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Standard Guide for Characterization of Spent Nuclear Fuel in Support of Geologic Repository Disposal[1]

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1. Scope

1.1 This guide provides guidance for the types and extent of testing that would be involved in characterizing the physical and chemical nature of spent nuclear fuel (SNF) in support of its interim storage, transport, and disposal in a geologic repository. This guide applies primarily to commercial light water reactor (LWR) spent fuel and spent fuel from weapons production, although the individual tests/analyses may be used as applicable to other spent fuels such as those from research and test reactors. The testing is designed to provide information that supports the design, safety analysis, and performance assessment of a geologic repository for the ultimate disposal of the SNF.

1.2 The testing described includes characterization of such physical attributes as physical appearance, weight, density, shape/geometry, degree, and type of SNF cladding damage. The testing described also includes the measurement/examination of such chemical attributes as radionuclide content, microstructure, and corrosion product content, and such environmental response characteristics as drying rates, oxidation rates (in dry air, water vapor, and liquid water), ignition temperature, and dissolution/degradation rates. Not all of the characterization tests described herein must necessarily be performed for any given analysis of SNF repository performance, particularly in areas where an extensive body of literature already exists for the parameter of interest.

1.3 It is assumed in formulating the SNF characterization activities in this guide that the SNF has been stored in an interim storage facility at some time between reactor discharge and dry transport to the geologic repository. The SNF may have been stored either wet (for example, a spent fuel pool), or dry (for example, an independent spent fuel storage installation (ISFSI)), or both, and that the manner of interim storage may affect the SNF characteristics.

1.4 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C 170/C 170M Test Method for Compressive Strength of Dimension Stone

C 696 Test Methods for Chemical, Mass Spectrometric, and Spectrochemical Analysis of Nuclear-Grade Uranium Dioxide Powders and Pellets

C 698 Test Methods for Chemical, Mass Spectrometric, and Spectrochemical Analysis of Nuclear-Grade Mixed Oxides ($(U, Pu)O_2$)

C 859 Terminology Relating to Nuclear Materials

C 1174 Practice for Prediction of the Long-Term Behavior of Materials, Including Waste Forms, Used in Engineered Barrier Systems (EBS) for Geological Disposal of High-Level Radioactive Waste

C 1380 Test Method for the Determination of Uranium Content and Isotopic Composition by Isotope Dilution Mass Spectrometry

C 1413 Test Method for Isotopic Analysis of Hydrolyzed Uranium Hexafluoride and Uranyl Nitrate Solutions by Thermal Ionization Mass Spectrometry

C 1454 Guide for Pyrophoricity/Combustibility Testing in Support of Pyrophoricity Analyses of Metallic Uranium Spent Nuclear Fuel

C 1553 Guide for Drying Behavior of Spent Nuclear Fuel

E 170 Terminology Relating to Radiation Measurements and Dosimetry

2.2 *U.S. Government Documents*[3]

Code of Federal Regulations, Title 10, Part 60 Disposal of

[1] This guide is under the jurisdiction of ASTM Committee C26 on Nuclear Fuel Cycle and is the direct responsibility of Subcommittee C26.13 on Spent Fuel and High Level Waste.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from U.S. Government Printing Office Superintendent of Documents, 732 N. Capitol St., NW, Mail Stop: SDE, Washington, DC 20401, http://www.access.gpo.gov.

High-Level Radioactive Wastes in Geologic Repositories, U.S. Nuclear Regulatory Commission, January 1997

Code of Federal Regulations, Title 10, Part 63 Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada, U.S. Nuclear Regulatory Commission

Code of Federal Regulations, Title 10, Part 71 Packaging and Transport of Radioactive Materials

Code of Federal Regulations, Title 10, Part 72 Licensing Requirements for the Independent Storage of Spent Nuclear Fuel and High-Level Radioactive Waste

Code of Federal Regulations, Title 10, Part 961 Standard contract for the Disposal of Spent Nuclear Fuel and/or High Level Waste

Code of Federal Regulations, Title 40, Part 191 Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes

Code of Federal Regulations Title 40, Part 197 2005 Protection of Environment: Public Health and Environmental Radiation Standards for Yucca Mountain, Nevada

3. Terminology

3.1 *Definitions:* Definitions used in this guide are as currently existing in Terminology C 859 or Test Method C 170/C 170M, or as commonly accepted in dictionaries of the English language, except for those terms defined below for the specific usage of this standard.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *alteration*, *n*—any change to the form, state, or properties of a material.

3.2.2 *attribute test*, *n*—a test conducted to provide material properties that are required as input to materials behavior models, but are not themselves responses to the materials environment (for example, thermal conductivity, mechanical properties, radionuclide content of waste forms, etc).

3.2.3 *characterization test*, *n*—any test conducted principally to furnish information for a mechanistic understanding of alteration (for example, electrocheimical polarization tests, leach tests, solubility tests, etc).

3.2.4 *combustible*, *adj*—capable of burning or undergoing rapid chemical oxidation.

3.2.5 *breached fuel*, *n*—(per Code of Federal Regulations, Title 10, Part 72, Section 122(h)) any spent fuel with extreme degradation or gross rupture, such that fuel particulates or pieces can be released from the fuel rod. (“The spent fuel cladding must be protected during storage against degradation that leads to gross ruptures or the fuel must be otherwise confined such that degradation of the fuel during storage will not pose operational safety problems with respect to its removal from storage,” Code of Federal Regulations, Title 10, Part 72, Section 122(h)). It is not expected that minor cladding defects such as pinhole cracks would permit significant release of particulate matter from the spent fuel rod.

3.2.6 *damaged fuel*, *n*—spent nuclear fuel elements or assemblies that as a result of their irradiation or handling (or both) have significantly altered dimensions or cladding through-wall cracks or penetrations such that it cannot fulfill its direct or indirect regulatory or design function. For example any SNF assembly with rod(s) that are significantly displaced for purposes of criticality calculations (application dependent and function of the stage in the nuclear fuel cycle).

3.2.7 *degraded cladding*, *n*—spent fuel cladding which has corroded or been physically altered in-reactor or during subsequent interim storage (or both), to the extent that the alteration must be accounted for in the evaluation of its behavior during transport, storage, or disposal (for example, cladding corrosion/thinning, hydride embrittlement, delayed hydride cracking, etc.).

3.2.8 *failed fuel (geologic disposal)*, *n*—any significant alteration in the shape, dimensions, or configuration of a spent fuel assembly or fuel element, or through-wall crack in the cladding, that could degrade or open further under long-term exposure to the repository environment.

3.2.9 *failed fuel (interim storage and transport)*, *n*—fuel rods/assemblies whose cladding has been perforated to the extent that powder or pieces of the fuel can relocate or be released from the cladding.

3.2.9.1 *Discussion*—Code of Federal Regulations, Title 40, Part 191, the Standard Contract between the USDOE and the US commercial nuclear utilities defines categories of commercial LWR spent fuel as “Standard,” “Non-Standard,” and “Failed.” These categories are based on the type of handling—normal or special—required for transport and storage of the SNF. The “Standard” classification includes most normal and handle-able LWR (PWR and BWR) spent fuel. “Non-Standard” spent fuel included non-LWR spent fuel, consolidated fuel, older design fuel, etc. “Failed” fuel includes: Class F-1: (via visual examination) visual failure or damage—“Assemblies which (i) are structurally deformed or have damaged cladding to the extent that special handling may be required or (ii) for any reason can’t be handled with normal fuel handling equipment …” Class F-2: radioactive “ leakage” or “any fuel that allows gaseous communication between the inside and the outside of the cladding.” Class F-3: Encapsulated—Note that the terms used in this guide for failed fuel, damaged fuel, and degraded cladding can fit the “Failed Fuel” definition of Code of Federal Regulations, Title 40, Part 191. Also, the Code of Federal Regulations, Title 40, Part 191 categories of spent fuel are partially based on the fact that the repository is required by statute to accept all commercial LWR spent fuel, including damaged/failed.)

3.2.10 *ignite*, *v*—to cause to burn and reach a state of rapid oxidation, which is maintained without requiring an external heat source.

3.2.11 *model*, *n*—a simplified representation of a system or phenomenon, often mathematical.

3.2.12 *performance assessment (PA)*, *n*—an analysis that identifies the processes and events that might affect the disposal system; examines the effects of these processes and events on the performance of the disposal system; and, estimates the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant processes and events. These estimates shall be incorporated into an overall probability distribution of cumulative release to the extent practicable (see Code of Federal Regulations, Title 10, Part 63 Section 2) and Code of Federal Regulations, Title 40, Part 191 Section 15).

3.2.13 *pyrophoric*, *adj*—capable of igniting spontaneously under temperature, chemical, or physical/mechanical conditions specific to the storage, handling, or transportation environment.

3.2.14 *sibling sample*, *n*—one of two or more test samples that are nearly indistinguishable with respect to their chemical and physical properties.

3.2.15 *spent nuclear fuel (SNF)*, *n*—nuclear fuel that has been exposed to, and removed from, a nuclear reactor.

3.2.16 *waste form (WF)*, *n*—(from Practice C 1174) the radioactive waste materials and any encapsulating or stabilizing matrix in which it is incorporated.

3.2.17 *waste package (WP)*, *n*—(from Practice C 1174) the waste form and any containers, shielding, packing and other absorbent materials immediately surrounding an individual waste container.

4. Summary of Guide

4.1 The characterization of spent nuclear fuel (SNF)—in support of interim dry storage, transport, and disposal in a geologic repository—described in this guide includes the examination/testing of such physical attributes as physical appearance, weight, density, shape/geometry, degree and type of cladding damage, etc. It also includes the measurement/examination of such chemical aspects as drying characteristics, water content, radionuclide content, microstructure, zirconium hydride content (of commercial SNF cladding), uranium hydride content (of metallic uranium SNF), and such environmental response characteristics as oxidation rate (in dry air, water vapor, and liquid water), ignition temperature, and dissolution/degradation rates.

4.2 The primary issues involved in the characterization of uranium dioxide-based commercial light water reactor (LWR) SNF are the fraction of fuel rods with non-intact cladding (that is, the amount of "failed fuel" as defined in Section 3 above), the structural integrity of the fuel assembly (that is, the amount of "damaged fuel" as defined in Section 3 above), the amount and structure of zirconium hydride in the cladding (for example, "degraded cladding" as defined in Section 3 above), particularly with respect to high burnup LWR SNF. Also, the radionuclide content of the fuel, the thickness of the zirconium oxide on the external surface of the cladding, and the leaching/dissolution behavior characteristics when in contact with the (repository-relevant) air/water environment are factors that could affect SNF behavior in repository disposal.

4.3 The primary issue involved in characterization of metallic uranium SNF is the extent of damage to the cladding (that is, exposure of metallic uranium to air and water) and its consequently enhanced chemical activity and pyrophoricity/combustibility characteristics. Metallic uranium SNF, largely from plutonium production reactors, has been temporarily stored in water basins in several countries prior to reprocessing or ultimate direct disposal of unreprocessed fuel. In some cases the manner of discharge (for example, those involving physical trauma to the fuel element) of the fuel elements from these reactors, and the type of wet storage environment in which they were emplaced after discharge, has resulted in significant amounts of fuel cladding damage and extensive corrosion of the consequently exposed uranium metal. This corrosion and damage has resulted in alteration of the physical integrity/dimensions of the elements and the chemical reactivity of the material such that the physical and chemical properties of the material no longer straightforwardly resemble, or can be represented by, the properties of the as-fabricated, unirradiated fuel.

5. Significance and Use

5.1 In order to demonstrate conformance to regulatory requirements and support the postclosure repository performance assessment information is required about the attributes, characteristics, and behavior of the SNF need to be determined. These properties of the SNF in turn support the transport, interim storage, and repository preclosure safety analyses, and repository postclosure performance assessment. The interim dry storage of commercial LWR SNF is regulated per Code of Federal Regulations, Title 10, Part 72, which requires that the cladding must not sustain during the interim storage period any "gross" damage sufficient to release fuel from the cladding into the container environment. However, cladding damage insufficient to allow the release of fuel during the interim storage period may still occur in the form of small cracks or pinholes. These cracks/pinholes could be sufficient to classify the fuel as " failed fuel" or "breached fuel" per the definitions given in Section 3 for repository disposal purposes, because they could allow contact of water vapor or liquid with the spent fuel matrix and thus provide a pathway for radionuclide release from the waste form. Also, pinholes/cracks in fuel rods in dry or wet interim storage can also develop into much larger defects (for example, the phenomenon of cladding "unzipping") under long-term repository conditions. Therefore SNF characterization should be adequate to determine the amount of "failed fuel" for either usage as required. This could involve the examination of reactor operating records, ultrasonic testing, sipping, and analysis of the residual water and drying kinetics of the spent fuel assemblies or canisters.

5.2 In the U.S. the disposal of spent nuclear fuel (SNF) and high level waste (HLW) in a geologic repository is regulated under the Code of Federal Regulations, Title 10, Part 60 (which pertains to any geologic repository built in the U.S.), Code of Federal Regulations, Title 10, Part 63 (which pertains to the repository located at Yucca Mountain, Nevada), and Code of Federal Regulations, Title 40, Part 191 (which established the radiation protection levels the repository must meet). Each of these regulations contains constraints and limitations on the chemical or physical (or both) properties and long-term degradation behavior of the spent fuel and HLW in the repository. Evaluating the design and performance of the WF, WP, and the rest of the engineered barrier system (EBS) with respect to these regulatory constraints requires knowledge of the chemical/physical characteristics and degradation behavior of the SNF that could be provided by the testing and data evaluation methods provided by this guide, as follows:

5.2.1 Code of Federal Regulations, Title 10, Part 60 Sections 135 and 113 require that the waste form be a material that is solid, non-particulate, non-pyrophoric, and non-chemically