IRP - Fuel Aging in Storage and Transportation (FAST):

Characterization Methods to Evaluate the Aging of Used Nuclear Fuel in Storage

Sean M. McDeavitt & FAST Team

Nuclear Energy Advisory Committee
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FAST IRP Team

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Program Overview

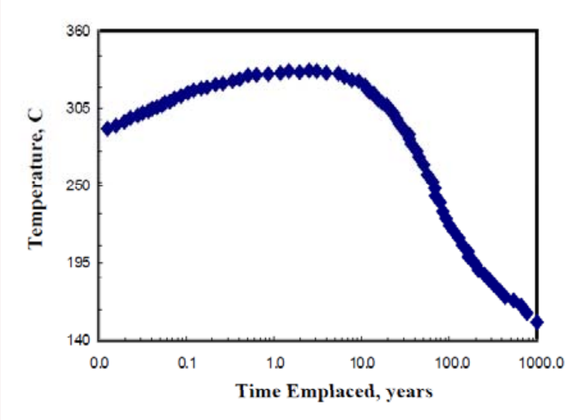
- Basic Objectives
  - Method Development
  - Phenomena Characterization
  - Predictive Modeling

- Four Technical Missions
  - TMA1: Low temperature Creep
  - TMA2: Hydrogen Behavior and Delayed Hydride Cracking (DHC)
  - TMA3: Cannister Corrosion
  - TMA4: Novel System Monitoring

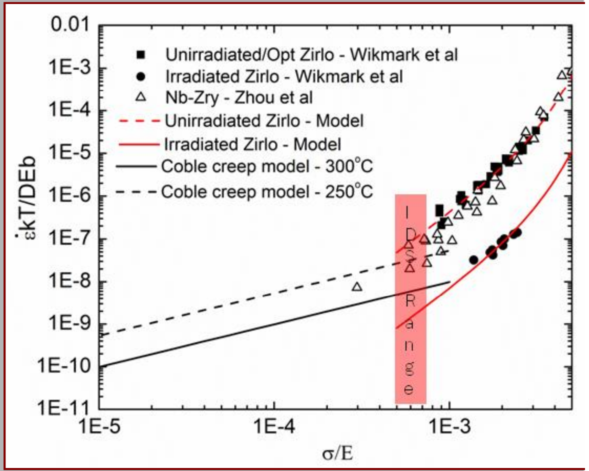
TMA1: Low Temperature Creep

- Context:
  - Irradiated cladding degraded during service.
    - Waterside corrosion, hydride formation, and interface interactions.
  - Dry storage raises fuel rod temperature and pressure.
  - Creep rupture is potential degradation mechanism.

- Objectives:
  - Characterize low temperature creep behavior for unirradiated, irradiated, oxidized, and hydrided Zircaloy (or Zr alloy) cladding under high burnup conditions (62,000 MWD/MTU).
  - Generate relevant models that may be inserted into FRAPCON fuel performance code to predict cladding behavior forhigh burnup fuel in long term storage.



Estimated fuel temperature variation during dry storage. (Hoop stress ~ 60 Mpa)[1]



Comparison of Zirlo and Zircaloy data from literature[2,3] showing mechanistic transition.

1. Murty, K.L. The internal pressurization creep of Zr alloys for spent-fuel dry storage feasibility. Jom-J Min Met Mat S **52**, 34-38 (2000).
2. Y. Zhou et al., Nuclear Engineering and Design 228 (2004) 3-13.
3. G. Wikmark et al., Water Reactor Fuel Performance meeting, Chengdu, China, Sep-2011.

FAST Team Members

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TMA1: Low Temperature Creep

- Assembled database of international creep data (UIUC and UF)
  - Fit to analytical models is good at higher temperatures and uncertain at low temperatures.
  - Data shows that irradiation strengthens Zr alloys (i.e., creep resistant)

- Creep testing is in various stages of operation.
  - Thermal burst and creep studies on highly oxidized and hydrided tubing to simulate in-reactor conditions (NCSU).
  - In-situ and ex-situ creep experiments using synchrotron methods in simulated corrosive atmospheres (UIUC).
  - Stress relaxation testing to generate creep data over a wide range of temperatures and strain rates (UF).
  - Preparations for extensive transmission electron microscopy are underway at UIUC and NCSU.

- Atomistic simulations to understand of the long term creep behavior with emphasis on effects of oxygen, hydrogen, and neutron irradiation (NCSU).
  - Microstructural interactions in radiation creep are being studied using dislocation dynamics and the code ParaDis (from LLNL).

- Translation of data as input to FRAPCON and other codes to predict UNF behavior in dry storage (UF and PNNL).

- Significant international exchanges with Korea (KAERI and Hanyang University) and Spain (Ciemat).

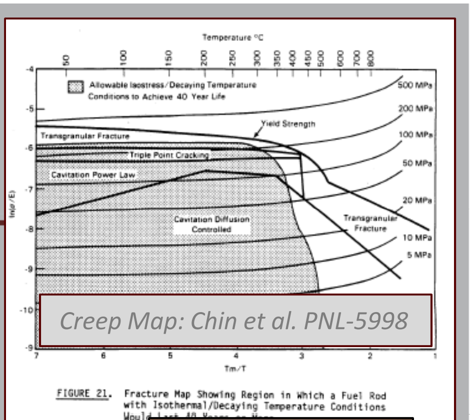
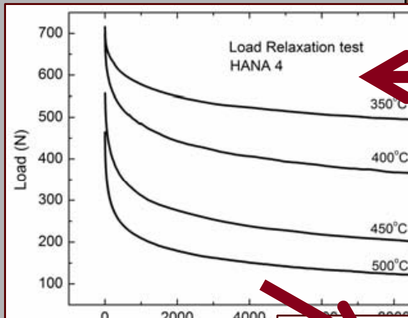
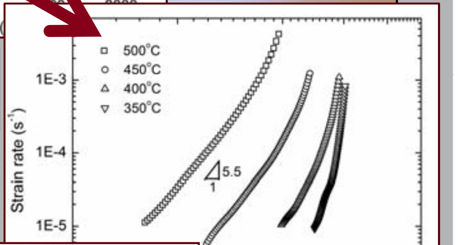


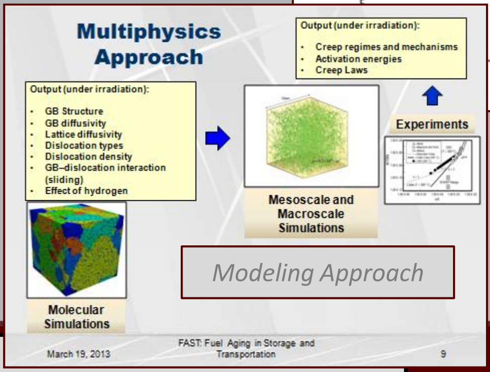
FIGURE 21. Fracture Map Showing Region in Which a Fuel Rod with Isothermal/Decaying Temperature Conditions

Creep Map: Chin et al. PNL-5998





Ring Compression Tests (HANA 4 Alloy)



Multiphysics Approach

Output (under irradiation):

- GB Structure
- GB diffusivity
- Lattice diffusivity
- Dislocation types
- Dislocation density
- GB–dislocation interaction (sliding)
- Effect of hydrogen

Output (under irradiation):

- Creep regimes and mechanisms
- Activation energies
- Creep Laws

Modeling Approach

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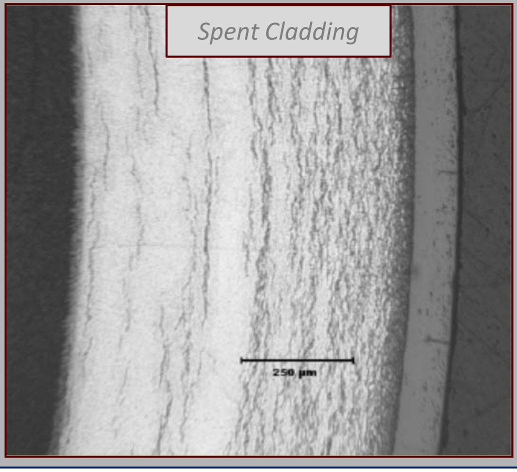
TMA2: Hydrogen Behavior and DHC

- Context:
  - Cladding strength is severely degraded after normal operation.
  - After storage, vacuum drying (up to ~400°C) and transfer to dry storage, the fuel sits under load at low-moderate temperatures.
  - Stress-directed redistribution of hydrogen creates a potential failure mechanism: Delayed Hydride Cracking (DHC).
- Objectives:
  - Consider/compare various methods of hydrogen insertion into Zircaloy.
  - Perform mechanistic evaluations using advanced materials characterization methods.
  - Use advanced materials science modeling methods to interpret data.
  - Create predictive model for DHC that may be used in FRAPCON or similar code.



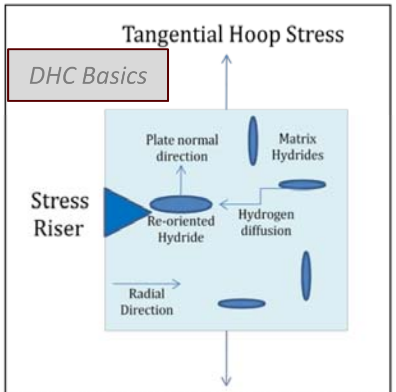


Figure 1. Schematic diagram showing hydride re-orientation mechanism during an applied tangential hoop stress. Dissolution of matrix hydride particles is induced by the formation of re-oriented hydride particles at stress risers such as crack tips. Hydrogen diffusion results in mass transfer from matrix particles to the re-oriented particles. Crack propagation then occurs through the brittle hydride particles at the crack tips.

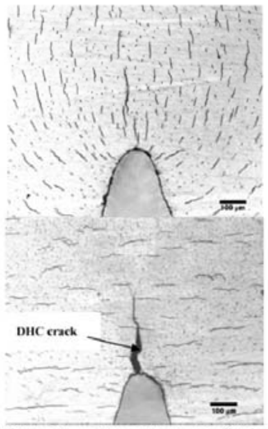


Figure 2. Post-treatment metallurgical analysis of hydride re-orientation at a stress riser (top) and subsequent crack propagation after thermal cycling and load removal (bottom). From Reference 9.

Kim *et al.*, J. Alloys Compounds, 429 (2007) 221.

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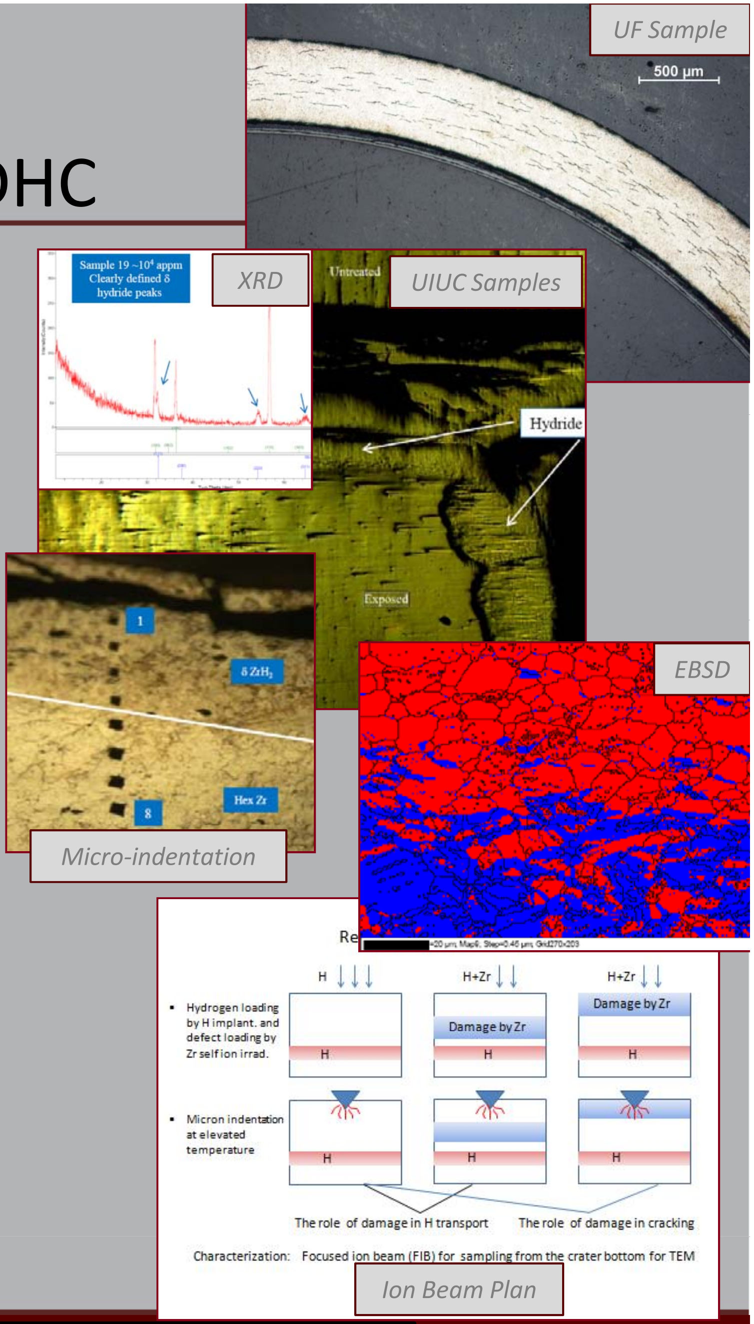
TMA2: Hydrogen Behavior and DHC

- Multiple hydride methods in operation across the FAST universities.
  - Electrochemical methods (TAMU and NCSU).
  - High vacuum vapor phase insertion (UIUC).
  - Aqueous autoclave and flowing gas method (UF).
- Characterization methods underway:
  - X-ray diffraction.
  - Electron Backscattered Diffraction (EBSD).
  - Nano-indentation.
  - Small angle X-ray scattering (SAXS) at the Advanced Photon Source (APS) to quantify reorientation.



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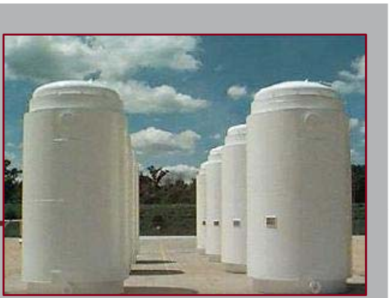
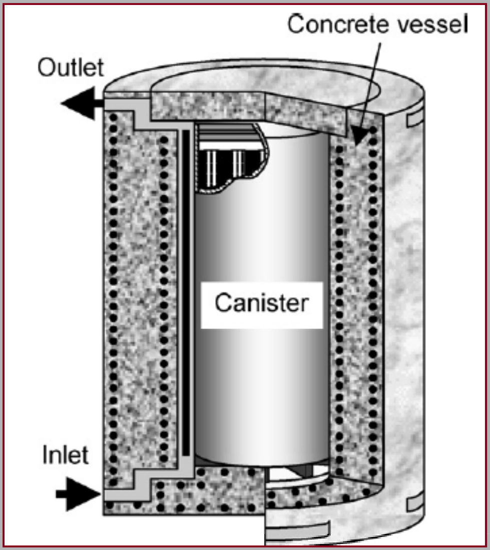
TMA3: Canister Corrosion



- Context
  - The stainless steel canisters will be exposed to environmental conditions for a very long time and containment is critical.
  - Corrosion and stress corrosion cracking (SCC) particularly at welds is a concern.
  - Pitting of the surface must be understood since probabilistically a fraction of pits can become crack initiators for SCC.
  - Stainless steel canister temperature, and humidity of air, and salt concentration at the canister surface must be determined
  - In certain parameter space of temperature, and humidity, and salt concentration (in the presence of tensile residual stress as at welds, due to salt deliquescence) SCC will initiate
- Ongoing collaborations with DOE Disposition Program (PNNL and Sandia), MIT NEUP project, and EPRI-ESCP program.



FAST Team Members

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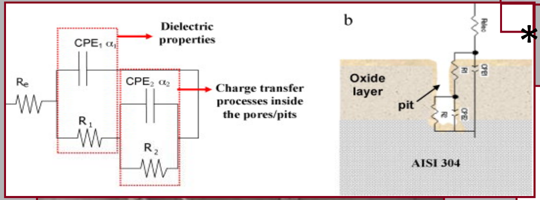
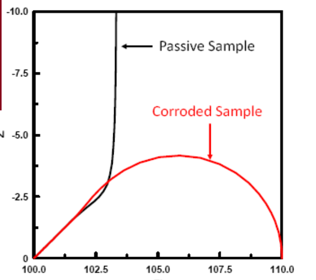
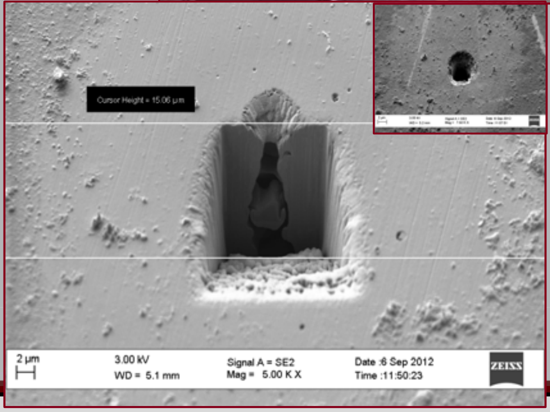
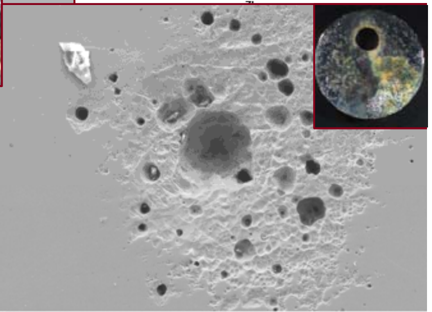
TMA3: Canister Corrosion

- Methods Underway:
    - Electrochemical corrosion testing
        - Potentiodynamic and potentiostatic
        - Pitting Susceptibility
    - Salt spray corrosion testing
        - Basic exposures
        - Stressed C-ring samples
    - Direct salt corrosion (controlled sludge) exposures
    - Electrochemical Impedance Spectroscopy (EIS)
    - Fatigue-driven and static load crack-growth testing









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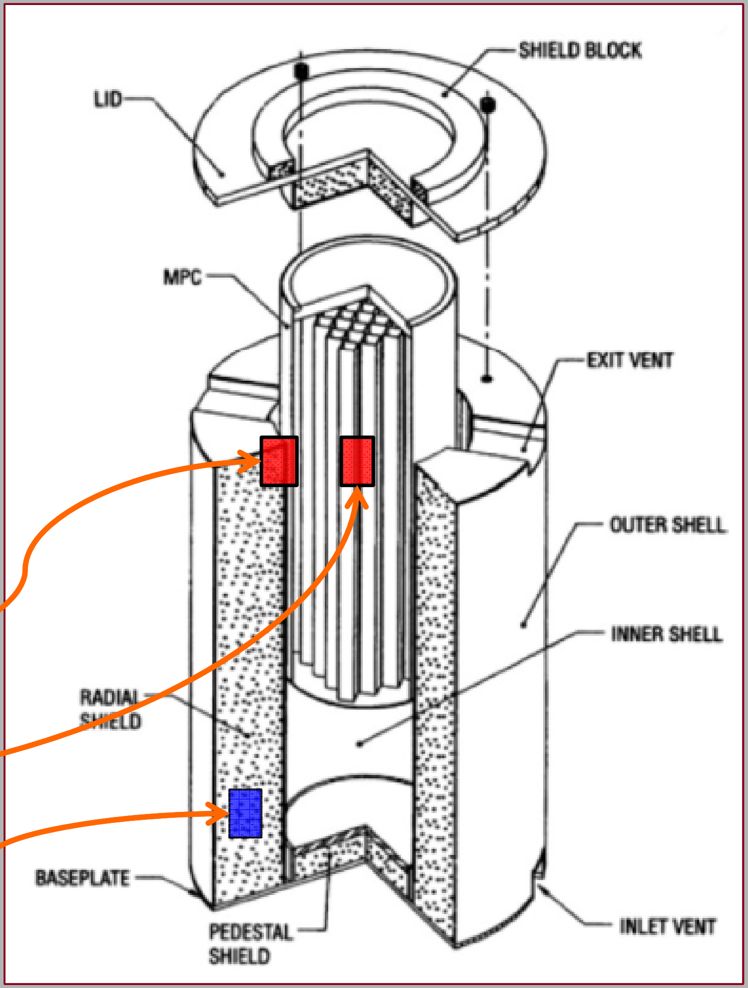
TMA4: Novel System Monitoring

Objective to develop a monitoring system for SNF dry storage to ensure:

- Retrievability
- Sub-criticality
- Fuel Confinement

a monitoring system is needed

Effective monitoring will detect degradation of all SNF dry storage components, for the entire lifetime of the system



Canister Exterior

Canister Internals

Concrete Overpack

FAST Team Members

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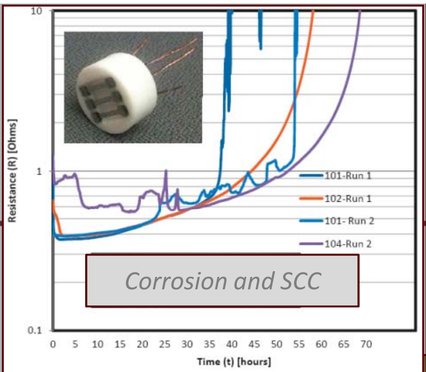
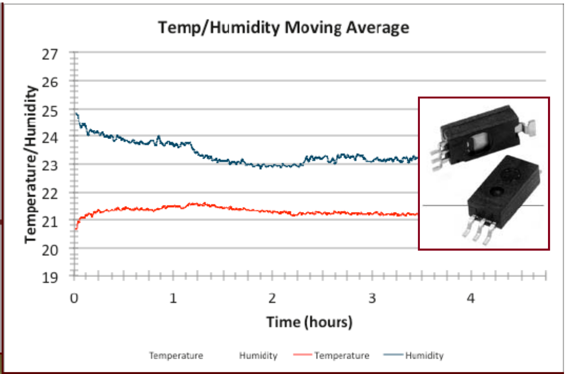
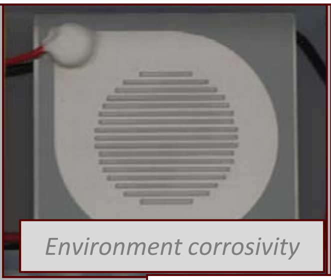
TMA4: Novel System Monitoring

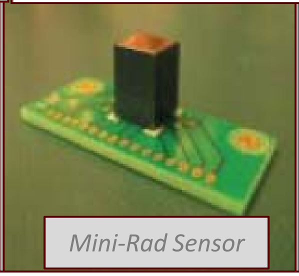
- Developing:
  - Sensor selection and miniaturization.
  - External and internal packages.
  - Communication and power methods.



Corrosion and SCC

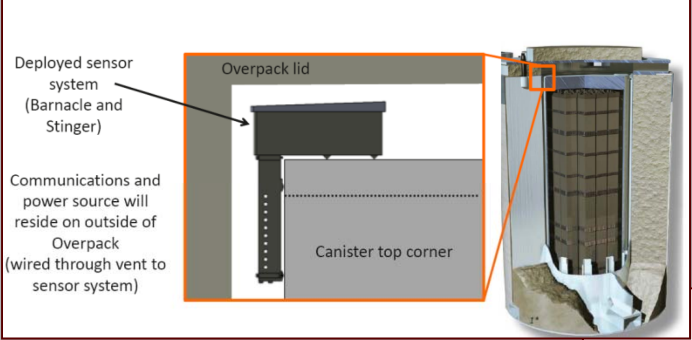

Temp/Humidity Moving Average


Environment corrosivity


Mini-Rad Sensor

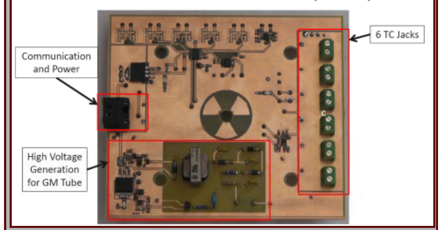

Wetness

System Packaging Design


Deployed sensor system (Barnacle and Stinger)

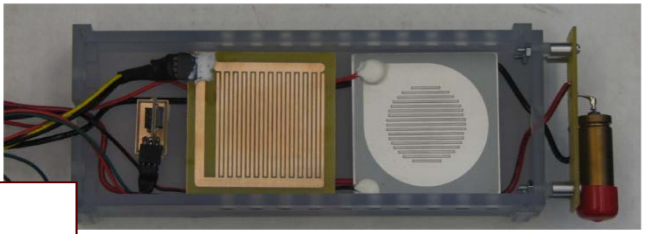
Communications and power source will reside on outside of Overpack (wired through vent to sensor system)

Barnacle Sensor Board (front)



Sensor Stinger

(Side facing away from canister surface)
Behind radiation shielding, except rad sensor

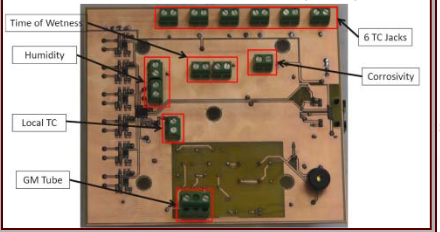

Humidity

Time of Wetness

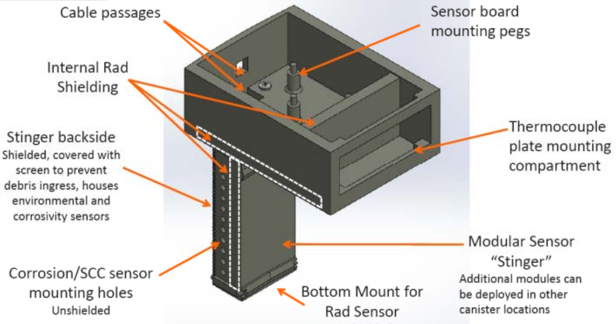
Corrosivity

Radiation

Barnacle Sensor Board (back)



Barnacle Packaging Design


Cable passages

Sensor board mounting pegs

Internal Rad Shielding

Stinger backside
Shielded, covered with screen to prevent debris ingress, houses environmental and corrosivity sensors

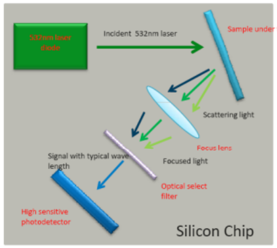
Thermocouple plate mounting compartment

Modular Sensor "Stinger"
Additional modules can be deployed in other canister locations

Corrosion/SCC sensor mounting holes
Unshielded

Bottom Mount for Rad Sensor
Unshielded

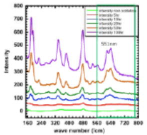
On-Chip Raman Scattering Optical System Design

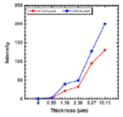


In this portable Raman spectrometer, there are four major components:

1. 532nm laser diode (~10mW) to provide incident light signal.
2. Focus lens to collect the scattered light signal from surface of sample under test.
3. Optical select filter to block other wavelength signal, but allow 551nm scattering signal to go through.
4. High sensitive photodetector to detect the intensity of 551nm scattering signal.

Estimated dimension: ~1cm×1cm.
All these components can be fabricated from semiconductor materials by Microfabrication technology and process of Micro-optical MEMs.





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FAST-IRP Project Well Underway

- The UNF dry storage system is complex and the mission is bigger than our team.
  - The project comprises a matrix of applied research with strong elements of basic science.
  - We will strongly collaborate with ongoing programs.
- Our emphasis is on method development, phenomena characterization, and predictive modeling.
  - Four technical mission areas have been defined
    - Low temperature creep
    - Delayed hydride cracking
    - Canister corrosion
    - Novel system monitoring