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EXTENDED DRY STORAGE AND TRANSPORTATION: MODEL FOR EVALUATING VACUUM DRYING ADEQUACY

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2013 International High-Level Radioactive Waste Management Conference (IHLRWMC), April 28 – May 2, 2013, Albuquerque, New Mexico, U.S.A.

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ACKNOWLEDGMENTS

The authors thank Dr. C. Markley of the NRC for his review of this paper.

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Introduction

- **Potential excessive residual moisture following incomplete drying of spent nuclear fuel (SNF)**

- **A time-dependent integration model, to assess potential radiolysis, producing oxygen and hydrogen, and potential effects on the integrity of SNF, cladding, internals, and flammability**

- **Interim progress made for the process of model abstraction, model integration, and uncertainty assessments. Quantitative results will be presented in the future.**

Outline

- **Quantity of Water Remaining after Drying: water reacts with SNF, cladding and internals**
- **Temperature: affects reactions**
- **Radiolysis: produces oxygen and hydrogen; affects reactions; poses flammability potential**
- **Relative Humidity (RH): affects reaction**
- **Oxidation and Hydration of SNF: affect SNF integrity**
- **Cladding Oxidation: affects cladding integrity**

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Outline (continued)

- **Cladding Splitting - Strain Estimate due to SNF Swelling: affects integrity of SNF and cladding**
- **Flammability**
- **Hydrogen-Absorption-Induced Damage**
- **Aqueous Corrosion: affects reactions**
- **Integration and Benchmarking**

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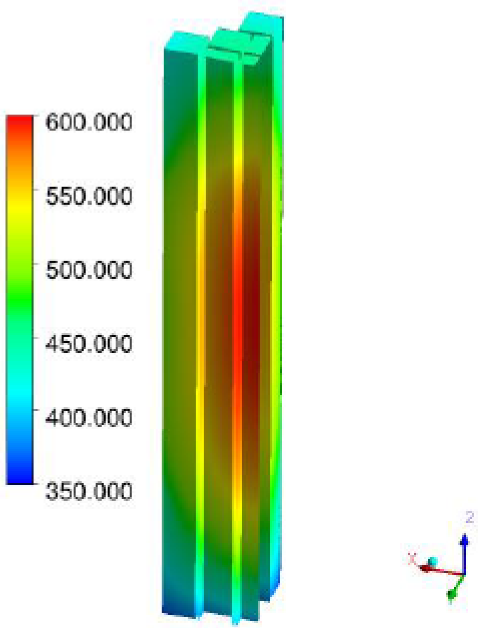
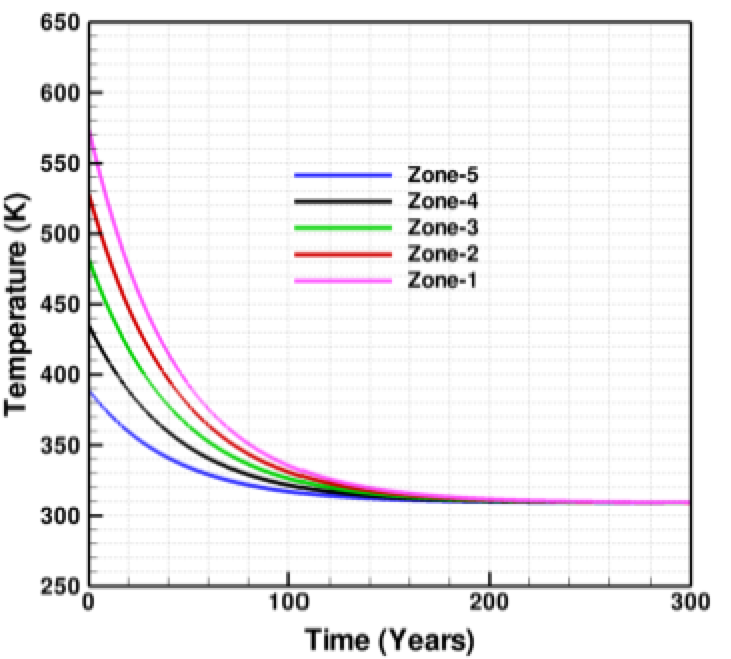
Quantity of Water Remaining after Drying and Temperature

- **Quantity of Water Remaining after Drying**
  - **Unbound residual liquid water, unbound water vapor, and water chemically bound to hydroxide and hydrate species**
  - **Properly executed vacuum drying procedure result in: 1 to 5 moles (0.02 to 0.1 L [0.7 to 3.5 oz]) water inventory**
  - **up to 55 moles (~ 1 L [35 oz]) are conservatively assumed**
- **Temperature**
  - **Spatially distributed and decreases over time**

Temperature (continued)

- **Temperature distribution in the SNF basket assembly (left). The scales for temperature are in K (F = 1.8 K – 459.4); SNF and cladding in the five zones calculated using mean values of low-end SNF and cladding initial temperatures (right)**





Radiolysis and Relative Humidity (RH)

- **Radiolysis: Global Approximation for Various Intermediate Species**

  $$2H_2O \leftrightarrow 2H_2 + O_2$$

  - **Decomposition rate of water by radiolysis: exponential time function**
  - **Recombination – additional steps for molecular collision needed, compared with decomposition**

- **Relative Humidity (RH)**
  - **The radiolysis removes water molecules by dissociating them into oxygen and hydrogen**
  - **RH is modified by radiolysis**

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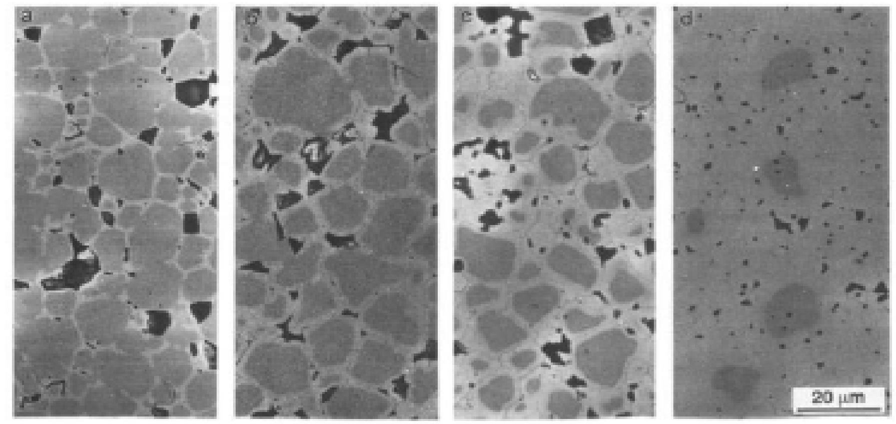
Oxidation and Hydration of SNF

- Upon cladding breach, the UO_2 could be oxidized to form:

  - U_4O_9, U_3O_7, and U_3O_8 in dry air (less than 40 percent RH)

  - Hydrated uranium oxides, such as schoepite ($UO_3 \cdot xH_2O$, x = 0.5 to 2), in humid air (greater than 40 percent RH) or in an aqueous environment



Grain boundary oxidation of AM-105 spent nuclear SNF to U_4O_9. Optical ceramographs, as polished: (a) 95 hrs, Bulk O/M = 2.05; (b) 420 hrs, bulk O/M=2.17; (c) 775.5 hrs, bulk O/M = 2.24; and (d) 1,677 hrs, bulk O/M = 2.31 (Einziger, et al., 1992)

- Chemical Arrhenius-type Kinetics

- Actual Rates are Controlled by Radiolysis Kinetics or Chemical Kinetics

Cladding Oxidation, and Cladding Splitting: Strain Estimate due to SNF Swelling

- **Cladding Oxidation**

  - **$Zr + O_2 = ZrO_2$ for dry air and**

  - **$Zr + 2H_2O = ZrO_2 + 2H_2$ for water or humid air (e.g., steam)**

  - **Model by Hillner, et al (1994) and 8 other similar kinetics**

  - **Large surface area of cladding**

  - **Actual Rates Controlled by Radiolysis Kinetics or Chemical Kinetics**

- **Cladding Splitting: Strain Estimate due to SNF Swelling**

  - **Oxidation of UO_2 to U_3O_8 can generate stress on cladding as U_3O_8 swells (36 percent when there is 100 percent conversion to U_3O_8).**

  - **Various threshold values of strain are assessed to determine the cladding splitting condition.**

  - **Observed threshold values:**
    6.5% strain (100% conversion);
    5.1% volume expansion correlation (25 % conversion);
    2% strain (50% conversion)

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Flammability and Hydrogen-Absorption-Induced Damage

- **Flammability**

  - The cladding will not absorb radiolysis-generated hydrogen.

  - The flammability criterion requires the volume fraction of any flammable gas to be more than 5 percent, with oxygen and ignition.

- **Hydrogen-Absorption-Induced Damage**

  - Cladding: Zirconium oxide is expected to limit the absorption of molecular hydrogen:

  Total possible amount of hydrogen from 55 mole water is assessed.

  - Canister Internals: the mechanical properties may or may not be degraded with hydrogen concentration exceeding a threshold value.

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Aqueous Corrosion, and Integration and Benchmarking

- **Aqueous Corrosion**

  - Aqueous corrosion could occur in vapor when RH is greater than a threshold value: At above the threshold RH

  (i) SCC of the canister's internal structural components could occur in carbon and stainless steels; no relevant data available

  (ii) Shadow corrosion (a form of galvanic corrosion) between cladding and spacer-grid material could occur.

- **Integration and Benchmarking**

  - In each time step, all reactions and gas generations are assessed

  - Bench marking with long-term demonstration data (e.g., hydrogen amount)

Summary

Program is under development that evaluates:

- **Time-dependent integrated models for temperature, relative humidity, and radiolysis kinetics to decompose water into oxygen and hydrogen.**
- **Various abstracted models for temperature, radiolysis, relative humidity, and chemical reactions of SNF, cladding and internals.**
- **Time integrated model: in each time step, all reactions and gas generations are assessed.**
- **Assess degradation of SNF, cladding and internals.**
- **Possibility of flammability conditions.**