Advanced surface plasma nitriding for development of corrosion resistant and accident tolerant fuel cladding

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Program: Nuclear Energy Enabling Technologies
This project aims to develop a new plasma nitriding technique which is able to uniformly nitride fuel cladding tube surfaces, including both the outer and inner tube surfaces. The key is to use a cathodic cage to stabilize plasma distribution, providing a uniform layer, minimizing edge effects, increasing temperature uniformity, and reducing arcing. Furthermore, the proposed technique is suitable for scaling up to industrial fabrication.
Unique material issues in nuclear engineering

- Corrosion Cracking
- Swelling
- Reconstructing
- Blistering
- Fracture
- Hydride cracking
- Creep
- Segregation
- Hardening
Issues of current techniques

Traditional plasma nitridation techniques
• plasma spatial non-uniformities due to the combined effects of particle diffusion, standing wave formation, and edge effects

Vapor deposition or laser ablation
• de-bonding of deposited layers
Active Screen v.s. DC Plasma Nitridation

DCPN

ASPN

Already installed in PI’s lab
## Overview of Collaboration

<table>
<thead>
<tr>
<th>Organization</th>
<th>Investigator</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Texas A&amp;M University (Lead Institution)</strong></td>
<td>Lin Shao</td>
<td>Lead investigator, plasma nitridation and ion irradiation</td>
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<tr>
<td></td>
<td>Frank Garner</td>
<td>Microstructural characterization</td>
</tr>
<tr>
<td><strong>Oklahoma State Univ.</strong></td>
<td>Don Lucca</td>
<td>Mechanical property characterization</td>
</tr>
<tr>
<td><strong>MIT</strong></td>
<td>Michael Short</td>
<td>Corrosion testing in water loop and sodium loop</td>
</tr>
</tbody>
</table>
Deliverables and Outcomes

Year 1
• Optimization of plasma nitriding process and identifying governing factors determining microstructure changes in Grade 92, Alloy 709, HT-9, T-91, and Zircaloy 2/4
• Effects of nitriding on mechanical property changes

Year 2
• Integrity and radiation tolerance of nitrided cladding after high dpa irradiation
• Effects of high dpa irradiation on mechanical property changes
• Compatibility of nitrided samples with water and liquid sodium coolants

Year 3
• Interface phase formation and diffusion kinetics in DU-cladding diffusion couples with or without the surface nitriding process
• Understanding effects of nitriding on fuel-cladding interactions
Nitriding Process
The three most important variables in the nitriding process are pressure, voltage and time. Systematic studies on the parameter dependence of resulting structural changes will define and optimize the conditions to achieve a transition from dispersed nitride particle formation to continuous nitride thin films.

Ion irradiation
Using He and Fe ion irradiation at elevated temperatures
1) to introduce high dpa damage to test mechanical property changes;
2) to study radiation tolerance of the nitride layer and nitride particles, i.e., their amorphization threshold dpa values; and
3) to study radiation effects at the nitride/matrix interface.

Microstructural, Mechanical and Thermal Properties Characterization
The principal techniques to be used will be cross-sectional transmission electron microscopy (XTEM), 3-D atomic probe tomography (APT), X-ray diffraction (XRD), and nanoindentation.

Corrosion Testing
For the LWR application, Zircaloy 2 and 4 will be tested in an existing water coolant loop, capable of up to PWR conditions, in both hydrogen water chemistry (PWR) and normal water chemistry (BWR), in the temperature regions of 288°C to 340°C. For fast reactor applications, Grade 92, Alloy 709, HT-9, and T-91 will be tested in liquid sodium from 400°C to 700°C.
F/A-18CD

400 kV  140 kV  10 kV

1.7 MV  3 MV  1 MV

TAMU Irradiation Facility (PI’s lab)
Preliminary studies on low activation EK-181 alloys

Plasma Nitried

Annealed
400°C/1h + 600°C/1h

Nitride layer is very stable

Highly ordered cellular layers
Unlike plasma nitridiation, ion implantation could not provide required local energy deposit to form stable nitride layers.
Thank You!

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