SWEPT FREQUENCY EDDY CURRENT TECHNIQUE FOR POOL-SIDE INSPECTION OF ZR-ALLOY FUEL ASSEMBLY MEMBERS

G. ANTONELLI
CESI S.p.A. - Italy

J. RENSHAW, R. DAUM
EPRI - USA

B. ANDERSSON
Westinghouse Electric Sweden AB - Sweden

D. LUTZ
Global Nuclear Fuel - Americas - USA
A simple idea, developed together with EPRI - Electric Power Research Institute:

- Estimating nondestructively the hydrogen content of Zr-alloys members of nuclear fuel assembly components
- By exploiting the presumed electrical conductivity reduction of the alloy induced by the precipitation of hydrides.
- We started from a nondestructive testing solution originally developed by CESI in the mid ‘90s to characterize the high-temperature coatings used in gas turbines.
**F-SECT: a Unique Solution to Characterize Property Gradients Close to the Surface of Metallic Materials**

- **Mid 90's:** CESI S.p.A. developed the F-SECT system to measure: - thickness and - Al content of high-temperature coatings applied on GT blades.

- **Year 2011:** CESI and EPRI started working together to develop a nuclear application of the F-SECT system aiming at estimating: - hydrogen content, - residual wall thickness and - oxide thickness of Zr-alloys.

**Similarities between the two problems:**
- detecting small electrical conductivity variations, as induced by Al depletion or precipitation of Zr hydrides;
- dealing with layered metallic structures;
- compensating for disturbing effects caused by magnetic iron oxides on GT blades or crud on fuel cladding.
A Unique Solution to Change a Weakness into a Strength.

The large number of potentially significant variables is both a strength and a weakness of the eddy-current technique.

All these variables have to be taken into account to obtain reliable results.
F-SECT: Frequency Scanning Eddy Current Technique

Combining state-of-the-art techniques:

- Multi-frequency approach to deal with Multi-layer structures
- Model-based analysis to deal with multi-variable problem

...and built around a new idea of NORMALIZED IMPEDANCE to greatly simplify the equations behind the model.
Multi-Frequency Approach to Measure Normalized Impedance vs. frequency curves

Frequency sweep:
- 24 frequencies between 0.4-8 MHz
- 2-second measurement time
- Probe must remain still in position

Test frequency: 0.4 MHz
Multi-Frequency Approach to Measure Normalized Impedance vs. frequency curves

Test frequency: 8.0 MHz

Frequency sweep:
- 24 frequencies between 0.4-8 MHz
- 2-second measurement time
- Probe must remain still in position
From Complex (\(Z\)) to Normalized Impedance (\(NI\))

\[ \sigma_A \quad \text{Homogeneous samples} \quad \sigma_C \quad \text{2-Layer sample} \quad (\text{green curve}) \]

\[ Im(Z) \quad \text{Increasing frequency} \quad Re(Z) \]

\[ NI \quad \text{Depends on:} \]
- Probe
- Cable
- Frequency response of equipment
- Material’s properties

Advantages:
- Simpler model
- More stable inversion
- More reliable results

\[ \text{Normalized Impedance (\(NI\))} \]

\[ \text{Frequency (Hz)} \]

1.1
Model-Based Analysis of Measured Normalized Impedance vs. Frequency Curves

**Input:** Measured normalized impedance vs. frequency curve

**Model-based analysis**

**Quantitative Output:**
- Best Estimates of Model Parameters:
  - $L_j$ thickness values
  - $\sigma_j$ electrical conductivity values

**Diagnostic quantities, e.g.:**
- Residual cladding thickness ($L_2$)
- Average electrical conductivity ($\sigma_{av}$) correlated with the hydrogen content through alloy-specific reference curves
Different Models for Different Sample Conditions

2-layer model (2 unknowns): uniformly hydrided cladding

3-layer model (4 unknowns): hydride rim

4-layer model (7 unknowns): hydride rim + crud
F-SECT Validation on Irradiated Channel Box and Cladding Samples - Performed at hot cells together with the fuel manufacturers
Estimated Conductivity vs. Hydrogen Levels
Studsvik, 2012

Channel box samples: almost the same sensitivity (slope) for different Zr-alloys from the same fuel manufacturer.
Estimated Conductivity and Hydrogen Content along Water Rods
Studsvik, 2013

- ▲ H-content – reference destructive measurements
- ◊ Electrical conductivity – F-SECT estimates
Effect of Hydrogen and Fluence on the Electrical Conductivity $\sigma$ of Different Zr-Alloys

Studsvik, 2013

Fluence-compensated $\sigma$ vs. H content

H-content-compensated $\sigma$ vs. fluence
Hot Cell Measurements on Cladding with Intentional Secondary Degradation
Kjeller, 2014

Conductivity maps:
- Inner layer
- Outer layer
Poolside Inspections

Self-nulling sensor to compensate to some extent for water temperature variations at different depths in the pool.

Halogen-free, waterproof probes, with up to 20m-long connecting cable.

1-2: Probe delivery system
3: Under water calibration
4: Measurement on channel box
Oxide Thickness and Zr-alloy Residual Thickness of crudded fuel rods. Poolside inspection at KKL NPP, Sept. 2014

**Compensated lift-off:** oxide + crud thickness

**Zr-alloy residual thickness:**
- sinusoidal-like pattern due to manufacturing
- wall thickness reduction due to oxidation
Future work

Several additional technology improvements are currently being investigated:

• to better assess the influence of fast neutron fluence on hydrogen content estimates,

• to better compensate for the effect of ferromagnetic crud layers,

• to provide robust and sound procedures to carry out the inspection on duplex and other types of cladding,

• to improve some manufacturing details of the probe to further increase its service life in the quite high radiation field near the test components.
Gas Turbine applications

Nuclear applications

References
Thank you for your attention