Damage in Spent Nuclear Fuel Defined by Properties and Requirements

- RE Einziger, CL Brown, GP Hornseth, SR Helton,
- NL Osgood, and CG Interrante
- US Nuclear Regulatory Commission
- Spent Fuel Project Office
- Washington, DC

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Reasons to Minimize Amount of "Damaged Fuel"

- Damaged fuel might require non-conventional handling protocol
- Identifying Damaged fuel is difficult and not always accurate
- Special handling costs : Time, Money, Dose

Topics for Discussion

- Current Definitions of Damaged Fuel
- Functional Methodology Definition
  - "Damaged" depends on ability to meet function
- Regulations, Guidance, and Definitions
  - NRC, IAEA, ANSI
- Degradation Mechanisms
  - Oxidation, hydride reorientation
- Examples of Methodology

Existing U.S. Guidance for Defining Damaged Fuel

- NRC Interim Staff Guidance[1]
  - ISG-1 Rev 1 – Damaged Fuel
  - ISG-2 Rev 2 – Retrievability
  - ISG-11, Rev 3 – Fuel Cladding Considerations
- ANSI Standard
  - N14.33-2005 Characterizing Damaged Spent Nuclear Fuel for the Purpose of Storage and Transportation, Sept 2005

1-http://www.nrc.gov/reading-rm/doc-collections/isg/spent-fuel.html

Comparison of ISG-1 and ANSI Definitions of Damaged Fuel

	ISG-1 Rev1	ANSI
Fuel rod breach	Known or suspected cladding defects greater than a pinhole leak or hairline crack that have the potential for release of significant amounts of fuel particles	Cladding defects greater than pinhole leaks or hairline cracks; fuel assembly still remains intact
Debris	The fuel is no longer in the form of an intact fuel bundle; debris, loose fuel pellets, rod segments, etc	Debris, loose pellets and particles, rod segments, etc.
Structural damage	Assemblies/structural hardware of assemblies: •damaged such that its structural integrity is impaired •missing or displaced structural components • missing fuel pins which have not been replaced by dummy rods •damaged such that they cannot be handled using normal (i.e., crane and grapple) handling methods •degraded material properties impair ability to withstand the normal and accident conditions	Assemblies have structural damage such that they can not be handled by normal methods

Pinhole Leaks and Tight Cracks vs. Gross Breaches

- Not explicitly defined in Regulations, staff guidance or Standards
- Pinhole leaks and tight cracks don't allow fuel to escape the cladding confinement
  - Maximum size of tight crack might be any crack that allows fuel to be visible
- Gross breaches diminish containment

Old vs Proposed Definitions

- Current - FIXED set of characteristics defining damaged spent fuel
- Proposed - allows VARIABLE set of characteristics of damaged fuel based on function of the fuel in particular application

Functional Approach to Defining “Damaged”

- Identify functions of cladding
  - Retrievability/Structural Integrity
  - Shielding
  - Criticality Control
  - Containment/Confinement
  - Thermal Considerations
- Consider function vs. condition of the fuel
- “Damaged” $\Rightarrow$ fuel cannot support function

Damage is not an Intrinsic Property

- Definition of "damaged fuel" depends on:
  - Ability to perform required functions, e.g.
    - » No gross breaches
    - » No geometric rearrangement
    - » Retrievability
  - Stages in the fuel cycle
    - » Storage
    - » Transportation
    - » Both

Steps to Define Damaged Fuel -1

- Identify the stages in the back end of the fuel cycle for which damaged fuel is being defined? Storage?, Transportation?, Disposal?, All?
- Identify the regulatory and system specific functions placed on the fuel (assembly) to meet the safety requirements
- Identify Atmospheric Conditions (temperature, cover gas, etc.) that might affect behavior.

Steps to Define Damaged Fuel -2

- Determine how those functions are compromised by the characteristics or behavior of the fuel (assemblies)
- Establish Baseline Intact Fuel (assemblies) as all entities that have the characteristics and behavior that meets the identified functions
- Damaged fuel, for this application is any fuel that does not qualify as baseline intact

USNRC Regulations for SNF Storage and Transportation

- Regulations directly related to condition of SNF
  - 72.122(1) Retrievability
  - 72.122(1) Protection from gross ruptures
  - 72.236(h), 71.43(d) Compatibility with rest of system
  - 71.55(d)(2) No substantial fuel rearrangement under normal transport conditions
- Regulations indirectly related to condition of SNF
  - 71.51 limits on radioactivity release and dose under normal and transport conditions
  - 71.55 & 71.59 subcriticality requirements

Comparison of USNRC and IAEA Transport Regulations

	10 CFR 71	IAEA (TS-R-1)
Subcriticality	71.55 & 71.59	671(a), 679
No substantial fuel rearrangement under normal transport conditions	71.55(d)(2)	651(a)
Limits on radioactivity release and dose under normal and transport conditions	71.51	656, 501
Compatibility of materials	71.43(d)	613

Degradation Mechanisms Determine Initial Conditions that Affect Behavior

- Fuel Oxidation and Cladding splitting
- Hydride content and Reorientation in the cladding
- Cladding Creep
- Gas Release from Fuel Meat

Fuel Pellet Oxidation Process and Cladding Splitting

- 36% expansion due to oxidation of UO_2 to U_3O_8
  - Expansion places hoop stress on cladding
- Cracks propagate at 2-6% cladding strain
- Splitting rate determined by
  - Time-at-temperature
  - Burnup
  - Cladding material (maybe)
- Fuel fragments become grain size powder

Cladding Hydride Reorientation

- H goes into solution in cladding when fuel is heated
- H precipitates as hydrides as fuel is cooled
- Precipitates are radial if a critical stress limit is exceeded
- Hoop stress may exceed the critical stress
- Mechanical properties of the cladding may degrade

Examples of This Approach to Determine Damage

- Retrievability/Structural
  - Temperature and environment in storage
  - Environment in cask loading
- Assembly damage
- Shielding/Containment/Criticality/Thermal
  - Change of cask design basis
  - Stress induced damage

Temperature and Environment During Cask Loading

- Fuel Function – Containment & Retrievability
- Recommended maximum fuel temperature 400^{o}C (ISG-11)
- Intact fuel may have pinhole leaks and hairline (tight) cracks (ISG-1)
  - Valid in inert atmosphere
  - Fuel stored in oxidizing atmosphere requires

    Reanalyzing the maximum storage temperature, **or**

    Redefining damaged fuel to include pinhole leaks and tight cracks

Redefining “Damage” for the Environment in Cask Loading

- Air is sometimes used to “blow down” cask prior to lid welding
  - Air is an oxidizing environment
  - Exposed rods may exceed 350^{o}C for 24 hours
- Pinhole leaks or tight cracks in cladding may become gross breaches
  - “Intact” fuel (ISG-1) becomes “damaged”
- Blow down in air may require
  - Redefining damaged fuel to include pinhole leaks and tight cracks or changing blow down temperature

Assembly Damage

- ISG-1 definition of damaged fuel assembly
  - Vacant rod slot(s)
  - Damaged grid spacers
  - Missing elements
- Analysis may be used to show that assemblies with missing elements or parts of elements will:
  - Maintain structural integrity for retrieval purposes
  - Not reconfigure into a critical, uncontained, overheated, or under-shielded configuration
- Fuel with missing elements might be considered undamaged for these functions

Change of Cask Design Basis

- Fuel must not rearrange under normal conditions of transport (10 CFR 71.55)
- Design basis assumption
  - Fuel configuration and cladding integrity
  - "Damaged" ⇒ assembly has more damage than specified in design basis
- Change the design basis
  - Less reliance on the cladding integrity
  - More reliance on design of transportation package
  - Definition of "damaged" fuel might change

Summary

- Damage is not an intrinsic property of the fuel.
- Definition of “damaged” should be based on ability of the fuel to fulfill its function’s.
- Function is based on meeting regulations, which refer both directly and indirectly to the state of the fuel
- Function dictates degradation mechanisms of concern
- Degradation & Function translate to Fuel/assembly characteristics identifying damaged fuel
- Regulations vary with phases of the fuel cycle
  – Varying definitions of damaged fuel may be appropriate, depending on phase of fuel cycle

Back-up Slides

Indirectly Related Regulations

- Performance requirements are placed on the fuel for the system to meet the regulations
- Performance requirements dictate limits on fuel characteristics and properties.
- By changing design of the system, designer can change the requirements on the fuel.
- Fuel is undamaged only if it can fulfill its performance requirements.

Stress Driven Damage

- The cask design will dictate the stresses placed on a fuel rod during normal and accident transport
- Radial hydrides will form if the hoop-stress threshold for reorientation is exceed
- Some rods will have stress exceeding the hoop-stress threshold
- Response of the fuel rod will depend on its cladding's mechanical properties, which in turn may depend on the orientation of the hydrides. Should data on hoop stress threshold prove unfavorable, excessive cladding hoop stress might be considered as a basis for the definition of "damage"