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Standard Guide for Pyrophoricity/Combustibility Testing in Support of Pyrophoricity Analyses of Metallic Uranium Spent Nuclear Fuel¹

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1. Scope

1.1 This guide describes testing protocols for pyrophoricity, or combustibility characteristics, or both, of metallic uranium-based SNF. The testing will provide basic data for input into more detailed computer codes or analyses of thermal, chemical, and mechanical SNF responses. These analyses would support the engineered barrier system (EBS) design bases and safety assessment of extended interim storage facilities and final disposal in a geologic repository. The testing also could provide data related to licensing requirements for the design and operation of a monitored retrievable storage facility (MRS) or independent spent fuel storage installation (ISFSI).

1.2 This guide describes testing of metallic uranium spent nuclear fuel (SNF) in support of transportation (in accordance with the requirements of 10CFR71), interim storage (in accordance with the requirements of 10CFR72), and geologic repository disposal (in accordance with the requirements of 10CFR60). The testing described herein is designed to provide basic data related to the evaluation of the pyrophoricity/combustibility characteristics of containers or waste packages containing metallic uranium SNF in support of safety analyses (SAR), or performance assessments (PA) of transport, storage, or disposal systems, or a combination thereof.

1.3 Spent nuclear fuel that is not reprocessed must be emplaced in secure temporary interim storage as a step towards its final disposal in a geologic repository. In the United States, SNF, from both civilian commercial power reactors and defense nuclear materials production reactors, will be sent to interim storage, and subsequently, to deep geologic disposal. U.S. commercial SNF comes predominantly from light water reactors (LWRs) and is uranium dioxide-based, whereas U.S. Department of Energy (DOE) owned defense reactor SNF is in several different chemical forms, but is predominantly (~80 % by weight of uranium) metallic uranium-based.

1.4 Knowledge of the pyrophoricity/combustibility characteristics of the SNF is required to support licensing activities for extended interim storage and ultimate disposition in a

geologic repository. These activities could include interim storage configuration safety analyses, conditioning treatment development, preclosure design basis event (DBE) analyses of the repository controlled area, and postclosure performance assessment of the EBS.

1.5 Metallic uranium fuels are clad, generally with zirconium, aluminum, stainless steel, or magnesium alloy, to prevent corrosion of the fuel and to contain fission products. If the cladding is damaged and the metallic SNF is stored in water the consequent corrosion and swelling of the exposed uranium may enhance the chemical reactivity of the SNF by further rupturing the cladding and creating uranium hydride particulates and/or inclusions. The condition of the metallic SNF will affect its behavior in transport, interim storage or repository emplacement, or both, and therefore, influence the engineering decisions in designing the pathway to disposal.

1.6 The interpretation of the test data depends on the characteristics of the sample tested. The type and the size of the SNF sample must be chosen carefully and accounted for in the usage of the data. The use of the data obtained by the testing described herein may require that samples be used which mimic the condition of the SNF at times far into the future, for example, the repository postcontainment period. This guide does not specifically address methods for 'aging' samples for this purpose. The section in Practice C 1174 concerning the accelerated testing of waste package materials is recommended for guidance on this subject.

2. Referenced Documents

2.1 ASTM Standards:

C 1174 Practice for Prediction of Long-Term Behavior of Materials, Including Waste Forms, Used in Engineered Barrier Systems (EBS) for Geologic Disposal of High-Level Radioactive Waste²

G 86 Test Method for Determining Ignition Sensitivity of Materials to Mechanical Impact in Pressurized Oxygen Environments³

2.2 CFR Documents:⁴

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 Annual Book of ASTM Standards, Vol 12.01.

³ Annual Book of ASTM Standards, Vol 14.04.

⁴ Available from

10CFR60, US Code of Federal Regulations Title 10, Part 60, Disposal of High Level Radioactive Wastes in Geologic Repositories

10CFR72, US Code of Federal Regulations Title 10, Part 72, Licensing Requirements for the Independent Storage of Spent Nuclear Fuel and High-Level Radioactive Waste

10CFR71, US Code of Federal Regulations Title 10, Part 71, Packaging and Transport of Radioactive Materials

40CFR191, US 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

3. Terminology

3.1 *Definitions*—Terms used in this guide are as defined in Practice C 1174 or, if not defined therein as per their common usage, except where defined specifically for this guide as described as follows.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *attribute test, n*—a test conducted to provide material properties that are required as input to behavior models, but that are not themselves responses to the environment.

3.2.2 *characterization test, n*—in high-level radioactive waste management, any test conducted principally to furnish information for a mechanistic understanding of alteration.

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

3.2.4 *design bases, n*—that information that identifies the specific functions to be performed by a structure, system, or component of a facility and the specific values or ranges of values chosen for controlling parameters as reference bounds for design (see 10CFR72).

3.2.5 *design basis event (DBE), n*—postulated internal and external events evaluated to determine the structures, systems, and components important to preclosure radiological safety (see 10CFR60).

3.2.5.1 *category 1 DBE, n*—those natural and human-induced events that are reasonably likely to occur regularly, moderately frequently, or one or more times before permanent closure of the geologic repository operations area.

3.2.5.2 *category 2 DBE, n*—other natural and human-induced events that are considered unlikely, but sufficiently credible to warrant consideration, taking into account the potential for significant radiological impacts on public health and safety.

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

3.2.7 *interim storage facility, n*—a facility for the storage of spent nuclear fuel for 20 years or longer, and which meets the intent of the requirements of an independent spent fuel storage installation (ISFSI) or a monitored retrievable storage facility (MRS) as described in 10CFR72.

3.2.8 *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 40CFR191.12).

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

3.2.10 *safety analysis, n*—an analysis whose purpose is to determine whether spent fuel or high level waste can be received, handled, packaged, stored, and retrieved without risk to the health and safety of the public.

3.2.11 *service condition test, n*—a test of a material conducted under conditions in which the values of the independent variables characterizing the service environment are in the range expected in actual service.

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

3.2.13 *waste form, n*—the radioactive waste materials and any encapsulating or stabilizing matrix (see 10CFR60.2).

3.2.14 *waste package, n*—the waste form and any containers, shielding, packing, and other absorbent materials immediately surrounding an individual waste container (see 10CFR60.2).

4. Significance and Use

4.1 Disposition of SNF will involve isolation from the accessible environment, placement in a safe and environmentally-sound extended interim storage facility (ISFSI or MRS), and preparation for final disposal in a geologic repository. Disposition will be further complicated in the case of metallic uranium-based SNF if it is damaged/corroded.

4.2 Metallic uranium-based SNF has some unique physical and chemical characteristics, which must be considered in the design, safety analysis, and performance assessment of the planned U.S. geologic repository, that is, those of a reactive metal in a corroded condition. The metallic uranium SNF could be pyrophoric, or combustible, and determination of these characteristics is necessary for the development of EBS design bases and the safety and performance assessment analyses associated with those designs. In particular, repository preclosure design basis event (DBE) analyses and post-containment performance assessment analyses could require pyrophoricity/combustibility data.

4.3 The U.S. Nuclear Regulatory Commission (NRC) has licensing authority over the transportation in the public domain, and the repository emplacement, or interim dry storage, or both, in an ISFSI or MRS, of spent nuclear fuel and high level radioactive waste under the requirements set forth in 10 CFR Parts 71, 60, and 72, respectively. These requirements specifically include the following limitations:

4.3.1 10CFR60.135 requires that the waste package shall not contain explosive or pyrophoric materials or chemically reactive materials in an amount that could compromise the ability of the underground facility to contribute to waste isolation or the ability of the geologic repository to satisfy the performance objectives, and that all combustible radioactive wastes shall be reduced to a noncombustible form unless it can be demonstrated that a fire involving the waste package

containing combustibles will not compromise the integrity of other waste packages, adversely affect any structures, systems, or components important to safety, or compromise the ability of the underground facility to contribute to waste isolation. The pyrophoricity constraint concerns the systems level performance of the repository, that is, the capability of the underground facility to meet performance requirements, whereas, the waste form combustibility constraint concerns EBS component performance, that is, the effect of waste form combustion on other individual waste packages. A combustible waste form thus does not necessarily mean a pyrophoric waste package. The repository system performance assessment, however, must demonstrate that the assumed combustion of combustible waste forms in their waste packages will not adversely affect other (noncombustible-containing) waste packages, and ignition either will not occur or, if it does occur, will not adversely affect overall repository performance.

4.3.2 Section 43 of Part 71 requires that a package must be of materials and construction, which assure that there will be no significant chemical, galvanic, or other reaction among the packaging components, or between the packaging components and package contents, including possible reaction from inleakage of water to the maximum feasible extent.

4.3.3 Section 122 of Part 72 requires that components, important to safety, must be designed so that they can continue to perform their safety functions effectively under credible fire and explosion exposure conditions. Noncombustible and heat-resistant materials must be used whenever practical throughout the ISFSI or MRS.

4.4 The metallic uranium SNF characterization activities described in this guide apply to the assessment of such issues as geologic repository disposal waste form combustibility under normal repository (post-closure) environment conditions and waste package pyrophoricity under preclosure DBE or off-normal conditions, interim storage off-normal event consequence analyses, and public domain transportation safety analyses.

5. Information Needs Related to Pyrophoricity for Interim Storage, Transport, and Disposal

5.1 SNF characterization testing should focus on those information needs most pertinent to the SNF form and disposition pathway chosen. This guide addresses certain information needs pertinent to the emplacement of metallic uranium-based SNF in an MRS/ISFSI, or geologic repository, or both, such as its pyrophoricity, and combustibility. Other characteristics of the SNF, such as oxidation kinetics, hydrogen/water content, geometric, or specific surface area of exposed uranium metal, uranium hydride content, and microstructural characteristics can affect these parameters. These information needs are addressed through tests whose environmental conditions represent those of the metallic SNF in the transport, storage, or disposal environment and which conform to the testing, data usage, and modeling logic of Practice C 1174.

5.2 Information needs related to pyrophoricity/combustibility addressed by characterization, or service condi-

tion tests, or both, in accordance with Practice C 1174. There are restrictions on the pyrophoricity of the waste package system and combustibility of the SNF within the waste package both for interim storage (10CFR72.122) and for repository disposition (10CFR60.135). Metallic uranium particles, both unirradiated and irradiated, have in the past displayed pyrophoric behavior upon exposure to air in storage containers, ranging from smoldering to active burning with a flame. Ignition has been initiated thermally and by mechanical trauma, friction, sparks, or a combination thereof. Knowledge of the propensity towards pyrophoric behavior of the metallic uranium SNF, either as particles, in pieces, or in bulk, is therefore essential for waste package design, the evaluation of design basis air ingress events, and decisions concerning treatment of exposed uranium surfaces prior to interim storage or repository disposition, or a combination thereof.

5.2.1 *Ignition Temperature/Conditions*—The environmental conditions under which uranium metal SNF surfaces will ignite spontaneously can be inferred from carefully controlled and characterized ignition tests. Uranium metal and uranium metal SNF can be made to spontaneously ignite under mechanically quiescent conditions by external heating or by self-heating due to oxidation, and under conditions of mechanical trauma by the action of friction, sparks, or physical impact. Ignition testing can provide controlled thermal, oxidant exposure, and configuration conditions, and thus, can support analyses of the propensity of a given SNF condition toward pyrophoric behavior.

5.2.2 *Oxidation Kinetics*—The rate of oxidation of uranium in dry air, humid air, and oxygen-free water vapor may be enhanced by the extent to which the uranium has undergone irradiation swelling, or become corroded, or both. The degree of enhancement may vary with the nature of the damage and is not readily predictable for any particular fuel element. The rate of oxidation in oxygen-containing environments is an important factor in providing reaction heat input for waste container thermal analyses. The rate of corrosion also is important in determining the condition of the SNF as it evolves, or 'ages', in the container in the interim storage, or repository environments, or both. Aging can result from long term reactions between the SNF and any oxygen or water not removed from the SNF or the storage container prior to emplacement.

5.3 Information needs related to pyrophoricity/combustibility addressed by attribute tests in accordance with Practice C 1174.

5.3.1 *Hydrogen/Water Content*—Knowledge of the amount of hydrogen, or water, or both, included or trapped in the metallic uranium-based SNF is needed to evaluate both the criticality aspects of emplacement and the potential for further corrosion reactions during storage.

5.3.2 *Surface Area*—The surface area of exposed irradiated uranium metal is needed to evaluate the amount of material available to react with the oxidizing environment and the consequent heat generated by the reactions. The surface area to which the measured oxidation rate is to be normalized may be