed after 15 years of dry storage that would affect cask performance or SNF integrity.

- There was little or no cladding creep and annealing of irradiation damage during the storage period. The cladding retained significant creep ductility after 15 years of dry storage.

- There was no additional hydrogen pickup or evidence of hydride reorientation in the cladding during the storage period.

- There was little or no FGR from the SNF pellets during the storage period.

Contrary to the detailed postdemonstration performance evaluation of the cask and SNF, predemonstration characterization was very limited. As noted in the report (Kimball and Billone, 2002), comparing the postdemonstration condition of the SNF rod with data obtained from similar rods introduces considerable uncertainty in qualifying cladding creep that may have accumulated during storage. It would be preferable to perform a detailed predemonstration examination using nondestructive examination methods on the actual test rods as a baseline to accurately determine cladding creep that may have occurred during thermal-benchmark testing and dry storage.

1.2.2 Electric Power Research Institute and the U.S. Department of Energy Dry Storage Demonstration for High Burnup Spent Nuclear Fuel—Feasibility Study

Volume of high burnup SNF with burnup greater than 45 GWd/MTU is expected to substantially increase in the coming years. The mechanical integrity of high burnup SNF has been a concern with respect to extended storage and transportation. NRC Spent Fuel Project Office Interim Staff Guidance No. 11 (SFST–ISG–11) (NRC, 2003) addressed the acceptance criteria for the storage of SNF assemblies with average burnup exceeding 45 GWd/MTU. However, transportation licenses for high burnup SNF will be handled on a case-by-case basis. Confirmatory data are needed to augment the technical basis supporting dry storage and transportation of high burnup SNF. A DOE-funded feasibility study was performed to examine the options available for conducting a confirmatory experimental program to obtain regulatory acceptance for dry storage of SNF with burnup exceeding 45 GWd/MTU (McKinnon and Cunningham, 2003). This feasibility study identified three options for the confirmatory experimental program.

- Augmentation of an existing utility program. Several utilities are conducting programs to characterize in-reactor SNF performance. These programs could be expanded and augmented with high burnup SNF. This option would provide information on the condition of the SNF prior to storage, but it would not provide results for SNF performance during storage.

- A combination of demonstration at an existing independent SNF storage installation and post-irradiation examination at a national laboratory. For this option, poolside examination of selected SNF would be conducted prior to dry storage. Cask system modifications would be required to accommodate SNF temperature measurements and backfill gas sampling during the storage period. At the conclusion of the demonstration period, selected SNF rods would be examined at a national laboratory to determine the effects of dry storage on the mechanical properties of the cladding.

- Demonstration at a national laboratory. This option would transfer selected SNF to a national laboratory, place the SNF in a modified cask, and then perform interim and final examinations of the SNF. The effects of dry storage on the mechanical properties of the cladding would be determined after dry storage.

1.2.3 Historical and Projected Cask Demonstration Programs From Japan and Canada

This section discusses historical and projected cask demonstration programs in Japan and Canada. The strengths and weaknesses of their programs and insights gained from these cask demonstration programs are also discussed. Even though many other countries currently operate SNF dry storage facilities, such as South Korea and Germany, these countries are not included in this discussion, because these countries have not extensively studied or actively involved in a research or demonstration program concerning long-term integrity of a dry storage system. Research activities and operational experiences in foreign countries can be found elsewhere (International Atomic Energy Agency, 2003, 2002, 1999, 1992; Schneider and Mitchell, 1992). Currently, it seems that no country has attempted or conducted a program of extended dry storage beyond 100 years.

1.2.3.1 Japan

Completed Demonstration Program

In Japan, a dry storage system has been in operation since 1982 at the Japanese Atomic Energy Research Institute with a capacity of 30 MTU of Japan Research Reactor No.3 (JRR–3) uranium SNF with an average burnup of 0.8 GWd/MTU. The JRR–3 SNF canister was first investigated in 1987 after 5 years' storage in a helium-gas-filled stainless steel canister (International Atomic Energy Agency, 1988). Visual inspection of the spent SNF elements and canisters revealed no defects such as cracks or corrosion. No leaky canisters were detected after conducting helium leak testing and gamma-ray measurements. Oxidation and creep tests of the intact and *a prior* defected SNF rods were conducted. Based on the test results, the allowable maximum temperatures of the dry storage system were determined to be 328 or 160 °C [622 or 320 °F] for intact or defected SNF, respectively, for a safe storage of 30 years (Kawasaki and Nakamura, 1991).

In 1997, a demonstration program for spent fuel dry storage in Japan commenced, and the related research activities have been conducted mainly by the Central Research Institute of Electric Power Industry (CRIEPI) and the Japan Nuclear Energy Safety Organization to ensure long-term integrity of the SNF and cask storage system (Saegusa, et al., 2010; Shirai and Saegusa, 2004). The demonstration tests conducted by CRIEPI included (i) a heat removal test, (ii) a canister drop test, (iii) a seismic test using the full-scale concrete casks, (iv) stress corrosion cracking (SCC) evaluation tests of the stainless steel canister, and

(v) long-term confinement performance tests of the metal cask. The testing overview and results are summarized next.

For heat removal tests, a reinforced cask and a concrete-filled steel cask were used. In both types of casks, the canister surface temperature was below 100 °C [212 °F] in the final storage stage, which is under the allowable maximum temperature limit for the short term {i.e., 175 °C [347 °F] within 24 hours} regulated in Japan. The drop tests in horizontal and vertical orientations with the full-scale multipurpose canister were conducted for nonmechanistic and impact events during handling, and the drop heights were 1 and 6 m [39 and 234 in], respectively. The test results showed that the measured helium leakage rates for both cases were under the limit of 1.0×10^{-9} Pa•m^3/sec for Japan, indicating the integrity of leak-tightness at the welded lids and canister shell after dropping. The test results indicated that the cask would not tip over and the integrity of SNF could be maintained under typical design seismic loads.

CRIEPI has evaluated SCC susceptibility of stainless steel canisters (type 304 and 312) due to salt deposition since 2004 (Shirai, et al., 2011a). The CRIEPI study focused on two key parameters: (i) minimum critical salt concentration for rust formation followed by SCC initiation and (ii) a humid wetting period during storage, causing crack growth. When considering a typical airborne salt concentration of 20 g/m^3 [1.6×10^{-10} lb/gal] at the Japan seashore, it was predicted that the SCC initiation of the stainless steel would not occur for more than 100 years. When considering temperature decrease over the lifetime of the canister surface and an actual absolute humidity at the central east coast in Japan, the estimated crack propagation length was 0.5 mm [0.02 in] and the humid period was approximately 15,000 hours during a 60-year storage period, assuming SCC can occur when the relative humidity exceeds 15 percent. CRIEPI has also explored how to mitigate the potential risk of SCC by considering (i) use of a highly corrosion-resistant canister material (e.g., UNS S31260 stainless steel and UNS S31254 stainless steel), (ii) use of engineered methods to reduce or remove salt particles contacting the canister surface, and (iii) reduction of residual stress on the welded parts.

For the long-term confinement performance test, two types of cask lid structures with a full-scale metal cask were tested: (i) a forged carbon steel cask body and lids with double metal gaskets enveloped with aluminum and (ii) a cast iron cask body and stainless steel lids with an inner metal gasket enveloped with silver and an outer rubber gasket (Shirai, et al., 2011b). Shirai, et al. (2011b) conducted confinement tests at a constant temperature of 130–140 °C [266–284 °F] to simulate the temperature at the primary lid gasket with 43 GWd/MTU PWR SNF stored. It was predicted that the lid may maintain its containment performance for more than 100 years (Shirai, et al., 2011b).

CRIEPI evaluated the long-term integrity of spent fuel rods in a dry storage environment for PWR-UO_2 SNF with a burnup of 58 GWd/tHM (Sasahara and Matsumura, 2008). After 20 years' storage in the air-filled metal cask with an initial helium gas pressure of 3.3 MPa, CRIEPI examined the postdemonstration fuel rods by various methods, including (i) visual inspection of the cladding surface, (ii) puncture test and gas analysis, (iii) ceramographic examination and hydrogen content in the cladding, (iv) hydride orientation measurement, (v) tensile test of cladding, and (vi) hydrogen redistribution under a temperature gradient along the fuel rod. The surfaces of the fuel cladding were covered with a thin oxide layer and were not different from the fuel before storage. Fractional FGR obtained by the puncture test was 2.2 percent. This fraction was not significantly different from the fraction of the irradiated fuel without storage, indicating no significant additional release of FGR during storage. The outer oxide thickness of the cladding after storage ranged from 16 to 22 µm [0.63 to 0.87 mils]. There was no marked difference of oxide thickness and grain size compared to that before storage.

Projected Demonstration Program

Some Japanese electric companies recently initiated a new demonstration program to ensure long-term safety of SNF dry storage during storage and postdemonstration transportation (Shigemune, et al., 2010). The PWR SNF that exceeded the limited amounts in the reactor pools will be stored in the Japanese first interim dry storage facility in Mutsu City, Aomori prefecture. The SNF will be stored for a maximum of 50 years, and the operation is scheduled to start in 2014. The demonstration program considers a maximum of 60 years of storage and monitoring of 2 high burnup PWR SNF assemblies (48 and 55 GWd/tHM) using a multipurpose metal canister. Initial maximum SNF temperatures for the loaded casks will be approximately 250 or 230 °C [482 or 446 °F] for SNF with burnups of 48 and 55 GWd/tHM, respectively, and the temperature of the test container will be controlled by thermal insulators. With visual inspection of SNF rods before storage, monitoring during the storage period will include (i) temperature of the outer canister surface to estimate temperature history of SNF rods, (ii) helium gas pressure to ensure containment performance at the lid boundary, and (iii) cover gas sampling every 5 years in the test container to confirm SNF leakage. Visual inspection of the outside of the canister container and maintenance of monitoring instruments will be performed periodically during the test.

Strengths and Weaknesses

Some Japanese work that may be useful in demonstration program developed in this study includes three areas: (i) SCC of metal canister, (ii) long-term confinement performance test, and (iii) long-term SNF rod tests.

Acknowledging a potential risk of SCC degradation of the metal canister, especially in a marine environment, CRIEPI has extensively evaluated SCC susceptibility of a stainless steel canister by performing both accelerated laboratory tests and field tests. The studies mainly focused on determining two important parameters: (i) critical minimum salt concentration (mainly chloride) to initiate SCC and (ii) a wetting period to grow the preexisting pits and considering several factors, such as temperature, humidity, stress level, and material type. Finally, the dry storage time for SCC initiation and the penetration depth of the preexisting pit during the wetting period were predicted under actual environmental conditions in Japan.

In long-term confinement performance tests CRIEPI conducted, the temperature was controlled at 130–140 °C [266–284 °F] for long-term monitoring. The evaluation results based on this narrow range of test temperatures would not be appropriate to apply to a higher {e.g., up to 400 °C [752 °F]} or lower temperature (e.g., room temperature). The test results and models may need to be justified to be applicable to other temperature ranges.

CRIEPI conducted a 20-year long-term SNF integrity test using a relatively high burnup PWR SNF (58 GWd/tHM), which could be valuable to complement the lack of information on especially high burnup SNF in the United States (Sasahara and Matsumura, 2008). The characterization project in the United States discussed in Section 1.2.1 was for an average burnup of 31.5 GWd/MTU. Most of CRIEPI's postdemonstration examinations after 20 year's storage are also applicable to the postdemonstration examination items identified in Section 2.3 for a demonstration program in this study, including visual inspection of SNF rod, gas pressure and composition analysis, ceramographic examination, hydrogen concentration and hydride measurement, and mechanical tests. In conducting a demonstration program in the United States, it may be beneficial to interact with Japanese counterparts and exchange any necessary technical information.

1.2.3.2 Canada

The AECL conducted a long-term SNF test exposing intact and intentionally defected CANDU SNF to moisture-saturated air at 150 °C [302 °F] for up to 93 months (Wasywich, et al., 1993, 1986; Wasywich and Frost, 1992). To test and simulate a situation in which pool storage water can be transferred on the bundle surface or in the defected elements, a moisture environment was facilitated by adding 100 ml [3.38 oz] of distilled water to the stainless steel pressure vessel with a free volume of 4.7 L [0.17 ft^3]. Some SNF were intentionally defected by drilling a 3-mm [0.12-in]-diameter hole on the SNF rods through the sheath before storage, and the average bundle burnup ranged from 6.8 to 10 GWd/MTU. Due to the low free air volume in the pressure vessel, only a small fraction of the exposed UO_2 was oxidized.

After 93 months' storage, the SNF bundles were examined using various nondestructive and destructive methods including visual inspection, end-plate/cap torque test, ring tensile test, hydrogen and deuterium analysis, fission gas analysis, dimensional measurement of SNF rods, gamma scanning, metallurgical examination, and ceramography. The SNF was further examined using various surface sensitive analysis tools to determine the extent of UO_2 oxidation. Major findings from the tests are as follows:

- There were no significant changes to SNF rods, equivalent hydrogen concentration, outer surface of stainless steel pressure vessels, and dimension. For the case of multiple fracture areas, the end-cap element showed up to a 1.2 percent increase in diameter over the predemonstration value. However, it was suspected that the fracture damage had been introduced during the predemonstration period.

- There was no migration of fission products from the SNF pellet matrix to the gap region during storage.

- There was no apparent movement of radionuclides for both intact and defected bundles; this was determined by measuring Cs-137 activity along the elements after 93 months.

- Grain boundary oxidation occurred for defected SNF rods when there was 100 ml [3.38 oz] of distilled water introduced into the test cell. On the contrary, a very thin oxide layer was present on the oxidized SNF fragments when the test was conducted in dry air only For both cases, there was no evidence of bulk oxidation of the individual UO_2 grains for intact or defected SNF.

- The presence of moisture promoted a more generally distributed oxidation of SNF grain boundaries.

Based on the observation results up to 93 months, it was concluded that the intact and defected CANDU SNF could be stored safely in a moisture-saturated environment at 150 °C [302 °F] for at least 93 months without loss of SNF integrity, although there were detectable changes in the condition of the SNF. To ensure that the integrity of SNF can be maintained for a long-term period in dry storage allowing for possible defected SNF, the Canadian study recommended that the SNF bundles and containers should be dried as thoroughly as possible before dry storage.

Strengths and Weaknesses

As described in ASTM C1553-08, an unknown amount of residual water remains in the SNF and containers after drying (ASTM International, 2008), and the Canadian study concerning moisture-related SNF degradation may be useful to gain insight into potential effects of residual water on the degradation of SNF and internal components inside the canister. This study may also help in developing the hot cell demonstration. However, the SNF type and atmosphere inside the canister would be different (i.e., the inert helium-filled canister used in the United States versus the air-filled canister with extra moisture in the Canadian experiment).

No information on degradation or integrity of other storage system components, except for SNF rods, is available from Canadian programs.

1.3 Objectives and Scope

A number of technical issues and research and data needs have emerged from recent gap assessments led by NRC, DOE, the U.S. Nuclear Waste Technical Review Board, and the EPRI-ESCP with a focus on long-term aging issues important to the performance of the structures, systems, and components of the dry cask storage systems. As part of future activities for a high burnup demonstration project, various configurations of dry storage cask systems and experiments may be used. The goals for such a demonstration include (i) benchmarking and validating the predictive models that will be developed from short-term testing for aging of dry storage cask system components and (ii) building confidence in the ability to predict the performance of these systems over extended time periods. Aging effects that can be missed in short-term studies may become apparent in the demonstration program. At present, no specific cask demonstration program has been developed to assess long term storage with aging issues (e.g., no specific selection of casks, SNF types, and test configurations); consequently, this report evaluates potential cask demonstration program options that consider various types of casks and SNF types and other parameters. These cask demonstration options are evaluated against one another to identify differences between potential program option data that can be obtained for each demonstration of extended storage of SNF in light of other program requirements, including activities that would be necessary for each option (e.g., transportation of SNF and opening cask to access SNF). Specifically, this effort will technically evaluate a range of potential cask demonstration options. However, the intent of this effort is only to provide a technical evaluation for a range of options and no recommendations of these options are provided in this report.

The key elements and factors and their variations in a cask demonstration program to support regulation of SNF storage for extended periods are examined in Section 2. A series of cask demonstration options developed by permuting the key elements and factors developed in Section 2, along with data to be obtained in determining the performance of the components, is provided in Section 3. The pros and cons of the demonstration options are summarized in Section 4.

2 KEY ELEMENTS AND FACTORS FOR CASK DEMONSTRATION PROGRAMS

To develop cask demonstration options, a number of potential cask configurations, environments, and additional parameters have been considered. In the present report, these parameters are referred to as "elements and factors" and include aspects like the SNF-assembly-type pressurized water reactor (PWR) and boiling water reactor (BWR), SNF cladding materials (Zircaloy-4, lined Zircaloy-2, Zirlo, M5), SNF burnup condition, cask system components, and environments (highly industrial, coastal/marine). Combinations of these elements and factors are used to develop the cask demonstration options.

Table 2-1 summarizes the key elements and factors to be considered and their variations in developing the cask demonstration programs.

2.1 Spent Nuclear Fuel Assemblies

2.1.1 Spent Nuclear Fuel

In the United States, PWR and BWR reactor fuels are either low enriched uranium (LEU) (UO_2) or mixed oxide (MOX) fuels. Because MOX fuel inventories are currently extremely limited, they will not be considered in the demonstration program.

During reactor operation, the fuel and cladding will undergo both compositional and structural changes, which will be related to fuel burnup. The UO_2 will generate actinides and fission products, while the cladding, structural materials, and impurities in the fuel will produce activation products. The activation products may affect the long-term disposal of SNF, but their impact on issues surrounding extended dry storage may be minimal due to their low concentrations.

Decay Heat and Neutron Activity

Xu, et al. (2005) examined the differences in total, actinide, and fission product activity for a typical PWR LEU SNF at 33 and 50 GWd/MTU. Their analysis shows that the fission product and actinide content increases roughly proportionally with discharge burnup level. As a result of the increased fission product and actinide content, the decay heat in the SNF would increase with increased burnup. Although the decay heat increases, the decay of fission products and actinides in the LEU SNF with time is similar, and after 20 years, there is a significant reduction in the decay heat. It takes roughly 10 to 20 years for the decay heat for an LEU assembly to drop below 1 kW (Sindelar, et al., 2011). Xu, et al. (2005) showed that based on the unit electricity generation, the decay power of high burnup SNF is greater than a low-burnup SNF over the period from 4 to 150 years. The decay heat will impact the evolution of cask storage temperatures with time. Also, between 10 and 100 years' cooling time, the neutron activity drops by one order of magnitude, and beyond 100 years, the neutron activity remains relatively constant (Sindelar, et al., 2011). This will impact shielding requirements for the SNF.

Storage issues related to criticality should take into account that no burnup credit is allowed for LEU-BWR SNF, and criticality safety calculations for these assemblies are based on fresh-SNF assemblies (NRC, 2005).

Table 2-1. Key Elements and Factors and Their Variations of Interests in Cask Demonstration

Elements and Factors in Cask Demonstration	Variations of Interests				
1. SNF assembly	Pressurized water reactor	Boiling water reactor			
2. SNF type	UO_2				
3. SNF burnup	High (>45 GWd/MTU)	Low (<45 GWd/MTU)			
4. SNF cooling period in SNF pool	Minimum of 5 years*				
5. Cladding material	Traditional Zircaloy–4 (high tin)	Traditional Zircaloy–2 (regular/improved with Zirconium lining)	Zirlo	M5	Others†
6. SNF rod condition	Intact	Partially defective (pinhole breach)	Damaged and canned		
7. Dry cask storage system type	a) Canister-based storage system (mostly welded)	Vertical configuration in bolted overpack			
		Horizontal configuration in concrete storage module or vault			
	b) Direct-load metal cask storage system (generally bolted and thick walled in vertical configuration)				
8. Cask system components	a) Canister-based storage system with stainless steel canister body, concrete overpack, or concrete module				
	b) Direct-load metal cask storage system with carbon steel or cast iron cask body, gaskets (metallic and/or polymeric), closure bolts and seals				
	Neutron absorbers (Boral, borated stainless steel, Metamic)	Aluminum-based or steel baskets	Polymeric shielding material		
9. Demonstration site environment	Seasonal inland	Coastal/Marine	Highly industrial		
10. Bolted metal cask opening frequency, years	5	10	15		
11. Predemonstration examination	The predemonstration examination of SNF rods being stored in the test and sibling rods serve as the baseline for comparison with results from the postdemonstration examinations.				
	Nondestructive examination (NDE) and destructive examination (DE) of SNF NDE: Visual examination, rod diameter measurement, profilometry, eddy current measurement of oxide thickness and locating cladding defects, measurement of Kr-85 activity in the plenum, vacuum sipping for radionuclide leaking, ultrasonic testing for water inside rod, axial gamma scan to determine fission product movement for cesium and total activity DE: Examination of cracks on inner and outer surfaces of cladding, gap between cladding and the SNF matrix, cladding microstructure and properties at different locations of the rod, such as midplane, above, and below midplane to observe hydrogen migration and other degradation caused by thermal gradient; thickness of the interior and exterior oxide layers; hydrogen concentration and distribution; microstructure of the hydrides; cladding fracture toughness measurements; cladding creep measurements; microhardness, yield strength; ultimate strength; ductility; fission gas; heat-affected zones, such as spacer, bearing pad, welded locations, SNF condition at rim, and interior; SNF grain size; fission gas release to the rod plenum; CRUD thickness; other SNF parameters on the gas, volatile, fines, and CRUD source terms; rod internal pressure; void volume, gas composition				

Table 2-1. Key Elements and Factors and Their Variations of Interests in Cask Demonstration (continued)

Elements and Factors in Cask Demonstration	Variations of Interests			
12. Monitoring and surveillance during-demonstration ‡	a) For canister-based storage system	Periodic inspection for cracking or other degradation of concrete module or bolted overpack		
		Periodic inspection for canister cracking, external corrosion		
	b) For direct-load metal cask storage system	Periodic visual inspection for coating degradation and external corrosion		
		Periodic examination of bolts and seals		
		Periodic removal of SNF and other internals for destructive examination		
	c) Generic for both systems without additional confinement penetration	*In-situ* monitoring of "airborne" contamination for gaseous and volatile fission products, storage system pressure, external temperature, relative humidity, corrosion of metal reinforcement		
		Periodic radiation monitoring (external monitoring of gamma spectra and neutron and gamma dose)		
		Periodic monitoring of surface debris buildup including salts and particles		
		Periodic monitoring of concrete pad degradation		
	d) Advanced monitoring for both systems requiring confinement penetration	Periodic sampling of backfill gas without opening the cask for analysis of gas thermal conductivity; backfill gas composition including gamma spectroscopy for Kr-85; compositional analysis for O_2, H_2O, helium, and H_2		
		Internal temperature monitoring at varied locations of individual SNF rods, SNF assemblies, and cask		
		Internal camera inspection for SNF cladding and cask internal conditions including corrosion, cracking or swollen SNF, other material degradation		
13. Postdemonstration examination	All as in Item 11, predemonstration examination and cladding integrity (e.g., cracks and fragmentation) and materials dispersion (e.g., fines)			
	Cask and assembly measurement: cask exterior surface, bolts, SNF assembly temperatures, cask surface gamma and neutron dose rates, visual inspection of cask external/internal surfaces, SNF basket components, SNF assembly exteriors, primary lid seals, analysis of cask interior CRUD samples, analysis of helium backfill gas samples			
14. Most adverse expected normal conditions	Incomplete drying with the presence of moisture	Cladding defects (e.g., pinhole breaches)	High burnup SNF	Low burnup SNF

*For a demonstration program that begins a with new cask or hot cell, the minimum of 5 years may need to be adjusted if future change indicates a shorter cooling period or a higher heat load SNF would be used.

†For a demonstration program that begins a with new cask or hot cell, the cladding materials may need to be adjusted if future change indicate other cladding materials would be used.

‡Every site is different, and no two casks are identical. This item needs to be performed as much as feasible.

SNF Condition

During reactor operation, SNF and cladding undergo significant changes that can impact the performance of the SNF under dry storage conditions, particularly for SNF irradiated to burnups beyond 45 GWd/MTU. Hanson, et al. (2011) and Sindelar, et al. (2011) have discussed these changes in detail.

For SNF pellets, in-reactor operation results in microstructural changes, cracking, and fission product buildup that increase with increased burnup. The SNF pellet develops cracks by thermal and irradiation effects which results in fragmentation that enables fission gas release (FGR) to the cladding gap. The quantity of fission gases, such as xenon and krypton released to the SNF/cladding gap increases with increasing burnup (duty cycle operating temperature, power level). During high burnup operation, a rim is produced at the pellet surface, which has higher porosity, lower thermal conductivity, and higher burnup than the bulk SNF. As the fuel burnup increases, more fission products are generated and swelling occurs in the pellet matrix. This swelling occurs in response to the internal gas formation from fission gas production and production of He gas from alpha-decay and their coalescing into high pressure bubbles in the matrix. When assessing the choice of SNF for a dry storage demonstration, it is important to consider the burnup and power history, which can result in differences in the physical integrity of both the SNF and cladding.

During storage in the SNF pool, cladding defects in SNF could result in (i) oxidation of the SNF by reaction with water or water radiolysis products within the rod and (ii) the release of fission gases, fission products, or actinides through the defect. Pinhole defects or hairline cracks may not compromise the use of SNF in a dry storage cask. These possibilities need to be considered when assessing the initial condition of the SNF rods and their inclusion in a dry storage cask demonstration program.

Sindelar, et al. (2011) concluded accurate data are needed to support the extrapolation of FGR and pellet swelling and their impact on cladding stress during storage. Additionally, the lower thermal conductivity of the rim in high burnup SNF will result in higher pellet centerline temperatures during storage; however, since the rim will also restrict heat transfer, the cladding temperature will not increase.

Under off-normal conditions, such as failed SNF or cladding during storage, SNF could be potentially exposed to air/oxygen or react with water radiolysis products and oxygen, which will lead to oxidation from UO_2 to U_3O_8 and result in powdering of the SNF. Some evidence suggests that high burnup SNF may be more resistant to oxidation, so there may be less concern or risk for high burnup SNF compared to low burnup SNF, depending on temperature.

Einziger and Beyer (2007) have detailed the source term for radionuclide releases from failed SNF. This includes the effects of pellet rim; SNF grain size; FGR; CRUD thickness; cladding oxide thickness; and other SNF parameters on the gas, volatile, and SNF fines as source terms of high burnup SNF (Sindelar, et al., 2011). These source terms would need to be addressed if there is the potential for either oxidation of the SNF during pool storage or failure of a SNF rod during dry storage under off-normal conditions.

The degradation issues of SNF that could potentially affect SNF integrity during extended storage and transportation are not discussed in this report, but they are summarized in Table 2-2 based on recent U.S. Nuclear Regulatory Commission (NRC) (Sindelar, et al., 2011), U.S. Department of Energy (DOE) (Hanson, et al., 2011), U.S. Nuclear Waste Technical Review

Board (NWTRB) (2010), and EPRI (2011) investigations into dry cask storage material degradation mechanisms.

Table 2-2. Summary of Materials Degradation Issues* and Mapping of Issues to Cask Demonstration Options in Section 3

Spent Nuclear Fuel and Structures, Systems, and Components		Degradation Under Extended Storage and Transportation	Related Items in Table 2-1	Demonstration Options in Section 3 To Address Degradation Issues
Cladding		Off-normal air oxidation	1–6	None
		Hydrogen embrittlement	1–6	A, B, C, D, E-Alternate, F, G, and G-Alternate
		Delayed hydride cracking	1–6	A, B, C, D, E-Alternate, F, G, and G-Alternate
		Annealing of radiation damage	1–6	A, B, C, D, E-Alternate, F, G, and G-Alternate
		Low temperature creep	1–6	A, B, C, D, E-Alternate, F, G, and G-Alternate
		Stress corrosion cracking and fission product attack on cladding	1–6	A, B, C, D, E-Alternate, F, G, and G-Alternate
		Galvanic corrosion	1–6	A, B, C, D, E-Alternate, F, G, and G-Alternate
		Propogation of existing flaws	1–6	A, B, C, D, E-Alternate, F, G, and G-Alternate
Spent Nuclear Fuel		Off-normal air oxidation	1–6	None
		Fragmentation, restructuring-swelling, , oxidation under normal condition, rim structure degradation, fission gas release during accident, He release	1–6	A, B, C, D, E-Alternate, F, G, and G-Alternate
Spent Nuclear Fuel Assembly Hardware		Wet corrosion and stress corrosion cracking, metal fatigue caused by temperature fluctuations	1	A, B, C, D, E-Alternate, F, G, and G-Alternate
Canister-Based Storage System (Mostly dual-purpose canister system, welded canister in bolted overpack or concrete storage module)	Canister body and weld (stainless steel)	Atmospheric corrosion (pitting and crevice corrosion including marine environment), stress corrosion cracking near the marine or highly industrial environments, aqueous corrosion	7a	A, B, C-Alternate, D, E F, and G
	Concrete and steel overpack or concrete vault-type overpack	Corrosion of embedded steel, freeze–thaw	7a	A, B, C-Alternate, D, E F, and G

Table 2-2. Summary of Materials Degradation Issues* and Mapping of Issues to Cask Demonstration Options in Section 3 (continued)

Spent Nuclear Fuel and Structures, Systems, and Components		Degradation Under Extended Storage and Transportation	Related Items in Table 2-1	Demonstration Options in Section 3 To Address Degradation Issues
Direct-Load Metal Cask Storage System (Generally bolted, thick-walled)	Steel cask (carbon steel, nodular cast iron, low-alloy steel)	Atmospheric corrosion (including marine environment), aqueous corrosion	7b	A, B, C, D, E-Alternate, F, and G-Alternate
	Metallic seals and gaskets	Stress relaxation, crevice corrosion, microbial influenced corrosion, plastic deformation, creep, thermo-mechanical fatigue	7b	A, B, C, D, E-Alternate, F, and G-Alternate
	Bolts	Corrosion, stress corrosion cracking, creep, thermo-mechanical fatigue, embrittlement	7b	A, B, C, D, E-Alternate, F, and G-Alternate
SNF Basket (Stainless steel, aluminum, Inconel, carbon steel)		Loss of geometry due to creep, metal fatigue, general corrosion, galvanic corrosion, weld embrittlement	8	A, B, C, D, E-Alternate, F, G, and G-Alternate
Neutron Absorbers (Borated stainless steel; other metals; metal matrix composites, such as Boral, Metamic)		Corrosion (blistering), thermal aging effects, creep, embrittlement, and cracking	8	A, B, C, D, E-Alternate, F, G, and G-Alternate
		Oxidation-induced mechanical property changes leading to slump within the overpack	8	A, B, C, D, E-Alternate, F, G, and G-Alternate
Reinforced Concrete Pad		Corrosion of steel in reinforced concrete leading to concrete spallation and loss of structural function for cask and retrieval equipment foundation, freeze–thaw cycle, effect of elevated temperature	9	All

*Based upon the following references:

- EPRI (Electric Power Research Institute). "Extended Storage Collaboration Program Progress Report and Review of Gap Analyses." EPRI 1022914. Palo Alto, California: Electric Power Research Institute. 2011.
- Hanson, B., H. Alsaed, C. Stockman, D. Enos, R. Meyer, and K. Sorenson. "Draft Report: Gap Analysis To Support Extended Storage of Used Nuclear Fuel." FCRD–USED–2011–000136. PNNL–20509. Washington, DC: U.S. Department of Energy. 2011.
- Sindelar, R.L., A.J. Duncan, M.E. Dupont, P.-S. Lam, M.R. Louthan, Jr., and T.E. Skidmore.
- NUREG/CR–7116, "Materials Aging Issues and Aging Management for Extended Storage and Transportation of Spent Nuclear Fuel." SRNL–STI–2011–00005. Washington, DC: U.S. Nuclear Regulatory Commission. 2011.
- NWTRB (U.S. Nuclear Waste Technical Review Board). "Evaluation of the Technical Basis for Extended Dry Storage and Transportation of Used Nuclear Fuel." Washington, DC: U.S. Nuclear Waste Technical Review Board. 2010.

2.1.2 Cladding

Various zirconium-based nuclear fuel cladding materials have been developed for commercial reactor applications. Traditional nuclear fuel cladding for light water reactors is fabricated from two zirconium-tin alloys—Zircaloy-2 (Zr-1.5Sn-0.12Fe-0.1Cr-0.05Ni in wt%) in BWRs and Zircaloy-4 (Zr-1.5Sn-0.2Fe-0.1Cr in wt%) in PWRs—because of their low neutron cross sections and excellent corrosion resistance to a variety of environmental conditions. Zircaloy-4 is a nickel-free variant of Zircaloy-2 with similar corrosion resistance. The absence of nickel in Zircaloy-4 as an alloying element has been shown to reduce hydrogen pickup in high-temperature water. Zircaloy-4 is used in PWRs because more reducing conditions prevail in the core of a PWR reactor as a result of hydrogen overpressure, which tends to promote hydrogen entry. The specifications of these two reactor grade zirconium-tin alloys are provided in ASTM B811–02 (ASTM International, 2007).

In recent years, better corrosion resistance has been required to assure fuel reliability and improve fuel cycle economy by increasing fuel burnup through longer cycle operation, longer total residence time, and higher heating rating. This need for better corrosion resistance has prompted refinements in Zircaloy-4 composition (e.g., lower tin content) and an improved cladding fabrication and control process. Optimized Zircaloy-4 was developed with iron in the upper range of the ASTM B811–02 specification and an optimized microstructure (Garzarolli, et al., 2001). Daum, et al. (2006) and Einziger, et al. (2005) expressed concern that the mechanical integrity of Zircaloy cladding degrades as the burnup increases because of a higher susceptibility to premature fracture resulting from hydride-induced embrittlement, wall thinning by oxidation, and other degradation mechanisms during SNF handling, storage, and transportation. Other advanced zirconium alloys have been developed to improve the in-reactor fuel performance, thereby relieving the burnup limitation.

Two zirconium-niobium alloys, which have been successfully introduced into commercial reactor cores, are Zirlo (Zr-1Nb-1Sn-0.1Fe in wt%) and M5 (Zr-1Nb-0.04Fe in wt%) developed by Westinghouse and AREVA, respectively. Sabol (2005) reviewed development of the Zirlo alloy for PWR applications. The addition of small amounts of tin and iron improves corrosion resistance and mechanical strength of zirconium-niobium alloys. Zirlo improved in-reactor performance relative to Zircaloy-4 at high burnups by lowering the corrosion rate by about 40 percent, reducing the growth rate in the longitudinal direction by about 40 percent, and lowering the diametral creep rate by about 20 percent (Sabol, 2005). To further improve the corrosion resistance of Zirlo in the environment, optimized Zirlo was developed with a tin level reduced to a range of 0.6 to 0.8 wt%. As a result, optimized Zirlo has been approved for use in PWRs since 2005.

The M5 alloy contains no tin and has a fully recrystallized microstructure that remains stable under irradiation (Mardon, et al., 2010). This stable microstructure is the result of a low-temperature aging process, providing optimum size and distribution of the β-Nb precipitates in the zirconium matrix. The absence of tin in M5 contributes greatly to its high corrosion resistance. Under high-duty and high burnup conditions, the oxide layer thickness for M5 in PWRs was less than 40 μm [1.6 mil], and the hydrogen pickup was low with a hydrogen content less than 100 ppm. The M5 alloy is currently the reference alloy for SNF rod cladding for all AREVA PWR designs.

Among the most important factors associated with the initial condition of the SNF cladding prior to dry storage is the burnup. High burnup increases the thickness of the oxide layer on cladding, the amount of absorbed hydrogen in cladding, the fission gas production, and the internal SNF rod pressure. These material changes could potentially reduce the structural integrity of the cladding. A number of degradation mechanisms have been identified that could affect the performance of the SNF cladding during extended SNF storage and subsequent transportation, including hydrogen embrittlement, delayed hydride cracking, oxidation, creep, and others (Hanson, et al., 2011; Sindelar, et al., 2011; NWTRB, 2010; EPRI, 2011). Degradation issues are not discussed in this report, but they are summarized in Table 2-2. Confirmatory data on the long-term performance of SNF cladding would be necessary to support dry storage and transportation of high burnup SNF for extended periods of time. Residual water from the cask drying process could affect degradation of cask system components, which will be addressed elsewhere.

2.2 Cask System Components

Dry storage systems provide several key functions for maintaining safe storage and ready retrieval of SNF, including providing shielding, removing decay heat, maintaining subcriticality, and maintaining a confinement barrier to prevent release of radioactive material and maintain an inert environment for the SNF assemblies. Dry storage systems come in several design variations; however, the major designs can be grouped loosely into two main types: (i) metal-storage-cask-based systems where assemblies are loaded directly into a cask and (ii) canister-based systems where assemblies are loaded into a relatively thin-walled canister that is stored in an overpack or module (Hanson, et al., 2011).

Generic schematics for the two main types of dry storage systems are included in Figures 2-1 and 2-2. Some examples of metal storage system designs include the General Nuclear Systems, Inc., Castor V/21, X/32, and X/33; the Transnuclear, Inc., TN series of casks [TN–(24/32/32/40/68)]; and the Westinghouse MC–10. Examples of canister-based systems include the Holtec International HI–STAR 100 and HI–STORM 100; the NAC International, Inc., NAC–MPC, NAC-UMS, and the MAGNASTOR systems; and the Transnuclear NUHOMS® System.

For the canister-based systems, several design variations merit discussion. The majority of canister-based designs emplace the canister vertically within the overpack structure. However, some designs load and store the canister in a horizontal configuration, similar to that depicted in Figure 2-2. Another design variation that has been introduced with the intent of reducing seismic risks (cask tipover) and lowering the profile of the storage cask is the loading of canisters into below-grade vaults or modules. Lastly, in more recent cask designs, the trend has been toward increasing the amount of SNF assemblies that can be stored in a single cask (Hanson, et al., 2011). For example, some newer large cask systems can store up to 37 PWR or 87 BWR SNF assemblies in comparison to other systems that load up to 32 PWR or 68 BWR assemblies.

The components typically considered important to safety, as described in NUREG/CR–6407 (McConnell, et al., 1996), are identified for the two main types of dry storage systems depicted in Figures 2-1 and 2-2. In general, dry cask storage systems consist of a large number of components and materials that can vary by design. Here, the discussion of cask system components will focus on those that are considered most important in terms of long-term degradation for both types of cask systems (NWTRB, 2010).

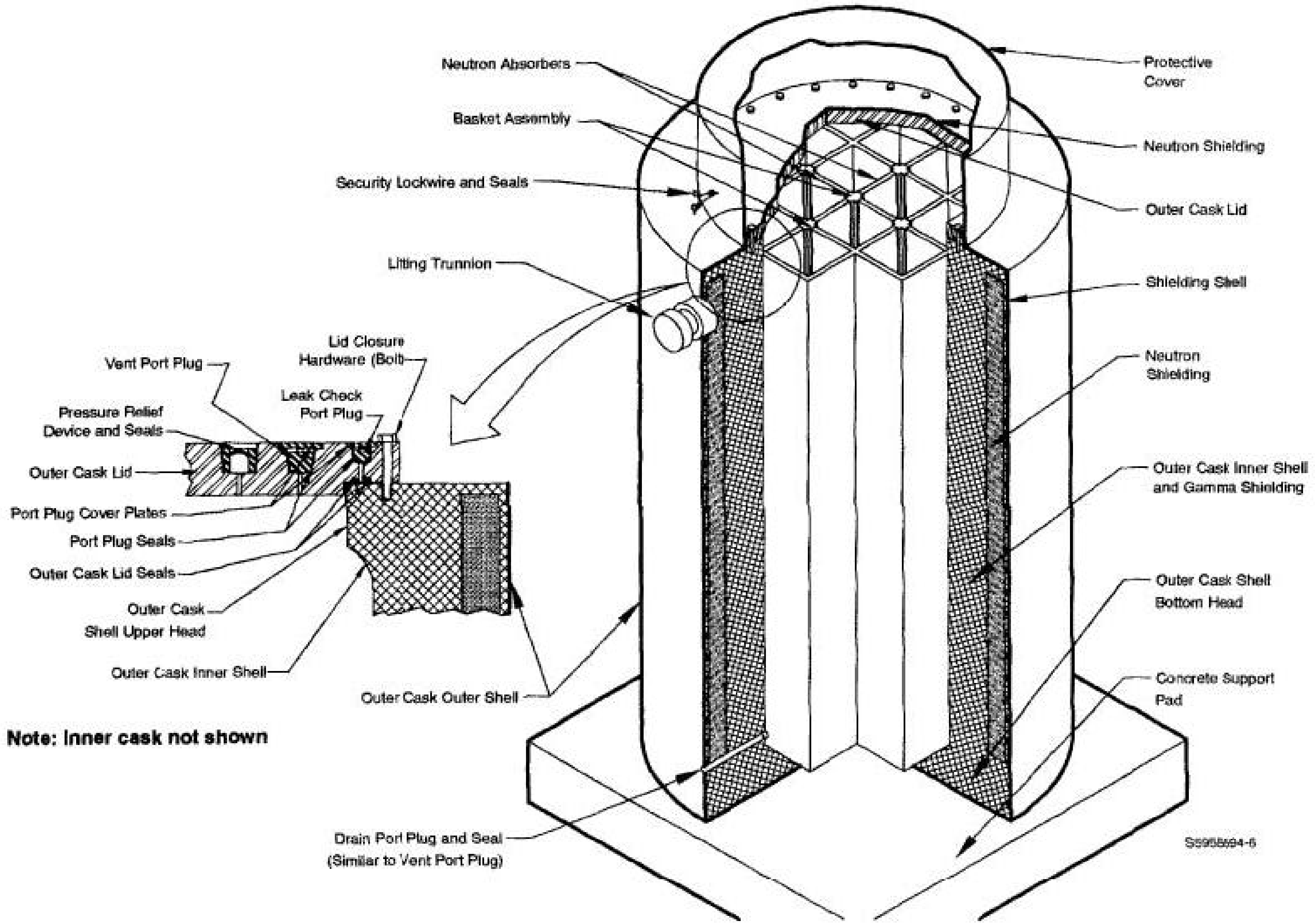

Figure 2-1. Schematic of a Hypothetical Metal Cask Dry Storage System (McConnell, et al., 1996, Figure 8)

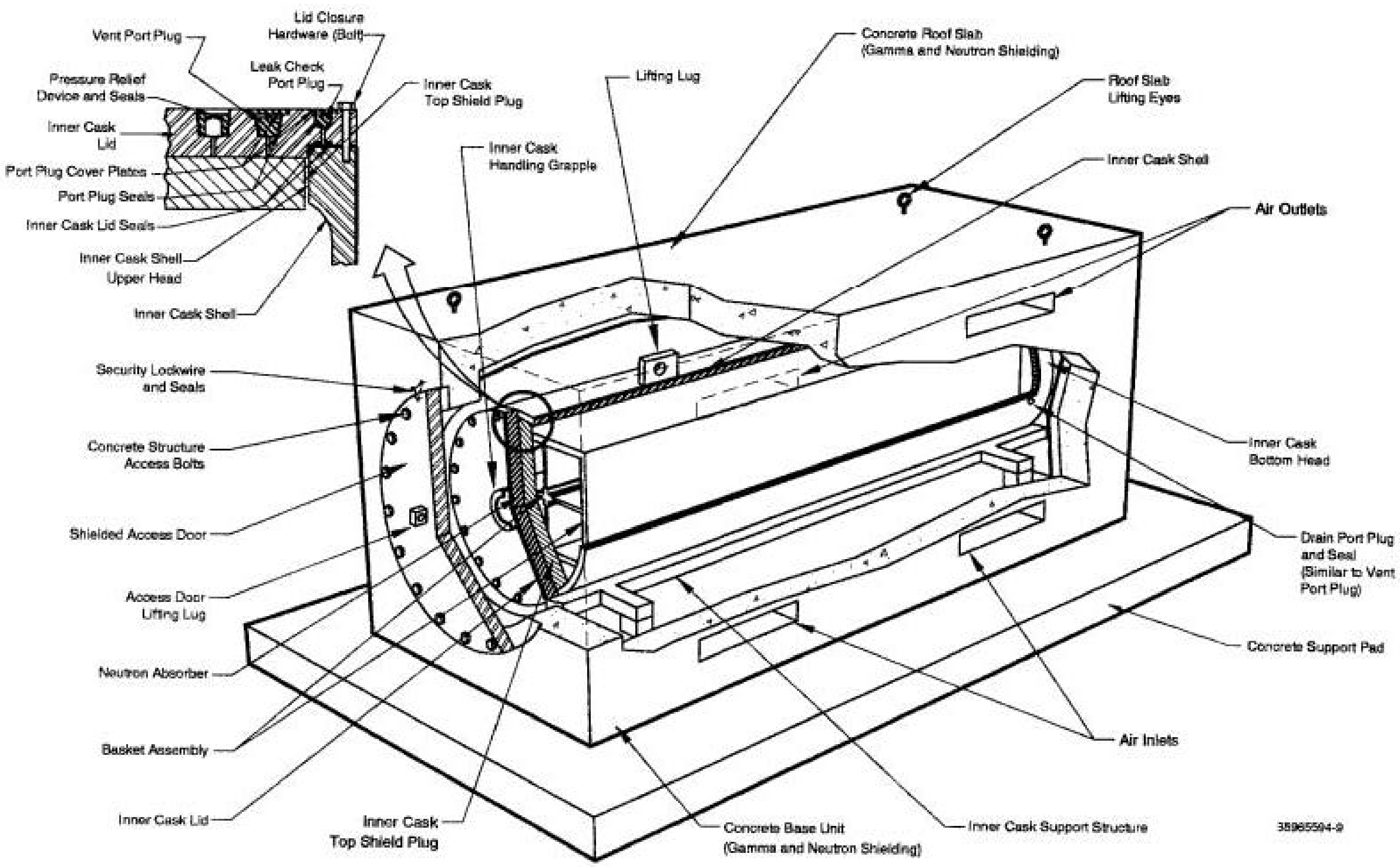

Figure 2-2. Schematic of a Hypothetical Canister-Based Dry Storage System (McConnell, et al., 1996, Figure 9)

One of the major components for a dry cask system is the confinement barrier. The dry cask system confinement relies on the sealing of the metallic canister or cask vessel. When sealed, the confinement vessel is filled with an inert gas (e.g., helium or nitrogen). Canisters are typically composed of stainless steel materials and are sealed by welding. For direct-load metal casks, sealing of the confinement environment is most commonly achieved via vessel closure from primary and secondary lids, which are fastened to the metal cask vessel using bolts and gaskets made from metallic or elastomeric materials. The materials used for metallic cask vessels are typically nodular cast iron, carbon steel, low-alloy steel, forged steel, and stainless steel (NWTRB, 2010). Materials used for confinement lids include 304/304L SS, 193 Gr B7, 230 Gr L43, SB637 Gr N07718, SA 564, and Type 630 H1150 (NWTRB, 2010). Commonly used gaskets are Inconel X730 spring, aluminum jacket, Nimonic 90 spring, Inconel X750, aluminum, and 304L SS for metallic gaskets and ethylene propylene copolymer, silicone rubber, propylene, Viton, and polytetrafluoroethylene for elastomer gaskets (NWTRB, 2010).

Another component for consideration is the SNF basket assembly. The SNF basket assembly consists of the SNF basket and neutron absorbers and plays an important role in maintaining subcriticality by keeping the SNF assemblies and neutron-absorbing material in a favorable geometry. Examples of neutron absorber materials used in the SNF basket assemblies include metal matrix composites like the boron carbide/aluminum matrix that may be clad in aluminum (e.g., Boral) (NWTRB, 2010). In some cases, neutron-absorbing materials are incorporated directly into the basket material (e.g., borated stainless steel). Materials typically used for the SNF basket include 304SS with boron, 6061–T651 aluminum, SA 705 Type 630 SS, Inconel, SA 516 Gr 70, and 479 SS (NWTRB, 2010).

Lastly, storage system shielding materials are important components that may be subject to degradation. For systems with thick metal walls, the steel or iron materials provide shielding from gamma radiation. Storage system concrete structures (e.g., overpack or module) can provide shielding from both gamma and neutron radiation and are important components that are subject to degradation. Lead (ASTM B–29 chemical lead) is often imbedded inside cask walls or end caps to provide additional gamma shielding (NWTRB, 2010). Neutron-shielding materials are also inserted between layers of steel or concrete. The materials used are typically polyethylene, polypropylene, and borated polymer shielding (NWTRB, 2010).

The degradation of cask system components that could potentially affect cask integrity during extended storage and transportation is not discussed in this report, but is summarized in Table 2-2 based on recent investigations into dry cask storage material degradation mechanisms by NRC (Sindelar, et al., 2011), DOE (Hanson, et al., 2011), NWTRB (2010), and Electric Power Research Institute (EPRI) (2011). Residual water from the cask drying process could affect degradation of cask system components, which will be addressed elsewhere.

2.3 Examination and Monitoring for Cask Demonstration

This section describes the items identified for examination before and after demonstration and the items to be monitored during the demonstration period, and how the examination and monitoring relate to determining the performance of dry storage system components.

2.3.1 Predemonstration Examination of Spent Nuclear Fuel

Predemonstration examination of SNF rods determines the initial conditions before storage. The examination results serve as the baseline data to compare with the results from the postdemonstration examinations to determine the performance of dry storage system components. SNF rods can be examined by either nondestructive examination (NDE), destructive examination (DE), or both types of methods. The NDE testing can include

- Visual inspection of SNF rod assemblies to examine visible defects or deposits
- Diameter measurement and profilometry of SNF rods to determine rod ovality
- Eddy current measurement of oxide thickness and presence and location of cladding defects (cracking and/or pinholes)
- Measurement of Kr-85 activity in the SNF rod plenum and vacuum sipping for radionuclide leaking
- Ultrasonic testing for water inside rod

For DE, such as metallography and hydrogen analysis of the SNF rods, several segments of SNF rods can be taken at the different positions along the rod height because the rods are exposed to varying temperature and radiation fields during in-reactor operations and cracks can form on the inner and outer cladding surface. Rods can be characterized in terms of microstructures, SNF-cladding gap, SNF rod diameter, cladding oxide thickness, hydride content and orientation, and hydrogen distribution in the cladding. To measure the outer and inner oxide thickness of cladding, optical tools, such as transverse ceramography, can be applied. For hydrogen analysis, the SNF may need to be removed chemically and the hydrogen content and distribution in the cladding can be measured in accordance with the procedures described in ASTM E1447–09 (ASTM International, 2009). Mechanical properties, such as cladding fracture toughness, hardness, yield and ultimate strength, ductility, and creep, can also be characterized to support the predemonstration examination results.

The initial rod internal pressure primarily results from helium gas backfill, and FGR from the SNF into the rod void volume can be determined by gas analysis with rod puncture and void-volume measurement. Gas composition analysis can include helium and fission gases (e.g., C-14, xenon, and krypton). The measurement results can be used to estimate possible FGR during the storage period.

Additionally, NDE and DE can characterize some sibling rods along with the rods to be stored and left in the water pool for later examination at the end of demonstration. The data obtained from the sibling rod examination can be used to further support the baseline data in terms of data accuracy and uncertainty in comparison with the results from the postdemonstration examination of rods after dry storage.

All the examinations are summarized in Table 2-1, Item 11.

2.3.2 Monitoring and Surveillance During Demonstration

During the demonstration period, monitoring and surveillance of the storage system are needed to ensure safe operation of dry storage facilities at the sites and to determine the performance of SNF and storage system components. Every site is different, and no two casks are exactly the same. Monitoring and surveillance should be performed as much as possible. Some monitoring techniques can be done by *in-situ* methods or periodic monitoring without modifying the system; however, some (i.e., canister-based systems) advanced monitoring will require system modification (e.g., drilling a hole in confinement). In foreign cask programs (Shigemune, et al., 2010), cask monitoring (e.g., pressure) has been implemented using penetrations. However, current U.S. regulations would not allow cask penetrations for monitoring. Advanced monitoring using cask penetration(s) requires license exemptions.

The monitoring and surveillance that can be done without system modifications

- "Airborne" contamination for possible gaseous and volatile fission products
- External temperature, relative humidity, and corrosion of metal reinforcement monitoring
- Visual inspection for external coating degradation, canister cracking, external corrosion, concrete pad degradation, and buildup of surface debris including salts and particles
- Radiation (external monitoring of gamma spectra and neutron and gamma dose)

The advanced monitoring and surveillance items that require license exemption in the United States for additional confinement penetration prior to demonstration include the following:

- Canister pressure
- Internal temperature at varied locations of individual SNF rods, SNF assemblies, and casks
- Internal camera inspection for SNF cladding and cask internal conditions including corrosion, swollen SNF, and other material degradation, which may be very difficult to operate
- Sampling of backfill gas without opening the cask for analysis of gas thermal conductivity; backfill gas composition including gamma spectroscopy for Kr-85; and mass spectroscopy and radiochemical analysis for O_2, H_2O, helium, and H_2. The radioactive gases are indicative of cladding integrity. The compositions of O_2, H_2O, helium, and H_2 gases are indicative of the amount of residual water from the cask drying process, radiolysis decomposition, and consumption of water.

If there is visible corrosion or degradation of the storage system components, such as metal welded parts or the concrete pad, these should be examined more exclusively to reevaluate their structural integrity to maintain the extended storage period.

If gas sampling shows a marked increase in concentration of fission gases in the backfill gas, the system can be opened and the SNF and other internals can be removed for DE.

All monitoring and surveillance procedures during demonstration are summarized in Table 2-1, Item 12.

2.3.3 Postdemonstration Characterization

Postdemonstration examinations should be comprehensive to evaluate the effects of storage on the integrity of SNF rods and the storage system. By comparing pre- and postdemonstration examination results, it is also possible to estimate potential degradation of the SNF rods and storage system during very long extended storage periods, such as beyond 100 years. Before opening the canister, the parameters monitored during demonstration (e.g., temperature, gas pressure and composition, and radiation) should be remeasured to confirm the safety and final conditions.

The postdemonstration examination items should include all items that were performed for predemonstration examination, especially for comparison purposes. These include

- Visual inspection of SNF rods; internal surface of canister and lids; metal and polymer gaskets; and internal structures, such as SNF assembly hardware, SNF basket, neutron absorber, and neutron shielding
- SNF microstructure characterization to determine grain size, fission product distribution, and possible grain boundary oxidation
- SNF rod diameter measurement using profilometry
- Examination of cladding integrity (e.g., for presence of cracks, fragmentation), materials dispersion (e.g., fines)
- Metallography of cladding to measure the outer and inner oxide thickness
- Mechanical testing of the cladding to obtain several mechanical properties, such as tensile and creep strength, hardness, and ductility
- Hydrogen and hydride analysis of the cladding to evaluate any detrimental hydrogen pickup and redistribution due to thermal diffusion, and hydride reorientation to the radial direction
- CRUD or any deposits on the SNF assemblies
- For the bolted canister, NDE and DE of bolts

All postdemonstration characterizations are summarized in Table 2-1, Item 13.

2.4 Storage Site Environment

As mentioned in Section 2.2, most dry storage systems use canisters that are made of austenitic stainless steel, including UNS S30400 (304 stainless steel), UNS S30403 (304L stainless steel), UNS S31600 (316 stainless steel), and UNS S31603 (316L stainless steel). The stainless steel canisters are placed either horizontally in concrete vaults or vertically inside steel and concrete outer casks that provide radiation shielding. The vertical outer storage casks and the concrete vaults are designed with air passages for passive air circulation so that the environment surrounding the cask interacts with outside air. Therefore, the stainless steel canisters may be subject to potential atmospheric corrosion over time. Other metallic and nonmetallic components, such as the concrete overpack, coating of the dry storage system, and the concrete pad, also undergo atmospheric degradation with time.

A variety of atmospheric factors, climatic conditions, and air–chemical pollutants determines the corrosiveness of the atmosphere and contributes to the degradation process in distinct ways. Metallic components often degrade through various corrosion processes. Degradation mechanisms relevant to concrete structures include corrosion of reinforcing steel, chloride attack, alkali–silica reactions, sulfate attack, carbonation, freeze–thaw, dry out, shrinkage, creep, thermal fatigue, aggregate growth, decomposition of water, and leaching of calcium (Sindelar, et al., 2011). The environment is typically categorized as rural, marine, urban, and industrial, and the material degrades by different mechanisms in each of these environments.

Climatic factors that can directly affect material degradation are sun radiation; air temperature; relative humidity; air chemistry; precipitation; winds; and the mechanical and chemical action of natural forces, such as sand and rock particles, soil dust, volcanic dust, organic matter, and industrial dust. The atmospheric degradation process can be further complicated and accelerated when micro- and/or macroorganisms are present. In humid tropical and subtropical climates, microbial corrosion or biocorrosion is commonly observed.

The most important factors affecting atmospheric degradation are

- Temperature and relative humidity, and their temporal variation
- Air chemistry
- Annual precipitation
- Time of wetness, during which moisture exists on the metal surface and corrosion may occur; this moisture layer on the metal surface can be generated by rain, fog, snow, dew condensation, capillary condensation, and salt deliquescence.
- Content of chlorides (airborne salinity) and sulfur dioxide (SO_2) in atmosphere

The particles in the urban environment tend to have higher percentages of elemental carbon and organic carbon, and the rural particles are relatively higher in sulfate ion. The urban and rural environments are more benign compared to the marine and industrial environment. Depending on the location of the cask storage site, the extent of degradation of system components will be different.

Coastal Marine Environment

In marine environments, the chloride-containing atmospheric aerosols that are ubiquitous under such conditions, combined with high relative humidity levels, can lead to corrosion of the canister itself, along with the sealing system (i.e., welds, bolts, or metallic seals). Localized corrosion (i.e., pitting or crevice corrosion) may take place whenever sufficient moisture and contamination are present. In addition, in locations where dissimilar metals are in contact, such as where a metallic seal contacts the container body or lid, galvanic corrosion could potentially take place. In regions where sufficient stress is present, such as within bolts or in the heat-affected zone around welds, SCC may take place. In all cases, the actual corrosion mechanisms, if any, that become active will be dictated by the environment and the materials under consideration. The potential impact of corrosion on a storage container will be controlled by the operative corrosion mechanisms over the period of performance of the storage system as well as the period over which the corrosion occurred.

The factors that influence marine atmospheric corrosion include moisture and time of wetness, temperature, material composition, airborne contaminants (e.g., chlorides, sulfur dioxide, carbon dioxide), and solar radiation. The location (i.e., the proximity to the ocean), elevation above sea level, sunlight, prevailing winds and wave action, and the shelter of a component also strongly influence corrosion behavior (Gustafsson and Franzén, 1996; Meira, et al., 2006; Larrabee, 1953).

The tendency of the canister to crack when exposed to marine environments is dependent on the salt content, temperature, relative humidity, and stress. The salt deliquescence and efflorescence occur at specific relative humidity values at a given temperature. Because of the kinetic effects, the deliquescence and efflorescence relative humidity values are not typically equal and the relative humidity where a salt undergoes efflorescence can be significantly lower than the relative humidity for salt deliquescence. Salts will deliquesce at various relative humidities depending upon their unique chemistry (Twomey, 1953; Owens, 1926; Winkler, 1988). The concentration and composition of atmospheric sea salts vary by geography. However, the typical constituents dictating the deliquescence and efflorescence points tend to be sodium and magnesium chlorides, or the mixed salt effects.

Highly Industrial Environment

In a highly industrial environment, chlorides (airborne salinity) and sulfur dioxide (SO_2) are the principal pollutants in the atmosphere that can accelerate certain types of corrosion by several orders of magnitude. The principal source of chlorides is aerosols from the contaminated environment around industrial plants which produce hydrogen chloride and sodium hypochloride. SO_2 gas is found in urban and industrial atmospheres and, in the presence of oxygen, is easily converted to sulfuric acid in the condensed moisture layer on the metal surface, which results in a lower pH (often below 4.5). The addition of SO_2 air contamination (acid rain) results in a highly accelerated corrosion rate. Some atmospheric gases, such as carbon dioxide (CO_2), nitrogen dioxide (NO_2), ozone (O_3), ammonia (NH_3), hydrogen sulfide (H_2S), and hydrogen chloride (HCl), and organic acids, such as formic (HCOOH) and acetic (CH_3COOH), are also known to be highly corrosive for several commonly used metals. Most aerosol particles absorb water, increasing the wet period and the corrosive process.

3 CASK DEMONSTRATION OPTIONS

This section describes the approaches to develop the cask demonstration options and the details of the proposed seven cask demonstration options, and analyzes the demonstration activities and data to be obtained from each option.

3.1 Approaches To Develop Cask Demonstration Options

As summarized in Table 2-2, recent investigations into dry cask storage material degradation mechanisms by the Electric Power Research Institute (EPRI) (2011); Hanson, et al. (2011); Sindelar, et al. (2011); and the U.S. Nuclear Waste Technical Review Board (NWTRB) (2010) identified a number of significant issues that could potentially affect SNF and cask integrity during extended storage and transportation and the research and data needs to address the issues. The cask demonstration program allows for lead test assemblies and benchmarking of the predictive models that will be developed from short-term testing. Thus, anything that might have been missed by short-term studies could be detected through the demonstration program.

The cask demonstration options were developed by permuting the key elements and factors that were identified in Table 2-1. Because limited information is available on the long-term behavior of high burnup SNF (>45 GWd/MTU) and because the inventory of high burnup SNF is growing, high burnup SNF integrity was identified as an important issue. Thus, this demonstration program focuses on high burnup SNF only when the objective is to assess SNF degradation. To assess corrosion of storage system components (e.g., cask body, bolts, seals, and cask internal materials) that is more likely to occur at lower temperatures where condensation or deliquescence conditions may exist, low burnup SNF is proposed to be included in some storage systems to create a cooler system compared to the system with high burnup SNF only. In addition, cladding integrity is identified as an important technical issue (EPRI, 2011; Hanson, et al., 2011; Sindelar, et al., 2011; NWTRB, 2010), especially because incomplete drying condition may exist (the effect of incomplete drying is examined in a separate project and will not be discussed here). As discussed in Section 2.1, with an increasing SNF burnup level, newer cladding materials, such as Zirlo and M5, are being used and there are very limited publicly available data to determine how these materials may perform under extended storage and subsequent transportation conditions, including assessing the extent of SNF swelling and fragmentation. Thus, this demonstration program focuses on newer cladding materials and assessing SNF condition.

The technical issues and data needs identified in Table 2-2 have also been mapped to the cask demonstration options. In the following sections, the selections of key elements and factors in Table 2-1 for each of the cask demonstration options, along with data to be obtained in determining the performance of the system components, are provided.

Three general classes of demonstration testing configurations are incorporated into the cask demonstration options.

Class 1—Use of new cask storage system(s), including the following features:

- Installation of new cask(s) for the demonstration (Table 2-1, Item 7)
- Selection of SNF assemblies from spent SNF pool (Table 2-1, Items 1–6)

- Predemonstration examination (Table 2-1, Item 11)
- During-demonstration monitoring (Table 2-1, Item 12). No site is the same, and no two casks are exactly the same. The during-demonstration monitoring should be performed as often as feasible to detect any leak that could happen.
- Modifications for storage system for enhanced monitoring (would require licensing approval)
- Possible periodic removal of SNF and examination for direct-load metal cask (Table 2-1, Item 12b)
- Postdemonstration examination (Table 2-1, Item 13)
- SNF access for canister-based system, which would only be done at termination of demonstration program (Table 2-1, Item 13)

Class 2—Utilize already-in-use casks at Independent Spent Fuel Storage Installation (ISFSI) site(s) with two possible options

(1) Monitoring of selected cask(s)

- Monitoring during-demonstration (Table 2-1, Item 12)
- Possibly obtaining an exemption to add penetrations for monitoring access to inside of cask; however, monitoring options may be less than those for Class 1 because the already-in-use casks are loaded and configured
- Possible periodic removal of SNF and examination for direct-load metal cask (Table 2-1, Item 12b)
- For canister-based cask, SNF would not be removed until program termination (Table 2-1, Item 13)

(2) Accessing a cask system to assess cask system component conditions

- Only considering the cask system non-SNF components (postdemonstration examination of SNF is optional)
- Monitoring of appropriate parameters related to cask system components provided there was a need {e.g., monitoring a cooler cask with temperature <100 °C [212 °F] with a stainless steel canister in a coastal environment to assess stress corrosion cracking (SCC)}

Class 3—Perform a hot cell demonstration

- A full demonstration for SNF and potentially other materials exposed to the same normal environments inside the dry storage system

- Supplementary to Class 1 or Class 2 where SNF characterization is not feasible

Several cask demonstration options were developed to reflect sets of hypothetical conditions that could arise for a cask demonstration program. The conditions were used to constrain resources and focus the development of demonstration options so that an analysis could determine the optimal amount of data obtained. The cask demonstration options developed include the following:

<u>Options A–C: New cask (Class 1) storage systems</u>

Option A—Multiple new casks with multiple SNF types and other conditions

Option B—Limited number (>1) of new casks with multiple SNF types and other conditions

Option C—Single new cask with limited SNF types and other conditions

<u>Options D–E: Already-in-use (Class 2) casks</u>

Already-in-use casks will be monitored, and cask systems will be assessed. The SNF assembly may not have been well characterized before storage depending on the utility record. SNF may be accessed periodically for direct-load casks. After storage, the SNF may be examined in detail.

Option D—Assess multiple, already-in-use casks with multiple SNF types
Option E—Assess single, already-in-use cask with one SNF type

<u>Options F–G: Already-in-use casks and hot cell demonstration</u>

These options use demonstration test configurations like those described in Class 2b for assessing cask system components (not SNF) combined with the hot cell demonstration described in Class 3 to assess the SNF. Already-in-use casks will be accessed to assess nonSNF cask system components. The SNF will be assessed separately through the hot cell demonstration.

Option F—Assess multiple, already-in-use casks and a hot cell demonstration
Option G—Assess a single, already-in-use cask and a hot cell demonstration

The cask demonstration program options are detailed in the following sections. In constraining the options, it is necessary to consider additional criteria for prioritizing the selection of dry cask system(s), SNF type(s), and other parameters. For example, the selection of the dry cask system type is an important consideration because the system design and components will limit the range of SNF types and materials that can be assessed for a particular demonstration option. This becomes a particularly important factor for options where the number of casks is limited. To select SNF cladding type, data collected for one representative data type can potentially be extended to other SNF and cladding; however, ideally, a broader range of representative cladding types would be selected to ensure that any variations in potential material degradation effects may be observed. In general, duplication of data gathering should be avoided so that the overall number of casks and tests (and costs) will be minimized. However, when the number of cask systems selected for a given demonstration option is minimized and potential for duplication of data exists, the collection of additional representative data should be considered providing the additional costs would be acceptable. In the development process for the demonstration options, the following considerations were viewed as the most important for selection of parameters:

- Obtaining maximum collection of data for technical issues identified as high and medium priority in Table 2-2

- Timeframe or urgency for collecting data

- Obtaining measurable data for selected high burnup SNF types and cladding [pressurized water reactor (PWR) and boiling water reactor (BWR) UO_2 SNF, with newer cladding materials]

- Obtaining data from major dry cask system design variations (direct-load metal cask system, canister-based system in concrete overpack or module in vertical or horizontal configurations)

- Costs, feasibility, and regulatory and operational requirements (e.g., the canister-based system is welded; because of the complicated welding procedure, it is considered not feasible to cut open the cask during demonstration to access SNF and other internal components, and weld it back on; however, opening the direct-load bolted cask is considered to be feasible because the procedure is less complicated)

In selecting the demonstration sites, coastal/marine or highly industrial environments are the preferred choice for representing the most adverse normal condition and obtaining data in a shorter timeframe.

The storage duration is not specified in all demonstration options. Depending on the results obtained during demonstration and the priority, demonstration may end earlier or may proceed without a predictable ending. If degradation requiring remediation is not identified, the demonstration will likely continue until a path forward for the back end of the fuel cycle is identified and implemented. If the storage ends, detailed postdemonstration examination (as in Table 2-1, Item 13) will be performed.

3.2 Option A: Multiple New Casks With Multiple Fuels and Other Conditions

This option is the most detailed and thorough cask demonstration with new casks; it involves multiple casks, SNF types and conditions, cask designs, and demonstration sites to ensure a broad coverage of representative data of interest in Table 2-2. The demonstration program casks and descriptions are included in Table 3-1 and in the following subsections.

3.2.1 Option A: Cask A1

The Cask A1 demonstration resolves several data needs summarized in Table 2-2. This cask demonstration focuses the effort on assessing the long-term effects of marine environments on corrosion of the welded stainless steel canister.

Table 3-1. Option A—Multiple New Casks With Multiple Fuels and Other Conditions

Elements and Factors in Cask Demonstration	Cask A1	Cask A2	Cask A3	Cask A4	Cask A5	Cask A6
Focus of demonstration	Effects of marine environment on stainless steel canister	Effects of highly industrial environment on stainless steel canister	Effects of marine environment on direct-load bolted cask, bolts, and seals	Effects of highly industrial environment on direct-load bolted cask	Degradation of high burnup PWR* SNF, including newer cladding	Degradation of high burnup BWR† SNF, including lined Zircaloy-2 cladding
SNF type	UO_2 (PWR or BWR)	UO_2 (PWR or BWR)	UO_2 (PWR or BWR)	UO_2 (PWR or BWR)	UO_2 (PWR)	UO_2 (BWR)
SNF assembly average burnup	<45 GWd/MTU	<45 GWd/MTU	<45 GWd/MTU	<45 GWd/MTU	55–62 GWd/MTU	55–62 GWd/MTU
Cladding material	Zircaloy-4 or Zircaloy-2	Zircaloy-2 or Zircaloy-4	Zircaloy-4 or Zircaloy-2	Zircaloy-2 or Zircaloy-4	Zirlo or M5	Lined Zircaloy-2
Cask type	Stainless steel canister-based cask in horizontal or vertical configuration	Stainless steel canister-based cask in horizontal or vertical configuration	Direct-load metal cask	Direct-load metal cask	Direct-load metal cask	Direct-load metal cask
Cask system components	Reinforced concrete overpack or concrete module, basket, neutron absorber, shielding materials	Different and supplementary materials and configurations from Cask A1	Carbon steel or cast iron cask body, metallic bolts and seals, SNF basket, neutron absorber, shielding materials	Different and supplementary materials and configurations from Cask A3	Carbon steel cask body, metallic bolts and seals, SNF basket, neutron absorber, shielding materials	Different and supplementary materials and configurations from Cask A5
Demonstration sites	Coastal/Marine	Highly industrial-seasonal	Coastal/Marine	Highly industrial	Inland-seasonal	Inland-seasonal
Frequency of opening cask, years	Not applicable	Not applicable	10–20	10–20	10–20 or earlier	10–20 or earlier
Predemonstration examination				Table 2-1, Item 11		
At-demonstration monitoring and surveillance		Table 2-1, Items 12 a, c, and, d		Table 2-1, Items 12 b, c, and d	Table 2-1, Items 12 b, c, and d	

*Pressurized water reactor
†Boiling water reactor

To verify experimental results and models of temperature and other environmental effects on stainless steel canister material performance and to allow for potential corrosion processes to occur under monitoring conditions in a short timeframe, PWR or BWR assemblies with low burnup levels and Zircaloy-4 or Zircaloy-2 as cladding material will be loaded in the cask for demonstration. The cooling period of the SNF assemblies is at least 5 years. Selective loading of the cask to create a cooler environment (including loading of low burnup SNF) can provide insights in a shorter timeframe (e.g., 10 years).

The proposed demonstration site environment is coastal/marine. Because some existing ISFSI sites, along with the utilities, are at the coast, these sites may be augmented for demonstration. The storage system used in the demonstration will match that being used or planned at that site to minimize the impact of the demonstration on normal plant operations. Selected SNF would be examined in the SNF pool and then placed into dry storage in the selected dry cask storage system. The dry storage period would take place at the utility site. Sibling rods similar to the ones selected for storage will be left in the pool as a baseline demonstration. These sibling rods will be stored in the pool until the end of the dry storage demonstration and then shipped to a national lab for examination along with rods at the end of dry storage.

3.2.2 Option A: Cask A2

Cask A2 is the same type of cask as Cask A1; however, it is dedicated to assess the long-term effects of highly industrial and seasonal environments on corrosion of the welded stainless steel canister and the concrete overpack, which are also considered high and medium priority in Table 2-2. The data to be obtained are intended to supplement those obtained from Cask A1. The configuration of the cask is either vertical if Cask A1 is in horizontal configuration or horizontal if Cask A1 is vertical. The selections of SNF, cladding, neutron absorber, shielding, and basket materials are also different from those in Cask A1 and intended to supplement the data obtained from Cask A1. SNF with lower burnup is also used to create a cooler environment to allow for the earliest examination of potential atmospheric and aqueous corrosion of the stainless steel canister and concrete overpack degradation from the freeze–thaw cycle.

3.2.3 Option A: Cask A3

The Cask A3 demonstration focuses on obtaining data to assess degradation of a metallic (carbon steel or cast iron) cask, bolts, and seals in a marine environment that are considered high and medium priority in Table 2-2. In a marine environment, the chloride-containing species may attack the metallic cask body and initiate corrosion as the temperature decreases to allow condensation or deliquescence to occur. Compared to the stainless steel canister described in Sections 3.2.1 and 3.2.2, the predominant degradation modes may be general corrosion, pitting corrosion, or crevice corrosion.

For bolted casks, the features most susceptible to degradation are the closure bolts and seals. Although the seals are normally dry and protected by a weather cover, there may be residual borated water trapped within the seals due to incomplete drying after being loaded in the pool or water from the external environment deposited via capillary condensation (Hanson, et al., 2011). Corrosion may occur during extended storage. Failure cases of bolts and seals have been observed in the past (Excelon Generation Company, LLC, 2010), so this cask is also observed for degradation of bolts and seals. In addition to assessing material degradation from outside of the cask, bolts, and seals, the selection of a metallic bolted system allows the cask to be opened to assess degradation of other internal materials, such as the neutron absorber, SNF basket, and shielding materials. As shown in Table 3-1, PWR or BWR SNF assemblies with a lower burnup and Zircaloy-4 or Zircaloy-2 are selected. SNF with lower burnup is used to create a cooler environment to assess corrosion in a shorter timeframe. The frequency of opening the cask can be between 10 and 20 years, and the actual frequency can be determined from monitoring results during demonstration.

3.2.4 Option A: Cask A4

As summarized in Table 2-1, the bolted metal cask body could be made from carbon steel, cast iron, or other materials. Some more modern bolted casks have a double metallic O-ring seal, but some older designs had a metallic inner and elastomeric O-ring secondary seal. In these older designs, primary containment was achieved with a metal seal and secondary containment either with an elastomeric seal or a second metal seal (Hanson, et al., 2011). The internal components also vary depending on the types of casks.

Cask A4 is selected to obtain data to assess degradation of the same type of metallic bolted canister in a highly industrial environment. This cask was selected to supplement data obtained from Cask A3. Cask body material, bolts and seals, and materials inside the cask different from Cask A3 are selected. As shown in Table 3-1, low burnup SNF was selected. The SNF basket, neutron absorber, and shielding materials will be different, but supplementary to those selected in Cask A3. SNF with lower burnup is used to create a cooler environment to assess corrosion in a shorter timeframe.

3.2.5 Option A: Cask A5

The Cask A5 demonstration is selected to assess the effects on storage from the highest feasible burnup PWR SNF and use of newer cladding materials and assemblies to obtain insights on high burnup SNF in a short timeframe, including extent of SNF swelling and fragmentation, assessing SNF-cladding gap, and cladding degradation. The selected SNF for this cask is high burnup UO_2 PWR SNF with Zirlo or M5 as cladding material. Obtaining data on high burnup SNF in the shortest time would inform regulatory needs to support potential relicensing efforts that may occur for ISFSI facilities containing high burnup SNF and could provide nearer term feedback to guide or enhance long-term cask demonstration program efforts.

A bolted metal cask is selected for this demonstration. This cask demonstration allows for periodic opening of the cask to assess SNF and cladding degradation, especially SNF swelling and fragmentation, cladding gap, hydride reorientation and other hydrogen-induced cladding degradation issues, as included in Table 2-2. The opening frequency can be 10–20 years or earlier, depending on the urgency to obtain data and the monitoring results during demonstration. The SNF assembly hardware will also be examined. The selection of high burnup SNF also allows the examination of bolt and seal degradation from thermo-mechanical fatigue and creep. This demonstration also allows assessment of radiation-induced polymeric shielding materials degradation.

The inland and seasonal environment is selected to observe concrete degradation especially due to the freeze–thaw cycle. During demonstration, concrete degradation will be monitored periodically. As the temperature for the cask with high burnup SNF may be higher, depending on loading and cask system design specifics, it may take a long time for the cask to cool down to observe any corrosion; however, this is not the focus of this cask demonstration. After the storage, all the cask components and the concrete storage pad will be examined for any degradation.

3.2.6 Option A: Cask A6

The Cask A6 demonstration is intended to supplement that of Cask A5. Different from Cask A5, the selected SNF for this cask is high burnup UO_2 BWR SNF with lined Zircaloy-2 as cladding material. This demonstration focuses on assessing degradation of high burnup BWR SNF and the cladding material. Opening the cask also allows degradation of bolts, seals, and other internal components to be assessed, as described in Section 3.2.5.

3.2.7 Option A: Summary of Activities and Data To Be Obtained During Demonstration

Table 3-2 summarizes the activities associated with Option A, and Table 3-3 summarizes the data to be obtained in Option A to address technical issues summarized in Table 2-2.

The operation of Option A will require coordination among utilities, cask vendors, SNF vendors, research and development facilities at national labs, and regulators.

The cost of this cask demonstration would include upfront costs, incremental costs, predemonstration examination costs, annual operating and monitoring costs, postdemonstration examination costs, and decommissioning costs. Some of the detailed costs are

- Cost of storage casks (e.g., modifications of a standard design to allow temperature measurement of the SNF during demonstration and cover gas sampling)
- Cost associated with getting SNF to the storage site, especially if the site is not an existing ISFSI
- Cost of obtaining exemptions from certified cask/storage system designs to accommodate the needs of the testing

Table 3-2. Demonstration Activities for Option A

Demonstration Activities	Cask A1	Cask A2	Cask A3	Cask A4	Cask A5	Cask A6
Transportation of SNF to site for monitoring in hot cell						
Predemonstration examination	🟩	🟩	🟩	🟩	🟩	🟩
Internal monitoring of SNF conditions					🟩	🟩
Exemption(s) required for penetrations for additional monitoring in cask environment					🟩	🟩
External monitoring for components	🟩	🟩	🟩	🟩	🟩	🟩
Opening of cask to access SNF during demonstration					🟩	🟩
Opening of cask to access internal non-SNF components during demonstration			🟩	🟩	🟩	🟩
Postdemonstration examination	🟩	🟩	🟩	🟩	🟩	🟩
Transportation of SNF for examination	🟩 *	🟩 *	🟩 *	🟩 *	🟩	🟩

Shaded area denotes that activities will be assessed in the demonstration.
*Transportation of SNF only before and at the end of demonstration.

Table 3-3. Data To Be Obtained in Option A To Address Technical Issues Summarized in Table 2-2

SNF, Cladding, and System Components		Cask A1	Cask A2	Cask A3	Cask A4	Cask A5	Cask A6
Newer cladding						🟩	🟩
High burnup SNF						🟩	🟩
SNF assembly hardware						🟩	🟩
Canister-based storage system	Canister body and weld (stainless steel)	🟩	🟩				
	Concrete and steel overpack or concrete vault-type overpack	🟩	🟩				
Direct-load metal cask storage system	Steel cask (carbon steel, nodular cast iron, low-alloy steel)			🟩	🟩	🟩	🟩
	Metallic seals and gaskets			🟩	🟩	🟩	🟩
	Bolts			🟩	🟩	🟩	🟩
SNF basket (stainless steel, aluminum, Inconel, carbon steel)				🟩	🟩	🟩	🟩
Neutron absorbers (borated stainless steel; other metals; metal matrix composites, such as Boral, Metamic)				🟩	🟩	🟩	🟩
Polymeric shielding material (e.g., borated polymers)				🟩	🟩	🟩	🟩
Reinforced concrete pad		🟩	🟩	🟩	🟩	🟩	🟩

Shaded area denotes that technical issues will be addressed in the demonstration.

- Construction costs: site preparation, road improvements, concrete storage pad, electrical system, lighting, and security system

- Augmentation of a storage site to accommodate the storage container used for the demonstration

- Monitoring, maintenance, and surveillance of the site for the duration of the demonstration

- Pre-, interim-, and postdemonstration nondestructive and destructive characterization of the cladding, SNF, and other structures, systems, and components

- Possible storage container disposal cost

- Disposal of the SNF and SNF samples at the conclusion of the demonstration

- Others

The total cost for this option is estimated to be high. However, a detailed cost analysis is out of the scope of this work and is not included.

3.3 Option B: Limited Number (>1) of New Casks With Multiple Fuels and Other Conditions

This option includes one cask for the first storage system type and two casks for the second type (as delineated in Table 3-4), which involves multiple SNF types and conditions to obtain an optimal amount of data to address some of the technical issues in Table 2-2. Compared to Option A, the coverage on SNF, cladding, and other system component materials is limited. The first cask is the variant of Cask A1, and the second and third casks are the variants of Casks A4 and A5.

3.3.1 Option B: Cask B1

The Cask B1 demonstration resolves several data needs that are considered high and medium priority in Table 2-2. This cask demonstration focuses on assessing the long-term effects of marine environments on corrosion of the welded stainless steel canister. The corrosion modes assessed include general corrosion; pitting corrosion; and SCC, especially at the welds. During demonstration, the external condition of the canister will be monitored periodically to observe any sign of corrosion. In addition, the canister surface dust buildup will be monitored and sampled for salt and particle composition analysis along with other monitoring items for welded canisters in Table 2-1, Items 12 a and c. PWR or BWR assemblies with low burnup levels and Zircaloy-4 or Zircaloy-2 as cladding material will be loaded in the cask for demonstration. The lower burnup SNF will create a cooler environment as insights can be gained in a shorter timeframe (e.g., 10 years).

Table 3-4. Option B—Limited Number (>1) of New Casks With Multiple Fuels and Other Conditions

Elements and Factors in Cask Demonstration	Cask B1	Cask B2	Cask B3
Focus of demonstration	Effect of marine environment on stainless steel canister	Effect of highly industrial environment on direct-load bolted cask	Degradation of high burnup SNF and newer cladding
SNF type	UO_2 (PWR* or BWR†)	UO_2 (PWR or BWR)	UO_2 (PWR or BWR)
SNF assembly average burnup	<45 GWd/MTU	<45 GWd/MTU	55-62 GWd/MTU
Cladding material	Zircaloy-4 or Zircaloy-2	Zircaloy-2 or Zircaloy-4	Zirlo or M5 or lined Zircaloy-2
Cask type	Stainless steel canister-based cask in horizontal or vertical configuration	Direct-load metal cask	Direct-load metal cask
Cask system components	Reinforced concrete overpack or concrete module, basket, neutron absorber, shielding materials	Cast iron or carbon steel cask body, bolts and seals, SNF basket, neutron absorber, shielding materials	Carbon steel cask body, metallic bolts and seals, SNF basket, neutron absorber, shielding materials
Demonstration sites	Coastal/Marine	Highly industrial-seasonal	Coastal/Marine
Frequency of opening cask, years	Not applicable	10–20	10–20 or earlier
Predemonstration examination	Table 2-1, Item 11		
At-demonstration monitoring and surveillance	Table 2-1, Items 12a, c, and d	Table 2-1, Items 12b, c, and d	Table 2-1, Items 12b, c, and d
Postdemonstration examination	Table 2-1, Item 13		
*Pressurized water reactor †Boiling water reactor			

3.3.2 Option B: Cask B2

The Cask B2 demonstration focuses on obtaining data to assess degradation of a metallic (carbon steel or cast iron) cask, bolts, and seals in a highly industrial and seasonal environment; these are considered high and medium priority in Table 2-2. In such an environment, the chloride-containing and SO_2-containing contaminants may attack the metallic cask body and initiate corrosion as the temperature decreases to allow condensation or deliquescence to occur. The selection of a metallic bolted canister system allows for opening of the cask to assess degradation of other internal materials, such as the neutron absorber, SNF basket, and shielding materials. The frequency of opening may be between 10 and 20 years depending on the needs. SNF with lower burnup and longer cooling time is used to create a cooler environment to assess corrosion in a shorter timeframe.

3.3.3 Option B: Cask B3

To obtain insights on high burnup SNF and cladding degradation in a short timeframe, the Cask B3 demonstration is selected to assess the effects on storage from the highest feasible burnup SNF and use of newer cladding materials and assemblies. The selected SNF for this cask is high burnup UO_2 PWR or BWR SNF with Zirlo or M5 or lined Zircaloy-2 as cladding material. A bolted metal cask is selected for this demonstration. A coastal/marine environment is selected to represent the most adverse normal condition. This cask demonstration allows the cask to be opened periodically and SNF and cladding degradation to be assessed, especially SNF swelling and fragmentation, hydride reorientation and other hydrogen-induced cladding degradation issues as in Table 2-2. The selection of high burnup SNF also allows bolts and seals to be examined for degradation from thermo-mechanical fatigue and creep and radiation-induced polymeric shielding materials to be assessed for degradation. During demonstration, concrete degradation will be monitored periodically.

3.3.4 Option B: Summary of Activities and Data To Be Obtained During Demonstration

Table 3-5 summarizes the activities associated with Option B, and Table 3-6 summarizes the data to be obtained in Option B to address technical issues summarized in Table 2-2.

Compared to Option A, the range of materials covered will be limited.

Table 3-5. Demonstration Activities for Option B

Demonstration Activities	Cask B1	Cask B2	Cask B3
Transportation of SNF to site for monitoring in hot cell			
Predemonstration examination	🟩	🟩	🟩
Internal monitoring of SNF conditions			🟩
Exemption(s) required for penetrations for additional monitoring in cask environment		🟩	🟩
External monitoring for components	🟩	🟩	🟩
Opening of cask to access SNF during demonstration			🟩
Opening of cask to access internal nonSNF components during demonstration		🟩	🟩
Postdemonstration examination	🟩	🟩	🟩
Transportation of SNF for examination	🟩 *	🟩 *	🟩

Shaded area denotes that activities will be assessed in the demonstration.
*Transportation of SNF only before and at the end of demonstration.

Table 3-6. Data To Be Obtained in Option B To Address Technical Issues Summarized in Table 2-2

SNF, Cladding, and System Components		Cask B1	Cask B2	Cask B3
Newer cladding				🟩
High burnup SNF				🟩
SNF assembly hardware				🟩
Canister-based storage system	Canister body and weld (stainless steel)	🟩		
	Concrete and steel overpack or concrete vault-type overpack	🟩		
Direct-load metal cask storage system	Steel cask (carbon steel, nodular cast iron, low-alloy steel)		🟩	🟩
	Metallic seals and gaskets		🟩	🟩
	Bolts		🟩	🟩
SNF basket (stainless steel, aluminum, Inconel, carbon steel)			🟩	🟩
Neutron absorbers (borated stainless steel; other metals; metal matrix composites, such as Boral, Metamic)			🟩	🟩
Polymeric shielding material (borated polymers)			🟩	🟩
Reinforced concrete pad		🟩	🟩	🟩

Shaded area denotes that technical issues will be addressed in the demonstration.

3.4 Option C: Single New Cask With Limited Fuel and Other Conditions

This option includes a single new cask with limited SNF types and conditions delineated in Table 3-7. Table 3-7 outlines one cask type only, limited SNF conditions, and limited SNF types to obtain an optimal amount of data to address some technical issues in Table 2-2. Depending on the priority in the industry, one alternate cask is also proposed.

3.4.1 Option C: Cask C1

This cask demonstration is a mix of Casks A3, A4, and A5 that will help resolve several data needs which are considered high and medium priority in Table 2-2. This option focuses on assessing the effects of coastal/marine environments on the metallic bolted cask storage system. The selection of the bolted cask allows for opening of the direct-load cask to examine bolts and seals and to access SNF assemblies and other internal components. The mix of low burnup and high burnup SNF creates a cooler environment than loading with high burnup SNF only. PWR SNF is selected to obtain data on newer Zirlo or M5 cladding materials. The timeframe for monitoring this cask is shorter to gain needed data in a near-term timeframe.

3.4.2 Option C: Cask C1–Alternate

This alternate cask demonstration uses the welded canister-based system in a coastal/marine environment and will help resolve several data needs that are considered high and medium priority in Table 2-2 related to the welded canister. The mix of low burnup and high burnup SNF creates a cooler environment than loading with high burnup SNF only. This cask will be monitored outside of the canister to ensure all relevant high and medium priority data needs

Table 3-7. Option C—Single New Cask With Limited Fuels and Conditions

Elements and Factors in Cask Demonstration	Cask C1	Cask C1–Alternate
Focus of demonstration	Effect of marine environment on direct-load bolted cask and degradation of high burnup SNF and newer cladding	Effect of marine environment on stainless steel canister and degradation of high burnup SNF and newer cladding
SNF type	UO_2 (PWR*)	UO_2 (PWR)
SNF assembly average burnup	Mix of low and high burnup SNF	Mix of low and high burnup SNF
Cladding material	Mix of Zircaloy-4 and Zirlo or M5	Mix of Zircaloy-4 and Zirlo or M5
Cask type	Direct-load metal cask	Stainless steel canister-based cask in horizontal or vertical configuration
Cask system components	Carbon steel or cask iron cask body, metallic bolts and seals, SNF basket, neutron absorber, shielding materials	Reinforced concrete overpack or concrete module, basket, neutron absorber, shielding materials
Demonstration sites	Coastal/Marine	Coastal/Marine
Frequency of opening cask, years	10–20 or earlier	Not applicable
Predemonstration examination	Table 2-1, Item 11	Table 2-1, Item 11
At-demonstration monitoring and surveillance	Table 2-1, Items 12b, c, and d	Table 2-1, Items 12a, c, and d
Postdemonstration examination	Table 2-1, Item 13	Table 2-1, Item 13

*Pressurized water reactor

can be characterized for this cask design. PWR SNF is selected to obtain data on newer Zirlo or M5 cladding materials. The welded canister doesn't allow access to SNF during demonstration; however, the SNF assemblies and internal components will be examined thoroughly at the end of the storage.

3.4.3 Option C: Summary of Activities and Data To Be Obtained During Demonstration

Table 3-8 summarizes the activities associated with Option C, and Table 3-9 summarizes the data to be obtained in Option C to address technical issues summarized in Table 2-2.

3.5 Option D: Assess Multiple, Already-In-Use Casks With Multiple Fuel Types

This option utilizes four, already-in-use casks to assess potential degradation effects on dry storage system components. Two of the casks are used to assess potential degradation effects for SNF, cladding, and assembly hardware. The casks considered in this option are presented in Table 3-10.

3.5.1 Option D: Cask D1

This cask is selected to assess the stainless steel canister weld and material degradation effects in a coastal/marine environment. This cask is similar to Cask A1, it should be selected

Table 3-8. Demonstration Activities for Option C

Demonstration Activities	Cask C1	Cask C1–Alternate
Transportation of SNF to site for monitoring in hot cell		
Predemonstration examination	🟩	🟩
Internal monitoring of SNF conditions	🟩	🟩
Exemption(s) required for penetrations for additional monitoring in cask environment	🟩	🟩
External monitoring for components	🟩	🟩
Opening of cask to access SNF during demonstration	🟩	
Opening of cask to access internal non-SNF components during demonstration	🟩	
Postdemonstration examination	🟩	🟩
Transportation of SNF for examination	🟩	🟩 *

Shaded area denotes that activities will be assessed in the demonstration.
*Transportation of SNF only before and at the end of demonstration.

Table 3-9. Data To Be Obtained in Option C To Address Technical Issues Summarized in Table 2-2

SNF, Cladding, and System Components		Cask C1	Cask C1–Alternate
Newer cladding		🟩	
High burnup SNF		🟩	
SNF assembly hardware		🟩	
Canister-based storage system	Canister body and weld (stainless steel)		🟩
	Concrete and steel overpack or concrete vault-type overpack		🟩
Direct-load metal cask storage system	Steel cask (carbon steel, nodular cast iron, low-alloy steel)	🟩	
	Metallic seals and gaskets	🟩	
	Bolts	🟩	
SNF basket (stainless steel, aluminum, Inconel, carbon steel)		🟩	
Neutron absorbers (borated stainless steel; other metals; metal matrix composites, such as Boral, Metamic)		🟩	
Polymeric shielding material (e.g., borated polymers)		🟩	
Reinforced concrete pad		🟩	🟩

Shaded area denotes that technical issues will be addressed in the demonstration.

Table 3-10. Preferences for Selection of Multiple, Already-In-Use Casks for Option D

Elements and Factors in Cask Demonstration	Cask D1	Cask D2	Cask D3	Cask D4
Focus of demonstration	Effect of marine environment on stainless steel canister	Effect of highly industrial environment on direct-load bolted cask	Degradation of high burnup PWR* SNF and newer cladding	Degradation of high burnup BWR† SNF and cladding
SNF type	UO_2 (PWR or BWR)‡	UO_2 (PWR or BWR)§	UO_2 (PWR)‖	UO_2 (BWR)‖
SNF assembly average burnup	Any already-in-use SNF at an ISFSI¶ would be acceptable; however, some preferences should be considered‡	Any already-in-use SNF at an ISFSI would be acceptable; however, some preferences should be considered§	Cask should have some high burnup SNF, 55–62 GWd/MTU‖	Cask should have some high burnup SNF, 55–62 GWd/MTU‖

Table 3-10. Preferences for Selection of Multiple, Already-In-Use Casks for Option D (continued)

Elements and Factors in Cask Demonstration	Cask D1	Cask D2	Cask D3	Cask D4
Cladding	Any cladding utilized for already-in-use SNF at an ISFSI would be acceptable as the SNF and cladding will not be assessed	Any cladding utilized for already-in-use SNF at an ISFSI would be acceptable as the SNF and cladding will not be assessed	Zirlo or M5	Lined Zircaloy-2
Cask type	Canister-based system loaded in a horizontal or vertical configuration	Direct-load metal cask	Direct-load metal cask	Direct-load metal cask
Cask system components	Stainless steel canister, concrete reinforced module or overpack	Steel or cast iron body, bolted enclosure, metallic gasket	Steel or cast iron body, bolted enclosure, metallic gasket	Steel vessel body or cast iron body, bolted enclosure, metallic gasket
Demonstration site environment	Coastal/marine	Highly industrial	Inland-seasonal; should select an environment where there will be regular freeze–thaw cycles	Inland-seasonal; should select an environment where there will be regular freeze–thaw cycles
Frequency of opening cask, years	Not applicable	10–20	10–20 or earlier	10–20 or earlier
Predemonstration examination	None	None	None	None
At-demonstration monitoring and surveillance	Some in Table 2-1, Items 12a, c, and d	Some in Table 2-1, Items 12b, c, and d	Some in Table 2-1, Items 12b, c, and d	Some in Table 2-1, Items 12b, c, and d
Postdemonstration examination	Table 2-1, Item 13	Table 2-1, Item 13	Table 2-1, Item 13	Table 2-1, Item 13

*Pressurized water reactor

†Boiling water reactor

‡Any already-in-use SNF at an independent spent fuel storage installation would be acceptable providing preference is given for selecting casks that have experienced conditions for observing stress corrosion cracking {e.g., temperatures below 100 °C [212 °F]}.

§Any already-in-use SNF at an independent spent fuel storage installation would be acceptable. Selection should be made so that the cask temperature is lower {e.g., below 100 °C [212 °F]}.

‖Preference in selection should be made so that the cask temperature would have been higher for the longest period feasible to maximize potential for creep.

¶Independent spent fuel storage installation

when it has likely experienced conditions favorable to SCC of the canister for the longest time period {e.g., temperatures below 100 °C [212 °F]}. Therefore, a cask that has had sufficient time to decay to lower thermal output and temperatures should be selected. The internal environment for the canister is not monitored, and the SNF is not accessed; only external components of the cask are monitored.

3.5.2 Option D: Cask D2

This cask is selected to assess degradation effects on direct-load metal cask components, including metallic gaskets, bolts, and the steel cask vessel. Cask D2 focuses on assessing the effects of corrosion on the cask components. This cask is similar to Cask A4. A highly industrial environment is preferred to ensure the most aggressive expected environment for corrosion. This cask should be selected because it has been at relatively cooler temperature for an extended period of time to ensure corrosion processes would have occurred {e.g., below 100 °C [212 °F]}. The cask should be opened on a decadal or bidecadal year frequency to assess the condition of cask gaskets and internal components. The SNF is not assessed during the periodic access, because the focus is on obtaining data on corrosion effects in the most rapid time period (requiring a cooler cask) and determining whether SNF-related degradation mechanisms are covered by other casks in this option.

3.5.3 Option D: Casks D3 and D4

These casks are selected to assess degradation effects for newer cladding materials and high burnup SNF. Casks D3 and D4 are similar to Casks A5 and A6, respectively. Direct-load metal casks have been selected so that the SNF condition can be assessed throughout the monitoring process and may include assessment of SNF swelling and fragmentation, SNF-cladding gap, hydride reorientation and other hydrogen-induced cladding degradation issues as identified in Table 2-2. This option also focuses on assessing degradation effects on direct-load metal cask components, including metallic gaskets, bolts, and the steel cask vessel, with an emphasis on effects that occur due to higher temperatures. When selecting already-in-use casks, a preference should be made for a cask where the temperature would have been higher for the longest period feasible to maximize potential for creep. To include additional monitoring of the canister internal environment (i.e., gas sampling and temperature), an exemption may be needed to add the necessary modifications to the casks. Because this option utilizes an already-loaded cask, precharacterization of the SNF is not feasible. Therefore, data obtained for some SNF characteristics (i.e., cladding creep) will have additional uncertainty.

3.5.4 Option D: Summary of Activities and Data To Be Obtained During Demonstration

Table 3-11 summarizes the activities associated with Option D, and Table 3-12 summarizes the data to be obtained in Option D to address technical issues summarized in Table 2-2.

3.6 Option E: Assess Single, Already-In-Use Cask With One Fuel Type

This option utilizes one, already-in-use cask to assess potential degradation effects for a dry cask system with newer cladding materials and high burnup SNF. For this option, high burnup SNF with newer cladding materials was selected because the degradation of these components is considered high and medium priority under several potential extended storage conditions, as specified in Table 2-2. Additionally, because a hot cell demonstration is not selected, the SNF will be assessed at the termination of the dry cask storage monitoring. For this option, the assessments of the canister body and closure weldment for SCC are considered to be of highest priority. Therefore, a canister-based dry cask system is selected for this option. The preferences for the cask considered in this option are presented in Table 3-13. Because there may be several competing priorities for data needs (i.e., obtaining data for SCC of stainless steel canisters in coastal/marine environments versus obtaining data on bolts and metallic seals and gaskets), a second alternative set of preferences for single cask selection is also provided in Table 3-13.

Table 3-11. Demonstration Activities for Option D

Demonstration Activities	Cask D1	Cask D2	Cask D3	Cask D4
Transportation of SNF to site for monitoring in hot cell				
Predemonstration examination				
Internal monitoring of SNF conditions		🟩	🟩	🟩
Exemption(s) required for penetrations for additional monitoring in cask environment		🟩	🟩	🟩
External monitoring for components	🟩	🟩	🟩	🟩
Opening of cask to access SNF during demonstration			🟩	🟩
Opening of cask to access internal non-SNF components during demonstration		🟩	🟩	🟩
Postdemonstration examination	🟩	🟩	🟩	🟩
Transportation of SNF for examination			🟩	🟩

Shaded area denotes that activities will be assessed in the demonstration.

Table 3-12. Data To Be Obtained in Option D To Address Technical Issues Summarized in Table 2-2

SNF, Cladding, and System Components		Cask D1	Cask D2	Cask D3	Cask D4
Newer cladding				🟩	🟩
High burnup SNF				🟩	🟩
SNF assembly hardware				🟩	🟩
Canister-based storage system (mostly dual-purpose canister system, welded canister in bolted overpack or concrete storage module)	Canister body and weld (stainless steel)	🟩			
	Concrete and steel overpack or concrete vault-type overpack	🟩			
Direct-load metal cask storage system (generally bolted, thick walled)	Steel cask (carbon steel, nodular cast iron, low-alloy steel)		🟩	🟩	🟩
	Metallic seals and gaskets		🟩	🟩	🟩
	Bolts		🟩	🟩	🟩
SNF basket (stainless steel, aluminum, Inconel, carbon steel)			🟩	🟩	🟩
Neutron absorbers (borated stainless steel; other metals; metal matrix composites, such as Boral, Metamic)			🟩	🟩	🟩
Polymeric shielding material (e.g., borated polymers)			🟩	🟩	🟩
Reinforced concrete pad		🟩	🟩	🟩	🟩

Shaded area denotes that technical issues will be addressed in the demonstration.

Table 3-13. Preferences for Selection of Single, Already-In-Use Cask for Option E

Elements and Factors in Cask Demonstration	Cask E1	Cask E1–Alternate
Focus of demonstration	Effect of marine environment on stainless steel canister	Degradation of direct-load bolted cask
SNF type	UO_2 (PWR*)†	UO_2 (PWR)‡
SNF assembly average burnup	>45 GWd/MTU The cask should contain some high burnup SNF assemblies; some additional preferences should be considered†	>45 GWd/MTU The cask should contain some high burnup SNF assemblies; some additional preferences should be considered‡
Cladding material	The cask should have at least some SNF assemblies that have newer cladding materials like Zirlo or M5	The cask should have at least some SNF assemblies that have newer cladding materials like Zirlo or M5
Cask type	Canister-based system loaded in a horizontal or vertical configuration	Direct-load metal cask
Cask system components	Stainless steel canister, concrete reinforced module or overpack	Steel vessel body or cast iron body, bolted enclosure, metallic gasket
Demonstration site environment	Coastal/marine	Inland-seasonal; should select an environment where there will be regular freeze–thaw cycles
Frequency of opening cask, years	At end of monitoring activities	10–20
Predemonstration examination	None	None
At-demonstration monitoring and surveillance	Table 2-1, Item 12§	Some in Table 2-1, Item 12 cask metallic body, bolts, gaskets, and internal components, SNF, and cladding
Postdemonstration examination	Table 2-1, Item 13	Table 2-1, Item 13

*Pressurized water reactor

†Any already-in-use SNF at an independent spent SNF storage installation would be acceptable providing preference is given for selecting casks that have experienced conditions for observing stress corrosion cracking {e.g., temperatures below 100 °C [212 °F]}.

‡Ideally, the cask temperature would have been higher for the longest period feasible to maximize potential for creep. This cask selection is also intended to observe effects of corrosion. Therefore, preference should also be given to a cask that would have likely experienced conditions favorable for corrosion processes for the longest time period {e.g., temperatures below 100 °C [212 °F]}.

§For monitoring and surveillance, additional penetrations may be made to the canister to include additional monitoring of the canister internal environment (i.e., gas sampling and temperature).

3.6.1 Option E: Cask E1

This cask is selected to assess the stainless steel canister weld and material degradation effects in a coastal/marine environment. This cask is similar to Cask A1 and should be selected such that the cask would have likely experienced conditions favorable to SCC of the canister for the longest time period {e.g., time spent at temperatures below 100 °C [212 °F]}. The cask differs from Cask A1 in that the SNF will be accessed at the termination of the program, inclusion of high burnup SNF with newer cladding materials is needed, and at-demonstration monitoring would include additional monitoring of canister internal conditions. To include additional monitoring of the canister internal environment (i.e., gas sampling and temperature), an exemption would be needed to add the necessary modifications to the canister. Because this option utilizes an already-loaded cask, precharacterization of the SNF is not feasible. Therefore, data obtained for some SNF characteristics (i.e., cladding creep) will have additional uncertainty.

3.6.2 Option E: Cask E1–Alternate

For the alternative selection for Cask E1, a direct-load metal cask is selected to focus efforts on assessing corrosion, stress relaxation, creep, and thermo-mechanical fatigues on cask system bolts and metallic seals and gaskets. This cask is similar to Cask D3. Ideally, the cask temperature would have been higher for the longest period feasible to maximize potential for creep. This cask selection is also intended to observe effects of corrosion. Therefore, preference should also be given to a cask that would have likely experienced conditions favorable for corrosion processes for the longest time period {including time spent at temperatures below 100 °C [212 °F]}. Because of these competing effects, data for corrosion effects may require a longer timeframe to determine whether additional time is needed to further cool the cask. Also, because a direct-load metal cask is selected, during periodic access to the cask, the SNF can be assessed, providing an opportunity for obtaining data on SNF degradation during the monitoring period.

3.6.3 Option E: Summary of Activities and Data To Be Obtained During Demonstration

Table 3-14 summarizes the activities associated with Option E, and Table 3-15 summarizes the data to be obtained in Option E to address technical issues summarized in Table 2-2.

3.7 Option F: Assess Multiple, Already-In-Use Casks and a Hot Cell Demonstration

This option utilizes three, already-in-use casks to assess potential degradation effects on dry storage system components and uses a hot cell demonstration program to assess potential degradation effects for SNF, cladding, and assembly hardware. The casks considered in this option are presented in Table 3-16.

3.7.1 Option F: Cask F1

Cask F1 is selected to assess the stainless steel canister weld and material degradation effects in a coastal/marine environment. This cask is similar to Cask A1 and should be selected such that the cask would have likely experienced conditions favorable to SCC of the canister for the longest time period {including time spent at temperatures below 100 °C [212 °F]}.

Table 3-14. Demonstration Activities for Option E

Demonstration Activities	Cask E1	Cask E1–Alternate
Transportation of SNF to site for monitoring in hot cell		
Predemonstration examination		
Internal monitoring of SNF conditions	🟩	🟩
Exemption(s) required for penetrations for additional monitoring in cask environment	🟩	🟩
External monitoring for components	🟩	🟩
Opening of cask to access SNF during demonstration		🟩
Opening of cask to access internal nonSNF components during demonstration		🟩
Postdemonstration examination	🟩	🟩
Transportation of SNF for examination	🟩	🟩
Shaded area denotes that activities will be assessed in the demonstration.		

Table 3-15. Data To Be Obtained in Option E To Address Technical Issues Summarized in Table 2-2

SNF, Cladding, and System Components		Cask E1	Cask E1–Alternate
Newer cladding			🟩
High burnup SNF			🟩
SNF assembly hardware			🟩
Canister-based storage system (mostly dual-purpose canister system, welded canister in bolted overpack, or concrete storage module)	Canister body and weld (stainless steel)	🟩	
	Concrete and steel overpack or concrete vault-type overpack	🟩	
Direct-load metal cask storage system (generally bolted, thick walled)	Steel cask (carbon steel, nodular cast iron, low-alloy steel)		🟩
	Metallic seals and gaskets		🟩
	Bolts		🟩
SNF basket (stainless steel, aluminum, Inconel, carbon steel)			🟩
Neutron absorbers (borated stainless steel; other metals; metal matrix composites, such as Boral, Metamic)			🟩
Polymeric shielding material (e.g., borated polymers)			🟩
Reinforced concrete pad		🟩	🟩
Shaded area denotes that technical issues will be addressed in the demonstration.			

3.7.2 Option F: Cask F2

Cask F2 is selected to assess degradation effects on direct-load metal cask components, including metallic gaskets, bolts, and the steel cask vessel. Cask F2 focuses on assessing the effects of corrosion on the cask components. This cask is similar to Cask A4. This cask should be selected such that it has been at a relatively cooler temperature for an extended period of time to ensure corrosion processes would have occurred {below 100 °C [212 °F]}. A highly industrial environment is preferred to ensure the most aggressive expected environment for corrosion.

Table 3-16. Preferences for Selection of Multiple, Already-In-Use Casks and Hot Cell Demonstration for Option F

Elements and Factors in Cask Demonstration	Cask F1	Cask F2	Cask F3	Hot Cell Demonstration
Focus of demonstration	Effect of marine environment on stainless steel canister	Effect of highly industrial environment on direct-load bolted cask	Effect of seasonal environment on direct-load bolted cask	Degradation of high burnup SNF and newer cladding
SNF type	UO_2 (PWR* or BWR†)‡	UO_2 (PWR or BWR)§	UO_2 (PWR or BWR)‖	UO_2 (PWR and BWR)
SNF assembly average burnup	Any already-in-use SNF at an ISFSI¶ would be acceptable; however, some preferences should be considered‡	Any already-in-use SNF at an ISFSI would be acceptable; however, some preferences should be considered§	Any already-in-use SNF at an ISFSI would be acceptable; however, some preferences should be considered‖	>45 GWd/MTU
Cladding material	Any cladding utilized for already-in-use SNF at an ISFSI would be acceptable because the SNF and cladding were not assessed	Any cladding utilized for already-in-use SNF at an ISFSI would be acceptable because the SNF and cladding were not assessed	Any cladding utilized for already-in-use SNF at an ISFSI would be acceptable because the SNF and cladding were not assessed	Zirlo, M5, and lined Zircaloy-2 (or newer alloys as they become available)
Cask type	Canister-based system loaded in a horizontal or vertical configuration	Direct-load metal cask	Direct-load metal cask	Not applicable
Cask system components	Stainless steel canister, concrete reinforced module or overpack	Steel vessel body or cast iron body, bolted enclosure, metallic gasket	Steel vessel body or cast iron body, bolted enclosure, metallic gasket	
Demonstration site environment	Coastal/marine	Highly industrial	Seasonal; should select an environment where there will be regular freeze–thaw cycles.	Controllable moisture, O_2, temperature profile to be controlled
Frequency of opening cask, years	Not applicable	10–20#	10–20#	Not applicable
Predemonstration examination	None	None	None	All in Table 2-1, Item 11

Table 3-16. Preferences for Selection of Multiple, Already-In-Use Casks and Hot Cell Demonstration for Option F (continued)

Elements and Factors in Cask Demonstration	Cask F1	Cask F2	Cask F3	Hot Cell Demonstration
At demonstration monitoring and surveillance	Table 2-1, Items 12a and c	Some in Table 2-1, Items 12b and c	Some in Table 2-1, Items 12b and c	Radiation gas sampling, continuous as required**
Postdemonstration examination	Table 2-1, Item 13	Table 2-1, Item 13	Table 2-1, Item 13	Table 2-1, Item 13

*Pressurized water reactor
†Boiling water reactor
‡Any already-in-use SNF at an independent spent fuel storage installation would be acceptable providing preference is given for selecting casks that have experienced conditions for observing stress corrosion cracking {e.g., temperatures below 100 °C [212 °F]}.
§Any already-in-use SNF at an independent spent fuel storage installation would be acceptable {e.g., temperatures below 100°C [212 °F]}.
‖Any already-in-use SNF at an independent spent fuel storage installation would be acceptable. Preference in selection should be made so that the cask temperature would have been higher for the longest period feasible to maximize potential for creep.
¶Independent spent fuel storage installation
#Open to inspect seals, gaskets, and bolts only.
**Depending on hot cell container design, this could include laser profilometry of SNF rods if a glass containment vessel were used.

3.7.3 Option F: Cask F3

Cask F3 is similar to Casks A5 and A6. Because the SNF is not assessed for this cask, any already-in-use SNF at an ISFSI would be acceptable; however, preference should be made so that the cask temperature would have been higher for the longest period feasible to maximize potential for creep.

3.7.4 Hot Cell Demonstration

This demonstration involves multiple types of SNF and conditions with controlled atmospheres in a hot cell environment. This is a self-contained demonstration that would allow the assessment of SNF integrity at normal and potentially off-normal conditions in the presence of air and/or water. It is anticipated that SNF and components of the test would be periodically examined without the requirement of removing rods from a cask demonstration test for examination. A dedicated hot cell would be required and the demonstration should be designed to require a small footprint in the hot cell.

PWR and BWR UO_2 low and (to a lesser extent) high burnup SNF have been the subject of numerous studies; however, few studies address the long-term behavior of the SNF under anticipated extended storage conditions. For this reason, the hot cell demonstration plan focuses on high burnup UO_2 SNF where data are more limited. The hot cell tests should complement the tests being conducted in casks and should also complement examinations of cladding used in the cask demonstrations. Newer zirconium alloy cladding, such as lined zirconium, Zirlo, and/or M5, which are intended to reduce pellet–cladding interaction, would be preferred, but the choices for SNF and cladding would be driven by their availability.

The SNF rods (high burnup PWR/BWR UO_2) could include

- Intact SNF rods
- Intentionally defected SNF rods
- Defected rods during reactor operation if identifiable
- Any identified “pinhole leak” rods

Cask components, such as Boral neutron absorbers, and cask materials could also be potentially added as components of these tests.

Nondestructive examination (NDE) tests would be performed before and during the demonstration, including

- Visual examination/photodocumentation
- SNF rod profilometry before and during tests
- Axial gamma scanning Cesium and total activity before and during tests to determine if any fission product redistribution has occurred during storage
- Kr-85 FGR—scan before and during tests

Destructive examination (DE) tests would be performed on SNF rods before testing and on selected rods during testing, including

- FGR (xenon and helium); comparison with models

- Radial gamma scanning for cesium to assess potential redistribution

- Metallographic examination

- Ceramographic examination (x-ray photoelectron spectroscopy, x-ray diffraction, and scanning electron microscopy) for Pu, Ru, and other elements of interest

- Cladding microstructural examination; assess cracking on inner and outer surfaces, hydrogen embrittlement, hydrogen content, delayed hydride cracking, oxide thickness, creep characteristics, cladding tensile fracture test, pellet clad interaction (including gap width), SNF microstructure, and SNF fine production assessment

SNF would need to be identified with known burnup and power history, and rods for the hot cell demonstration should be extracted from a single bundle in the same SNF bundle location (i.e., sibling rods). SNF should be cooled for at least 5 years due to the high heat generation of fresh SNF. SNFs could be selected that span the range of high burnup SNF (e.g., 55 GWd/MTU and 65 GWd/MTU).

It is anticipated that separated SNF rods would be used from SNFs that have well-characterized in-reactor history. The NDE and DE tests can be used to compare any model data used to predict FGR. These rods would be further characterized by NDE tests before any hot cell demonstrations, and selected sibling rods would be characterized by DE. A number of sibling rods should be included in the test to allow for periodic DE to observe any changes in rods with time. The frequency of characterization could be adjusted depending on any observed changes in cladding or SNF behavior or the observation of FGR to the container.

Where necessary, SNF with failed cladding would require primary containment in a sealed (e.g., stainless steel) can with the environment of choice (normal conditions with helium and residual water). If desired, after observations are completed under normal conditions, off-normal conditions could be examined by adding air to simulate cask leakage. This may be deemed necessary if SCC occurs and there is a potential for cask failure and ingress of air into the cask.

Undefected SNF could be contained within a secondary vessel (e.g., stainless steel) also containing the environment of choice. The intact SNF rods and any “defected” rods contained in a sealed can would be supported in the secondary containment vessel using a basket assembly consisting of stainless steel tubes supported by basket rails and would be designed to accommodate the required number of SNF rods and any rods sealed in a primary containment can.

To maintain temperatures for SNF rods that would be representative of a full demonstration cask {300–400 °C [572–752 °F]} and/or to simulate the time dependency of SNF cooling, secondary heating and/or insulation would be required for the outer containment vessel because the low number of rods in the demonstration vessel may not be able to maintain the temperatures of interest.

One of the test objectives could be to examine the behavior of SNF under normal conditions in the presence of water to address the incomplete drying of the cask/SNF and the effects of corrosion of cladding and SNF by water radiolysis. The cladding for some SNF would be intentionally defected to allow water to access the SNF interior. Pinhole defect SNF that can be identified could also be included in the tests. UO_2 and Zircaloy characterization would be desirable at periodic intervals for at least 10 years. Test containers should be continuously monitored for internal temperature, humidity, pressure, atmosphere characterization, and measurement of any FGR to the containment vessel. It may be possible to utilize a thick glass containment vessel for the hot cell demonstration to allow tests such as laser rod profilometry to be conducted *in situ*; however, specialized instrumentation would need to be installed in the hot cell and it may be difficult to accommodate and arrange the rods to allow for such an examination.

Several regions of the cladding for both intact and defected SNF should be examined, including end-cap/weld region, inner and outer cladding surfaces and cladding/SNF gap width at several locations along the length, and bearing pad or support spacers. SNF would be examined at the start of the tests, perhaps as frequently as every 2–4 years for a period of 10 or 20 years, depending on the extent of SNF/cladding degradation observed.

The hot cell demonstration effectively decouples the examination of SNF behavior from the cask demonstration program. This would allow for the maximization of data collected from the hot cell demonstration and the use of casks that already have up to 20 years of exposure. Additional advantages of the hot cell demonstration are that it would

- Complement data gathered from the cask demonstration

- Not require opening the cask for SNF examination (no SNF/cask transport)

- Not require a license amendment for penetrating cask for internal monitoring prior to cask demonstration

- Provide continuous monitoring and an option for examination on frequent basis

- Provide potential *in-situ* examination of SNF condition (e.g., laser profilometry if a glass container vessel could be used

- Offer an option to examine SNF if/when monitored conditions observed to change (e.g., FGR to vessel, change in SNF dimensions, change in vessel pressure/atmosphere)

- Provide an option for comparison of measured SNF condition with any SNF examined in the cask demonstration

- Alter demonstration conditions or include new materials if desired (e.g., introduction of air, increased temperature, additional water, new cladding/SNF)

The costs of such tests cannot be estimated at present, and a full scope of tests would need to be identified before any cost projections could be made. Also, the duration of the tests would require the availability of a dedicated portion of one or more hot cells at a suitable laboratory and any ongoing activities in the hot cell should not adversely impact the viability of the tests. The transportation of SNF to the selected laboratory would also need to be considered, as would any potential damage to the SNF during transportation. However, the potential for damage to SNF can be further minimized by shipping of single assemblies so they are not exposed to high heat during transportation.

Logistical considerations for conducting the tests would include any license amendment exemptions, transport of SNF to the hot cell facility (SNF sources may be from different locations), the availability of appropriate SNF, safety and criticality analyses, and the availability of appropriate pre- and posttest SNF/cladding and monitoring equipment as outlined previously.

3.7.5 Option F: Summary of Activities and Issues To Be Addressed During Demonstration

Table 3-17 summarizes the activities associated with Option F, and Table 3-18 summarizes the data to be obtained in Option F to address technical issues summarized in Table 2-2.

3.8 Option G: Assess Single, Already-In-Use Cask and a Hot Cell Demonstration

This option utilizes one, already-in-use cask to assess potential degradation effects on dry storage system components to assess the effects of a coastal/marine environment on SCC of a stainless steel canister. This degradation effect was selected because it is considered to be a high priority item of potential high safety significance as indicated in Table 2-2. This option also uses a hot cell demonstration (as described in Section 3.7.4) to assess potential degradation issues for SNF, cladding, and assembly hardware. The cask considered in this option is presented in Table 3-19. Again, because there may be several competing priorities for data needs (i.e., obtaining data for SCC of stainless steel canisters in coastal/marine environments versus obtaining data on bolts and metallic seals and gaskets), an alternative set of preferences for single cask selection is also provided in Table 3-19.

Table 3-17. Demonstration Activities for Option F				
Demonstration Activities	**Cask F1**	**Cask F2**	**Cask F3**	**Hot Cell Demonstration**
Transportation of SNF to site for monitoring in hot cell				🟩
Predemonstration examination				🟩
Internal monitoring of SNF conditions				🟩
Exemption(s) required for penetrations for additional monitoring in cask environment				Not applicable
External monitoring for components	🟩	🟩	🟩	
Opening of cask to access SNF during demonstration				
Opening of cask to access internal nonSNF components (e.g., basket, neutron absorber) during demonstration				
Postdemonstration examination	🟩	🟩	🟩	🟩
Transportation of SNF for examination				
Shaded area denotes that activities will be assessed in the demonstration.				

Table 3-18. Data To Be Obtained in Option F To Address Technical Issues Summarized in Table 2-2					
		Option F			
SNF and Structures, Systems, Components		**F1**	**F2**	**F3**	**Hot Cell Demonstration**
Newer cladding					🟩
High burnup SNF					🟩
SNF assembly hardware					🟩
Canister-based storage system (mostly dual-purpose canister system, welded canister in bolted overpack or concrete storage module)	Canister body and weld (stainless steel)	🟩			
	Concrete and steel overpack or concrete vault-type overpack	🟩			
Direct-load metal cask storage system (generally bolted, thick walled)	Steel cask (carbon steel, nodular cast iron, low-alloy steel)		🟩	🟩	
	Metallic seals and gaskets		🟩	🟩	
	Bolts		🟩	🟩	
SNF basket (stainless steel, aluminum, Inconel, carbon steel)					🟩 *
Neutron absorbers (borated stainless steel; other metals; metal matrix composites, such as Boral, Metamic)					🟩 *
Polymeric shielding material (e.g., borated polymers)					🟩 *
Reinforced concrete pad		🟩	🟩	🟩	
Shaded area denotes that technical issues will be addressed in the demonstration. *Inclusion of basket, neutron absorber, or shielding material samples in hot cell demonstration could potentially be done.					

Table 3-19. Preferences for Selection of Single, Already-In-Use Cask and a Hot Cell Demonstration for Option G

Elements and Factors in Cask Demonstration	Cask G1	Cask G1–Alternate	Hot Cell Demonstration
Focus of demonstration	Effect of marine environment on stainless steel canister	Effect of highly industrial environment on direct-load bolted cask	Degradation of high burnup SNF and newer cladding
SNF type	UO_2 (PWR* or BWR†)‡	UO_2 (PWR or BWR)§	UO_2 (PWR and BWR)
SNF assembly average burnup	Any already-in-use SNF at an ISFSI would be acceptable; however, some preferences should be considered‡	Any already-in-use SNF at an ISFSI would be acceptable; however, some preferences should be considered§	>45 GWd/MTU
Cladding material	Any cladding utilized for already-in-use SNF at an ISFSI‖ would be acceptable because the SNF and cladding were not assessed	Any cladding utilized for already-in-use SNF at an ISFSI would be acceptable because the SNF and cladding were not assessed	Zirlo, M5, and lined Zircaloy-2
Cask type	Canister-based system loaded in a horizontal or vertical configuration	Direct-load metal cask	Not applicable
Cask system components	Stainless steel canister, concrete reinforced module or overpack	Steel vessel body or cast iron body, bolted enclosure, metallic gasket	
Demonstration site environment	Coastal/marine	Highly industrial	Hot cell
Frequency of opening cask, years	Not applicable	10–20¶	Not applicable
Predemonstration examination	None	None	Not applicable
At-demonstration monitoring and surveillance	Table 2-1, Items 12a and c	Table 2-1, Items 12b and c	All in Table 2-1, Item 11
Postdemonstration examination	Table 2-1, Item 13	Table 2-1, Item 13	Some in Table 2-1, Item 12

*Pressurized water reactor

†Boiling water reactor

‡Any already-in-use SNF at an independent spent fuel storage installation would be acceptable providing preference is given for selecting casks that have experienced conditions for observing stress corrosion cracking {e.g., temperatures below 100°C [212 °F]}.

§Ideally, the cask temperature would have been higher for the longest period feasible to maximize potential for creep. This cask selection is also intended to observe effects of corrosion. Therefore, preference should also be given to a cask that would have likely experienced conditions favourable for corrosion processes for the longest time period {e.g., temperatures below 100°C [212 °F]}.

‖Independent spent fuel storage installation

¶Opening cask to inspect seals, gaskets, and bolts only

3.8.1 Option G: Cask G1

This cask is selected to assess the stainless steel canister weld and material degradation effects in a coastal/marine environment. This cask is similar to the Cask A1 and should be selected such that the cask would have likely experienced conditions favorable to SCC of the canister for the longest time period {including time spent at temperatures below 100 °C [212 °F]}.

3.8.2 Option G: Cask G1–Alternate

For the alternative selection for Cask G1, a direct-load metal cask is selected to focus efforts on assessing corrosion, stress relaxation, creep, and thermo-mechanical fatigues on cask system bolts and metallic seals and gaskets. This cask is similar to Cask A2 or A3. Ideally, the cask temperature would have been higher for the longest period feasible to maximize potential for creep. This cask selection is also intended to observe effects of corrosion. Therefore, preference should also be given to a cask that would have likely experienced conditions favorable for corrosion processes for the longest time period {including time spent at temperatures below 100 °C [212 °F]}. Because of these competing effects, corrosion effects may require a longer timeframe to manifest if additional time is needed for further cooling of the cask.

3.8.3 Option G: Summary of Activities and Issues To Be Addressed During Demonstration

Table 3-20 summarizes all the activities associated with Option G, and Table 3-21 summarizes the data to be obtained in Option G to address technical issues summarized in Table 2-2.

Table 3-20. Demonstration Activities for Option G

Demonstration Activities	Cask G1	Cask G1–Alternate	Hot Cell Demonstration
Transportation of SNF to site for monitoring in hot cell			🟩
Predemonstration examination			🟩
Internal monitoring of SNF conditions			🟩
Exemption(s) required for penetrations for additional monitoring in cask environment			Not applicable
External monitoring for components	🟩	🟩	
Opening of cask to access SNF during demonstration			
Opening of cask to access internal nonSNF components (e.g., basket, neutron absorbers) during demonstration			
Postdemonstration examination	🟩	🟩	🟩
Transportation of SNF for examination			
Shaded area denotes that activities will be assessed in the demonstration.			

Table 3-21. Data To Be Obtained in Option G To Address Technical Issues Summarized in Table 2-2

Elements and Factors in Cask Demonstration		Cask G1	Cask G1–Alternate	Hot Cell Demonstration
Newer cladding				🟩
High burnup SNF				🟩
SNF assembly hardware				🟩
Canister-based storage system (mostly dual-purpose canister system, welded canister in bolted overpack or concrete storage module)	Canister body and weld (stainless steel)	🟩		
	Concrete and steel overpack or concrete vault-type overpack	🟩		
Direct-load metal cask storage system	Steel cask (carbon steel, nodular cast iron, low-alloy steel)		🟩	
	Metallic seals and gaskets		🟩	
	Bolts		🟩	
SNF basket (stainless steel, aluminum, Inconel, carbon steel)				🟩 *
Neutron absorbers (borated stainless steel; other metals; metal matrix composites, such as Boral, Metamic)				🟩 *
Polymeric shielding material (e.g., borated polymers)				🟩 *
Reinforced concrete pad		🟩	🟩	🟩

Shaded area denotes that technical issues will be addressed in the demonstration.
*Basket, neutron absorber, or shielding material samples in hot cell demonstration could potentially be included.

4 SUMMARY OF CASK DEMONSTRATION OPTIONS

The main objective of this cask demonstration program is to obtain data to (i) benchmark the predictive models that will be developed from short-term laboratory testing for aging of dry storage cask system components and (ii) build confidence in the ability to predict the performance of these systems over extended time periods. Aging effects that can be missed in short-term studies may become apparent in the demonstration program. Cask demonstration Options A–G were developed by permuting the key elements and factors that were identified in Table 2-1. In selecting parameters for demonstration, collecting maximum data for technical issues identified in Table 2-2 is viewed as most important (e.g., degradation of storage system in marine or highly industrial environment, bolts and seals degradation for direct-load cask, and degradation of high burnup SNF and newer cladding material). Three general classes of demonstration testing configurations are incorporated into the cask demonstration options, including using new cask storage system(s), utilizing already-in-use casks at independent spent fuel storage installation site(s), and performing a hot cell demonstration.

The hot cell demonstration is a full demonstration for SNF and potentially other materials exposed to the same normal environments inside the dry storage system. It decouples the demonstration of SNF behavior from the casks, maximizing data and using casks that already have up to 20 years' storage. It supplements data obtained from casks where SNF removal during demonstration is not feasible.

The cask demonstration options developed include

Options A–C: New cask storage systems

Option A—Multiple new casks with multiple fuel types and other conditions

Option B—Limited number (>1) of new casks with multiple fuel types and other conditions

Option C—Single new cask with limited fuel and other conditions

Options D–E: Already-in-use casks

Option D—Assess multiple, already-in-use casks with multiple fuel types
Option E—Assess single, already-in-use cask with one fuel type

Options F–G: Already-in-use casks and hot cell demonstration

Already-in-use casks will be accessed to assess non-SNF cask system components, and the SNF will be assessed separately through the hot cell demonstration.

Option F—Assess multiple, already-in-use casks and a hot cell demonstration
Option G—Assess a single, already-in-use cask and a hot cell demonstration

Table 4-1 summarizes the developed cask demonstration options, focusing on each cask demonstration and the overall pros and cons for each demonstration option.

Table 4-2 summarizes all the activities associated with all demonstration options, and Table 4-3 summarizes the data to be obtained in all options to address technical issues summarized in Table 2-2.

Table 4-1. Summary of All Cask Demonstration Options, Casks, Focus of Demonstration, Pros, and Cons

Options	Casks	Focus of Demonstration	Pros	Cons	Report Section
Option A (multiple new casks)	Cask A1	Effects of marine environment on stainless steel canister degradation.	Most detailed and thorough demonstration with low and high burnup SNF, two major cask types in various environments, and a broad coverage of materials and components to ensure a broad coverage of representative data of interest.	Many activities and several storage sites are needed. License amendment may be needed to allow for confinement penetration. The costs, and regulatory and operational requirements are likely to be high.	3.2.1
	Cask A2	Effects of highly industrial-seasonal environment on stainless steel canister and concrete overpack degradation.			3.2.2
	Cask A3	Effects of marine environment on direct-load cask, bolts, and seals degradation and effects of extended storage on internal neutron absorber, SNF basket, and shielding materials degradation.			3.2.3
	Cask A4	Effects of highly industrial environment on direct-load bolted cask, bolts, and seals degradation and effects of extended storage on degradation of other materials supplementary to those in Cask A3.			3.2.4
	Cask A5	Degradation of high burnup PWR* SNF, including newer cladding such as Zirlo or M5, thermo-mechanical degradation of bolts and seals, radiation-induced polymeric materials degradation.			3.2.5
	Cask A6	Degradation of high burnup BWR† SNF, including lined Zircaloy-2 cladding, and other materials supplementary to those in Cask A5.			3.2.6
Option B (limited number of new casks)	Cask B1	Effects of marine environment on stainless steel canister degradation (similar to Cask A1).	Covered a range of data needs that is considered high and medium priority with fewer casks than those in Option A. The cost, and regulatory and operational requirements are lower compared to Option A.	The range of data to be obtained is not as broad as Option A. Some data have been traded off.	3.3.1
	Cask B2	Effects of highly industrial-seasonal environment on direct-load cask, bolts, and seals degradation and effects of extended storage on degradation of internal neutron absorber, SNF basket, and shielding materials degradation (similar to Cask A4).			3.3.2
	Cask B3	Degradation of high burnup SNF, newer cladding, thermo-mechanical degradation of bolts and seals, radiation-induced polymeric materials degradation (similar to Casks A5 and A6).			3.3.3

Table 4-1. Summary of All Cask Demonstration Options, Casks, Focus of Demonstration, Pros and Cons (continued)

Options	Casks	Focus of Demonstration	Pros	Cons	Report Section
Option C (single new cask)	Cask C1	Effects of marine environment on direct-load bolted cask, bolts, seals, and degradation of high burnup SNF and new cladding.	Only a single cask is used to obtain some data that are considered high and medium priority. The cost is the least compared to Options A and B.	It requires mix of low and high burnup SNF in one cask. The regulatory requirements are likely to be high.	3.4.1
	Cask C1–Alternate	Effects of marine environment on stainless steel canister and degradation of high burnup SNF and new cladding.			3.4.2
Option D (multiple already-in-use casks)	Cask D1	Effects of marine environment on stainless steel canister degradation.	Demonstration covers low and high burnup SNF, two major cask types in various environments, and a broad coverage of materials and components.	Predemonstration examination may not be as detailed as for Option A depending on the record in utility. Already-in-use casks with high burnup SNF may be limited. License amendment may be needed to allow for confinement penetration for internal monitoring.	3.5.1
	Cask D2	Effects of highly industrial environment on direct-load cask, bolts, and seals degradation.			3.5.2
	Cask D3	Degradation of high burnup PWR SNF, including newer cladding such as Zirlo or M5, thermo-mechanical degradation of bolts and seals, radiation-induced polymeric materials degradation.			3.5.3
	Cask D4	Degradation of high burnup BWR SNF, including lined Zircaloy-2 cladding, and other materials supplementary to those in Cask D3.			3.5.3

Table 4-1. Summary of All Cask Demonstration Options, Casks, Focus of Demonstration, Pros and Cons (continued)

Options	Casks	Focus of Demonstration	Pros	Cons	Report Section
Option E (single already-in-use cask)	Cask E1	Effects of marine environment on stainless steel canister degradation.	Only single cask is needed to obtain some data that are considered high and medium priority. It is more feasible for a utility.	Only limited data are obtained. License amendment may be needed to allow for confinement penetration for internal monitoring.	3.6.1
	Cask E1–Alternate	Effects of seasonal environment on direct-load bolted cask degradation and effects of extended storage on degradation of bolts, seals, and gaskets.			3.6.2
Option F (multiple already-in-use casks and hot cell demonstration)	Cask F1	Effects of marine environment on stainless steel canister degradation.	It covers a broad range of data. Hot cell demo provides continuous *in-situ* monitoring and potential for frequent examination of SNF and cladding independent of casks. No additional confinement penetration is needed.	It requires multiple sites and a hot cell dedicated for demonstration. The cost and operational requirements are likely to be high.	3.7.1
	Cask F2	Effects of highly industrial environment on direct-load bolted cask degradation and effects of extended storage on degradation of bolts, seals, gaskets.			3.7.2
	Cask F3	Effects of seasonal environment on direct-load bolted cask and concrete structure degradation.			3.7.3
	Hot cell demonstration	Degradation of high burnup SNF, cladding, and other cask component materials.			3.7.4

Table 4-1. Summary of All Cask Demonstration Options, Casks, Focus of Demonstration, Pros and Cons (continued)

Options	Casks	Focus of Demonstration	Pros	Cons	Report Section
Option G (single already-in-use cask and hot cell demonstration)	Cask G1	Effects of marine environment on stainless steel canister degradation.	Only single cask is needed to obtain some data that are considered high and medium priority. It is more feasible for a utility. Hot cell demo provides continuous *in-situ* monitoring and potential for frequent examination of SNF and cladding independent of cask. No additional confinement penetration is needed.	Only limited data are obtained. Requires dedicated hot cell for demonstration.	3.8.1
	Cask G1–Alternate	Effects of highly industrial environment on direct-load bolted cask degradation and effects of extended storage on items such as degradation of bolts, seals, and gaskets.			3.8.2
	Hot cell demonstration	Degradation of high burnup SNF, cladding, and other cask component materials.			3.7.4

*Pressurized water reactor
†Boiling water reactor

Table 4-2. Demonstration Activities for All Options A–G

Demonstration Activities	New Cask Storage Systems				Already-In-Use Casks			Already-In-Use Casks and Hot Cell Demonstration		
	Option				Option			Option		
	A	B	C	C-Alternate	D	E	E-Alternate	F	G	G-Alternate
Transportation of SNF to site for monitoring in hot cell								🟩	🟩	🟩
Predemonstration examination	🟩	🟩	🟩	🟩				🟩 *	🟩 *	🟩 *
Internal monitoring of SNF conditions	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 *	🟩 *	🟩 *
Exemption(s) required for penetrations for additional monitoring in cask environment	🟩	🟩	🟩	🟩	🟩	🟩	🟩			
External monitoring for components	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Opening of cask to access SNF during demonstration	🟩	🟩	🟩		🟩		🟩			
Opening of cask to access internal non-SNF components (e.g., baskets, neutron absorbers) during demonstration	🟩	🟩	🟩		🟩		🟩			
Postdemonstration examination	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Transportation of SNF for examination	🟩	🟩	🟩	🟩 †	🟩	🟩	🟩			

Shaded area denotes that activities will be assessed in the demonstration.
*For hot cell demonstration only
†Before and at the end of demonstration only

Table 4-3. Data To Be Obtained in All Options A–G To Address Technical Issues Identified in the Literature*

SNF, Cladding, and System Components		Degradation Under Extended Storage	New Cask Storage Systems				Already-In-Use Casks			Already-In-Use Casks and Hot Cell Demonstration		
			Option				Option			Option		
			A	B	C	C-Alternate	D	E	E-Alternate	F	G	G-Alternate
Cladding		Off-normal air oxidation†										
		Hydrogen embrittlement	🟩	🟩	🟩		🟩		🟩	🟩	🟩	🟩
		Delayed hydride cracking	🟩	🟩	🟩		🟩		🟩	🟩	🟩	🟩
		Annealing of radiation damage	🟩	🟩	🟩		🟩		🟩	🟩	🟩	🟩
		Low temperature creep	🟩	🟩	🟩		🟩		🟩	🟩	🟩	🟩
		Stress corrosion cracking	🟩	🟩	🟩		🟩		🟩	🟩	🟩	🟩
		Galvanic corrosion	🟩	🟩	🟩		🟩		🟩	🟩	🟩	🟩
		Propagation of existing flaws	🟩	🟩	🟩		🟩		🟩	🟩	🟩	🟩
SNF		Off-normal air oxidation										
		Fragmentation, restructuring-swelling, SNF oxidation under normal condition, rim structure degradation, fission gas release during accident, helium release	🟩	🟩	🟩		🟩		🟩	🟩	🟩	🟩
SNF Assembly Hardware		Wet corrosion and stress corrosion cracking, metal fatigue caused by temperature fluctuations	🟩	🟩	🟩		🟩		🟩	🟩	🟩	🟩
Canister-Based Storage System (Mostly dual-purpose canister system, welded canister in bolted overpack or concrete storage module)	Canister body and weld (stainless steel)	Atmospheric corrosion (pitting and crevice corrosion including marine environment), stress corrosion cracking near the marine or highly industrial environments, aqueous corrosion	🟩	🟩		🟩	🟩	🟩		🟩	🟩	
	Concrete and steel overpack or concrete vault-type overpack	Corrosion of embedded steel, concrete degradation because of freeze–thaw cycle	🟩	🟩		🟩	🟩	🟩		🟩	🟩	

Table 4-3. Data To Be Obtained in All Options A–G To Address Technical Issues Identified in the Literature* (continued)

SNF, Cladding, and System Components		Degradation Under Extended Storage	New Cask Storage Systems				Already-In-Use Casks			Already-In-Use Casks and Hot Cell Demonstration		
			Option				Option			Option		
			A	B	C	C-Alternate	D	E	E-Alternate	F	G	G-Alternate
Direct-Load Metal Cask Storage System (Generally bolted, thick walled)	Steel cask (carbon steel, nodular cast iron, low-alloy steel)	Atmospheric corrosion (including marine environment), aqueous corrosion.	🟩	🟩	🟩		🟩		🟩	🟩		🟩
	Metallic seals and gaskets	Stress relaxation, crevice corrosion, microbial influenced corrosion, plastic deformation, creep, thermo-mechanical fatigue.	🟩	🟩	🟩		🟩		🟩	🟩		🟩
	Bolts	Corrosion, stress corrosion cracking, creep, thermo-mechanical fatigue, embrittlement.	🟩	🟩	🟩		🟩		🟩	🟩		🟩
SNF Basket (Stainless steel, aluminum, Inconel, carbon steel)		Loss of geometry due to creep, metal fatigue, general corrosion, galvanic corrosion, weld embrittlement.	🟩	🟩	🟩					🟩 ‡	🟩 ‡	🟩 ‡
Neutron Absorbers (Borated stainless steel; other metals; metal matrix composites, such as Boral^{TM}, Metamic^{TM})		Corrosion (blistering), thermal aging effects, creep, embrittlement and cracking.	🟩	🟩	🟩					🟩 ‡	🟩 ‡	🟩 ‡
Shielding Material (e.g., borated polymers)		Oxidation-induced mechanical property changes leading to slump within the overpack.	🟩	🟩	🟩		🟩		🟩	🟩 ‡	🟩 ‡	🟩 ‡

Table 4-3. Data To Be Obtained in All Options A–G To Address Technical Issues Identified in the Literature* (continued)

SNF, Cladding, and System Components	Degradation Under Extended Storage	New Cask Storage Systems				Already-In-Use Casks			Already-In-Use Casks and Hot Cell Demonstration		
		Option				Option			Option		
		A	B	C	C-Alternate	D	E	E-Alternate	F	G	G-Alternate
Reinforced Concrete Pad	Corrosion of steel in reinforced concrete leading to concrete spallation and loss of structural function for cask and retrieval equipment foundation, freeze–thaw cycle, effect of elevated temperature.	🟩	🟩	🟩		🟩	🟩	🟩	🟩	🟩	🟩

Shaded area denotes that technical issues are covered in the demonstration.

*Based upon the following references:

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†Off-normal oxidation means oxidation when air leaks through the cask storage system.

‡Could potentially be done with hot cell demonstration.

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