SAND2014-4927C

Used Fuel Disposition Campaign

On the UQ methodology development for storage and transportation applications

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Uncertainty Quantification working group
Las Vegas, NV
June 4, 2014

Objective

The objective of this activity is to initiate the development of a UQ methodology to provide guidance on which data will have the greatest impact on meeting UFD ST R&D objectives.

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Meeting expectations

This workshop IS about reviewing the current activities:

- **Description of the work scope and technical details on the UQ methodology development.**
- **Description of mathematical framework.**
- **Description of the SCC model.**
- **Addressing cross-cutting gap.**
- **Identifying how existing experiments and models are anticipated to be used.**
- **Assign upcoming activities.**

This workshop IS NOT about proposing solutions:

- ***NOT selecting or ranking activities.***
- ***NOT discussing the gap analysis report priorities.***
- ***NOT defining the work scope.***

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Agenda

Time	Topic
Today	
3:10PM-3:40PM	Work scope presentation. (R. Dingreville, SNL)
3:40PM-4:30PM	Mathematical framework. (C. Sallaberry, SNL)
4:30PM-5:00PM	Discussions on UQ methodology. (All participants)
Tomorrow	
08:00AM-08:20AM	Using PCMM as a communication tool. (R. Dingreville)
08:20AM-09:00AM	SCC model. (C. Bryan)
09:00AM-09:50AM	Discussions on how development of SCC model. (All participants)
9:50AM-10:10AM	Break
10:10AM-11:30AM	Addressing cross-cutting gap. (All participants)
11:30AM-12:00PM	Action items.

There is a need for a more complete UQ characterization than initially used in the Gap Analysis report

- ***"An Uncertainty Quantification effort will be started this year to complement the prioritization of the Technical Data Gap Report. Given the large number of medium and high priority data needs that have been identified, the UQ effort will focus on the development of the methodology to provide guidance on which data, once obtained, will have the greatest impact on meeting the UFD ST R&D objectives. This will act to narrow the list of high and medium priority data gaps that need to be addressed with limited resources."***
  [*FY14 work packaging planning document, UFDC S&T Engineering Analysis*]

- **Two overarching objectives:**

  1. Development of a methodology to quantify and characterize the uncertainty associated with the degradation mechanisms impacting dry storage operations and normal conditions of transport.

  2. Demonstrate the effectiveness of this approach to rank the data gaps and parameters of interest.

This activity: 10,000 ft view

- **Uncertainty focused system analysis:**
  - Analyze high/medium priority data gaps to determine biggest impact.
  - Increase fidelity and accuracy of overall system response.
  - Address candidate high/medium priority gaps analysis only when/if possible.
  - Provide a framework that can be continually built by additional models/experimental data to provide useful engineering guidance quickly.

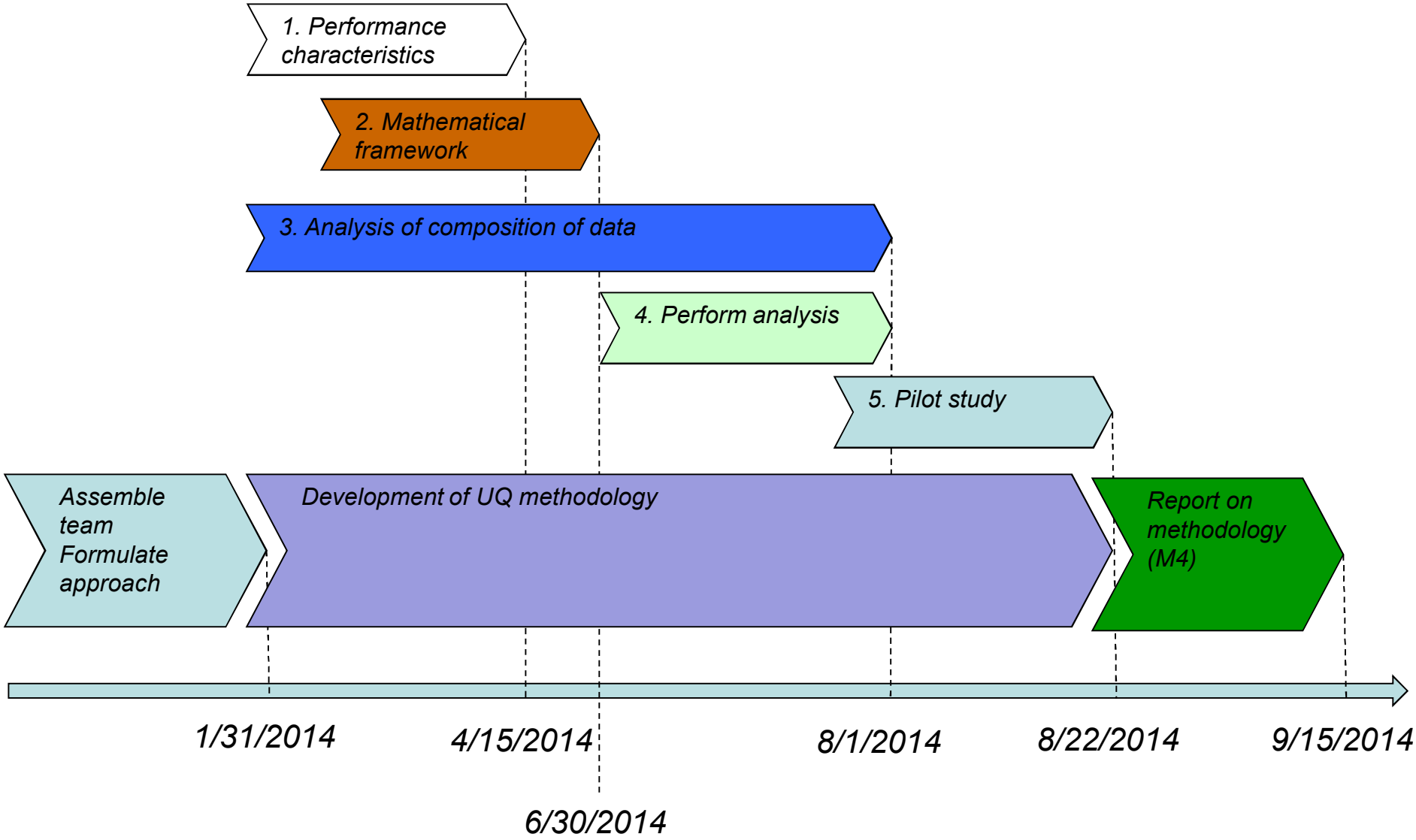
- **Integration within the UFD campaign:**
  - Help document/verify the overall responses of storage and transportation of current and future used fuel for DOE/NRC use.
  - Strong technical bases for risk and safety analysis.
  - Reduce costs by focused model development and experimental data based on UQ analysis.
  - Help inform experiment and model design.
  - Accelerate the development of technical bases for fuel retrievability and transportation after long storage.

The proposed conceptual UQ methodology provides a clear path from formal description to computational implementation to written documentation

Work scope plan:

1. **Identify performance characteristics:**
   SCC (technical gap) / thermal profile (cross-cutting gap)
2. **Understand performance threshold and requirements and frame it into a mathematical framework.**
   See Cedric Sallaberry's presentation to follow.
3. **Analysis of the composition of available data: experimental and numerical.**
   See Charles Bryan's presentation tomorrow.
4. **Perform preliminary decision making analysis.**
5. **Identify performance characteristics with insufficient data.**
   - UQ to vary each possible issues/concern/question with the handling/transport model, the data needed to support it, data needed to validate it and see which ones have the most impact on the overall figures of merit.
   - This type of approach has been used for NW (LEP).

Milestones and activities



Existing Gap prioritization report

- **UFD gap reports:**
  - Gap Analysis to Support Extended Storage of Used Nuclear Fuel (FCRD-USED-2011-000136 Rev. 0 PNNL-20509)

    "This report documents the initial gap analysis performed to identify data and modeling needs to develop the desired technical bases to enable the extended storage of UNF"

  - Used Nuclear Fuel Storage and Transportation Data Gap Prioritization (FCRD-USED-2012-000109 PNNL-21360)

    "The primary purpose of this report is to document the methodology and results of a more quantitative analysis used to prioritize the Medium and High priority data gaps from the initial Gap Analysis"

  - Review of Used Nuclear Fuel Storage and Transportation Technical Gap Analyses (FCRD-USED-2012-000215 PNNL-21596)

    "In order to verify that the UFDC identified all of the technical gaps and properly prioritized them, this report was commissioned to compare the UFDC Gap Analysis and UFDC Gap Prioritization reports to those recently published by others…"

- **Other gap reports:**
  - NRC, 2012: Identification and Prioritization of the Technical Information Needs Affecting Potential Regulation of Extended Storage and Transportation of Spent Nuclear Fuel, Draft for comment.
  - EPRI, 2011: Extended Storage Collaboration Program (ESCP) Progress Report and Review of Gap Analyses.
  - IAEA, 2002: Long Term Storage of Spent Nuclear Fuel - Survey and Recommendations.

Existing Gap prioritization report

UFDC's Gap Description	In atmospheric corrosion, sorption of water vapor from the air provides the water at the surface for corrosion to occur. This process is significant when atmospherically deposited contaminants deliquesce, forming a concentrated electrolyte solution that promotes corrosion. On stainless steel canisters, the corrosion of concern is localized including: pitting, crevice, galvanic, SCC, and if conditions are sufficient, MIC. Contaminants may include aggressive species such as chlorides from marine locations or oxidized sulfur species from polluted areas; organics can be significant, providing the nutrients needed for MIC. Research has shown that with deposited sea salt, relative humidities of 15 percent and above can support deliquescence and corrosion of the canister steels. In the presence of untreated welds, residual stresses are high enough to support SCC. Rates of all types of corrosion are highly dependent on the temperature. The research into atmospheric corrosion is mature enough to identify the conditions necessary for corrosion, but it is not clear if these conditions exist now, or will exist, at specific ISFSIs.
Alternate Description	The description of atmospheric corrosion is consistent in all the gap reports that discuss it.

Priority	UFDC	NWTRB	NRC	EPRI	IAEA	Germany	Hungary	Japan	ROK	Spain	UK
	VH	X	H1	H				H	H	L	VH

Consistency of Priority	All organizations that prioritize, and all countries that use welded canisters for long-term storage, assign a high priority to additional research.

UFDC's Gap Description	UFDC does not identify these as gaps, however, UFDC would group these needs under "Welded Canister – Atmospheric Corrosion," Section 3.9.7.
Alternate Description	Japan identified the following (EPRI 2012): "1. Code or guideline to evaluate initiation and propagation of Stress Corrosion Cracking (SCC) of stainless steel canister in a marine environment is needed. 2. SCC data of normal stainless steel in a realistic marine environment are needed. 3. Demonstrative tests of preventive measures for SCC of normal stainless steel with reduced residual stress are needed. 4. Monitoring of salt deposition on canister surface storing spent fuel on real sites near the sea is needed. 5. Formula to estimate the salt deposition on canister surface using salt concentration in the air at the site is needed. 6. Non destructive measurement method of the salt deposition on canister surface is needed. 7. Technology to mitigate salt concentration in the air of canister environment is needed."

Priority	UFDC	NWTRB	NRC	EPRI	IAEA	Germany	Hungary	Japan	ROK	Spain	UK
								H			

Consistency of Priority	Japan is the only country to identify these gaps.

UFDC's Gap Description	Because nearly all degradation mechanisms are temperature-dependent, thermal profile histories are needed to predict SSC performance. Therefore, temperature data are needed for all SSCs from the time the fuel is loaded into the cask, dried, through the storage period, and during subsequent transportation. The NRC issued guidance on temperature limits based on the need to maintain the integrity of the cladding (NRC 2010b). Therefore, when making approximations for modeling, most modelers have used conservative ones to ensure cladding does not exceed those limits. However, because some degradation processes only occur as the dry cask storage system (DCSS) cools below a threshold temperature, more realistic thermal calculations are needed. Similarly, conservatively high temperatures would over-predict various degradation rates.
Alternate Description	All analyses discussing thermal profiles are consistent in their definition.

Priority	UFDC	NWTRB	NRC	EPRI	IAEA	Germany	Hungary	Japan	ROK	Spain	UK
	VH	H	H1		X		H	C	H	M	H

Consistency of Priority	Except for Japan, which considers the thermal profiles it currently has as adequate, there is consensus that more thermal modeling is needed. Regulations in Japan limit peak cladding temperature to only 275°C, much lower than the 400 °C peak cladding temperature limit in the United States.

Work scope plan

1. **Identify performance characteristics.**
2. Understand performance threshold and requirements and frame it into a mathematical framework.
3. Analysis of the composition of available data: experimental and numerical [more discussions this afternoon].
4. Perform preliminary decision making analysis.
5. Identify performance characteristics with insufficient data.

1. Identify performance characteristics

- **Regulations for storage of spent nuclear fuel are set forth in Title 10 of the Code of Federal Regulations (10 CFR) Part 72.**

- **Revisit NRC requirements to frame and formulate them into QUANTIFIABLE METRICS.**
  - Convert regulatory requirements (regulatory verbiage) into a conceptual and computational structure (mathematically defined metrics)
  - Permits meaningful uncertainty and sensitivity analyses and establishes compliance (or non-compliance) with those requirements.
  - Enables comparing requirements on the same scale (normalization).

Objectives
Retrievability
Containment

SCC performance requirements

- 10 CFR.72: defines confinement systems as follows: “Confinement systems means those systems, including ventilation, that act as barriers between areas containing radioactive substances and the environment.”
- 10 CFR 72.166 requires for all activities, including storage, the establishment of measures to prevent damage or deterioration: “When necessary for particular products, special protective environments, such as inert gas atmosphere, and specific moisture content and temperature levels must be specified and provided.”
- Regulatory guidance is provided in NUREG-1536 and NUREG-1567.
- Welded storage canisters are designed and tested to be “leak tight”, with all of the newer canisters using the ANSI N14.5-1997 definition of “leak tight” (leak rate ≤1.0 x 10^{-7} reference cm^3/s).
- Meyer et al. (2013) cited compilations of SCC flaw characteristics which indicate a mean crack opening displacement for SCC flaws of 16–30 μm. For comparison using the equations and data in ANSI N14.5-1997, the leak rate through a 16 μm diameter round hole in a 0.5 inch thick canister wall under reference conditions is 3.9 x 10^{-4} $atm \cdot cm^3/s$. Note that exceeding the leak rate limit does not necessarily lead to exceeding the dose limits of 10 CFR 71.104 and 72.106 but do represent failure to meet the licensing condition.
- **The UQ analyses will use the performance requirement of no through-wall SCC penetrations.**

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Predictive Capability Maturity Model (PCMM)

- **PCMM is a communication tool we will be using for informing the overall project and stakeholders of the level of maturity of the various model capabilities. Namely the thermal profile and SCC models.**
  - It is a multidimensional, qualitative metric [W.L. Oberkampf et al., SAND2007-5948]
    - Determine readiness for UFDC UQ issues
    - Identify gaps in credibility of the various models
    - Measure progress of integrated simulation effort
  - Six dimensions for the PCMM matrix
    - Geometric fidelity (e.g. crack profile representation)
    - Physics fidelity (corrosion physics?)
    - Code verification (linearization? bug free?)
    - Solution verification
    - Model validation
    - Uncertainty Quantification (Uncertainty on inputs parameters? Uncertainty on physical mechanisms?)

We will use PCMM as a qualitative measure of credibility in our modeling and simulation effort

PCMM is a Framework for measuring and communicating progress in predictive capability

PCMM Practice		Level 0	Level 1	Level 2	Level 3
Representation and Geometric Fidelity (RGF)	Characterization			■	
	Computation Error		■		
	Verification		■		
Physics and Material Model Fidelity (PMMF)	Science basis for models			■	
	Model Accuracy			■	
	Extrapolation			■	
	Technical review		■		
Code Verification (CVER)	Software Quality Engineering practices			■	
	Software Quality Assessment		■		
	Test coverage		■		
	Computation Errors	■			
Solution Verification (SVER)	Numerical Solution Errors		■		
	Input/Output Verification		■		
	Technical Review		■		
Validation (VAL)	Validation hierarchy		■		
	Model Accuracy			■	
	Extrapolation		■		
	Technical review		■		
Uncertainty Quantification (UQ)	Uncertainty Characterization and Interpretation		■		
	Sensitivity Analysis			■	
	Numerical Propagation Errors	■			
	Aggregation of Evidence for Characterization of Uncertainties	■			
	Completeness		■		
	Strong Assumptions		■		
	Technical Review		■		
Documentation and Archiving	Documentation and Archiving			■	

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How much is enough? Graded approach from a computational simulation perspective

PCMM Practice		Maturity Level 0 Low Consequence, Minimal M&S Impact, e.g. Scoping Studies	Maturity Level 1 Moderate Consequence, Some M&S Impact, e.g. Design Support	Maturity Level 2 High-Consequence, High M&S Impact, e.g. Qualification Support
Representation and Geometric Fidelity (RGF) Are representation errors corrupting simulation conclusions?	Characterization (how close to as built are you representing the system)	• (unjustified) conceptual abstraction of the whole system	• Significant (unjustified) simplification or stylization of the system at the level of major elements	• Limited (unjustified) simplification or stylization of the system at the level of major and minor elements
	Computation Error (what impact does imperfect RGF have on computation results)	• Judgment only, numerical errors introduced because of imperfect RGF not addressed	• Sensitivity to imperfect RGF explored for some System Response Quant. (SRQs)	• Numerical errors estimated for imperfect RGF for relevant SRQs
	Verification (is what you represented really what was built)	• RGF not verified, RGF simply used without verification that it represents the actual system as built	• RGF verified only by the analysts	• RGF independently verified

Core Attribute **Best Practices** **Measured Against Standards Expressed in Terms of Increasing Rigor**

Level 0: Low consequence; minimal M&S impact (e.g. scoping studies)

Level 1: Moderate consequence; some M&S impact (e.g. design support or qualification test support)

Level 2: High consequence, high M&S impact (qualification support)

Level 3: High consequence; decision making based predominantly on M&S (dominant basis for qualification or certification)

PCMM measures and communicates the maturity of our simulation and model effort support the UQ methodology

PREDICTIVIE ATTRIBUTE	Maturity Level 1 Low-Consequence M&S-Informed, e.g., Scoping or Res Activities Score=0	Maturity Level 2 Low-Consequence M&S-Informed, e.g., Design Support Score=2	Maturity Level 3 High-Consequence M&S-Informed, e.g., Qualification Support, Score=4	Maturity Level 4 High-Consequence M&S-Based, e.g., Qualification Score=6
Representation or Geometry Fidelity Are you overlooking important effects because of defeaturing or stylization	• Grossly defeatured or stylized representation based on judgment or practical considerations	• Significant defeaturing or stylization based on judgment or practical considerations • or lower fidelity representation justified w a significantly defeatured or stylized representation	• Limited defeaturing or stylization judged to retain the essential elements of "as built" • or appropriate lower fidelity representation justified w a slightly defeatured or stylized representation	• Highest fidelity representation "as is" w/o sig defeaturing or stylization • or appropriate lower fidelity representation justified w highest fidelity representation
Physics and Material Model Fidelity How science-based are the models?	• Unknown model form represented with ad hoc knob non-uniquely calibrated to IET • Empirical model applied w significant extrapolation, non-uniquely calibrated with IET	• Empirical model applied w/o significant extrapolation, uniquely calibrated with SET • Physics informed model applied w significant or unknown extrapolation, unique calibrations with SET • Physics-informed model applied w/o significant extrapolation, non-unique calibrations with IET	• Physics informed models applied w/o significant extrapolation, unique calibrations with SET • Physics-based model applied w significant or unknown extrapolation	• Well accepted physics-based model applied w/o significant extrapolation
Code Verification Are software errors or algorithm deficiencies corrupting simulation results?	• Judgment only	• Code managed to SQE standards • Sustained unit/regression testing w significant coverage of required Features and Capabilities (F&Cs)	• Code managed and assessed (internally) against SQE standards • Sustained verification test suite w significant coverage of required F&Cs	• Code managed and assessed (externally) against SQE standards • Sustained verification test suite w significant coverage of required F&Cs and their interactions
Solution Verification Are numerical errors corrupting simulation results?	• Judgment only • Sensitivity to discretization and algorithm parameters explored in SRQs not directly related to the decision context	• Sensitivity to discretization and algorithm parameters explored in SRQs directly related to the decision context • Numerical errors estimated in SRQs not directly related to decision context	• Numerical errors estimated in SRQs directly related to the decision context • Rigorous numerical error bounds quantified in SRQs not directly related to the decision context	• Rigorous numerical error bounds quantified in SRQs directly related to the decision context
Validation How accurate are the models?	• Judgment only • Qualitative accuracy w/o significant SET coverage	• Qualitative accuracy w significant SET coverage • Quantitative accuracy w/o assessment of unc and w/o significant SET coverage	• Quantitative accuracy w/o assessment of unc • w significant SET coverage and IETs	• Quantitative accuracy w assessment of unc • w significant SET coverage, IETs, and full system test
UQ and Sensitivities What is the impact of variabilities and uncertainties on performance and margins?	• Judgment only • Deterministic assessment of margins (e.g., bounding analyses) • Informal "what if" assessments of unc, margins, and sensitivity	• Aleatory and epistemic uncertainties represented and propagated w/o distinction • Sensitivity to uncertainties explored	• Aleatory and/or epistemic uncertainties represented separately and propagated w significant strong assumptions • Quantitative sensitivity analysis w significant strong assumptions • Sensitivity to numerical errors explored	• Aleatory and/or epistemic uncertainties represented separately and propagated w/o significant strong assumptions • Quantitative sensitivity analysis w/o significant strong assumptions • Numerical errors quantified

PCMM measures and communicates the maturity of our simulation and model effort support the UQ methodology

PREDICTIVIE ATTRIBUTE	Maturity Level 1 Low-Consequence M&S-Informed, e.g., Scoping or Res Activities Score=0	Maturity Level 2 Low-Consequence M&S-Informed, e.g., Design Support Score=2	Maturity Level 3 High-Consequence M&S-Informed, e.g., Qualification Support, Score=4	Maturity Level 4 High-Consequence M&S-Based, e.g., Qualification Score=6
Representation or corrupting simulation results?	• Grossly defeatured or stylized	• Significant defeaturing or stylization not directly related to decision context	• Limited defeaturing or stylization related to the decision context	• Highest fidelity representation "as is"
Validation How accurate are the models?	• Judgment only • Qualitative accuracy w/o significant SET coverage	• Qualitative accuracy w significant SET coverage • Quantitative accuracy w/o assessment of unc and w/o significant SET coverage	• Quantitative accuracy w/o assessment of unc • w significant SET coverage and IETs	• Quantitative accuracy w assessment of unc • w significant SET coverage, IETs, and full system test
UQ and Sensitivities What is the impact of variabilities and uncertainties on performance and margins?	• Judgment only • Deterministic assessment of margins (e.g., bounding analyses) • Informal "what if" assessments of unc, margins, and sensitivity	• Aleatory and epistemic uncertainties represented and propagated w/o distinction • Sensitivity to uncertainties explored	• Aleatory and/or epistemic uncertainties represented separately and propagated w significant strong assumptions • Quantitative sensitivity analysis w significant strong assumptions • Sensitivity to numerical errors explored	• Aleatory and/or epistemic uncertainties represented separately and propagated w/o significant strong assumptions • Quantitative sensitivity analysis w/o significant strong assumptions • Numerical errors quantified

- **Key issues:**
  - Horizontal Axis – measures level of rigor in a mod/sim activity.
  - Vertical Axis – covers different aspects of mod/sim activity (geometric fidelity, physics fidelity, verification, validation, UQ, etc.).
  - PCMM provides a means to consistently document and communicate the status of a complex VV/UQ/QMU study to a non-ASC weapons customer.
  - Peer review is a critical component of PCMM (above level 0).

Work scope plan

1. Identify performance characteristics.
2. Understand performance threshold and requirements and frame it into a mathematical framework.
3. **Analysis of the composition of available data: experimental and numerical.**
   See Charles Bryan's presentation.
4. Perform preliminary decision making analysis.
5. Identify performance characteristics with insufficient data.

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3. Analysis of the composition of available data

- ***Identifying source of the data and models describing each degradation mechanism.***
  - *Composition of data will be collected from both experimental and numerical data available in the literature or being currently developed within UFDC.*
- ***For each degradation mechanism, identify applicable models and characterize them based on their maturity:***
  - *1. Models directly available and applicable to storage and transport.*
  - *2. Abstraction/simplified models or discrepancy in model characterization.*
  - *3. Models yet to be developed based on theoretical understanding.*
  - *4. No model available but correlation between input and output available.*
  - *5. No model available (missing physics) requiring expert solicitation.*
- ***Data source will be categorized into four levels based on appropriateness and confidence level:***
  - *1. Data directly applicable to transportation and storage (see discussion this afternoon).*
  - *2. Data from experiments and numerical models (upscaling/extrapolation of the data).*
  - *3. No data available (expert solicitation).*
  - *4. Categorical (no quantifiable data).*
- ***Identify and compile available data and quantify associated uncertainty.***

Quantification of the uncertainty…

- ***Applicable models:***
  - *1. Models directly available and applicable to storage and transport.*
  - *2. Abstraction/simplified models or discrepancy in model characterization.*
  - *3. Models yet to be developed based on theoretical understanding.*
  - *4. No model available but correlation between input and output available.*
  - *5. No model available (missing physics) requiring expert solicitation.*

Increasing uncertainty (decrease in knowledge)

- ***Data source:***
  - *1. Data directly applicable to transportation and storage.*
  - *2. Data from experiments and numerical models.*
  - *3. No data available (expert solicitation).*
  - *4. Categorical (no quantifiable data).*

Increasing uncertainty (decrease in knowledge)

- ***Inclusion of uncertainty:***
  - *In the form additional parameters represented with distribution functions based on the state of knowledge on a specific data (neither pessimistic nor optimistic).*
  - *Importance of uncertainty increases as knowledge decreases.*
  - The Predictive Capability Maturity Model (PCMM) will be used to ascertain credibility with this task and the overall UQ methodology.

Work scope plan

1. Identify performance characteristics.
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4. Perform preliminary decision making analysis

- ***Performing uncertainty characterization and propagation analysis throughout the system.***
  - *Uncertainty characterization using probabilistic approaches.*
  - *Uncertainty propagation will be based on Monte-Carlo techniques.*
  - *Sensitivity results using scatterplots, correlation analysis, regression analysis, partial correlation analysis, rank transformation, rank correlation coefficient test, etc…*

Work scope plan

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5. Identify performance characteristics with insufficient data

- ***Ranking degradation mechanisms and quantifying how much the data uncertainty affects the ranking.***
  - *Define of importance of each mechanism based on numerical results.*
  - *Inform on potential variations of importance and associated potential change in ranking of degradation mechanisms.*
  - *Define which of the data and/or model uncertainties are responsible for variability and how to reduce uncertainty.*
  - *Identify gaps that need further investigation.*

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Discussion on how to use existing experiments results and numerical models

All participants

Uncertainty Quantification Spring meeting
Las Vegas, NV
June 5, 2014

Workshop expectations

This workshop IS about defining the requirements and activities:

- Developing a consensus on the description of the work scope and technical details on the UQ methodology development.
- **Identifying analyses/measurements required to quantify metrics for this efforts.**
- **Identifying how existing experiments and models are anticipated to be used.**
- **Assigning work activities / allocate resources for individual involved.**
- Addressing communication challenges.

This workshop IS NOT about proposing solutions:

- *NOT selecting or ranking activities.*
- *NOT discussing the gap analysis report priorities.*
- *NOT discussing relevance of sensitivity analyses in other activities.*

Getting the most out of it…

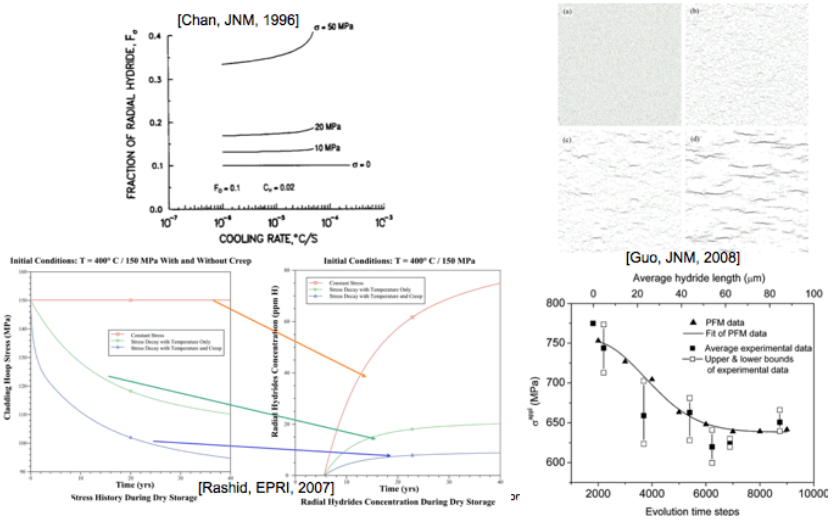
- **The discussions are the major focus of this workshop**
  - Provide an overview of your work area and potential application to the work scope discussed this morning.
  - State concisely what attributes makes this work relevant and why.
  - State the pros and the cons.
  - Summarize what is known and what is not known and path forward.

Examples of questions to keep in the back of your mind during the discussions…

- **What data already exist and relevance to the present work?**
  - Data collected within the UFD campaign.
  - Proprietary data.
  - What exactly is the data the test gives?
  - How do we interpolate the gap between data points?
  - Data/models to be used? Confidence in numerical models (and quantify it)?
- **What are the regulatory performance criteria for storage and transportation?**
  - Metrics extracted from 10CFR71, 10CFR72?
  - Definition of performance requirements: “We want to be X% confident that Y% of the fuel pin will not see quantity Q exceeding Z”?
  - Definition of performance requirements both at the assembly and fuel pin level? (NUREG-1567 accepts 1% rod breakage for normal conditions)
- **Where are the data gaps and why?**
  - High burnup data?
  - Additional data needed?
  - NRC and industry data needs?
- **What are and how do we decide which of the variables to consider?**
  - Sampling size? When do we stop collecting data?
  - How to represent the uncertainty for criteria for which no data exist?
  - Impact of uncertainty on risk?
  - Correlations?

H_2 effects: H embrittlement

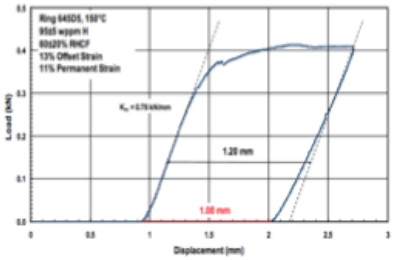
- **Influencing parameters**
  - Temperature.
  - H diffusion / H concentration.
  - Crystallography / microstructure morphology.
  - Defect density (irradiation, work hardening, etc..).
  - Stress level.
  - TSSP solvus, solution solvus. Solubility limit of the material (composition).
- ***Quantifiable measures***
  - *Volume fraction of radial hydride vs. time at different stress levels.*
  - *Volume fraction of radial hydride vs. cooling rate.*
  - *Hydride connectivity and length.*

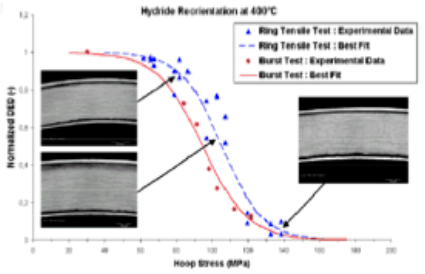


- ***Models/Experiments available***
  - *Terminal Solid Solubility (TSS): Differential scanning calorimetry experiments.*
  - *Microscopy quantification of precipitation morphology (Arborelius, Billone, Chung, Motta) for various configurations.*
  - *In-situ xRD.*
  - *Continuum, FEM, mesoscale models.*

H_2 effects: delayed hydride cracking

- **Influencing parameters**
  - Hydride length and connectivity.
  - Volume fraction of hydride / orientation.
  - Elasto-plastic properties of Zr and hydride phases.
  - Temperature.
  - Loading mode.
  - Crystallography / microstructure morphology.
  - Irradiation.



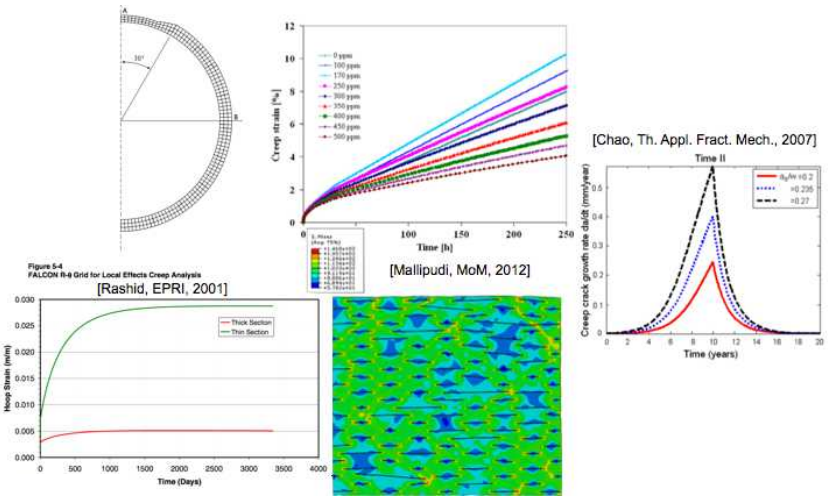


- ***Quantifiable measures***
  - *Constitutive behavior (stress vs strain).*
  - *Ductile-to-Brittle transition (DBT).*
  - *Fracture criteria.*

- ***Models/Experiments available***
  - *Tensile/Bend tests ring compression tests of hydrided specimen (Billone, Wang).*
  - *Ring tensile test, burst tests.*
  - *H.P. Robinson data with 72 GWD and 63 GWD burnup with a known neutron fluence.*
  - *Continuum, FEM models.*

Creep

- **Influencing parameters**
  - Stress level.
  - Burn-up/Fluence.
  - Temperature.
  - Elastic properties.
  - Crystallography / microstructure morphology.



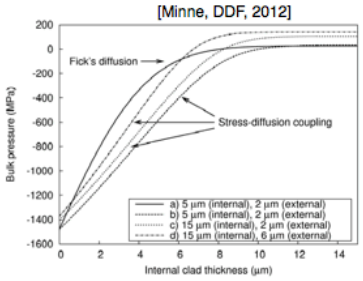
- ***Quantifiable measures***
  - *Creep behavior.*
  - *Fracture behavior.*
  - *Hydride connectivity and length.*

- ***Models/Experiments available***
  - *Creep tests.*
  - *Creep rupture tests.*
  - *Limited experiments.*
  - *Continuum, FEM models.*

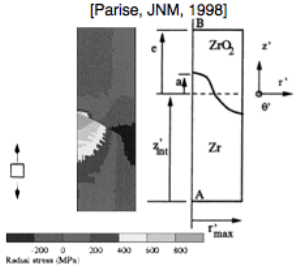
Oxidation

- **Influencing parameters**
  - Temperature.
  - H diffusion.
  - H concentration.
  - Stress level.
  - Oxide misfit strain.
  - Volume dilatation.

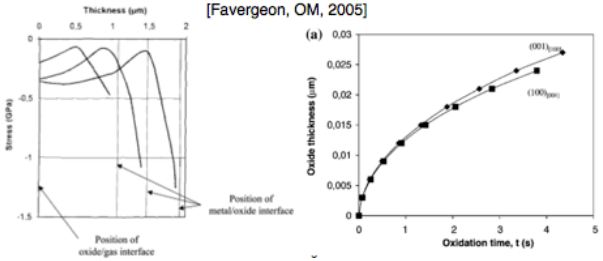
[Minne, DDF, 2012]



[Parise, JNM, 1998]



[Favergeon, OM, 2005]

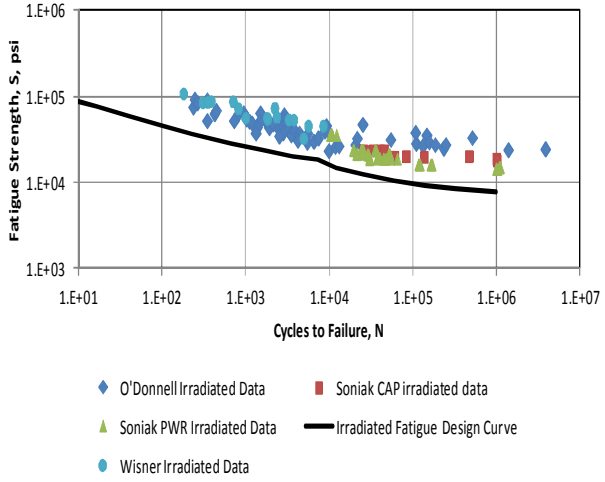


- ***Quantifiable measures***
  - *Rate of oxidation.*
  - *Thickness of oxide layer.*
  - *Mechanical properties of oxide layers.*

- ***Models/Experiments available***
  - *Delamination tests.*
  - *Oxidation experiments.*
  - *Ring compression tests and mechanical tests on oxidized cladding.*
  - *SEM, TEM measurements.*
  - *Continuum, FEM models.*

Thermo-mechanical fatigue

- **Influencing parameters**
  - Temperature.
  - Stress level /Loading mode.
  - Number of cycles.
  - Burn-up/Fluence.
  - Elastic properties.
  - H content.
  - Pellet-clad interaction.
  - Geometry.
  - Crystallography / microstructure morphology.
- ***Quantifiable measures***
  - *S-N curves.*
  - *Fracture toughness.*



[Geelhood, Beyer, 2013]

- ***Models/Experiments available***
  - *Fatigue pressure tests.*
  - *Continuum, FEM models.*

Annealing of radiation damage

- **Influencing parameters**
  - Temperature.
  - Stress level /Loading mode.
  - Burn-up/Fluence.
  - Composition.

- ***Quantifiable measures***
  - *Ductility.*
  - *Hardness.*

- ***Models/Experiments available***
  - *Hardness tests vs. annealing T (Ito, 2004).*
  - *Mechanical tests.*
  - *Continuum, FEM models.*

Thermal aging

- **Influencing parameters**
  - Temperature.
  - Stress level /Loading mode.
  - Composition.
  - Burn-up/Fluence.
  - Elastic properties.
  - H content.

- ***Quantifiable measures***
  - *Constitutive behavior (stress vs strain).*
  - *Ductile-to-Brittle transition (DBT).*
  - *Fracture criteria.*

- ***Models/Experiments available***
  - *Tensile/Bend tests ring compression tests of hydrided specimen (Billone, Wang).*
  - *Continuum, FEM models.*

List of action items

- Develop a plan on how we use proprietary data (after pilot study).
- Better define our problem.
- Define the regulatory end points that comprise our performance characteristics (component, system, and opinion based). Present these at a conference to get NRC buy-in.
- We need to define our decision maker.
- Add a section in the document that explains the methodology both numerically and textually to communicate to different learning types.
- Screening inputs.
- Use unified database? (c.f. J. Scaglione)