CAPACITANCE-BASED DIMENSIONAL CHANGE SENSORS FOR IN-PILE MATERIALS MEASUREMENTS

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ABSTRACT

Advanced fuel compositions, such as accident tolerate fuels (ATF), are an active area of developing in the nuclear power industry. The long-term performance of these newly developed fuels is estimated through physics-based simulation models of irradiation-, temperature-, pressure-, etc.-induced material degradation. As these fuels are deployed in test reactors, measurement and characterization of the fuel pin evolution is used to validate prediction models. In-pile material evolution parameters, such as fuel rod pressurization, fuel stack and cladding elongation, and cladding diameter, are commonly measured using a linear voltage differential transformer (LVDT). However, LVDTs are bulky and limited to lower (350-500C) temperature operation. The high power density and small size of most experimental positions in high performance research reactors used for accelerated materials irradiation studies generally precludes the use of LVDTs in these reactors. There is a critical need for sensors that provide real-time data regarding material evolution under highly accelerated irradiation. These sensors would ideally have a small profile and the ability to withstand irradiation at extremely high dose rates and temperatures for extended periods of time. A capacitance-based sensor is currently under development at the University of Tennessee to provide a direct measurement of in-pile dimensional change during irradiation. Sensor response was simulated using AutoCAD Electromagnetic field simulator (EMS) for a variety of sensor materials and configurations and fuel pin swelling conditions. Initial results of these simulations are summarized and areas of ongoing research and development are discussed.

Key Words: In-pile measurement; material evolution; fuel irradiation; capacitive sensor

1. INTRODUCTION

Pressurized creep tubes are commonly used to measure irradiation creep, which can be as small as a few microns, depending on the creep compliance of the material of interest, the applied hoop stress, the irradiation dose, and the initial diameter of the creep tube. Changes in the tube diameter are typically limited to post-irradiation examinations due to the difficulty in making precise *in situ* dimensional measurements in the intense environment of a materials test reactor. Advanced sensors that survive and reliably perform in harsh environments for extended periods are needed for materials characterization studies and use in future reactors. *In situ* creep measurements would be extremely valuable to improve the understanding of stress evolution during irradiation and would drastically reduce the time and cost associated with irradiating large numbers of creep tubes to varying dose levels and performing the currently required post-irradiation evaluations. The dimensional change sensor developed in this work could be used to measure irradiation creep for a thin-walled metal tube (creep tube) that is seal welded at high pressure to provide a constant hoop stress. The ultimate goal of this work is to develop a capability to measure in situ material deformation under irradiation conditions to validate and tune models of material and nuclear fuel evolution.

Capacitance-based sensors have been proposed and initial concepts demonstrated for axial dimensional change during irradiation experiments [1], suggesting this measurement approach may be robust to high

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radiation environments. The current work aims to extend this concept to radial measurement. This paper presents initial design and simulation for developing a capacitive dimensional change sensor. Section 2 briefly introduces the relevant theoretical background of the proposed sensor operation. Initial sensor design and simulation efforts are described in section 3; the results of sensor simulation in AutoCAD EMS as well as initial measurement testing are presented in section 4. Initial measurements with a surrogate creep tube and sensor design are also given in section 4. Areas of ongoing development and experimental deployment are summarized in section 5.

2. CAPACITIVE SENSOR DEVELOPMENT

Capacitance-based sensors measure displacement through the relative, non-parallel movement of a suspended electrode and a fixed electrode [2, 3]. An electric field is generated when a voltage passes through two conductive materials resulting in an opposing polarity on each material. An alternating voltage source causes these opposing polarities to alternate between the two objects, which in turn generates an alternating current signal; this signal is proportional to the capacitance between the two objects [4]. The relative geometry of each object (e.g., area and proximity) defines the capacitance between the objects and the resulting current signal. The resulting capacitance is directly proportional to the common surface area of the two objects, the dielectric constant of the material between them (in this case, air), and the inverse of the distance between them.

Capacitive sensors measure capacitance between fixed and suspended electrodes. In this work, the fixed electrode is manufactured in a ring surrounding the pressurized creep tube while the pressurized creep tube itself serves as the suspended electrode, shown in Figure 1. Physical models for the capacitance between the inner creep tube and the outer electrode have been derived in [5]. Approximations for cylindrical electrodes results in capacitance per unit length, $\frac{C}{L}$:

$$\frac{C}{L} = \frac{2\pi\epsilon_r\epsilon_0}{ln\left(\frac{r_o}{r_i}\right)} \tag{1}$$

where ϵ_r is the relative dielectric permittivity, r_i is the radius of the inner conductor (the outer radius of the creep tube), and r_o is the radius of the outer conductor (the inner radius of the sensor). The radius of the sensor remains fixed, but that of the creep tube will change due to irradiation swelling or creep, resulting in a change in the measured capacitance. More accurate estimates of capacitance can be generated through finite element simulation [6]. The AutoCAD add-on program EMS offers finite-element modeling capabilities that estimate capacitance for a variety of simple configurations. The EMS simulations conducted to evaluate candidate sensor designs are described in section 3.

3. SENSOR DESIGN AND SIMULATION

Effects of key design considerations on proposed capacitive sensor performance were evaluated in AutoCad-EMS. The generic sensor design used in this evaluation is shown in Figure 2. The sensor performance is simulated as two cylindrical rods (inner creep tube and outer sensor bar). In all simulations, the creep tube is 25.4 mm long based on the creep tube geometry commonly used at ORNL. The sensor is centered at the middle of the creep tube and is 10.0 mm long. This configuration will be sensitive only to swelling in the middle 10.0 mm of the creep tube; future efforts will investigate methods to improve coverage and localization. To measure the capacitance between the creep tube and sensor, a third rod composed of air, shown in blue in Figure 2, was placed between the rods. The sensor is surrounded by an air box for simulation; this insulator is expected to behave similarly to the plastic sensor holder design shown in Figure 3. The primary purpose of this casing is to hold the sensor at the midpoint of the creep tube without restricting potential swelling of the creep tube.

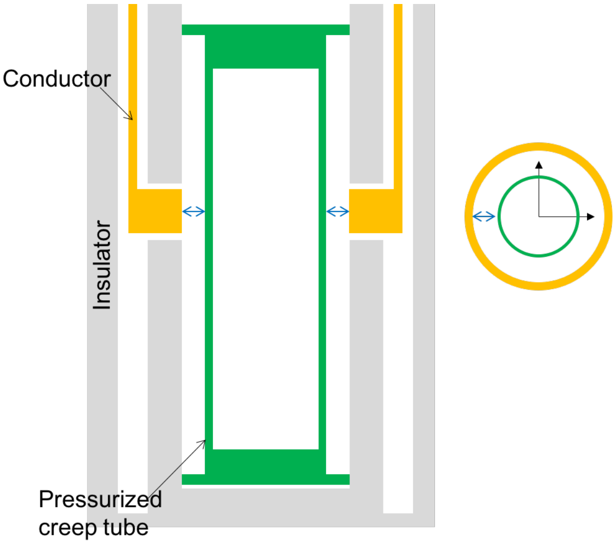


Figure 1. Capacitance-based radial dimensional change sensor design

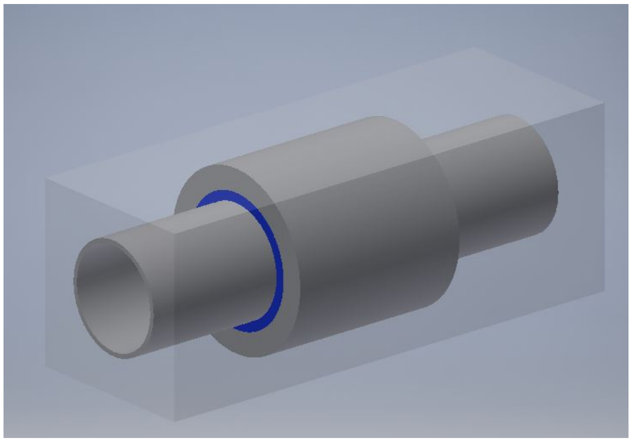


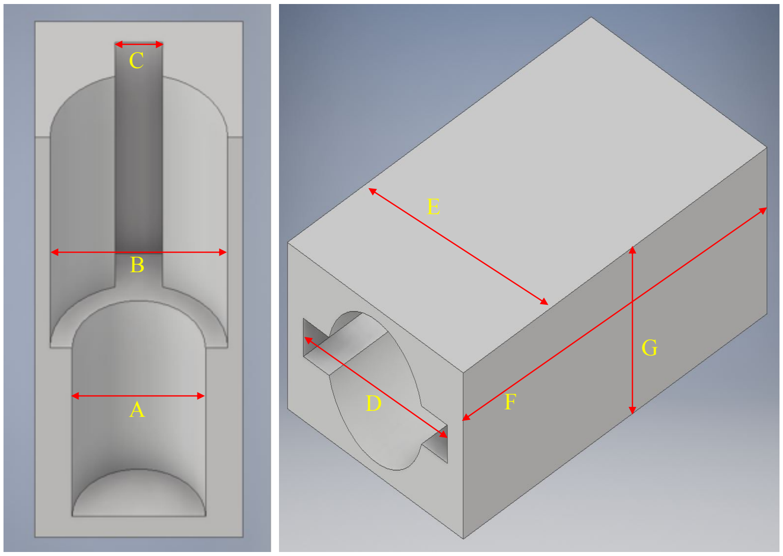
Figure 2. Generic capacitive sensor design in AutoCad-EMS

4. PRELIMINARY RESULTS

4.1. Simulation Results

Simulations were investigated for a variety of potential sensor configurations. Table I shows the simulation results for different combinations of creep tube and sensor materials. For each of these simulations, the creep tube dimensions were 4.78 mm OD and 3.76 mm ID and the sensor dimensions were 9.52 mm OD and 6.58 mm ID. This configuration represents the "base case" unswollen creep tube. Theoretically, the capacitance signals should not rely on the materials used for the creep tube and sensor, provided both are conductive materials [4]; the results in Table I are being investigated to determine accuracy and sensitivity to simulation set up.

In addition to investigating the relationship between materials and capacitance measurements, the response of the capacitance sensor during creep tube swelling was investigated for a stainless steel creep tube and sensor combination. In this series of simulations, the sensor dimensions were held constant while the creep tube inner and outer diameters were increased to simulate tube swelling. The results of these



Dimensions

A = 11.4 mm

B = 15.2 mm

C = 4.1 mm

D = 22.9 mm

E = 27.9 mm

F = 48.3 mm

G = 17.8 mm

Figure 3. Sensor casing to maintain sensor placement relative to creep tube

Table I. Simulation results for different combinations of creep tube and sensor materials

Creep Tube Material	Sensor Material	Capacitance (pF)
copper	copper	3.18
copper	stainless steel	3.68
stainless steel	copper	2.48
stainless steel	stainless steel	4.70
stainless steel	brass	1.37
aluminum	copper	3.94
aluminum	stainless steel	3.67

simulations are shown in Figure 4. For these simulations, the sensor geometry is maintained at 10 mm length, 7.01 mm ID and 9.57 mm OD. The creep tube length is held constant at 25.4 mm (i.e., no axial expansion is considered), but the OD varies from 1.51 to 6.51 mm at steps of 0.50 mm. Equation 1 was fitted to the full range of simulated data given a known inner radius of the sensor ($r_o = 3.54\,mm$) resulting in:

$$C = \frac{1.35 \times 10^{-12}}{ln\left(\frac{3.54mm}{r_i}\right)}. \tag{2}$$

The resulting fit is significantly affected by the simulated points at $d_o = 5.5\,mm$ and $6.0\,mm$ ($r_o = 2.75$ and $3.0\,mm$). The fit was recalculated excluding these two points, resulting in:

$$C = \frac{1.86 \times 10^{-12}}{ln\left(\frac{3.54mm}{r_i}\right)}. \tag{3}$$

These simulations are known to be sensitive to geometry mesh; further investigation of this effect is ongoing to evaluate confidence in simulation results.

4.2. Experimental Measurements

Experimental measurements were made for a variety of configurations of an unswollen creep tube. In these measurements, a stainless steel surrogate creep tube was used with three sensors: stainless steel,

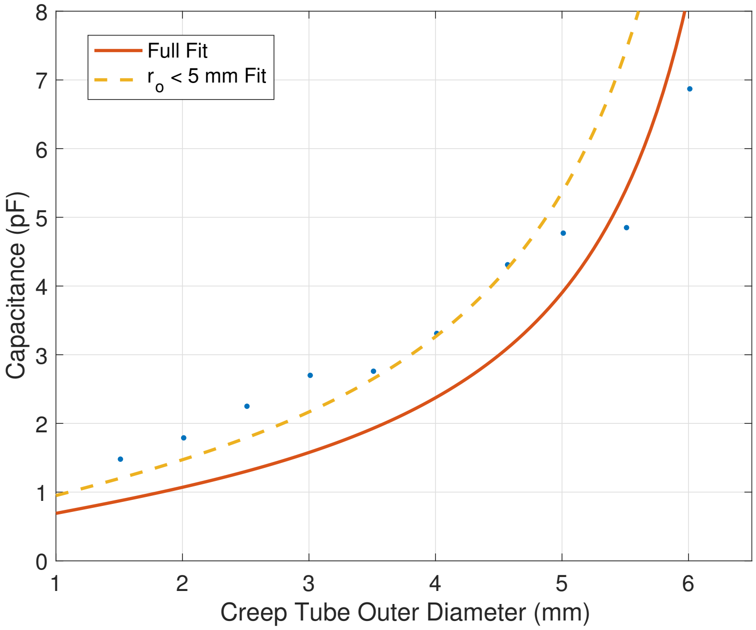


Figure 4. Simulated capacitance measurements during creep tube swelling. Solid line gives the line of best fit according to equation 1 fitted to the full range of simulated data; dashed line uses only $1.0 \leq r_o \leq 5.0\, mm$.

copper, and brass. The creep tube is approximately 25 mm long, with an ID of 3.76 mm and an OD of 4.76 mm ($3/16''$). The sensors are all approximately 10 mm long with OD of 9.5 mm ($3/8''$) and ID varying from 6.2 to 8 mm, depending on the material.

The capacitance value is measured and digitized using an Analog Devices AD7747 Evaluation Board [7]. AD7747 is a high-resolution capacitance-to-digital converter (CDC) that can be used to measure single-ended or differential capacitance; the current design uses a single-ended capacitance with the creep tube grounded and a potential applied to the sensor. The AD7747 also has an on-chip temperature sensor, which may be used to correct capacitance measures for temperature drift effects in early-stage experimental measurements [8]. This temperature measurement is unlikely to be compatible with future in-pile testing, but will give an early evaluation of temperature sensitivity.

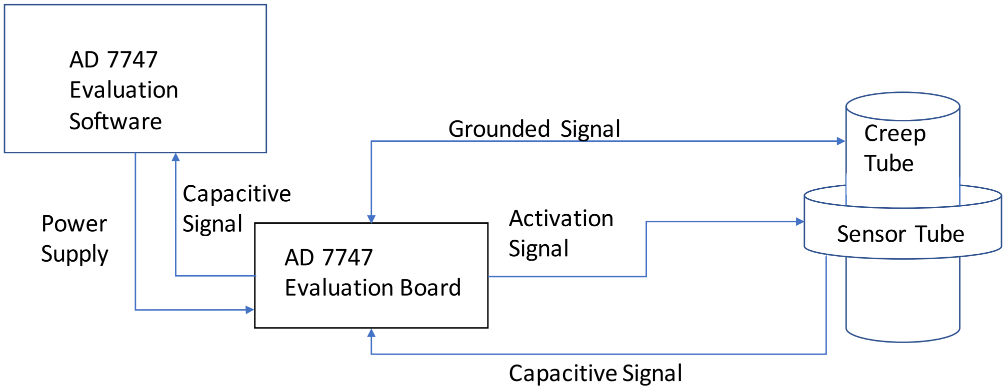


Figure 5. Experimental setup for initial sensor measurements

Figure 6 shows the measured capacitance values for a stainless steel sensor. These data are collected at 8.1 Hz for approximately a minute. The mean reading over this time is 2.93 pF with a standard deviation of 0.0048 pF. The plot indicates the measured data, the mean value, and the 95% measurement confidence interval. Similar data were collected for each sensor material; the results are summarized in Table II. The measured capacitance bears out the expectation that the measurement should be effectively independent of material for a common geometry. The simulation results are currently being investigated to identify possible issues.

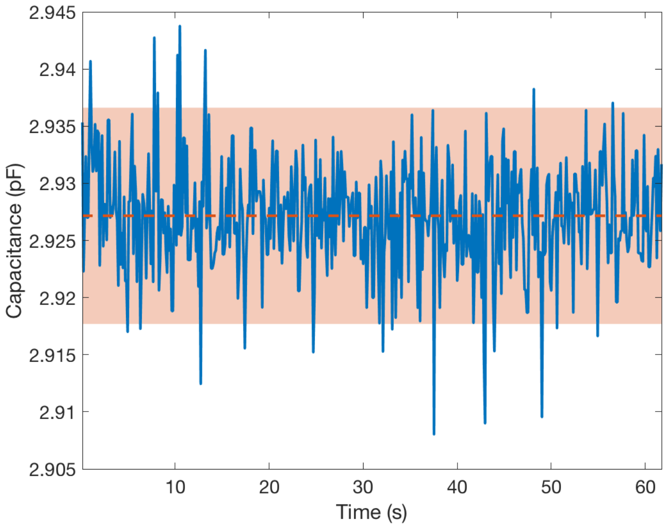


Figure 6. Example measurement of capacitance for a stainless steel sensor.

Table II. Comparison of simulated and measured capacitance values for different materials.

Material	Simulated Capacitance (pF)	Measured Capacitance (pF)	Error (%)
Stainless Steel	4.70	2.64	43.8
Copper	2.48	2.50	0.8
Brass	1.37	2.83	42.5

5. SUMMARY

A capacitance-based radial dimensional change sensor is being developed for prospective deployment in future fuel irradiation experiments. This has the potential to provide *in situ* data and measurement of the evolution of fuel behavior during irradiation, instead of collecting data only at discrete points during an irradiation campaign. Current efforts have focused on simulation and early measurement demonstration. Simulation results suggest that this approach should be sensitive to very small changes in fuel diameter due to swelling. Sources of mismatch between simulation and early experimental results are being investigated before we move to measurement of pressurized creep tubes to evaluate sensitivity.

Demonstration of the ultimate in-pile capacitive sensor will follow a three-stage campaign. First, the sensor will be tested in a non-radiation environment with pressurized creep tubes to monitor tube expansion under varying pressure conditions. Then, the sensor will be deployed in a gamma irradiation environment to test compatibility of the measurement modality with gamma flux. Following successful testing and demonstration in this out-of-pile environment, the capacitance-based sensor will be tested in-pile to evaluate the radiation resistance and long-term performance for measurement campaigns relevant to fuel and material performance.

5.1. Ongoing Research

The research described here begins to build the foundation for an in-pile measurement capability; however, several open questions and research inquiries remain to develop a deployable sensor. Current work is focused on evaluating the simulation results to identify sources of error and unexpected results. The sensor will be further evaluated in the simulation environment to demonstrate expected sensitivity to changes and to optimize the sensor design.

Another open issue is that capacitive sensors are known to have temperature dependence [8]. The temperature stability must be evaluated and quantified over a range of temperatures relevant to in-pile testing to determine the in-pile reliability of capacitance-based measurement. The current capacitance-to-digital evaluation board includes an integrated temperature sensor that will be used for initial evaluation of temperature dependence before the sensor is deployed in any radiation environment.

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