CHARACTARIZING THE SENSING PERFORMANCE OF ADDITIVELY MANUFACTURED IN-PILE STRAIN GAUGES IN HIGH HUMIDITY ENVIRONMENTS

Sarah E. Cole[1,2], Kaelee A. Novich[1,2], Timothy L. Phero[1,2], Richard Skifton[3], David Estrada[1,2], Brian J. Jaques[1,2]

1. Micron School Of Materials Science and Engineering, Boise State University
2. Center for Advanced Energy Studies
3. Idaho National Laboratory

BOISE STATE UNIVERSITY
COLLEGE OF ENGINEERING
Micron School of Materials Science and Engineering

I. INTRODUCTION

Background

Since the 2011 Fukushima Daiichi nuclear disaster, there has been a greater need for real-time monitoring of irradiation conditions to advance the safety and reliability of nuclear reactors. The nuclear industry has previously relied on time-consuming and costly methods, such as post-irradiation experimentation, to observe fuel rod deformation [1]. Current welded strain gauges, as shown in **Figure 1,** are unfit for extreme environments [2]. However, the rise of additive manufacturing (AM) could replace traditional methods for fabricating strain sensors.

AM sensors enable:

1. *In-situ* sensing of cladding deformation
2. Real-time data collection
3. Direct printing onto substrates **(Figure 2)**

Figure 1: A strain gauge welded onto a nuclear fuel rod [2]

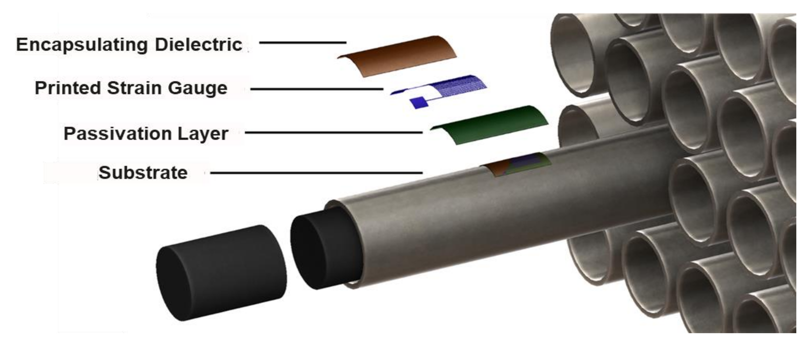

Figure 2: Model of an AM strain sensor printed directly on a fuel rod substrate

Motivation

In order to employ strain sensors in a reactor, their sensitivity to external factors aside from mechanical strain must be understood. One factor is relative humidity (RH). In certain nuclear reactors (i.e. boiling water reactors) high levels of steam may influence sensor response.

Solution

1. Characterize the mechanical sensing performance of capacitive strain gauges (CSG) made from silver ink printed on aluminum alloy 6061 with an aerosol jet printer
2. Quantify the influence of relative humidity on sensor accuracy using an environmental chamber

II. EXPERIMENTAL

Strain gauges were tested in an environmental chamber **(Figure 3)** programed to specified climatic conditions to replicate reactor-levels of relative humidity

Test Parameters:

1. High RH: 90%
2. Low RH: 20%
3. Temperature: 40°C

Stationary Testing:
CSG's and resistive strain gauges (RSG) were tested inside the environmental chamber without any induced mechanical strain

Deflection Testing:
CSG's were placed upon a cantilever beam and deflected with a micrometer to create strain in sample

1. Low deflection: 2.5 mm
2. High deflection: 19.1 mm (to meet 1100 με ASTM standard for tensile testing [3])

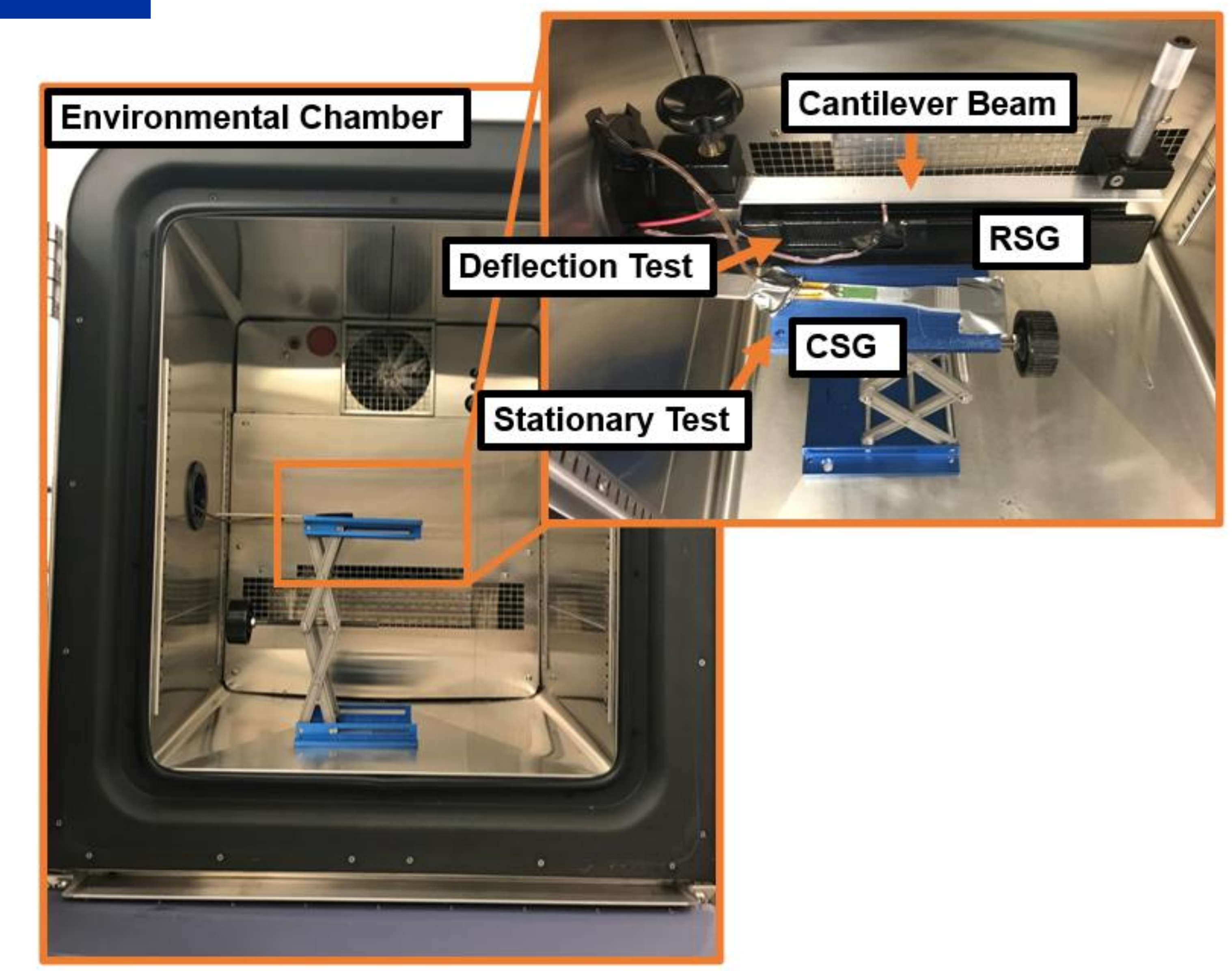

Figure 3: Environmental chamber setup with CSG deflection test and RSG stationary test

III. RESULTS

Initial Testing

- Preliminary 24-hour stationary CSG tests were performed to better understand CSG performance under a humidified environment **(Figure 4)**
- Capacitance continued to increase until hour 5 of the high RH experiment and then stabilized
- Each experiment was performed with the same test specimen over the duration of four days
- Based on these results, stationary and deflection testing were performed for 5 hours

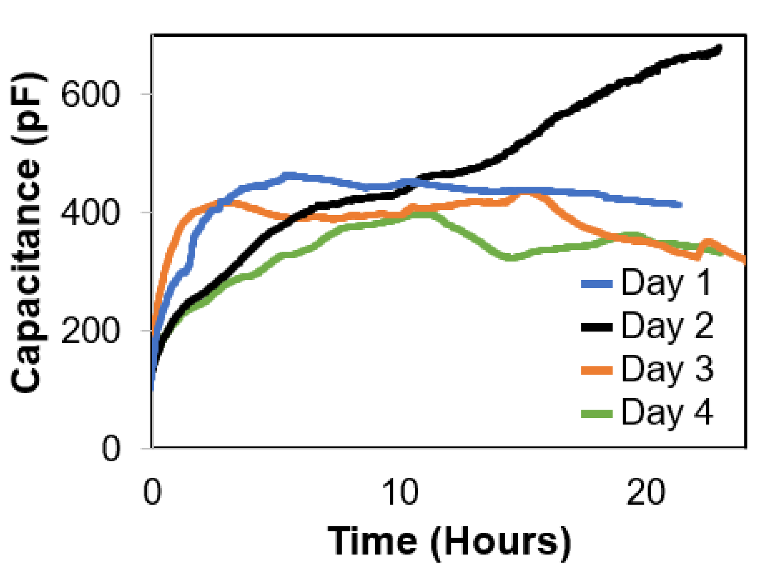

Figure 4: 24-hour stationary CSG test runs at 90% RH repeated on one sample for four days

Deflection Testing

Theoretical

- To validate deflection testing, beam deflection theory **(Equation 1)** and finite element analysis (FEA) **(Figure 6)** were used to correlate deflection and strain utilizing relative beam measurements **(Figure 5A)**
- COMSOL was used for FEA of beam deflection **(Figure 5B)**

$$\varepsilon = \frac{3\delta L_1 t}{2L_2^3} \quad \text{(Eq. 1)}$$

Nomenclature:
ε = Strain
δ = Deflection (m)

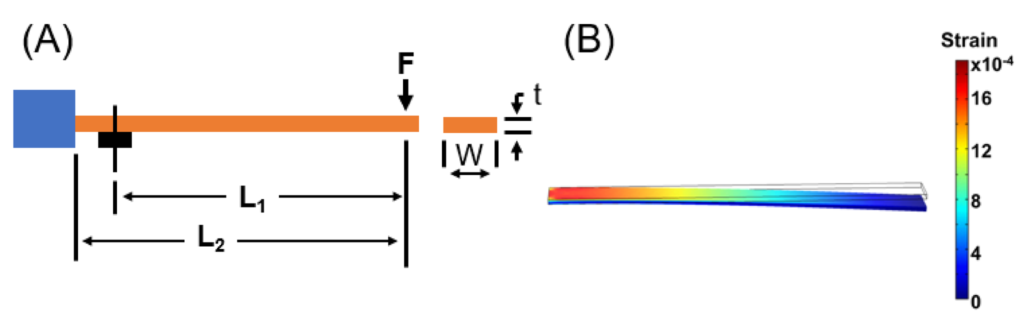

Figure 5: A) Schematic of cantilever beam and **B)** finite element analysis of beam deflection with strain contour

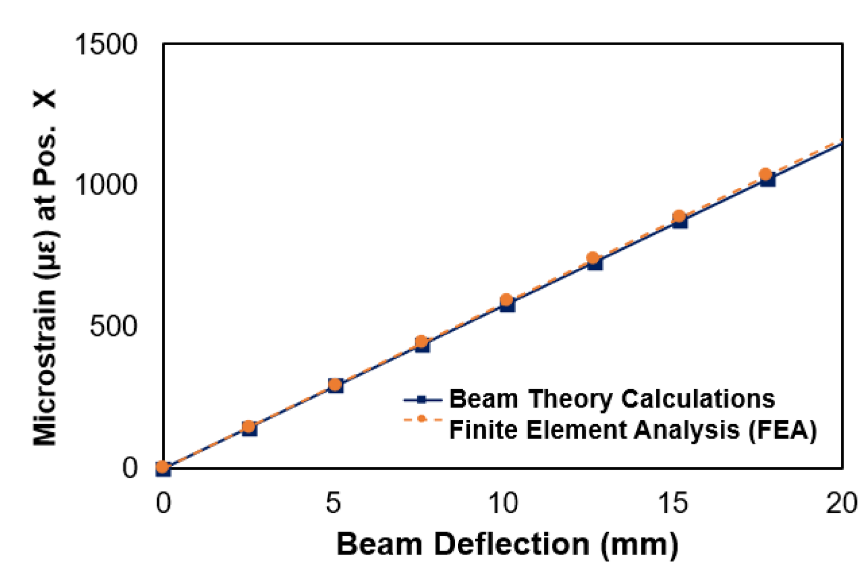

Figure 6: Correlation between beam deflection and microstrain

Experimental

- High deflection tests demonstrated higher capacitance than low deflection **(Figure 7)**
- A significant disparity in capacitance levels between the 90% and 20% RH runs was observed at 19.1 mm deflection

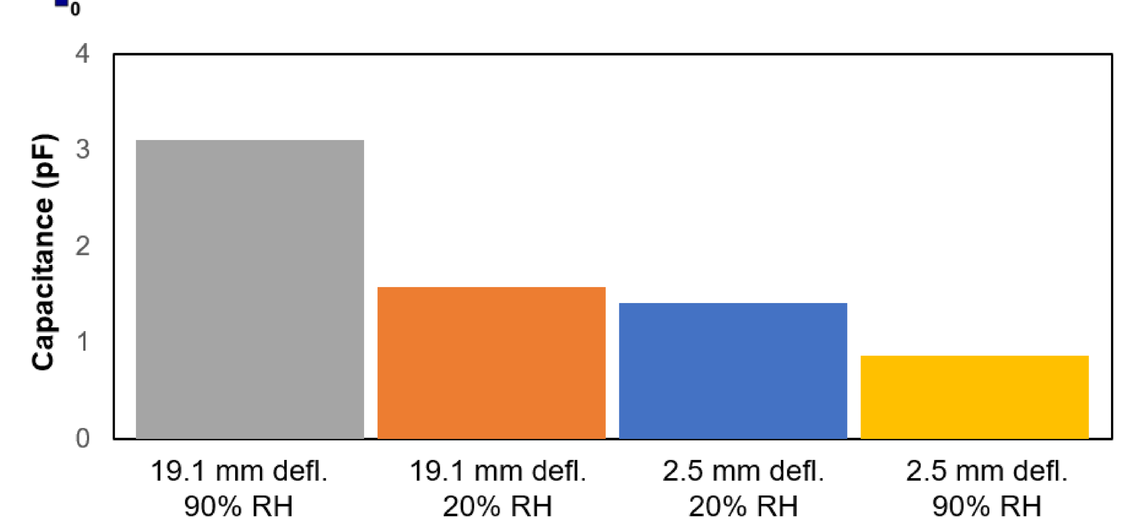

Figure 7: CSG deflection testing

Stationary Testing

CSG

- Strain sensors were not greatly affected by 20% RH whereas 90% RH influenced capacitance **(Figure 8)**
- Low RH displayed comparatively stable capacitance than high RH

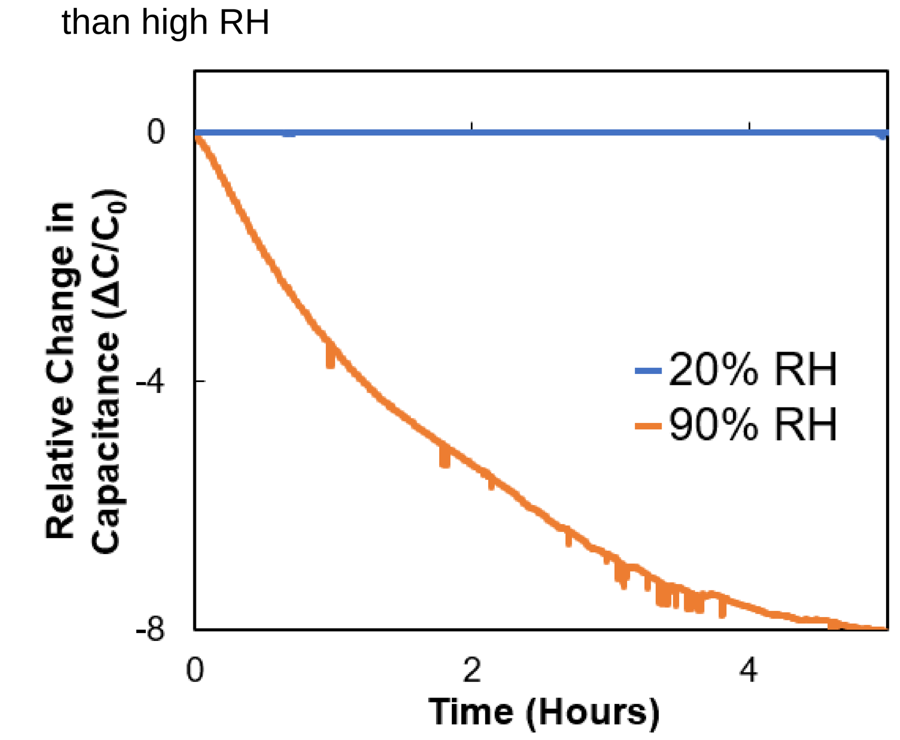

Figure 8: 5-hour stationary CSG test runs

RSG

- Similar to CSG results, RSG's were influenced by high RH but performed accurately at low moisture levels **(Figure 9)**
- A similar stability effect at 20% RH previously noted in CSG's was also observed in RSG's

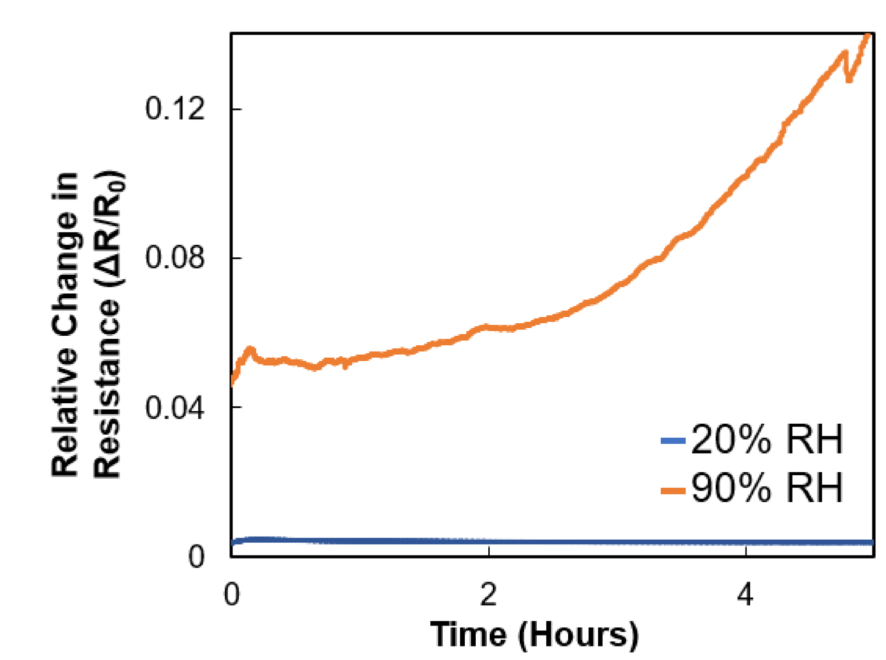

Figure 9: 5-hour stationary RSG test runs

IV. DISCUSSION

- Higher levels of mechanical strain (i.e. 19.1 mm deflection) increased capacitance readings
- CSG's and RSG's were not greatly affected by low levels of RH (i.e. 20%) but were influenced substantially by higher saturation degrees
- At greater RH, electrical signals displayed greater variation than comparatively stable readings at 20% RH
- If strain gauges were tested in a nuclear reactor, further research could submerge sensors in water to observe influence of 100% RH

REFERENCES

[1] Skifton, Richard et al. In-pile fuel rod deformation measurements using miniaturized LVDT technology. No. INL/EXT-17-43379-Rev000. Idaho National Lab.(INL), Idaho Falls, ID (United States), 2017.

[2] Pettigrew, Michel J. "The behaviour of weldable strain gauges under nuclear reactor core conditions." Nuclear Engineering and Design 263 (2013): 350-361.

[3] "ASTM E251 - 20a Standard Test Methods for Performance Characteristics of Metallic Bonded Resistance Strain Gages." n.d. Accessed July 9, 2021. https://www.astm.org/Standards/E251.htm.

ACKNOWLEDGEMENTS

This work was supported in part through the Department of Energy Advanced Sensors and Instrumentation program under DOE Idaho Operations Office Contract DE-AC07-05ID14517. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

AML Advanced Materials Laboratory
INL Idaho National Laboratory
NEET
CAES Center for Advanced Energy Studies
U.S. DEPARTMENT OF ENERGY