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ROK – US Joint Fuel Cycle Study, Fuel Cycle Alternatives Working Group: Task 3 - Spent Fuel Degradation and Durability over Geologic Time

David C. Sassani
Sandia National Laboratories
Department 6225, Advanced Systems Analysis

UFD Fuel Cycle Alternative Working Group (FCAWG)
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Used Fuel Disposition

Presentation Outline

- **FCAWG Task 3 - Spent Fuel Degradation and Durability over Geologic Time**
- **Used Fuel Disposition (UFD) Disposal Research Activities**
- **Used Fuel Degradation and Radionuclide Mobilization (UFD&RM) Activities**
  - Overview
  - Fiscal Year 2011 Accomplishments
  - Fiscal Year 2012 Activities and Milestones
    - *Modeling and Experimental Work at Collaborating National Laboratories*
      - **Sandia National Laboratories (SNL)**
      - **Pacific Northwest National Laboratory (PNNL)**
      - **Argonne National Laboratory (ANL)**
- **Summary and Discussion**
  - UFD&RM Activities Summary
  - Focus and discussion areas for Task #3

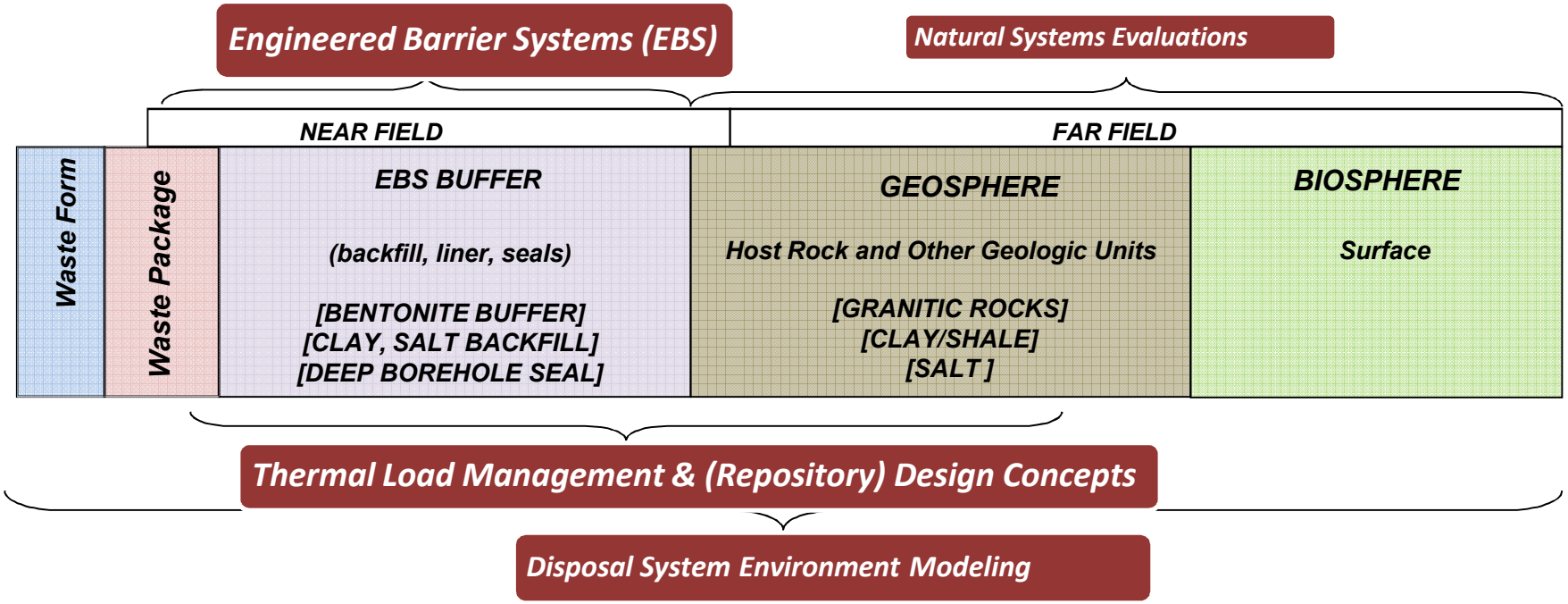
Used Fuel Disposition

FCAWG Task 3 - Spent Fuel Degradation and Durability over Geologic Time

- **Purpose – collaborative evaluation of constraints on**
  - **UO_2 (i.e., used/spent fuel) degradation rates in granite repository conditions including**
    - *Fission gas release*
    - *Cladding failure effects*
    - *Dissolution behavior*
- **U.S. Reports for Task 3**
  - **November 2012**
  - **Second report –**
    - *Currently scheduled for October 2013*
    - *Possible reschedule for April 2014 based on interactions/discussions of ROK-US POC*
- **Interactions to date (Task 3 POC - US UFD; KAERI; KMRC)**
  - **Exchange of email discussing relevant work being done within UFD and ROK programs**
  - **Distribution of SNL FY2011 Milestone Report on Used Fuel Degradation and Radionuclide Mobilization (FCR&D-USED-2011-000403; SAND2011-7289P)**
  - **Telecom (May 1, 2012 U.S. date)**
    - *Discussion of current focus within the UFD program and within ROK programs*
    - *Identification of possible areas of mutual benefit for Task 3 focus*
      - **This calendar year**
      - **Out years**

Used Fuel Disposition

UFD Disposal Research Activities



SUPPORT, ANALYSIS & EXPERIMENTAL ACTIVITIES

Engineered Materials Performance	(corrosion, degradation studies)
Features, Events & Processes	(how R&D is organized and prioritized)
Low Level Waste Disposition Issues	(part of total nuclear waste consideration)
Inventory Projections	(LLW/HLW, used fuel, open → closed fuel cycles)

Used Fuel Disposition

Used Fuel Degradation & Radionuclide Mobilization (UFD&RM) Overview

- **Collaborative Effort – ANL, PNNL, SNL**
- **Purpose**
  - **Investigating the long-term behavior of used fuel as a waste form**
    - *Developing a comprehensive understanding of the current technical bases for disposing of used fuel*
    - *Evaluating range of disposal environments*
    - *Identifying the opportunities for long-term research and development*
  - **Integrate with Waste Form Campaign for other waste forms**
- **Approach**
  - **Process Modeling**
    - *Implementation of Radiolysis Model (PNNL)*
    - *Implementation of the Mixed Potential Model (MPM) for Matrix degradation (ANL)*
    - *Molecular scale modeling of UO_2, alteration products, and surface reactions (SNL)*
    - *Molecular scale modeling of epsilon phase (noble metal particles) and surface reactions (PNNL)*
  - **Experimental Studies**
    - *Electrochemical cell studies to quantify the effects of noble metal particles (catalytic/cathodic) on matrix degradation (ANL)*
    - *Generation of radiolytic species and studies of used fuel degradation at future conditions (PNNL)*
  - **Integration and UFD&RM Model Implementation into GPAM**
    - *Constraints on the Fast/Instant Release fractions (SNL)*
    - *Integration of the process models into GPAM (SNL, ANL, PNNL)*
      - **GPAM staff working up new platform for implementation**

UFD&RM Fiscal Year 2011 (FY11) Activities Accomplishments

- **ANL, PNNL, SNL**
  - **Developed chemical-radiolysis model for evaluating the dissolution rate of used fuel**
    - *enhanced the model for in-package chemical conditions (UO_2, Cl, Carbonate)*
    - *investigated model parameters sensitivities to delineate effective uncertainty reduction*
    - *validated model through comparisons with literature (e.g., the AECL model)*
  - **Evaluated flow-through testing data to identify data sets relevant to fuel dissolution in a radiolytic field**
    - *obtained and evaluated MOX material as sufficient surrogate for testing used fuel dissolution with alpha-radiation*
    - *developed compositions for synthetic used fuel preparation*
  - **Conducted Literature review/gap analysis on UOX and MOX degradation rates and models**
    - *identified key gaps for modeling and testing work*
  - **Developed electrochemical studies of fuel matrix and radionuclide oxidation and dissolution**
    - *conducted shakedown testing of micro-electrochemical cell*
  - **Produced draft 3-5 year plan of UFD&RM activities**
  - **ANL Level 4 Milestone Report Completed 7/15/2011**
  - **PNNL Level 4 Milestone Report Completed 7/15/2011**
  - **SNL Level 3 Milestone Report Completed 10/07/2011 (SAND2011-7289P)**
    - *integrates input from the Level 4 milestone reports*

UFD&RM FY12 Activities Tasks/Milestones

- **For FY12 UFD&RM activities integrated within the Engineered Barrier System (EBS) Evaluation work**
  - **Work Package Generic EBS Evaluation**
    - *Carlos Jove-Colon, SNL Work Package Manager*
    - *Bill Spezialetti, DOE Technical Lead*
- **SNL tasks/milestone**
  - **Integrate ANL, PNL, and SNL activities to synthesize model and experimental results into overall model for Used Fuel Degradation and Radionuclide Mobilization**
  - **Facilitate coupling the radiolysis model with the baseline model for used fuel matrix degradation rate**
  - **Constrain fast/instantaneous release fraction for the UFD&RM model**
    - *Participate as Associate Group in EC FIRST-nuclides collaborative project*
  - **Implement the UFD&RM model into the Generic Disposal System Models (GDSM)**
    - *Generic Performance Assessment Model (GPAM) implementation*
      - **Currently contains simplified source-term models in four GDSM**
    - *First external EBS model implementation into the GPAM*
  - **Milestone:**
    - *Report on Integration of EBS Models with Generic Disposal System Models (09/07/2012 – M2)*

UFD&RM FY12 Activities Tasks/Milestones (Cont'd)

- **PNNL tasks/milestones**
  - **Evaluation of Radiolysis Models to Used Fuel Degradation and Radionuclide Migration in a Degraded EBS Environment**
  - **Experimental Investigation of Used Fuel Degradation at Future Conditions (radiation levels)**
  - **Milestones**
    - *Testing plan (12/02/2011 - M4)*
    - *Modeling Results (7/21/2012 - M3)*
    - *Experimental Results (8/24/2012 - M3)*
- **ANL tasks/milestones**
  - **Implement a used fuel matrix degradation rate model that accounts for key redox reactions (H_2, radiolytic oxidants) and chemical speciation**
  - **Experimentally investigate and quantify effect of Ru-Mo-Pd-Rh "noble metal particles" (NMP ~epsilon phase in used fuel) as catalysts for the destruction (scavenging) of oxidants (H_2 oxidation) for enhancement to the baseline matrix degradation rate model**
  - **Milestones**
    - *Experimental plan for electrochemical corrosion studies (1/6/2012 - M4)*
    - *Report results of electrochemical experiments (9/21/2012 - M3)*
    - *Waste form degradation model status report (8/9/2012 - M3)*

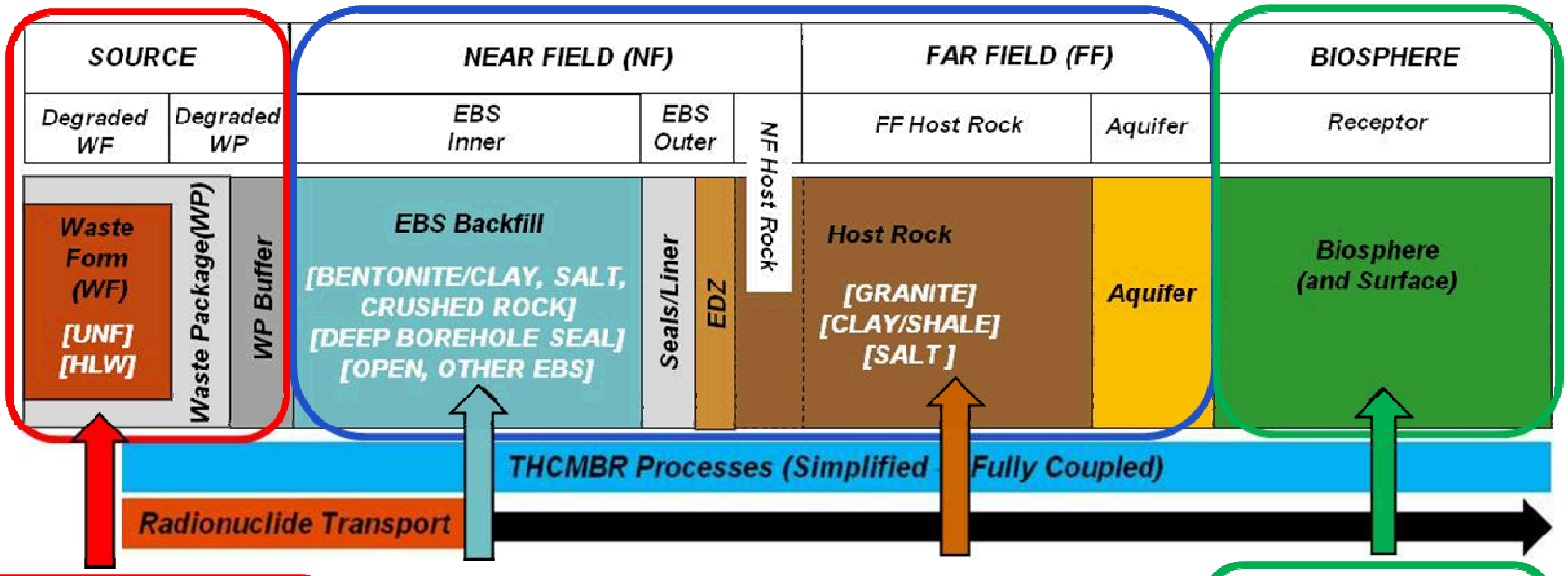
Used Fuel Disposition

SNL UFD&RM FY12 Activities

- **SNL Team: David Sassani, Philippe Weck, Carlos Jove-Colon**
- **Developing strategy for model implementation into Generic Performance Assessment Model (GPAM)**
- **Constraining instant release fractions from used fuel;**
  - **Data and models from YMP: Triangular Distributions for ^{137}Cs; ^{129}I; ^{99}Tc; ^{90}Sr (^{14}C from hardware) - these are conservative**
  - **Evaluating European data now for relevant application in reduced systems**
- **Molecular-scale modeling of UO_2 surface reactions**
  - **The first principle calculations for the optimized bulk UO_2 structural solution have been carried out**
    - *For uranium systems, strong electron-electron Coulomb interaction are being taken into account in these calculations (using a Hubbard term)*
      - **Being performed for ferromagnetic solution (as in previous FS work; Skomurski et al., 2008) and for the antiferromagnetic solution**
    - *The calculations will progress to O_2-H_2O-H_2O_2 surface interactions with the UO_2 slab*
    - *Will extend to other U minerals, e.g., studtite*

GPAM – Conceptual Framework

- **Can accommodate a range of processes and process model fidelities (from EBS and Natural Systems evaluations and FEP screening)**
  - Simplified process abstractions or relationships with reduced dimensionality
  - Highly coupled partial differential equations for THCMBR in full 3D

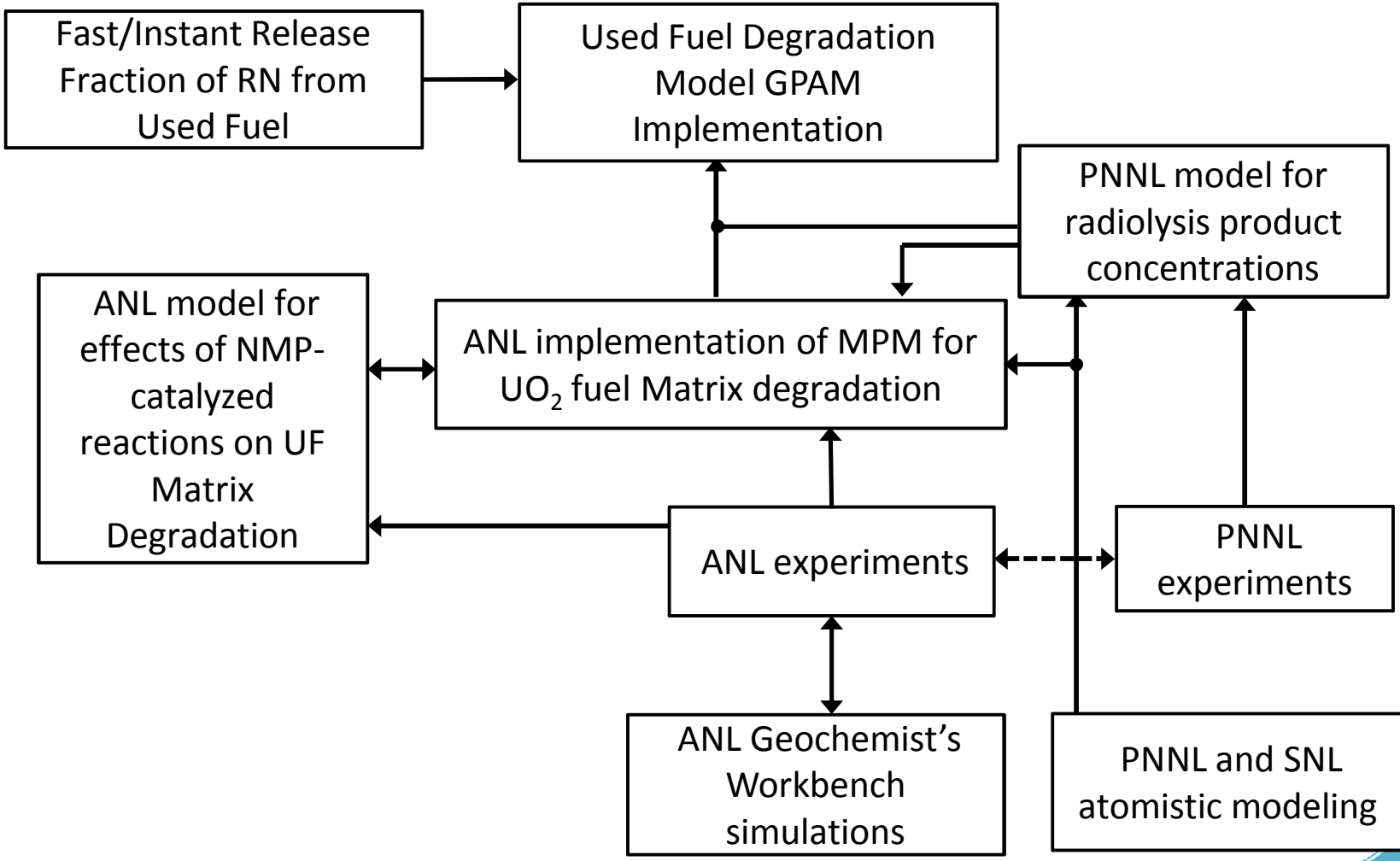


- WF Degradation
- WP Degradation
- Radionuclide Solubility

- Advection / Dispersion
- Diffusion
- Sorption
- Radionuclide Decay

- Water Consumption
- Dose Conversion Factors

GPAM – Conceptual Framework - UFD&RM Activities Context



UFD&RM Activities Overview of Model Structure

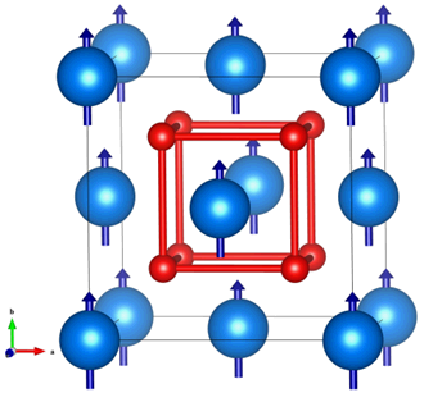
- **Used Fuel Degradation and Radionuclide Mobilization Model Concepts**
  - **The fast release fraction (or instant release) inventory that includes fission products located in**
    - *The fuel gap*
    - *The plenum regions (fission gases)*
    - *The accessible grain boundaries/pellet fractures*
  - **The matrix degradation inventory that includes the matrix itself and fission products located in**
    - *The inaccessible grain boundaries/pellet fractures*
    - *The matrix as solid solution or dissolved within the grain structure*
    - *The noble metal particles (which undergo their own degradation rate once exposed)*
  - **Focus on the major rate limiting processes (e.g., radiolysis, matrix degradation, noble metal particle degradation)**
  - **Future – couple with physical degradation of cladding and mechanical evolution of degrading fuel**

Molecular Modeling of UO_2 Surface Reactions

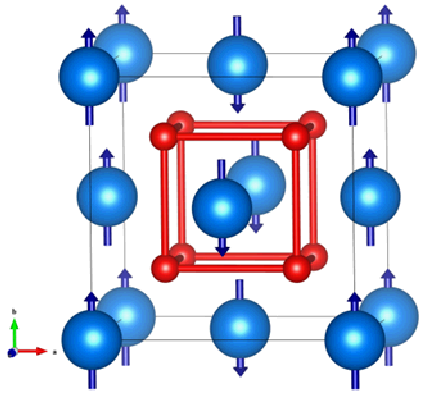
- **Investigate role of strong electron correlations in the surface properties of UO_2**
  - **Previous quantum-mechanical (Skomurski et al, 2008, *J. Nucl. Mater.*)**
    - *Low-index surface slab models from bulk UO_2 with a ferromagnetic ground state*
      - **experiment shows that UO_2 is antiferromagnetic**
      - **neglected strong electron correlations**
    - *strong electron correlations in UO_2 may affect the corrosion/dissolution process*
  - **Currently investigating the possible role of strong electron correlations in the properties and reactivity of the UO_2(111) surface**
    - *using density functional theory within the generalized-gradient approximation (DFT, GGA+U/PW91)*
    - *corrected with an effective Hubbard parameter to account for the strong on-site Coulomb repulsion between U 5f electrons (Dudarev's approach).*

Molecular Modeling of UO_2 Surface Reactions (continued)

- **GGA+*U* study of *bulk* UO_2: ordered and disordered oxygen lattice**
  - **Fluorite-type structure (CaF_2, Fm-3m space group) with ordered oxygen (OO) sublattice:**

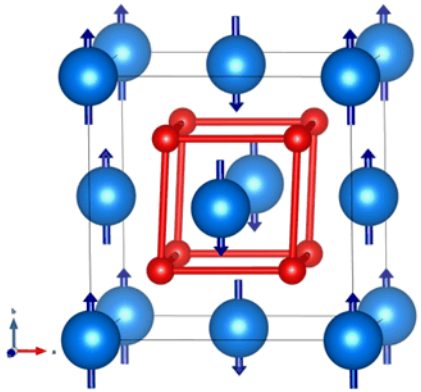


Ferromagnetic (FM)



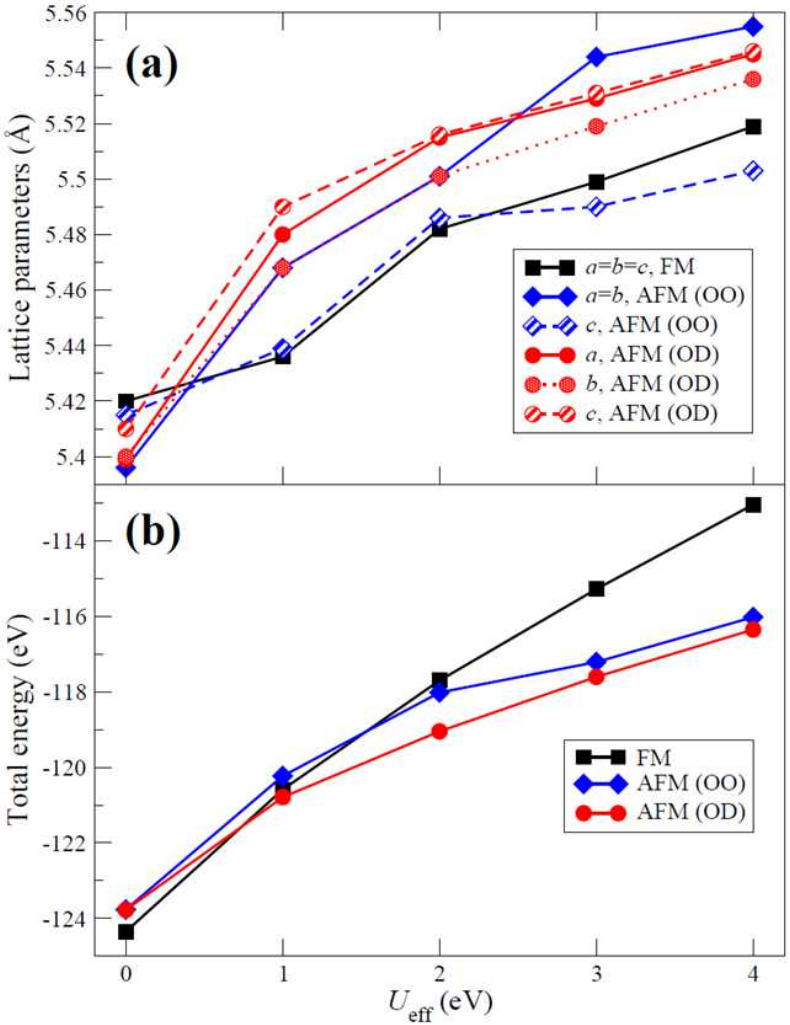
Antiferromagnetic (AFM type-I)

  - **Antiferromagnetic (AFM type-I) with oxygen sublattice distortion (OD) in the [111] direction:**
    - *(Thompson et al., Phys. Rev. B, 84 (2011), 134111)*



Molecular Modeling of UO_2 Surface Reactions (continued)

- **GGA+*U* study of *bulk* UO_2: ordered and disordered oxygen lattice results**
  - The FM solution is energetically favorable for standard DFT (*U* = 0 eV)
  - The AFM solution with oxygen distortion is preferable for *U* = 4 eV (i.e., the value suggested from the analysis of core-level X-ray photoemission spectra of UO_2).
- **Evaluate properties of the relaxed surface**
- **Evaluate surface reactions**
  - O_2, H_2O, H_2O_2



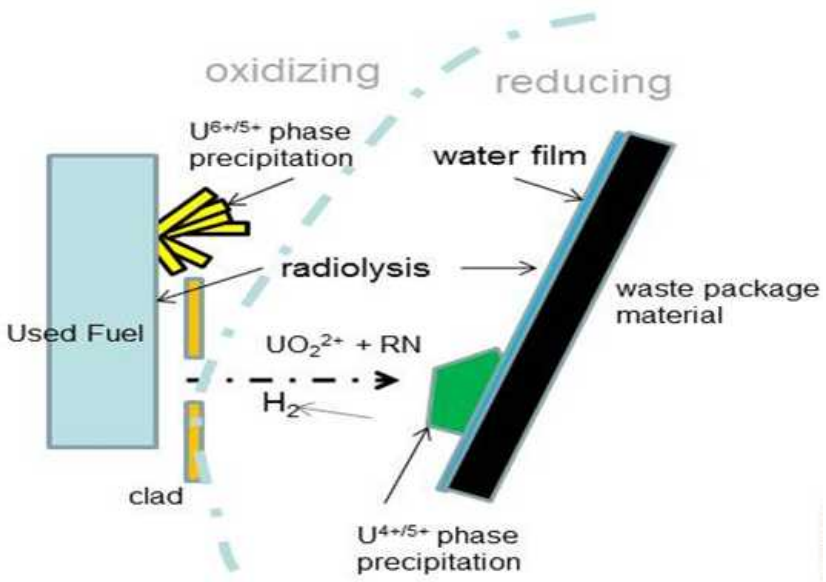
Used Fuel Disposition

PNNL UFD&RM FY12 Activities

- **PNNL Team: Edgar Buck, Rick Wittman, Bruce McNamara, Frances Skomurski**
- **Implementation of Radiolysis Models for Used Fuel Degradation and Radionuclide Migration in a Degraded EBS Environment**
  - Development of a quality user interface for radiolysis model
- **Development of Simulant Fuels for Experimental Investigation of Used Fuel Degradation at Future Conditions**
  - Experimental investigation of radiolysis on Simulated Fuels and MOX materials.
  - Test plan completed in December, 2011

Premises of UFD&RM Activities PNNL R&D Efforts

- **Assuming fuel will be placed in a 'reducing environment' for long term storage/disposal**
- **Radiolysis (alpha) will be the only long term driver for creating very localized oxidizing conditions**
  - **UO_2 will oxidize to $UO_{2.67}$ which is *1000x* more soluble.**
  - **Even if soluble U is precipitated at reducing fronts (e.g., Fe^{2+} redox processes, soluble radionuclides may migrate**
  - **However, groundwater corrosion of canister materials could produce H_2**
- **Behavior of the H_2-UO_2-H_2O system will be critical to limiting used fuel corrosion and the solubilizing of important radionuclides.**
- **Determining the conditions at which the waste package environment might no longer be reducing will be important.**

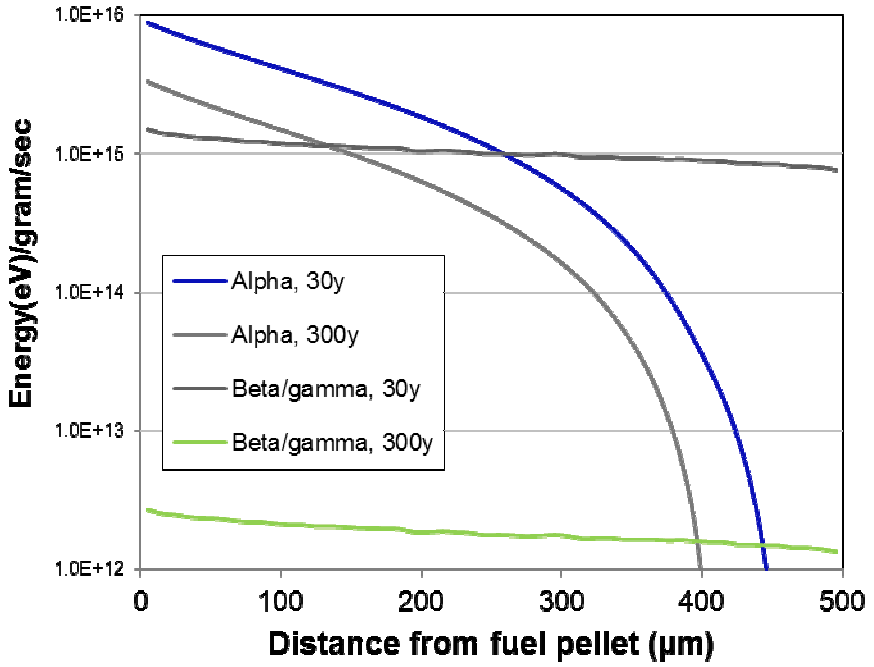


Schematic of processes in the EBS being investigated in this task

Used Fuel Disposition

Radiolysis Model Concepts

- The dose to the surface of used fuel is dominated by long-lived alpha even at relatively short times out of reactor
- Focused mainly on radiolysis modeling and testing
  - Useable program enables modeling of a three state system with UO_2, water and an atmosphere.
  - Reducing environments were examined
- The combined effects of engineered barrier system degradation and waste form degradation were considered
- Future systems of interest:
  - Carbonate; Chloride



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Evaluation and Development of Radiolysis Models

Radiolysis Model Development

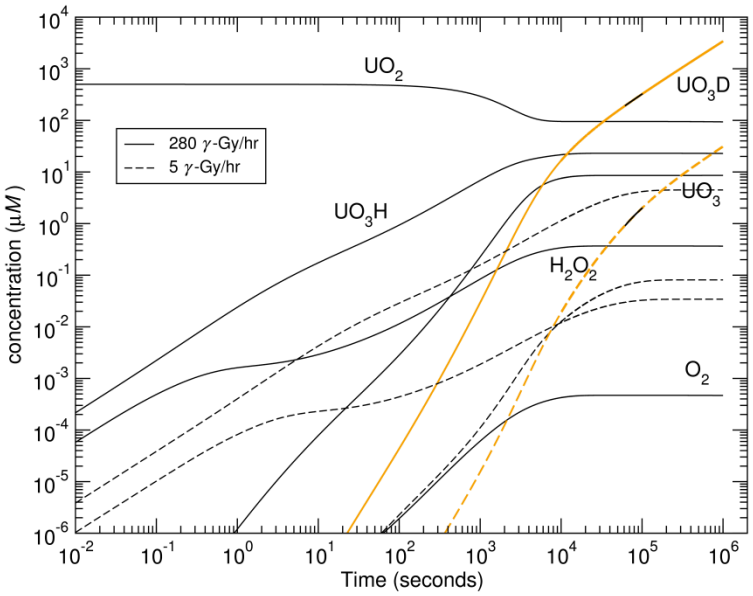


Figure 1

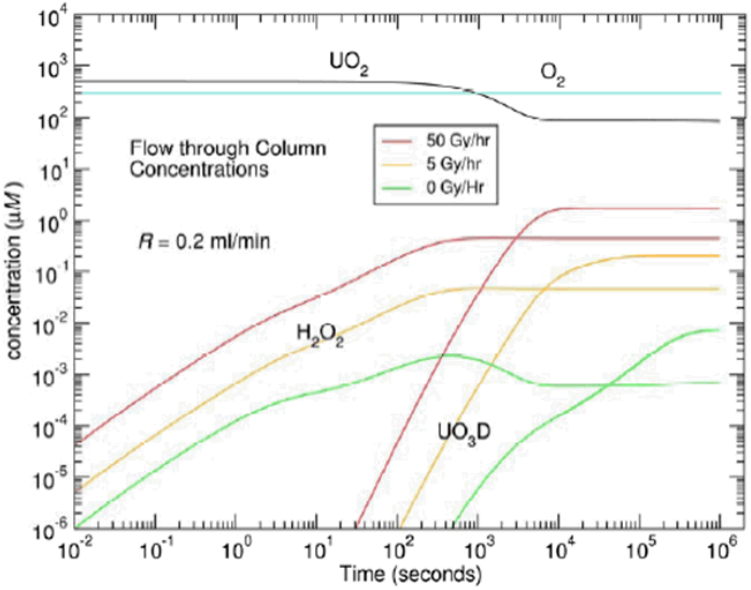


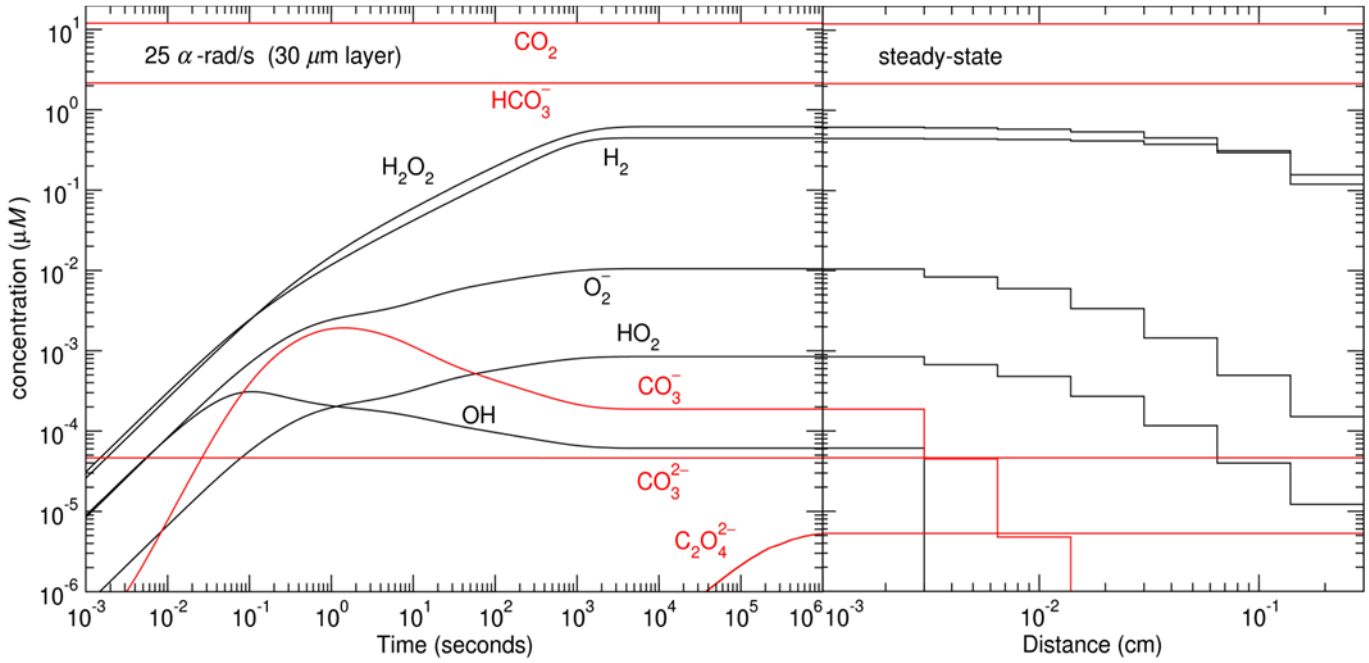
Figure 2

Figure 1. Shows the predicted dissolution rate with the radiolysis model.
Figure 2. Predicted dissolution UO_2 rate and H_2O_2 production at a range of doses

- **Working on model complexity and interfacing with geochemical software.**

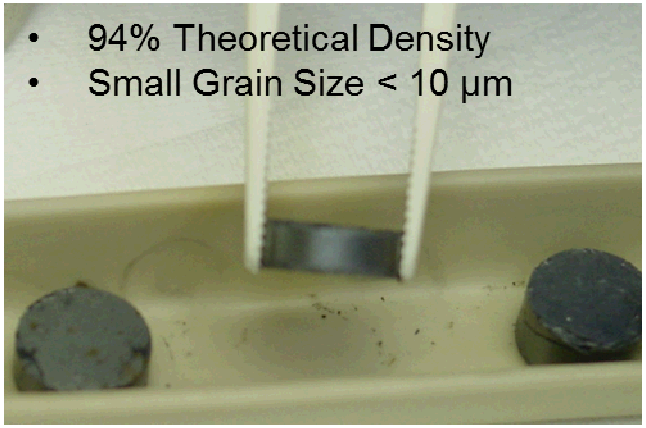
Carbonate System Study

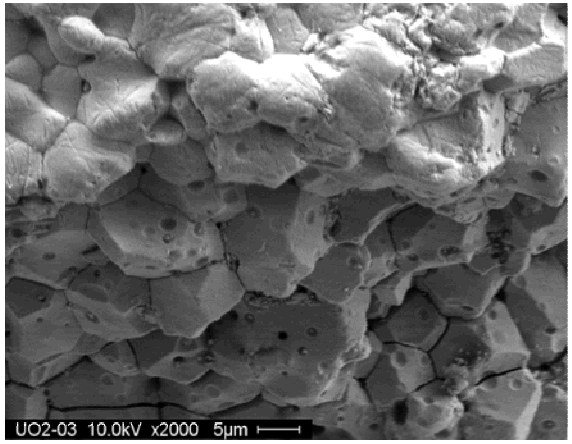
- Role of CO_2 in the system - OH• can generate CO_3^-, which is also a strong oxidant.
- Formation of oxalate in a U-Oxide system may be more important.



Development of Simulant Fuels for Experimental Investigation

- **Produce doped simulated fuels for experimental work**



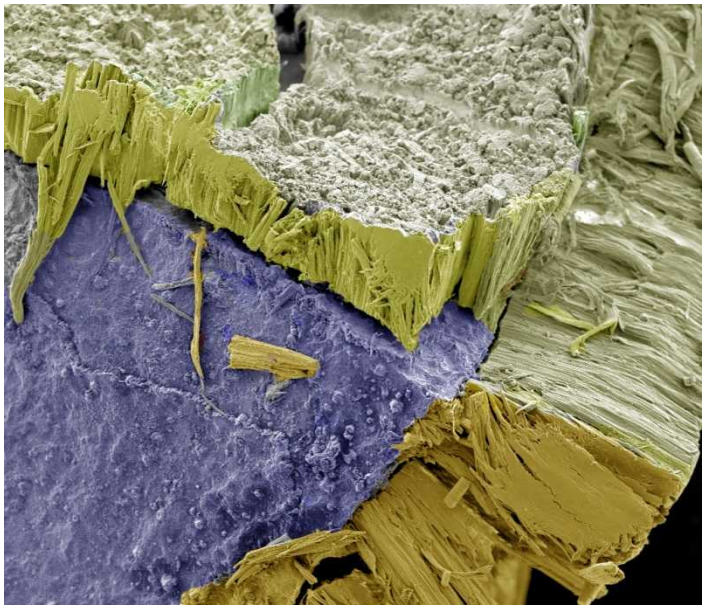


ID	MC	ME	RC	ZE	ZC	TM	TE	TR
OXIDE (WT%)	UO_2-MO-CE	UO_2-MO-EU	UO_2-RE-CE	UO_2-ZR-EU	UO_2-ZR-CE	UO_2-TH-MO	UO_2-TH-EU	**UO_2-TH-RE**
UO_2	93.89	90.74	92.28	88.59	91.59	82.19	79.06	**80.80**
ThO_2						15.07	14.50	**14.81**
ZrO_2				5.00	5.17			
MoO_3	2.78	2.69				2.74		
CeO_2	3.33		3.27		3.24			
ReO_2			4.45					**4.38**
Eu_2O_3		**6.57%**		**6.41**			**6.44**	

Investigation of Radiolysis Driven Fuel Oxidation

- New methods for producing SimFuels (RADFUELs)
- Using MOX as a simulant for tests
- Irradiation facilities for model validation experiments
- Collaboration with ANL with specimens

Studtite on UO_2



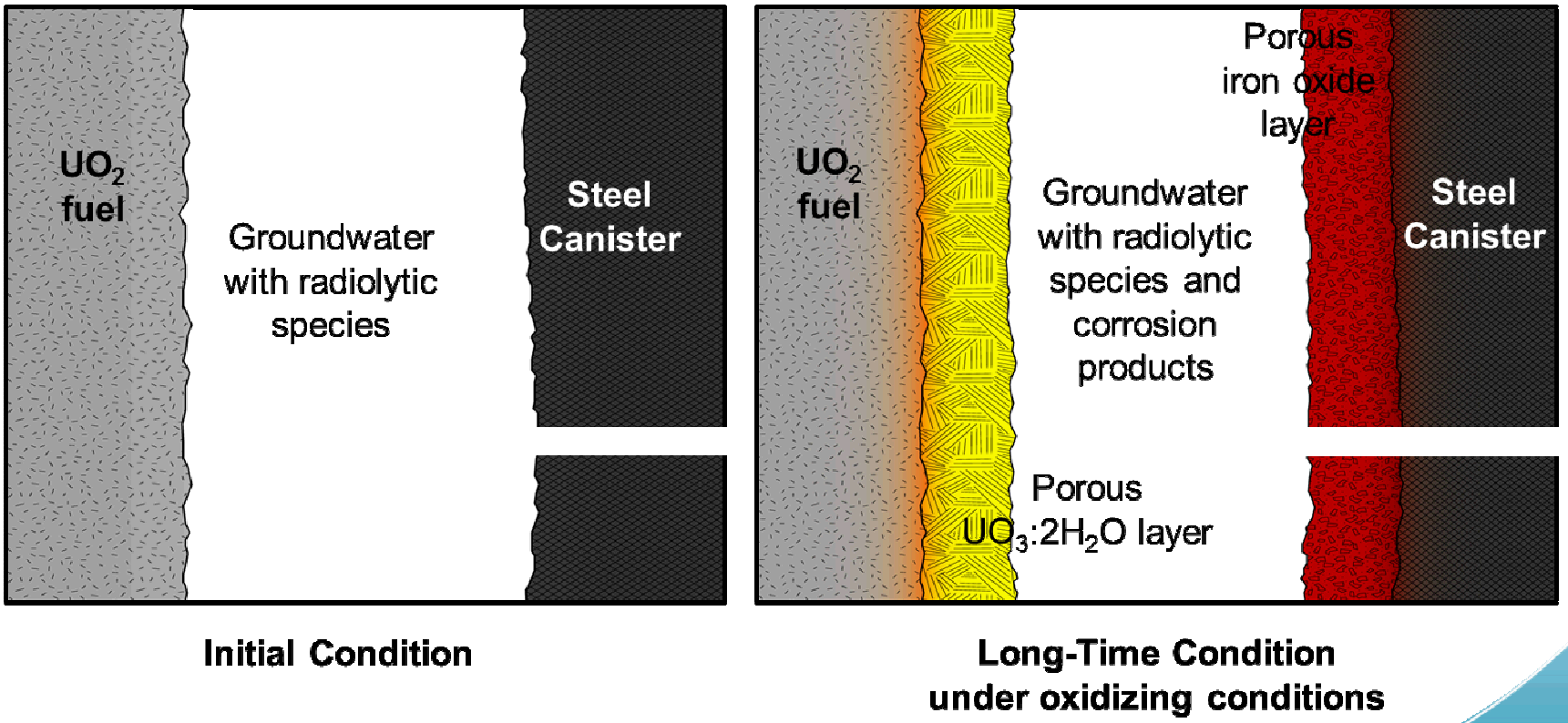
Used Fuel Disposition

ANL UFD&RM FY12 Activities

- ANL Team: Jim Jerden, Terry Cruse, Kurt Frey, Jeff Fortner, Bill Ebert
- Implement used fuel matrix degradation rate model
  - Based on the mixed potential model (MPM) of Shoesmith (2003, *Corrosion Sci. Sec.*)
- Quantify catalytic effect of NMP on UO_2 oxidative dissolution rate by electrochemical experiments
  - Coupled with detailed characterization of solids and solutions by microscopic and spectroscopic techniques
  - Test plan completed January 2012
- Quantify effects of NMP corrosion, alteration, and poisoning on catalytic efficiency
- Develop module for effect of NMP on UO_2 oxidative dissolution rate that can be included in used fuel matrix degradation rate model

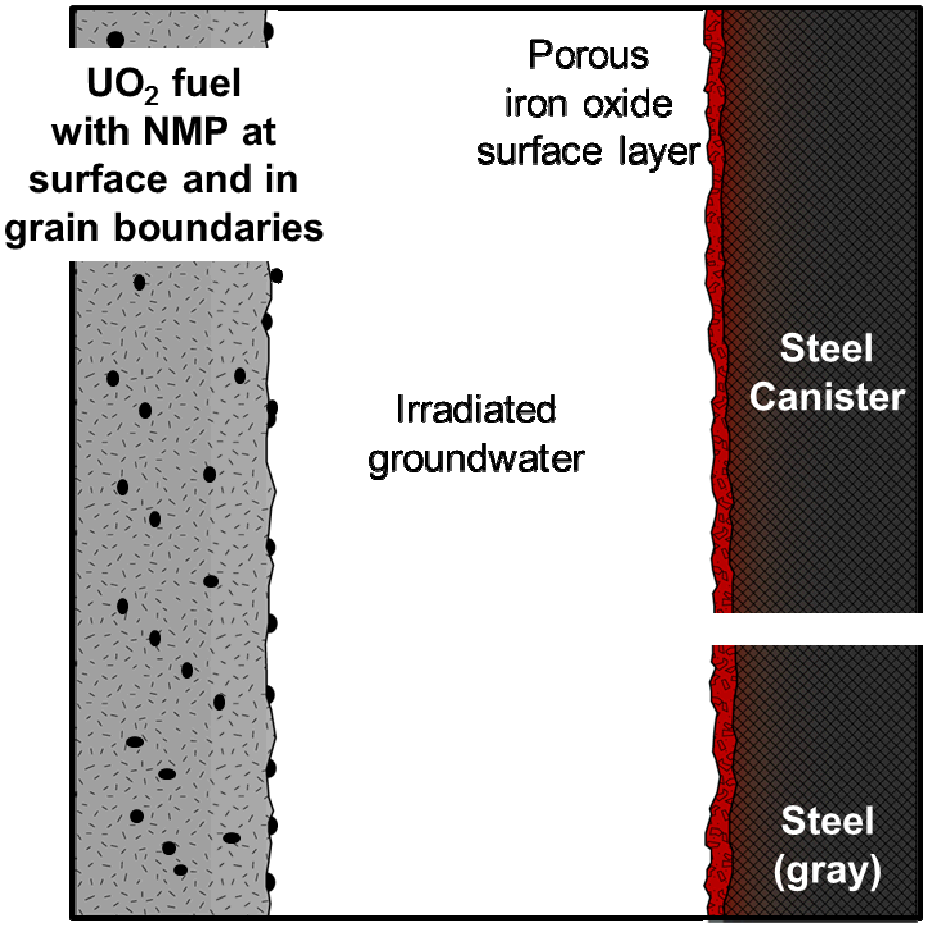
Mixed Potential Model (MPM) Concept for Used Fuel Degradation

- Simplified representation of breached canister system used in MPM for oxidizing conditions (Shoesmith (2003) Corrosion Sci. Sec.)



Extend MPM to Explicitly Account for Effects of NMP

- Incorporate the catalytic effect of noble metal particles (NMP) into MPM
- Account for corrosion or poisoning of NMP catalytic properties (experimental focus)



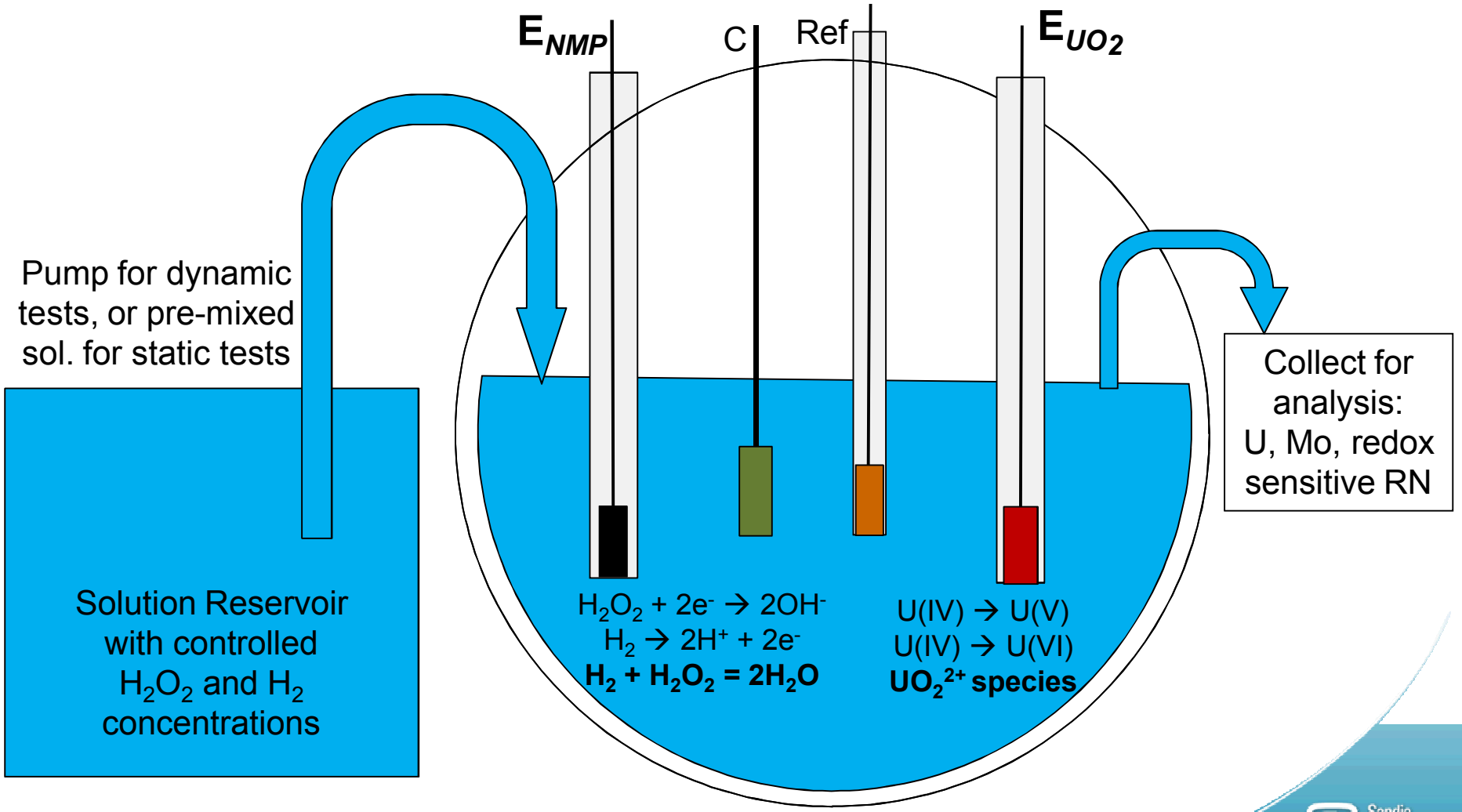
Electrochemical Experimental Plan

- Fabricate electrodes with surrogate alloys representing NMP and UO_2
  - Use separate electrodes to control potentials and isolate reactions
- Measure catalytic behavior of NMP alloys prior to corrosion
  - kinetics of competing redox reactions at various T, pH, H_2O_2 and H_2 concentrations, electrode surface areas, and imposed potentials

    $H_2O_2 + 2e^- \rightarrow 2OH^-$ coupled with $H_2 \rightarrow 2H^+ + 2e^-$ (*catalyzed by NMP)

    $H_2O_2 + 2e^- \rightarrow 2OH^-$ coupled with $UO_2 \rightarrow UO_2^{2+} + 2e^-$
  - Measure concentrations of U, Mo, Tc, etc. in solutions containing H_2O_2 and H_2 (separate tests with and without NMP alloys in system)
- Corrode surface of NMP under controlled conditions (*ex situ*)
  - Control potentials, T, pH, solution chemistry (H_2O_2, H_2, NaCl, NaBr, NaI, S, Se, etc.)
  - Characterize electrode surface electrochemically, with SEM, XAS, etc.
- Measure catalytic efficiency of corroded NMP alloys
  - kinetics of redox reactions at various pH, solution chemistries
  - Measure dissolution of UO_2 into solutions with dissolved H_2O_2 and H_2 in system with corroded NMP alloy

Electrochemical Experiment to Measure Effect of Metal Particles on UO_2 Dissolution



Determinations from Experiments

- Directly measure total U in solution at end of test
  - ICP-MS
- Measure current through UO_2 electrode during test
  - Is dissolution rate sufficiently sensitive to H_2O_2 concentration?
- Use floating UO_2 electrode potential
  - Will it react with H_2O_2 at a particular rate at a fixed potential?
- Electrically couple UO_2 and NMP alloy electrodes
  - Is dissolution rate sufficiently sensitive to H_2O_2 concentration?
- Using separate electrodes provides flexibility in electrochemical measurements

Used Fuel Disposition

UFD&RM FY12 Activities Summary

- **Experimental work is being initiated**
  - Based on gap analysis and for validation and testing models
  - Developed test plans and testing matrix (ANL and PNNL) - completed
  - Begin executing testing matrix (ANL and PNNL)
- **Development of used fuel degradation model**
  - Constraints on fast/instant release fractions of radionuclides
  - Molecular modeling of UO_2 surface reactions
  - Implementation of baseline matrix degradation rate model
  - Implement radiolysis model in more user oriented fashion
  - Include/couple radiolysis model with baseline matrix degradation rate model
  - Develop targeted enhancements for baseline matrix degradation rate model
    - *role of H_2*
    - *epsilon phase catalytic properties*

UFD&RM FY12 Activities Summary (continued)

- **Implement UFD model within Generic Repository System models**
  - Develop specific scenarios for system analyses
    - *create detailed integration with GPAM (Generic repository models)*
  - Implement used fuel degradation model into GPAM
  - Initiate analyses for highest priority scenarios
- **Further integration with Waste Form Campaign**
  - As additional waste form degradation models develop (e.g., glass waste form degradation model), define strategy for implementation into GPAM

Used Fuel Disposition

Focus and discussion areas for Task #3

- **First U.S. report – November, 2012**
  - Used fuel degradation in a repository environment (granite initial system)
    - *Fast/instant release fractions for radionuclides*
    - *Matrix degradation rate*
  - Radiolysis model
  - Implementation into generic performance assessment model (GPAM)
  - Relevance to storage evaluations
- **Second U.S. report - areas of possible emphasis/discussion**
  - Cladding model(s) integration with used fuel degradation
  - Other potential waste forms
  - Schedule

BACKUP MATERIALS

First-principles modeling of UO_2 fuel and its corrosion phases

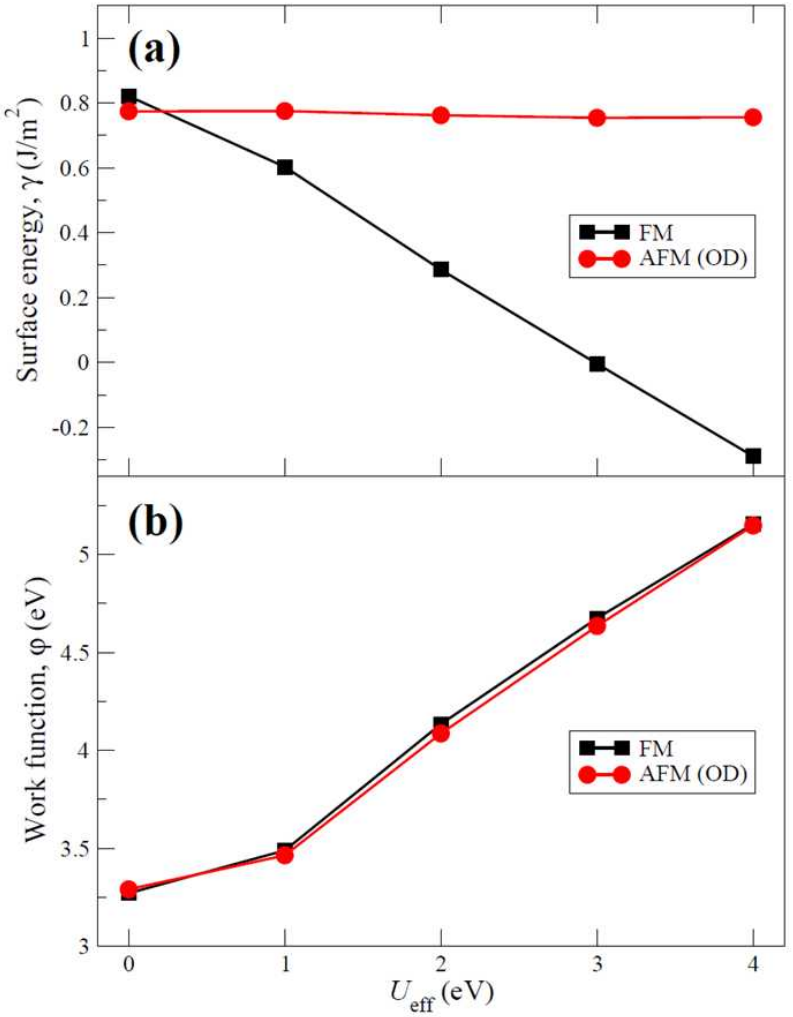
- **Objectives**
  - Investigate the role of strong electron correlations in UO_2 bulk and surface properties.
  - Study the structural properties of uranyl peroxide hydrates corrosion phases; determine the crystal structure of metastudtite using density functional theory (DFT).
  - Calculate the thermal properties of uranyl peroxide hydrates from first-principles.

- **Approach**
  - Quantify the role of strong electron correlations in UO_2 bulk and in a UO_2(111) slab model using the generalized gradient approximation corrected with an effective Hubbard parameter (GGA+*U*) to account for the strong on-site Coloumb repulsion between U 5f electrons (VASP code).
  - Use perturbation theory (PT) to calculate the phonon properties of uranyl peroxide hydrates structures relaxed with DFT and derive their thermal properties.

- **Milestones**
  - M2FT-12SN0806062 "Integration of EBS Models with Generic Disposal System Models" (September 2012)

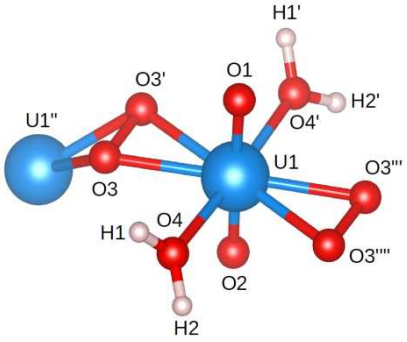
Molecular Modeling of UO_2 Surface Reactions (continued)

- **Variation of the surface energy and work function of the relaxed UO_2(111) surface**
  - **FM and AFM (OD) solutions**
    - *Only minor change for the +U correction on the surface energy of the AFM structure*
    - *Use of +U >3 eV leads to unphysical results for the FM solution.*
      - **Experimental estimate: γ = 0.85 J/m² with up to ±70% uncertainty (Hall et al., 1987, J. Nucl. Mater.)**
    - *Nearly-linear variation of the work function with +U*
      - **Experimental estimate: ϕ = 3.5 ± 0.5 eV (Page et al., 1974, *Combustion and Flame*)**

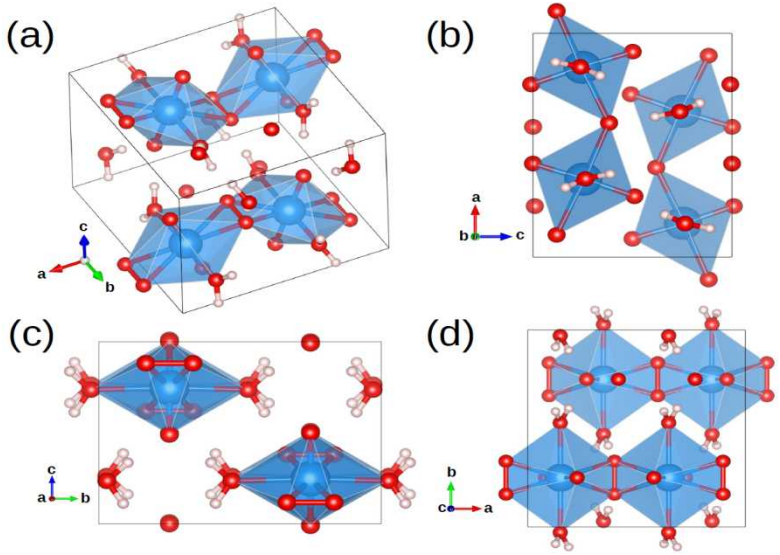


Used Fuel Disposition

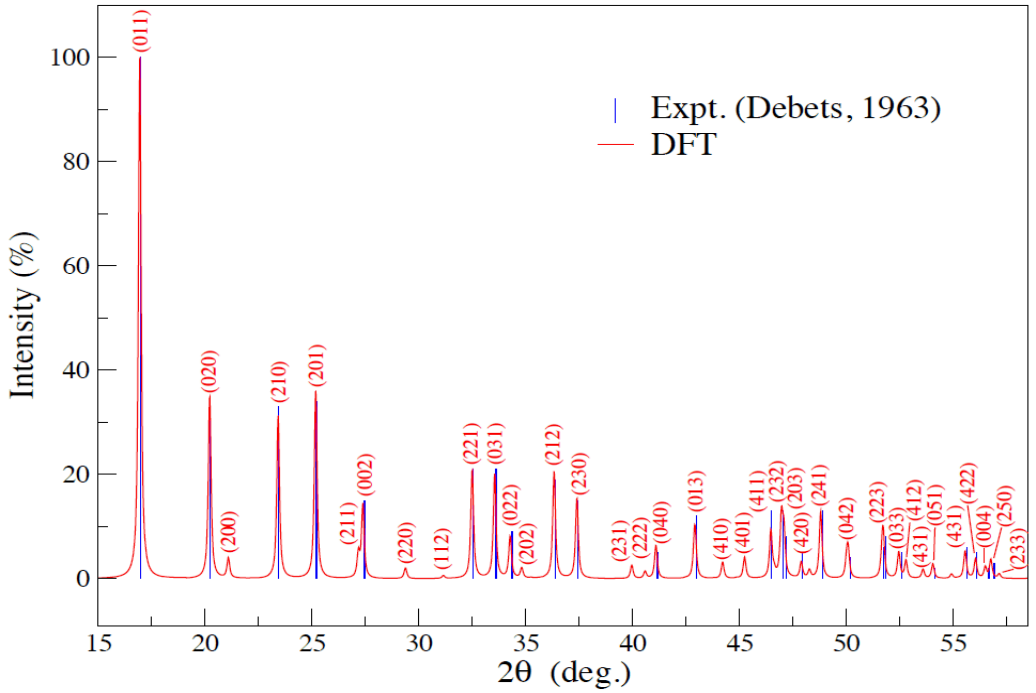
Structural properties of uranyl peroxide hydrates corrosion phases



Ball-and-stick representation of the $(UO_2)O(H_2O)$ complex composing metastudtite



Crystal unit cell of metastudtite $(UO_2)O_2(H_2O)_2$ (space group Pnma, Z = 4) relaxed with DFT at the GGA/PW91 level of theory.



X-ray diffraction pattern of metastudtite. The experimental powder diffraction pattern for Cu $K_{\alpha 1}$ radiation (Debets, 1963) is represented by blue lines. The diffraction pattern simulated from the orthorhombic structure (space group Pnma, Z = 4) reported in the present study is shown in red.

(Manuscript submitted to Dalton Transactions).

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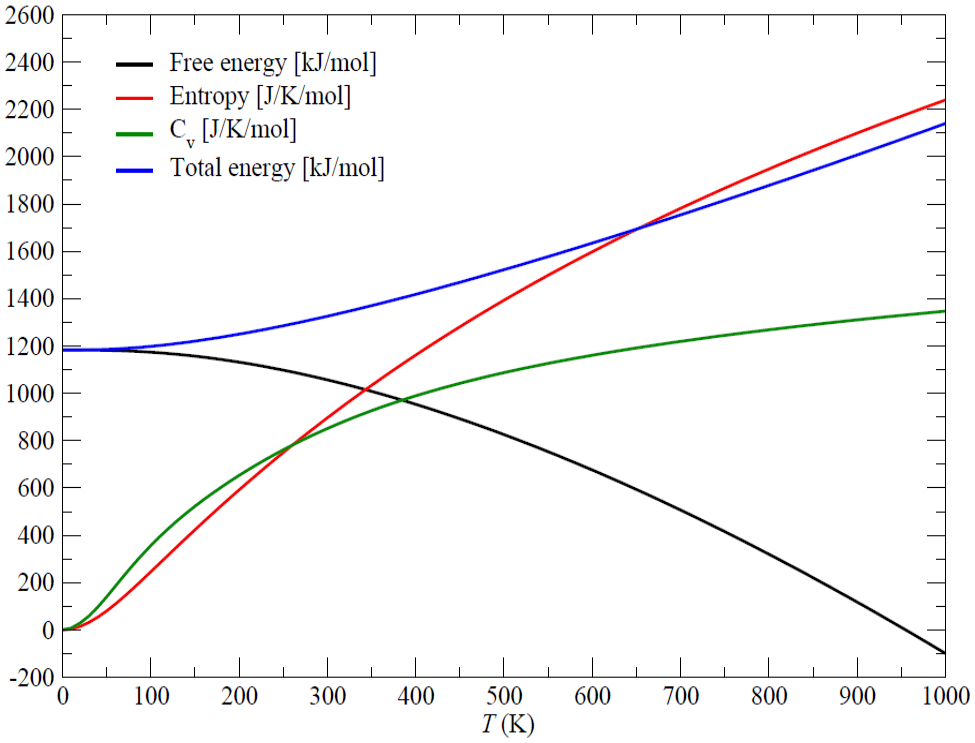
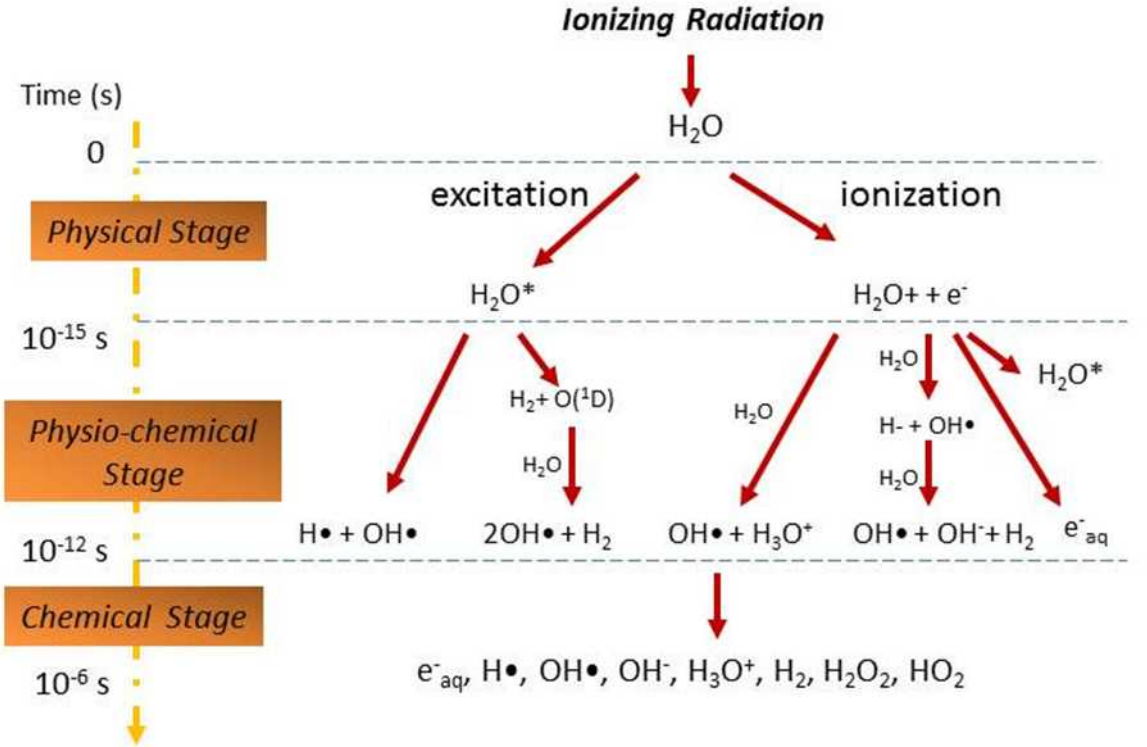
Thermal properties of uranyl peroxide hydrates corrosion phases: studtite



Evolution of the total energy and thermal properties of studtite $(UO_2)O_2(H_2O)_4$ (space group C2/c, Z = 4) calculated from the structure relaxed with DFT at the GGA/PW91 level of theory.

- **Thermal properties:**
  - Density functional perturbation theory (DF-PT) was used to calculate the phonon properties of the relaxed studtite structure
  - Thermal properties (free energy, entropy, heat capacity) were derived from phonon calculations.
- **Future work:**
  - Extend structural and thermal calculations carried out within the framework of DFT/DFPT to other phases that may be involved in the corrosion of UO_2 fuel (schoepite, metaschoepite, dehydrated schoepite, metastudtite,…)

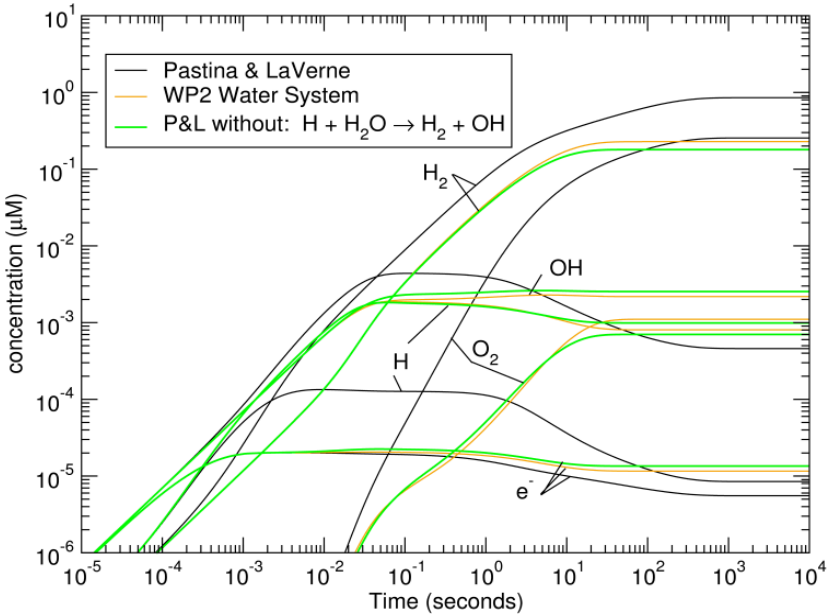
Radiolysis Model Description



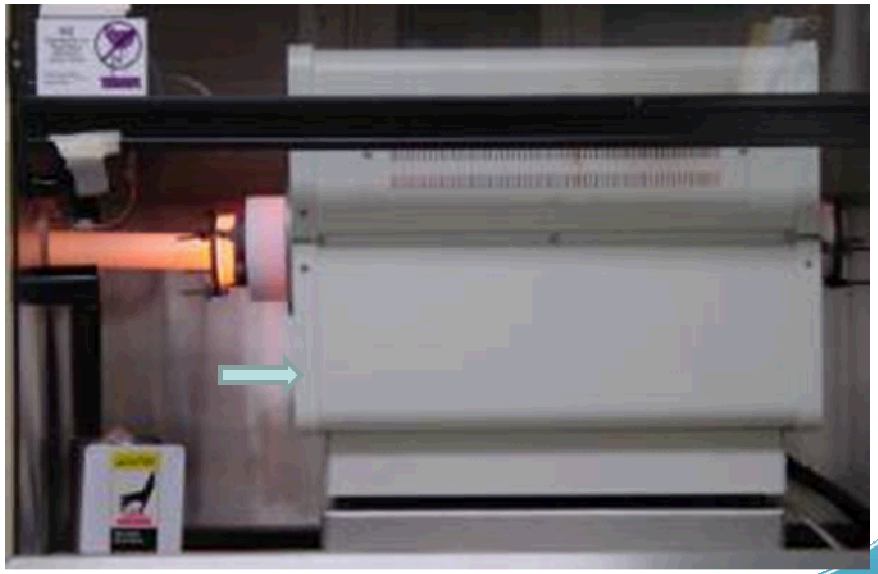
- ***Coupled Reaction Kinetics (146 reactions, 42 Species)***

$$\frac{d[A_i]}{dt} = G_i \dot{D}[A_i] + \sum_{r=1}^{N_r} k_{ir} \prod_{j_r=1}^{n_r} [A_{j_r}]^{O_{j_r}}$$

PNNL Radiolysis Model

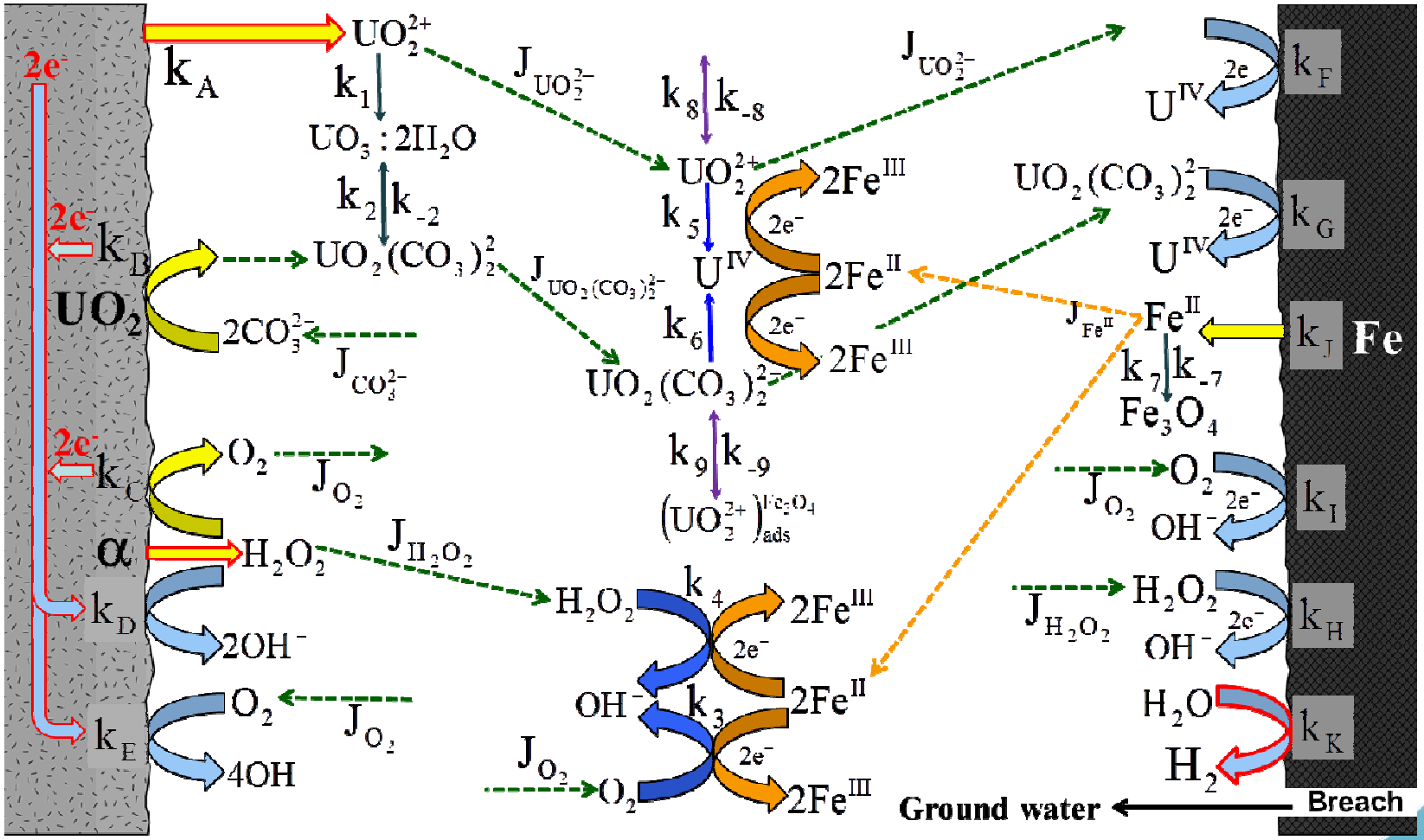


Fuel Fabrication – In the Laboratory



Used Fuel Disposition

Reaction Scheme for MPM (anodic: yellow/orange, cathodic: blue)



Shoesmith (2003) Corrosion Sci. Sec.

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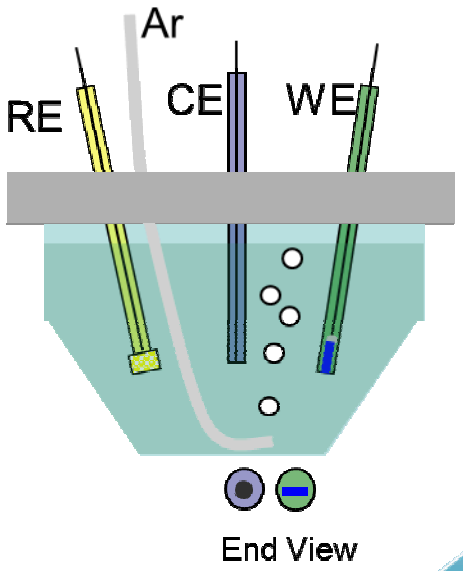
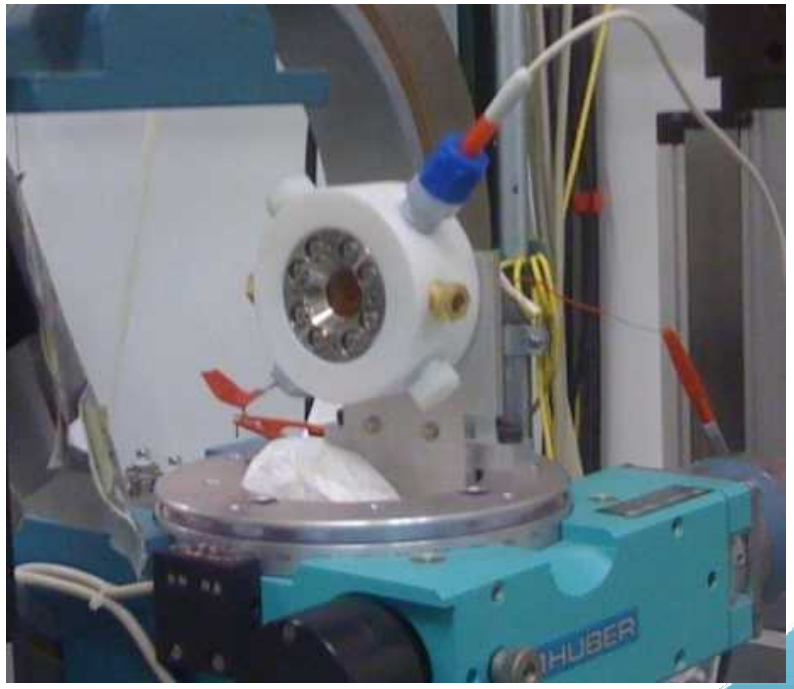
ANL Experimental Setup

- **Reference Electrode (RE): Ag/AgCl 3M NaCl/saturated Ag/Cl**
- **Counter Electrode (CE): 2 mm Diameter Pt Disk**
- **Microcell**
  - **Solution Volume: ~20 mL**
  - **Can de-air (Ar gas feed)**
  - **Use cover gas**
  - **Jacketed for temperature control via flowing water**



ANL Electrochemical Experiments: Capabilities for Radioactive Samples

- **Materials: Ru-Mo-Pd-Rh alloys & UO_2 electrodes: surrogates for NMP & used fuel matrix**
- **Multiple electrode electrochemical cell:**
  - Separate potentiostats used to control & monitor electrodes made with alloy and UO_2.
  - Tests run in static or flowing electrolytes with controlled H_2O_2 and H_2 concentrations.
- **Spectroelectrochemistry (Advanced Photon Source):**
  - *In-situ* X-ray absorption spectroscopy of solution, NM and UO_2 electrode surfaces under controlled redox conditions.
  - determine oxidation states & coordination environments of key radionuclides.
- **Full system characterization**
  - Electrochemistry
  - SEM, TEM, XRD, XAS surface analyses
  - Solution analyses: ICP-MS, LC…



Electrochemical cell for *in situ* XAS