Spent Fuel Project Office
Interim Staff Guidance - 15
MATERIALS EVALUATION

Issue

Due, in part, to a number of material-related issues identified during dry cask storage system (DCSS) and transportation package application reviews and field implementation, the staff has recognized the need for specific guidance for the review of materials selected by the applicant for its DCSS or transportation package.

Regulatory Basis

See the Attachment, Section III, “Regulatory Requirements.”

Applicability

This guidance applies to DCSS and radioactive material transportation package reviews conducted in accordance with NUREGs 1536, “Standard Review Plan for Dry Cask Storage Systems” (January 1997), 1567, “Standard Review Plan for Spent Fuel Dry Storage Facilities” (March 2000), 1609, “Standard Review Plan for Transportation Packages for Radioactive Material” (Draft, November 1997), and 1617, “Standard Review Plan for Transportation Packages for Spent Nuclear Fuel” (March 2000).

Discussion

There is no existing materials evaluation chapter in either NUREG-1536 or NUREG-1567 for the review of DCSS. Therefore, the staff has developed a materials evaluation chapter to address this need. Parts of this chapter also apply to NUREG-1609 and NUREG-1617. The materials evaluation chapter provides guidance to the staff in the Spent Fuel Project Office (SFPO) for performing materials reviews of DCSSs and transportation packages. The materials evaluation chapter will ensure quality and uniformity in reviews performed by new or current staff members in SFPO.

With respect to NUREGs-1536,-1567, and -1617, ISG-15 will supercede the following ISGs in their entirety:

- ISG-4, R1 - Cask Closure Weld Inspections
- ISG-11, R0 - Storage of Spent Fuel Having Burnups in Excess of 45,000 MWd/MTU
- ISG-11, R1 - Transportation and Storage of Spent Fuel Having Burnups in Excess of 45 GWd/MTU

Recommendation

NUREG-1536 should be revised as follows:

Replace the current contents of Chapter 8, “Operating Procedures,” with the attachment to this ISG in its entirety. This ISG then becomes a new Chapter 8. “Operating Procedures” becomes Chapter 9, and the following chapters will be renumbered sequentially. Revise the Table of Contents and Chapter references throughout the NUREG to reflect the new chapter numbers. Add reference to Chapter 8, as appropriate, to other chapters, and delete redundant material.

Revise Appendix C, “Glossary,” to include the following terms:

Commercial Spent Fuel Management program (CSFM)
Heat Affected Zone (HAZ)
Megawatt days per Metric Ton Uranium (MWd/MTU)
Nondestructive Examination (NDE)
Post-Weld Heat Treatment (PWHT)

NUREG-1567 should be revised as follows:

Replace the current contents of Chapter 10, “Conduct of Operations Evaluation,” with the attachment to this ISG in its entirety. This ISG then becomes the new Chapter 10. “Conduct of Operations Evaluation” becomes Chapter 11, and the following chapters will be renumbered sequentially. Revise the Table of Contents and Chapter references throughout the NUREG to reflect the new chapter numbers. Add reference to Chapter 10, as appropriate, to other chapters, and delete redundant material.

Revise the “Acronyms and Abbreviations” section to include the following terms:

Commercial Spent Fuel Management Program (CSFM)
Heat Affected Zone (HAZ)
Megawatt Days per Metric Ton of Uranium (MWd/MTU)
Post-Weld Heat Treatment (PWHT)

NUREG-1609 should be revised as follows:

Revise the listed NUREG-1609 section to incorporate the applicable material from this ISG:

NUREG section 2.5.2.1	ISG sections X.5.1 and X.5.2.4
NUREG section 2.5.2.2	ISG section X.5.3.1
NUREG section 4.5.1.1	ISG section X.5.2.9
NUREG section 5.5.1.1	ISG section X.5.2.6
NUREG section 6.5.3.2	ISG section X.5.2.7

Revise the “Acronyms and Abbreviations” section to include the following terms:

American Concrete Institute (ACI)
Safety Analysis Report (SAR)

NUREG-1617 should be revised as follows:

Revise the listed NUREG-1617 section to incorporate the applicable material from this ISG:

NUREG section 1.3.3	ISG section X.5.1.1
NUREG section 1.5.2.6	ISG section X.5.2.3
NUREG section 1.5.3.1	ISG section X.5.1
NUREG section 2.3.2	ISG section X.5.2.2
NUREG section 2.4.2	ISG section X.5.2.2
NUREG section 2.5.2.1	ISG sections X.5.2.2 and X.5.2.4
NUREG section 2.5.2.2	ISG section X.5.3.1
NUREG section 2.5.2.3	ISG section X.5.2.9
NUREG section 3.5.2.1	ISG section X.5.2.2
NUREG section 3.5.2.3	ISG section X.5.4
NUREG section 4.5.1.1	ISG sections X.5.2.9 and X.5.3.1
NUREG section 5.5.3.2	ISG section X.5.2.6
NUREG section 6.5.3.2	ISG section X.5.2.7

Revise the “Acronyms and Abbreviations” section to include the following terms:

American Concrete Institute (ACI)
American Welding Society (AWS)
Commercial Spent Fuel Management program (CSFM)
Dry Cask Storage System (DCSS)
Heat Affected Zone (HAZ)
Independent Spent Fuel Storage Installation (ISFSI)
Magnetic Particle examination (MT)
MegaWatt days per Metric Ton Uranium (MWd/MtU)
Nondestructive Examination (NDE)
Dye Penetrant examination (PT)
Post Weld Heat Treatment (PWHT)
Ultrasonic examination (UT)

Approved ________________***/RA/***____________________________01/10/2001___
E. William Brach **Date**

Attachment: “Materials Evaluation”

X MATERIALS EVALUATION

X.I Review Objective

In this portion of the dry cask storage system (DCSS) review, the NRC staff evaluates the DCSS to ensure adequate material performance of components important to safety of an independent spent fuel storage installation (ISFSI) or monitored retrievable storage facility (MRS) under normal, off-normal and accident conditions. To ensure an adequate margin of safety in the design basis of the ISFSI or MRS, the reviewer should obtain reasonable assurance that:

- The physical, chemical, and mechanical properties of components important to safety meet their service requirements.
- Materials for components important to safety have sufficient requirements to control the quality of the raw material, handling, and fabrication and test activities.
- Materials for components important to safety are selected to accommodate the effects of, and to be compatible with, the ISFSI or MRS site characteristics and environmental conditions associated with normal, off-normal and accident conditions.
- The spent fuel cladding is protected from gross rupture and from conditions that could lead to fuel redistribution.
- DCSS must be designed to allow ready retrieval of spent fuel.

X.2 Areas of Review

The principal purpose of the materials review is to obtain reasonable assurance that materials selected for each component are adequate for performance of the safety function(s) required of that component. As defined in Section 5 of this Chapter, the materials evaluation encompasses the following areas of review:

X.2.1 General

a. cask design/materials, fuel specifications, and environmental conditions
b. engineering drawings

X.2.2 Materials Selection

a. applicable codes and standards
b. material properties
c. weld design and specification
d. bolt applications
e. coatings
f. gamma and neutron shielding materials
g. neutron absorbing/poison materials for criticality control

h. concrete and reinforcing steel
i. seals

X.2.3 Chemical and Galvanic Reactions

a. loss of corrosion resistance
b. flammable gas generation

X.2.4 Cladding Integrity

a. temperature limits
b. high burnup fuel
c. cask reflooding

X.3 Regulatory Requirements

X.3.1 General

a. Structures, systems and components (SSCs) important to safety must be described in sufficient detail to enable reviewers to evaluate their effectiveness. [10 CFR 72.24(c)(3)]

b. In the design, consideration should be given to compatibility of the cask with wet or dry spent fuel loading and unloading facilities and with the requirements for removal from the reactor site. [10 CFR 72.236(m)]

X.3.2 Materials Selection

a. The SSCs important to safety must be designed, fabricated, erected, and tested to quality standards commensurate with the importance to safety of the function to be performed. [10 CFR 72.122(a)]

b. The materials used for shielding and criticality functions shall be adequate for performance of intended functions. [10 CFR 72.104(a), 106(b), 124, 128(a)(2)]

c. The materials of construction shall have adequate properties for anticipated service and environmental conditions, and quality standards shall be used to verify that the design bases for the SSCs are satisfied. [10 CFR 72.122(a), (b) and (c)]

d. Sufficient information shall be included for materials of construction to satisfy the design bases with an adequate margin for safety. [10 CFR 72.24(c)(3)]

e. The DCSS must be designed to store spent fuel safely for a minimum of 20 years and permit maintenance as required. [10 CFR 72.236(g)]

f. Non-combustible and heat resistant materials must be used wherever practical throughout the ISFSI or MRS so that the materials can perform their safety functions under credible fire and explosion exposure conditions. [10 CFR 72.122(c)]

g. The DCSS must reasonably maintain confinement of radioactive material under normal, off-normal, and credible accident conditions. [10 CFR 72.236(l)]

X.3.3 Chemical and Galvanic Reactions

The cask, and cask components, must be compatible with wet or dry spent fuel loading and unloading facilities. [10 CFR 72.236(h)]

X.3.4 Cladding Integrity

a. The spent fuel cladding must be protected from degradation which could lead to gross rupture and pose operational safety problems with respect to spent fuel retrievability. [10 CFR 72.122(h)(1)]

b. In the design of the DCSS, consideration should be given to removal of the spent fuel from a reactor site, transportation and ultimate disposition by the Department of Energy. [10 CFR 72.236(m)]

X.4 Acceptance Criteria

X.4.1 General

For this section, items that follow the acceptance criteria in square brackets ([ ]) refer to lettered paragraphs in Section X.3 of this Chapter.

The safety analysis report (SAR) should describe all materials used for DCSS components important to safety, and the reviewer should consider the suitability of those materials for their intended functions in sufficient detail to evaluate their effectiveness in relation to all safety functions. [1a, 2a]

The DCSS should employ materials that are compatible with wet and dry spent fuel loading and unloading operations and facilities. These materials should not degrade to the extent that a safety concern is created. [1b, 2c]

X.4.2 Materials Selection

The materials properties of a DCSS component should meet its service requirements in the proposed cask system for the duration of the license period. [2a, 2b, 2e]

The materials that comprise the DCSS should sufficiently maintain their physical and mechanical properties during all conditions of operations. The spent fuel should be readily retrievable without posing operational safety problems. [2a, 2b, 2c]

Over the range of temperatures expected prior to and during the storage period, any ductile-to-brittle transition of the DCSS materials, used for structural and nonstructural components, should be evaluated for its effects on safety. [2a, 2e, 2f, 2g]

DCSS gamma shielding materials (e.g., lead) should not experience slumping or loss of shielding effectiveness to an extent that compromises safety. The shield should perform its intended function throughout the licensed service period. [2b, 2e, 2f, 2g]

DCSS materials used for neutron absorption should be designed to perform their safety function. [2b, 2c]

DCSS protective coatings should remain intact and adherent during all loading and unloading operations within wet or dry spent fuel facilities, and during long-term storage. [1b, 2c, 2g, 3]

X.4.3 Chemical and Galvanic Reactions

The DCSS should prevent the spread of radioactive material and maintain safety control functions using, as appropriate, noncombustible and heat resistant materials. [2f, 3]

A review of the DCSS, its components, and operating environments (wet or dry) should confirm that no operation (e.g., short-term loading/unloading or long-term storage) will produce adverse chemical and/or galvanic reactions which could impact the safe use of the storage cask. [1b, 2c, 3]

Components of the DCSS should not react with one another, or with the cover gas or spent fuel, in a manner that may adversely affect safety. Additionally, corrosion of components inside the containment vessel should be effectively prevented. [1b, 3]

The operating procedures should ensure that no ignition of hydrogen gas should occur during cask loading or unloading. [3]

Potential problems from uniform corrosion, pitting, stress corrosion cracking, or other types of corrosion, should be evaluated for the environmental conditions and dynamic loading effects that are specific to the component. [1b, 2c]

X.4.4 Cladding Integrity

The integrity of the cladding should be protected by ensuring that non-combustible and heat-resistant materials are used wherever practical throughout the ISFSI. [2f, 4a]

The cladding temperature should be maintained below maximum allowable limits, and an inert environment should be maintained inside the cask cavity to maintain reasonable assurance that the spent fuel cladding will be protected against degradation that may lead to gross rupture, loss of retrievability, or severe degradation. DCSS distortions from debris, corrosion, or spalled coatings, should not impair removal of the spent fuel from the cask. [4a, 4b]

For Zircaloy-clad fuel, the temperature should be maintained below 570° C (1058° F) for short-term accident conditions, short-term off-normal conditions, and fuel transfer operations, as described in PNL-4835[1]. [4a]

Cladding should not rupture during re-flood operations. [2g, 4a]

Any degradation of DCSS coating material, including vapors or particulate that originate from a deteriorating coating, should not affect the safety functions of the cladding or the cask components. [1b, 2a, 2c, 2d, 2e, 2f 2g, 4a]

DCSS materials should be durable and compatible to demonstrate that the spent fuel is retrievable and the geometry of the spent fuel is maintained in a sub-critical configuration under all credible operating and accident conditions. [1b, 2g, 3, 4b]

X.5 Review Procedures and Guidance

Since the materials review is interdisciplinary, the materials reviewer should coordinate with other reviewers (e.g., structural, thermal, shielding, criticality), as necessary, for identification of materials related issues in other SAR chapters.

X.5.1 General

X.5.1.1 Cask Design/Materials, Fuel Specifications, and Environmental Conditions

The materials reviewer should consider the cask design and materials specifications, fuel specifications, environmental conditions (e.g., time, temperature, radiation, liquid and vapor exposures), and operating conditions of the DCSS, including conditions during loading/unloading, storage, and transfer operations. The reviewer should verify that material properties of the major nonstructural components (e.g., neutron absorbing materials, heat transfer disks, etc.) are also presented in the SAR. This general information can usually be found in Chapters 1 (General Description), 2 (Principal Design Criteria), 8 (Operating Procedures), or 12 (Technical Specifications). However, the reviewer should review the SAR to assess all aspects pertinent to the DCSS at an ISFSI.

In considering the suitability of components, consider the various environmental conditions and length of time that the component will encounter each condition during the licensed storage period, as in-service environmental conditions may affect material properties over time. Note that the magnitudes of radiation and temperature decrease over the ISFSI service period. Other environmental and operating conditions that may be encountered in loading, transport (on-site), storage, unloading, and transfer to another storage or transport system may degrade performance of the materials.

X.5.1.2 Engineering Drawings

Review the engineering drawings of the SAR to understand how the cask components are assembled. The reviewer should verify that the SAR drawings contain a bill of materials, including appropriate consensus code information [e.g., American Welding Society (AWS), American Society of Mechanical Engineers (ASME), American Society for Testing and Materials (ASTM), or American Concrete Institute (ACI) specification number, type, class, and/or grade of material) or other similar specification documents for fabrication, examination, assembly, and testing control. Further, verify that the drawings identify all cask components to be coated (if applicable).

X.5.2 Materials Selection

X.5.2.1 Applicable Codes and Standards

The reviewer should verify that the identified codes and standards are appropriate for the material control of the component. Verify that materials selections are appropriate for the environmental conditions to be encountered during loading, unloading, transfer and storage operations. The suitability of materials and fabrication of major structural components (e.g., shell, bottom plate, shield lid, structural lid, basket fuel tube) may be assessed using the applicable construction code of record.

X.5.2.2 Material Properties

The material properties provided for the major structural components (including stainless steel, precipitation-hardened steels, carbon steel bolting materials, aluminum alloys, concrete, neutron and gamma shielding materials, and neutron absorbing materials, etc.) can usually be ascertained from applicable codes and standards, such as the ASTM Standards. However, other references (e.g., Military Handbook Specifications or International Standards) may be used to obtain the values of mechanical properties specified in the SAR. The reviewer should obtain reasonable assurance that the particular class and grade of structural material are acceptable under the applicable construction code of record. Proposed alternative materials should be justified so that the reviewer can assess their acceptability for the given component under the intended service conditions.

In conjunction with the other technical disciplines (i.e., structural, confinement, thermal, shielding and criticality), verify, as needed, that selected parameters have been appropriately defined (e.g., the temperature dependent values for the stress allowables, modulus of elasticity, Poisson's ratio, weight density, thermal conductivity, and coefficient of thermal expansion).

The reviewer may find it useful to tabulate the major structural materials to facilitate the review. The following information could be tabulated: specification number; grade, type, and class of the material; nominal composition; product form; yield and tensile strength level; notes about the materials; etc.

X.5.2.3 Weld Design and Specifications

General

There are two nationally recognized codes that address welding, ASME[2] and AWS D1.1[3]. The ASME Code governs welded pressure vessels, from domestic water heaters to nuclear reactors. The AWS D1.1 "Structural Welding Code" is the applicable code for welding structural steel, such as the steel used for bridges and steel-framed skyscrapers. The NRC staff recommends the use of the ASME welding code as the preferred code for storage casks. However, the ASME Code is a voluntary consensus standard which has been adopted by most vendors. Some older cask designs used the AWS Code. Note that the various construction codes differ from one another in their requirements for materials and welding procedures because each code is specialized with a particular application in mind.

Standard weld and nondestructive examination (NDE) symbols may be found in AWS A2.4, "Symbols for Welding and Nondestructive Testing," to interpret such symbols found on the drawings submitted with the SAR.

Weld Design and Materials

Except for welded closure lids, discussed later, all welds of the confinement shell should be full penetration welds. Verify that the NDE for these confinement welds is volumetric.

All weld filler metals should be specified by ASME Section II, Part C, and an associated AWS classification.

Weld metals for austenitic stainless steels and nickel-based alloys are specified according to base material chemistry. For these materials, a slight degree of overmatching (i.e., more alloy content than the base material) is normal practice (e.g., type 308 filler is commonly used for type 304 base metals).

For any weld, the specified weld metal strength must equal or exceed the specified base metal strength. Consult ASME Section II, Part C, for weld metal properties. A weld schedule, showing the base and weld metal combinations to be used in the cask, should have been provided as an aid in comparing base and weld metal properties.

Fracture Control

For designs that use carbon or alloy steels, dynamic fracture toughness and nil-ductility or fracture appearance transition temperature test data should have been submitted for samples of weld metal, heat affected zone (HAZ) metal, and base materials that have been taken from weldments that use the same materials of construction and welding procedures as used for construction.

The air hardening propensity of such materials during welding may have a significant adverse influence on the fracture toughness of the weld zone. (Air hardening refers to a steel with sufficient carbon or other alloying elements which causes the steel to harden significantly during cooldown in air, resulting in hard, brittle weld deposits and HAZs.) Consequently, the importance of preheat and post-weld heat treatment (PWHT) is paramount. Adherence to PWHT Table WB-4622.1-1 of Section III, Division 3 (1998) is recommended. Staff experience has shown that the Code option of a lower temperature PWHT for a longer time is generally undesirable. It is especially detrimental when fracture toughness is important to the design. Therefore, Table WB-4622.4(c)-1 of Section III, Division 3 (1998), or similar, is generally unacceptable.

The reviewer should note that a full temperature PWHT of a closure lid may not be feasible due to the potential for overheating of the fuel cladding, thereby precluding welded closures for materials requiring PWHT.

Welded Lids

Most cask designs use two lids, an inner shield lid and an outer structural lid. The structural lid weld joint may be either a full-penetration weld or a partial-penetration groove weld.

Carbon and Alloy Steel Cask Designs

The reviewer should verify that the applicant has considered all the closure lid weld material and technique improvements that accrued from previous DCSS design and fabrication experience. For example, refer to the technical evaluation in NRC Confirmatory Action Letter 97-7-001, dated July 22, 1998. Some of the DCSS improvements resulting from that action include:

- shell plates made from low sulfur, calcium-treated, vacuum-degassed steel;

- application of minimum 200° F preheat;
- use of low-hydrogen electrodes;
- low carbon equivalent base metals and weld metals;
- magnetic particle (MT) examination of the root pass;
- maintenance of preheat as a postheat treatment for a minimum of one hour; and
- minimum of two-hour delay after postheat before performing final volumetric NDE.

The structural lid weld should be examined by ultrasonic testing (UT) or other volumetric methods. Review the applicant's evaluation of the critical flaw size using the linear-elastic fracture mechanics methodology based on service temperature, dynamic fracture toughness, and critical design stress parameters, as specified in Section XI of the ASME Code.

Progressive surface examinations, utilizing dye penetrant testing (PT) or MT, are permitted only if unusual design and loading conditions exist. In addition, a stress-reduction-factor of 0.8 is imposed on the weld strength of the closure joint to account for imperfections or flaws that may have been missed by progressive surface examinations. The weld design should be approved by the NRC on a case-by-case basis.

Austenitic Stainless and Nickel-Base Alloy Steels Cask Design

For designs employing austenitic lid materials and welds, either volumetric or multi-pass PT inspection methods are acceptable.

For either UT or PT examination, the minimum detectable flaw size must be demonstrated to be less than the critical flaw size. The critical flaw size should be calculated in accordance with ASME Section XI methodology; however, net section stress may be governing for austenitic stainless steels, and must not violate ASME Section III requirements. Flaws in austenitic stainless steels are not expected to exceed the thickness of one weld bead.

If using UT, the UT acceptance criteria are the same as those of NB-5332 for pre-service examination. In accordance with Code practice for supplementing volumetric examinations with a surface examination, UT examination must be performed in conjunction with a root pass and cover pass PT examination.

If PT is specified (i.e., no volumetric inspection), a stress reduction factor of 0.8 must be applied to the weld design.

X.5.2.4 Bolt Applications

The reviewer should verify that all bolts have the required tensile strength, resistance to corrosion and brittle fracture, and a coefficient of thermal expansion that is similar to the materials being bolted together. Confirm that the bolting materials are not sensitive to stress corrosion cracking under anticipated operating conditions.

X.5.2.5 Coatings

Coatings in DCSSs are used primarily as corrosion barriers or to facilitate decontamination. They may have additional roles, such as improving the heat rejection capability by increasing the emmisivity of cask internal components.

The reviewer should determine the appropriateness of the coating(s) for the intended application by reviewing the coating specification for each protective coating that is applied to an important to safety component. A specification that describes the scope of the work, required materials, the coating's purpose, and key coating procedures, should assure that the appropriate and compatible coatings have been selected by the DCSS designers. A coating specification should include the following:

- scope of coating application;
- type of coating system;
- surface preparation methods;
- applicable coating repair techniques; and
- coatings qualification testing, as applicable.

Additional guidance regarding coating specification details are described below.

Scope of Coating Application

The coating specification should identify the purpose of the coating, a list of the components to be coated, and a description of the expected environmental conditions (e.g., expected conditions during loading, unloading, and dry storage).

The reviewer should verify that the coatings will not react with the cask internal components and contents, and will remain adherent and inert when exposed to the various environments of a spent fuel cask. The most prevalent, potentially degrading environments include the immersion in borated spent fuel pool water during loading and unloading operations, and high temperature and high radiation (including neutrons) environments encountered during vacuum drying evolutions and long-term storage.

Coating Selection

The reviewer should verify that the coating specification identifies the manufacturer's name, the type of primers and topcoat(s) comprising the coating system, and the minimum and maximum dry coating thickness(es). The coating manufacturer's technical literature for all coatings specified for cask interiors must be submitted in the SAR for staff review.

The reviewer should verify that the coating selected for cask components is capable of withstanding the intended service conditions over the design service life. Failures can be prevented by ensuring that the selection and the application of the coating is controlled by adhering to the coating manufacturer's recommendations.

Surface Preparation

The reviewer should verify that the coating specification identifies whether solvent or abrasive cleaning methods should be used to prepare surfaces prior to coating application. This information should ensure that proper surface preparation techniques could be implemented during cask fabrication.

The reviewer should confirm that the specified type and degree of surface cleaning and the required surface profile meet the coating manufacturer's specification. Any deviations from the manufacturer's standards for surface preparation must be supported by appropriate tests that demonstrate acceptable coating performance under all design conditions.

Coating Repairs

The reviewer should verify that the coating specification identifies the general requirements for repairing damage to the coating. This information will assist the reviewer(s) in evaluating the effects of repairs on the integrity of the coating and whether the designated repair methods could be implemented during or after cask fabrication.

The reviewer should examine the design to determine whether the structure is assembled before or after its various parts are coated. If a complex structure is to be coated after assembly, it is very important that the consequences of a potential coating failure be analyzed to determine whether other cask functions or component features could be compromised by the failure.

The consequences of coating failure depend on the type of coating and service environment, and may include the following:

- Partial and/or complete coating failure that alters the corrosion resistance of DCSS structural and shielding components (primarily during loading/unloading operations);

- Partial and/or complete coating failure that alters the emmisivity and heat transfer of basket components;

- Particulates (cloudiness) that form in spent fuel pool water or cask during loading or unloading that may affect such operations; and/or

- Aggressive or reactive chemical species that form and consequently impact the performance of other cask components during long-term exposure to radiation (e.g., gamma and neutron).

Coating Qualification Testing

Coatings used on cask external surfaces may have been selected upon the basis of their performance requirements and exposure conditions. The applicant may have used related industrial conditions as a documented guide or basis for coating selection without performing further laboratory tests.

Any coating used inside a DCSS must have been tested to demonstrate the coatings performance under all conditions of loading and storage. The conditions evaluated should include exposure to radiation, high temperature during vacuum drying and storage, and immersion during loading, unloading and transfer operations. The coating must be demonstrated to remain intact and inert for the full duration of the DCSS design life.

There are a number of standardized ASTM tests for coatings performance. In reviewing ASTM (or other) tests used to qualify coatings for service in storage casks, consideration should be given to the applicability of a test to the service conditions.

Planning, execution, and interpretation of coating qualification tests must be performed by a qualified coatings engineer (e.g., certified by the National Association of Corrosion Engineers). The reviewer should ensure that appropriate, qualified expertise has been employed by the applicant for any coatings qualification program.

The reviewer should verify that the coating specification includes a description of the coating qualifications testing program, as applicable. The following information, which is important to qualifying a coating, includes, but is not limited to:

- The size and shape of samples used for the coating tests, as well as the type of material(s), and a description and results of any tests conducted on partial or full-size production mock-ups.

- The test sample surface preparation method(s) and expected or measured surface profile. Sample surface preparation should be performed in accordance with written production procedures, using the same equipment, materials, and qualified personnel as intended for production coating. Inspection methods and acceptance criteria should be included.

- Application method(s) and measured control parameters, including records of temperature and humidity, cure cycle and times, and any other monitoring or acceptance tests such as dry film thickness, hardness, and adhesion. The methods and parameters should be employed in accordance with written production procedures using the same equipment, methods, materials, and qualified personnel.

- A test plan description which clearly describes the rationale for and the types and sequences of all coating qualification tests, lab protocols, numbers of samples, inspection methods, and acceptance criteria. Raw test results should be tabulated or otherwise presented. The test plan should include (1) laboratory coupons for demonstrating coating suitability/qualification, and (2) partial or full size production mock-up tests that demonstrate that the selected coating can be applied successfully to real production parts under production shop conditions to give reasonable assurance that field performance will meet laboratory, test-based expectations.

- An interpretation and discussion of the test program results by a certified coatings engineer. This evaluation should examine, at a minimum, the coating performance against the specific tests and the overall requirements for coating performance. The overall program must be assessed as to whether it is likely to be an effective predictor of actual performance. A recommendation for the use of the coating, with specific restrictions, if any, must be included.

The application should also include general requirements applying to all tests:

- Test durations for immersion must equal or exceed the combined maximum design (or technical specification) durations for loading and vacuum drying.

- An evaluation of any observed gasses, bubbles or other evidence that a gas was produced during the test. Coatings that produce flammable gas require a mitigation program to prevent burnable or explosive gas concentrations during all phases of cask operations.

X.5.2.6 Gamma and Neutron Shielding Materials

Concrete, steel, depleted uranium, and lead typically serve as gamma shields, while filled polymers are often used for neutron shielding materials.

The reviewer should confirm that temperature-sensitive shielding materials will not be subject to temperatures at or above their design limits during both normal and accident conditions. The reviewer should determine whether the applicant properly examined the potential for shielding material to experience changes in material densities at temperature extremes. (For example, elevated temperatures may reduce hydrogen content through loss of water in concrete or other hydrogenous shielding materials.)

With respect to external, polymer neutron shields, the reviewer should verify that the application:

- Describes the test(s) demonstrating the neutron absorbing ability of the shield material.

- Describes the testing program and provides data and evaluations that demonstrate the thermal stability of the resin over its design life while at the upper end of the design temperature range. Describes the nature of any temperature-induced degradation and its effect(s) on neutron shield performance.

- Describes what provisions exist in the neutron shield design to assure that excessive neutron streaming will not occur as a result of shrinkage under conditions of extreme cold. This description is required because polymers generally have a relatively large coefficient of thermal expansion when compared to metals.

- Describes any changes or substitutions made to the shield material formulation. For such changes, describes how they were tested and how that data correlated with the original test data regarding neutron absorption, thermal stability, and handling properties during mixing and pouring or casting.

- Describes the acceptance tests that were conducted to verify that any filled channels used on production casks did not have significant voids or defects that could lead to greater than calculated dose rates.

X.5.2.7 Neutron Absorbing/Poison Materials for Control of Criticality

Neutron absorbing materials are used in storage casks to ensure that sub-critical conditions are maintained during normal and accident conditions. Typically, these neutron absorbing materials are in the form of fixed plates or rods for which no structural credit is given.

The boron isotope (^{10}B) is the principal neutron absorbing isotope in most of the absorber plate materials used or proposed for DCSS. However, cadmium and gadolinium are also common neutron absorbing elements.

For all boron-containing materials, the reviewer should verify that the SAR and its supporting documentation describe the material’s chemical composition, physical and mechanical properties, fabrication process, and minimum poison content. This description should be detailed enough to verify the adequacy and reproducibility of properties important to performance as required in the SAR. For plates, the minimum poison content should be specified as an areal density (e.g., milligrams of ^{10}B per cm^2). For rods, the mass per unit length should be specified.

In heterogeneous absorber materials, the neutron poisons may take the form of particles dispersed or precipitated in a matrix material. Materials with large poison particles (e.g., 80-micrometer particles of unenriched boron carbide) have been shown to absorb significantly fewer neutrons than homogeneous materials with the same poison loading [Burrus[4], Wells[5]]. The reduced neutron absorption in heterogeneous materials results from particle self-shielding effects, streaming and channeling of neutrons between poison particles. Therefore, the reviewer should verify that the absorber material's heterogeneity parameters (e.g., particle composition, size, dispersion) are adequately characterized and controlled, and that the criticality calculations employ appropriate corrections (e.g., reduced poison content) when modeling the heterogeneous material as an idealized homogeneous mixture.

Qualifying the Material Fabrication Process

Qualification tests should have been conducted at least once for a given set of materials and manufacturing processes to demonstrate acceptability and durability of the resulting neutron absorber product over the licensed service life. Qualification tests are generally conducted on one or more representative samples or coupons of the fabricated material. Acceptable qualification tests may include: neutron attenuation or reactivity worth measurements to assess the required minimum absorption characteristics; neutron radiography or radioscopy to check for uniform distribution of poison material in plates; immersion of the fabricated absorber in pool water to simulate the cask environment during loading; exposure of the absorber to a radiation field to assess the effects of radiolysis; and exposure of the absorber material to the full range of service temperatures.

The qualification tests and test samples should be evaluated for the following effects: redistribution of the neutron poison; dimension and weight changes due to material instability (e.g., cracking, spalling, debonding of absorber cladding from the poison matrix material or the matrix material from the poison particles; embrittlement; galvanic reactions; hydrogen generation in spent fuel pool water; weight reduction due to outgassing; oxidation or hydriding). The reviewer should verify that the qualification testing has been completed for each neutron absorbing material. These are minimum requirements for new materials.

The effects of material heterogeneity on poison effectiveness should be tested by performing neutron attenuation and/or reactivity worth measurements on material samples or coupons. The test measurements should be calibrated against identical measurements performed on known homogeneous materials of similar composition (e.g., zirconium diboride with an appropriate thickness of aluminum for calibrating measurements of Boral or borated aluminum [Gao[6]]. The true mass of poison material in the test samples should be determined by chemical assay or other appropriate measurements. Note that the heterogeneity effects can vary significantly with poison particle composition (e.g., ^{10}B enrichment), particle size, poison areal density, and poison volumetric density in the bulk material. It is therefore important to verify that qualification testing addressed the appropriate ranges of material heterogeneity parameters.

Acceptance Testing of Fabricated Materials

For all absorber materials, the reviewer should verify that the acceptance tests in Chapter 9 of the SAR include weighing and dimensional measurements (e.g., plate thickness) and visual examination of the material for evidence of defects such as cracks, porosity, blisters, or foreign inclusions.

To the extent practical, test coupons should be removed from every other plate in a lot and at random locations on a plate. Rejection of a given test coupon shall result in rejection of the contiguous plate(s). If absorption properties are repeatable in the first 25% of the lot, reduced sampling may be performed. A rejection of a test coupon during reduced sampling should invoke a return to 100% inspection of the lot (i.e., one test coupon from every other plate).

X.5.2.8 Concrete and Reinforcing Steel

The reviewer should verify that the materials and material properties used for the design and construction of reinforced concrete components that are important to safety comply with the requirements of American Concrete Institute (ACI) 359[7]. ACI 359 is also an acceptable standard for reinforced concrete components for radioactive material containment vessels. For concrete components not covered by ACI 359, ACI 349[8] is acceptable.

The reviewer should verify that the materials and material properties used for the design and construction of reinforced concrete components that are not important to safety comply with the requirements of ACI 318[9]. The NRC also accepts the use of ACI 349 for these applications.

For some DCSS or ISFSI applications, the concrete to be used for the storage pad may have to be reviewed for suitability. The structural reviewer will have the most significant input to the review in terms of strength-related requirements, but the materials aspects, in terms of durability and temperature limits of the concrete, are the responsibility of the materials reviewer.

Reactive materials (e.g., aluminum) that tend to react chemically with wet concrete should not be used as imbeds in concrete.

X.5.2.9 Seals

The reviewer should verify that radiation to be encountered by elastomer O-ring seals in storage service will not cause polymerization to an extent that would adversely affect the safety performance of the seals. In the range of 10^7 rads, an O-ring compound must be selected with care. For higher dose rate environments, elastomer O-rings should not be specified. At lower dose rates, factors other than radiation may be more significant.

The reviewer should verify that O-ring seals do not reach their maximum operating temperature limit during normal and off-normal conditions of storage. The applicant should include the O-ring manufacturer's data sheets specifying temperature and radiation tolerances in the SAR.

Review the applicant's evaluation demonstrating that at the minimum normal operating temperature (usually -40° F), the O-ring seal will neither fail by brittle fracture nor stiffen (loose elasticity) to an extent that prevents the seal from meeting its service requirements.

The reviewer should verify that under the environmental conditions expected in storage service, O-ring seals will not chemically react or decompose in a manner that would significantly affect other components of the DCSS.

X.5.3.1 Chemical and Galvanic Reactions

Loss of Corrosion Resistance

The SAR should include an analysis of whether any chemical, galvanic, or other reactions among the materials (e.g., moderator material, sealants, steels, neutron absorbers) and environments would occur. Pursuant to NRC Bulletin 96-04[10] , confirm that the DCSS will perform adequately under the operating environments expected (e.g., short-term loading/unloading or long-term storage) during the license period such that no adverse chemical or galvanic reactions are produced. The review should also include consideration of possible reactions resulting from the interaction of DCSS components with borated water.

Flammable Gas Generation

The reviewer should evaluate the possible generation of hydrogen or other flammable gases. If appropriate, consider embrittling effects of hydrogen taking into account the metallurgical state of the DCSS components.

Verify that temperatures inside the cask do not promote the formation of vapors from a coating material (e.g., zinc). Alternatively, the applicant should demonstrate that this vapor will not interact unfavorably with the fuel or any cask component important to safety. Absent this demonstration, the materials should not be approved.

In cooperation with the containment reviewer, verify that appropriate operating procedures (SAR Chapter 8) contain adequate guidance for detecting the presence of hydrogen and preventing the ignition of combustible gases during cask loading and unloading operations.

X.5.4 Spent Fuel Cladding Integrity

X.5.4.1 Temperature Limits

The cask system must be designed to prevent degradation of fuel cladding that results in a type of cladding breach, such as axial-splits, where irradiated spent fuel particles may be released into the cask cavity. Additionally, the fuel cladding should not degrade to the point where more than one percent (1%) of the fuel rods develop pinhole or hairline crack-type failures under normal storage conditions. This criterion is consistent with the assumptions of the confinement analysis for normal conditions of storage. The 1% failure assumption is for safety analysis purposes only, and relates to assumptions for thermal analysis, containment performance, and cask unloading operations. "Damaged fuel" is defined as fuel with a breach in the cladding that is larger than a pinhole failure or hairline crack.

The reviewer should verify that cladding temperatures for each fuel assembly type proposed for storage will be below their expected damage thresholds for normal conditions of storage. Zircaloy fuel cladding temperature limits at the beginning of dry storage are typically below

380° C (716° F) for a 5-year cooled fuel assembly and 340° C (612° F) for a 10-year cooled fuel assembly for normal conditions and a minimum of 20 years cask storage (PNL-4835). Temperature limits will be lower with increased fuel assembly cooling time (or increased burnup) mainly due to lower decay heat rates of older fuel.

It should be noted that fuel cladding temperature limits are a complex function of power history (including transients), cladding thickness, pre-pressurization of fuel rods during fabrication, burnup, fission gas, and hoop stress. Substantial variation in the end-of-life internal rod pressures and fuel design characteristics may warrant temperature limits lower than those noted above for certain fuel types. Therefore, fuel cladding limits for each fuel type should be calculated and presented in the SAR.

The reviewer should evaluate the method(s) used to determine the temperature limits and associated cladding hoop stresses. Note that the storage of fuel clad in materials other than Zircaloy-4 or Zircaloy-2 (e.g., advanced alloy cladding materials like M5 or Zirlo) will be approved on a case-by-case basis. At the present time, there is limited information available to the staff relative to the expected degradation modes of advanced alloy clad fuel under storage conditions. Therefore, temperature limit calculations using methods approved for Zircaloy-4 or Zircaloy-2 may need to be modified to account for differences in the degradation processes of fuel with advanced alloys.

The temperature limits may be calculated using methodologies that are based on expected cladding behavior during storage. NUREG-1536 endorses the diffusion controlled cavity growth methodology to calculate the maximum cladding temperature limits during dry storage. The use of other methodologies that account for the full range of materials behavior under the expected storage conditions, such as the Commercial Spent Fuel Management Program (CSFM) methodology as described in PNL-6189[11] and PNL-6364[12], is acceptable to the staff for calculation of cladding temperature limits. Alternative methodologies may be approved by the staff if they are sufficiently justified. However, these alternative methodologies must be validated with experimental data, and associated modeling uncertainties must be addressed.

Hoop stress calculations should be established on the basis of fuel and cladding properties that are representative of the spent fuel to be stored (e.g., cladding dimensions, internal rod pressures). High burnup fuel (i.e., fuel with burnups exceeding 45,000 MWd/MTU) may have unusual characteristics, such as wall thinning from increased oxidation and increased internal rod pressure from fission gas buildup and changes in fuel dimensions, which must be evaluated. The SAR should use conservative values for surface oxidation thickness. Note that oxidation may not be of a uniform thickness along the axial length of the fuel rods and average values may under-predict wall thinning. Temperature limits will be more restrictive with increased fuel cooling time (and/or increased burnup), largely as a result of the slower fuel heat decay as a function of time.

For short-term off-normal and accident conditions, the staff accepts Zircaloy fuel cladding temperatures maintained typically below 570° C (1058° F). This temperature limit is a suitable criterion for short term off-normal conditions including fuel assembly transfer operations, vacuum drying and backfilling the cask with inert gas. This limit may be lowered for high burnup fuel assemblies due to increased internal rod pressure from fission gas buildup. The applicant should have verified that these cladding temperature limits are below the limit for facility specific operations (e.g., fuel assembly transfer) and the worst case credible accident.

X.5.4.2 High Burnup Fuel

The staff may approve the storage of fuel assemblies having burnups greater than 45,000 MWd/MTU, provided that the applicant can demonstrate that the cladding will be protected from degradation which could lead to gross rupture and that the storage system is designed to allow ready retrieval of the spent fuel from the storage system. If such a demonstration cannot be performed, high burnup fuel assemblies could be enclosed by approved baskets to confine the fuel so that potential degradation of the fuel during storage will not pose problems with respect to redistribution of material during storage or subsequent transportation. Such an enclosure would also maintain subcriticality based on optimum moderation conditions and no potential for buckling and failure of fuel rods, grid spacers, and end fittings under accident conditions.

The staff believes that the Zircaloy cladding of a fuel rod can, in general, withstand uniform creep strains (i.e., creep prior to tertiary or accelerating creep strain rates) of about 1% before the cladding can become perforated, if the average hydrogen concentration in the cladding is less than about 400 to 500 parts per million (ppm)[13]. This amount of hydrogen corresponds to an oxide thickness of approximately 70-80 micrometers using the recommended hydrogen pickup fraction of 0.15 from Lanning, et al[14], and Garde[15]. The staff also believes that the strength and ductility of irradiated Zircaloy do not appear to be significantly affected by corrosion-induced hydrides at hydrogen concentrations up to approximately 400 ppm. Therefore, the staff has reasonable assurance that fuels having average assembly burnups exceeding 45,000 MWd/MTU can be safely stored if the following acceptance criteria are met:

I. A high burnup fuel assembly containing Zircaloy clad fuel may be treated as intact if both of the following conditions are met:

   A1. No more than 1% of the rods in an assembly have peak cladding oxide thicknesses greater than 80 micrometers; and

   A2. No more than 3% of the rods in an assembly have peak cladding oxide thicknesses greater than 70 micrometers.

II. A high burnup fuel assembly should be treated as potentially damaged fuel if either of the following conditions is met:

   B1. The fuel assembly does not meet both criteria A1 and A2; or

   B2. The fuel assembly contains fuel rods with oxide that has become detached or spalled from the cladding.

The administrative controls section of the SAR Technical Specifications should specify a program to be implemented by the cask licensee to assure the criteria described above are met prior to loading the cask with high burnup fuel. As part of this program, the applicant may use cladding oxidation thickness measurements or predictions based on consideration of reactor operation variables affecting peak cladding oxidation (e.g., in-core flux, length of a cycle, number of cycles, power excursions, coolant temperature and amount of time at that temperature, the coolant water chemistry, and the cladding material). In cases where there are no previously documented measurements of the oxide thickness to validate cladding oxidation predictions, the program may have to incorporate peak cladding oxide thickness measurements.

For the storage of Zircaloy-clad fuel assemblies meeting criteria A1 and A2, the reviewer should coordinate with the criticality, thermal, shielding, and confinement reviewers, as appropriate, to ensure the following assumptions are made in the applicant's analyses. For the confinement analysis, the applicant should assume that the source term of 50% of the rods with peak cladding oxide thicknesses greater than 70 micrometers are available for release from the cask unless justification for a different fraction is presented. This source term should be added to the source term for the assumed rod breakage fraction for normal and off-normal conditions. For the criticality, thermal, and shielding analyses, the applicant should demonstrate that 10 CFR Part 72 requirements are met assuming that the rods with oxide thickness greater than 80 micrometers in a high burnup fuel assembly are failed (e.g., the fuel is allowed to redistribute in a cask) under normal, off-normal, and accident conditions.

For Zircaloy-clad fuel with average assembly burnups greater than 45,000 MWd/MTU meeting criteria A1 and A2, the applicant should employ an acceptable methodology (e.g., CSFM) for calculating cladding temperature limits using a 1% creep strain limit. Further, the analysis should demonstrate that the reduced cladding thickness due to oxidation does not compromise the structural ability of the cladding to withstand the expected loads encountered under normal, off-normal, and accident conditions.

Zircaloy-clad fuel assemblies that meet criterion B1 or B2 should be treated as damaged fuel. Alternatively, these fuel assemblies may be treated as intact fuel provided the appropriate demonstration of cladding integrity for these assemblies under normal, off-normal, and accident conditions is included in the SAR. Acceptable data and analyses to support the demonstration of cladding integrity may include, but are not limited to, the following:

- An estimation of the peak cladding oxide thickness and amount of hydrogen absorbed by the cladding during reactor operation. This information will ensure that the oxide thickness and hydrogen concentration associated with hydride-embrittled zirconium alloys are below those that could significantly reduce the ductility or overall integrity of the cladding.

- A calculation of the cladding hoop stress to establish both the parameters of the accelerated creep tests and the accuracy of the cladding life prediction. The stress calculation should account for the effects of (1) a reduction of thickness due to cladding oxidation, and (2) the fuel rod internal pressure considering the initial fill gas, the release of fission gases to the rod-free volume, the generation of any other gases (e.g., helium) due to effects caused by the irradiation of any internal cladding coatings, and the gas temperature.

- Experimentally derived data and analyses to identify the cladding failure mechanism(s) under expected storage conditions.

X.5.4.3 Cask Reflooding

For cask unloading operations, cladding integrity should be maintained during reflooding so as not to interfere with fuel handling and retrieval. The SAR should include a quench analysis supporting specified minimum quench fluid temperature and maximum fluid flow rate during reflood. This analysis should also be referenced in Chapter 11 of the SAR as having been considered in the development of thermal models for the unloading procedures, and be included, as appropriate, in the Technical Specifications. The NRC accepts the fact that the total stress on the cladding must be maintained below the material's minimum yield stress. The total stress includes the thermal stress combined with the cladding hoop stress from internal rod pressure and the rod-gas plenum temperature. The analysis should account for high burnup effects on the fuel (e.g., waterside corrosion, high internal rod pressure) and minimum manufacturing wall thickness.

X.6 Evaluation Findings

The evaluation findings are prepared by the reviewer on satisfaction of the regulatory requirements of Section X.3. Review these requirements and provide a summary statement for each. These statements should be similar to the following examples:

> Section(s) _____ of the SAR adequately describe(s) the materials used for SSCs important to safety and the suitability of those materials for their intended functions in sufficient detail to evaluate their effectiveness.
>
> The applicant has met the requirements of 10 CFR 72.122(a). The material properties of SSCs important to safety conform to quality standards commensurate with their safety function.
>
> The applicant has met the requirements of 10 CFR 72.104(a), 106(b), 124, and 128(a)(2). Materials used for criticality control and shielding are adequately designed and specified to perform their intended function.
>
> The applicant has met the requirements of 10 CFR 72.122(h)(1) and 236(h). The design of the DCSS and the selection of materials adequately protects the spent fuel cladding against degradation that might otherwise lead to gross rupture of the cladding.
>
> The applicant has met the requirements of 10 CFR 72.236(h) and 236(m). The material properties of SSCs important to safety will be maintained during normal, off-normal, and accident conditions of operation so the spent fuel can be readily retrieved without posing operational safety problems.
>
> The applicant has met the requirements of 10 CFR 72.236(g). The materials properties of SSCs important to safety will be maintained during all conditions of operation so the spent fuel can be safely stored for a minimum of 20 years and maintenance can be conducted as required.
>
> The applicant has met the requirements of 10 CFR 72.236(h). The [cask designation] employs materials that are compatible with wet and dry spent fuel loading and unloading operations and facilities. These materials should not degrade over time or react with one another during any conditions of storage.

References

1. A. B. Johnson and E. R. Gilbert, Pacific Nuclear Laboratories, “Technical Basis for Storage of Zircalloy-Clad Spent Fuel in Inert Gases,“ PNL-4835, September 1983.

2. American Society of Mechanical Engineers, Boiler and Pressure Vessel Code, Section II, “Specification for Welding Rods, Electrodes and Filler Metals.”

3. American Welding Society, “Structural Welding Code Steel,” AWS D1.1.

4. W. R. Burns, “How Channeling Between Chunks Raises Neutron Transmission Through Boral,” *Nucleonics*, 16, 1, 91, 1958.

5. A. H. Wells, D. R. Mamon, and R. A. Karam, “Criticality Effect of Neutron Channeling Between Boron Carbide Granules in Boral for a Spent-Fuel Shipping Cask,” *Transactions of the American Nuclear Society*, Vol. 54, pp. 205-206, 1987.

6. J. Gao, “Modeling of Neutron Attenuation Properties of Boron-Aluminum Shielding Materials,” Masters dissertation, University of Virginia, August 1997.

7. American Concrete Institute and American Society of Mechanical Engineers (Joint Committee), “Code for Concrete Reactor Vessels and Containments,” ACI 359. (Also designated as ASME Boiler and Pressure Vessel Code, Section III, “Rules for Construction of Nuclear Power Plant Components,” Division 2.)

8. American Concrete Institute, “Code Requirements for Nuclear Safety Related Concrete Structures,” ACI 349.

9. American Concrete Institute, “Building Code Requirements for Reinforced Concrete,” ACI 318.

10. NRC Bulletin 96-04, “Chemical, Galvanic, or Other Reactions in Spent Fuel Storage and Transportation Casks,” July 1996.

11. I. S. Levy, et al, Pacific Northwest Laboratory, “Recommended Temperature Limits for Dry Storage of Spent Light-Water Zircalloy Clad Fuel Rods in Inert Gas,” PNL6189, May 1987.

12. M. E. Cunningham, et al, “Control of Degradation of Spent LWR Fuel During Dry Storage in an Inert Atmosphere,” PNL-6364, September 1987.

13. Pacific Northwest National Laboratory Technical Evaluation Report of WCAP-15168 (Dry Storage of High Burnup Spent Nuclear Fuel), February 2000.

14. D. D. Lanning, et al, Pacific Northwest National Laboratory, “FRAPCON-3: Modifications to Fuel Rod Material Properties and Performance Models for High Burnup Applications,” NUREG/CR-6534, Vol. 1 (PNNL-11513, Vol. 1), 1997.

15. A. M. Garde, “Hot Cell Examination of Extended Burnup Fuel From Fort Calhoun,” DOE/ET/34030-11, September 1986.