Fiber Optic Sensor for Corrosion Monitoring in Molten Salt Irradiation Experiments

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INTRODUCTION

The molten salt reactor (MSR) is a promising advanced reactor concept because it offers passive safety, high-temperature process heat, and the potential for improved fuel cycle economics through online reprocessing [1]. However, before MSRs can be reliably deployed, structural materials must be identified that can survive extended exposure to highly corrosive salts during irradiation at high temperatures. The US Department of Energy (DOE) is funding the design and eventual construction of a Versatile Test Reactor (VTR) that will include experimental facilities for testing under conditions representative of several advanced reactors, including MSRs [2]. These facilities will allow testing of candidate structural materials during irradiation with flowing salt. If properly designed, these experiments will allow for post-irradiation characterization of weight loss in the structural material coupons. However, significantly more information could be gained if the corrosion could be monitored in situ.

There are currently no commercially available sensors for in situ corrosion monitoring at temperatures in the range of 500–900°C [3]. An in situ corrosion sensor would be required to survive high-dose neutron irradiation and extended exposure to chemically aggressive media such as molten salts. While there are ongoing efforts to use the change in magnetic susceptibility of Cr-containing alloys, this technique is limited to Cr-containing structural materials, and there are concerns when using a magnetic susceptibility sensor at temperatures approaching the Curie temperature of iron (770°C) [4].

EXPERIMENTAL APPROACH

Fiber optic sensors are promising candidates for process monitoring in high-temperature applications. Fiber optic sensors have also been shown to withstand neutron irradiation to moderate displacement damage dose [5, 6]. This work investigates an in situ molten salt corrosion monitoring sensor using optical fibers embedded in a metal structure machined from the reactor piping material, or in the case of an irradiation test, the material to be tested for corrosion resistance. Fig. 1 illustrates the sensor concept and its implementation in a VTR irradiation experiment. The fiber is embedded using ultrasonic additive manufacturing. Previous work has demonstrated sensor embedding in aluminum and nickel, showing that the fiber can survive temperatures beyond 500°C [7, 8]. The sensor measures the deflection of a thin diaphragm at the end of the probe. For molten salt systems operating at low pressure, the sensor can be internally pressurized with inert gas to a known pressure. The diaphragm deflection is measured using spectral techniques such as fast Fourier transform (FFT) or period tracking techniques or low coherence interferometry (LCI) with phase demodulation [9, 10].

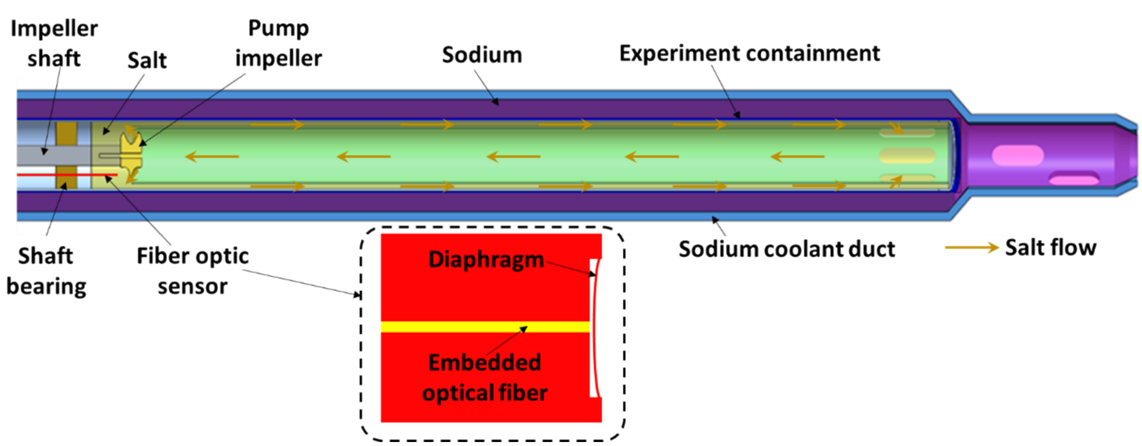

Fig. 1. Proposed sensor implementation in a cartridge-style VTR salt irradiation experiment.

The relationship between the maximum diaphragm deflection (u_{max}) and the difference in the external vs. internal pressure (ΔP) is determined during calibration based on the analytical equation for a thin circular diaphragm, as shown in Eq. (1).

$$u_{max} = \frac{3\Delta P(1-\nu^2)a^4}{16Eh^3} \qquad (1)$$

In this equation, E, a, and h are the elastic modulus, radius, and thickness of the diaphragm, respectively. If ΔP is known and u_{max} is measured, then the change in thickness h due to corrosion can be monitored.

RESULTS

Fabrication

A prototype sensor was fabricated using aluminum components to establish an initial proof of principle and to test the optical interrogation system and data acquisition. Fig. 2 shows the sensor assembly process. Efforts are ongoing to develop and test the LCI system that will ultimately be used to interrogate the sensor. However, initial testing has been performed using an alternative interrogation technique. A Luna Innovations optical backscatter reflectometer model 4600 (tunable laser with 42 nm range, centered near 1,550 nm) was used to measure the spectral interference produced by the two reflections within the sensor cavity. The cavity length can be determined using the FFT approach or through period tracking [10].

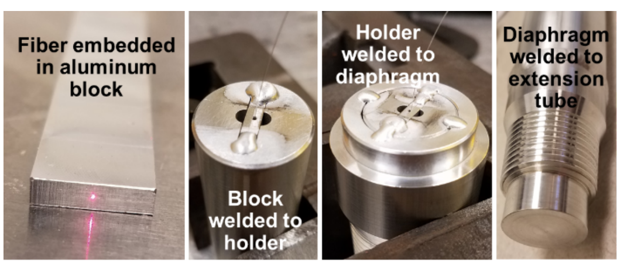

Fig. 2. Fabrication of prototype sensor.

Initial Pressure Testing

An initial test was performed to determine whether the diaphragm responds to changes in pressure and that the cavity length can be resolved by the fiber optic measurement system. The sensor body was externally pressurized using compressed air. The pressure was arbitrarily increased in steps over a range covering 0−80 psig while independently monitoring the pressure using a conventional pressure transducer. Fig. 3 summarizes the change in the fiber optic sensor cavity length determined using both a FFT approach and period tracking along with the pressure measured by the conventional transducer as a function of time.

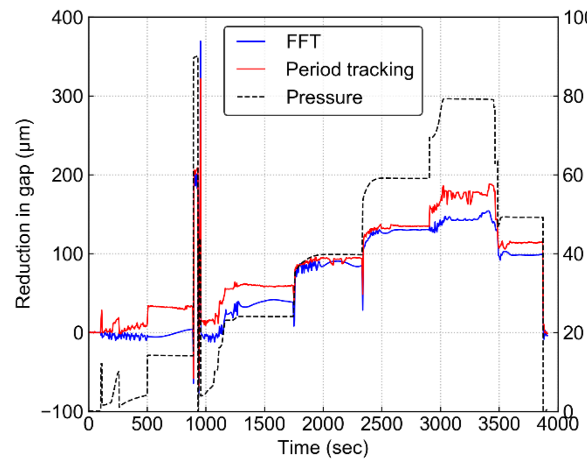

Fig. 3. Initial demonstration test showing change in fiber/ diaphragm gap (left axis) using FFT and period tracking approach as the external pressure (right axis) is varied vs. time.

A few observations can be made based on the results of this initial testing: (1) the sensor clearly responds to changes in pressure, (2) there is considerable noise in the data acquired by the fiber optic sensor, and (3) there are significant differences in the cavity length determined using the FFT approach vs. period tracking. The fact that the sensor responds to changes in pressure is encouraging. The issues that were observed can likely be mitigated using the LCI system under development, as this technique is much more stable.

The initial demonstration of the proposed sensor's pressure sensing capabilities gives confidence that the sensor could be improved to provide reliable corrosion measurements. The next step is to implement the LCI measurement system and determine if the new system improves measurement reliability. If not, then additional work will be required to determine if there are issues with sensing cavity itself, such as poor alignment, poor fiber surface condition, or poor surface finish on the metal diaphragm. If the LCI system resolves the reliability issues, then the next steps would be to (1) test the prototype sensor while pressurizing at elevated temperatures, (2) fabricate a prototype sensor made from salt-compatible materials such as nickel alloys, and (3) test the nickel alloy sensor in a molten salt environment.

CONCLUSIONS

This work summarizes recent efforts to develop a fiber-optic corrosion sensor for molten salt irradiation testing in the VTR. If successful, the sensor could also be deployed to monitor corrosion of piping in a future MSR. The sensor relies on embedding fiber optic sensors in a metal component and internally pressurizing the sensor with inert gas. The thin diaphragm that is machined into the sensor body deflects as a result of the pressure difference, and the amount of deflection is dependent on the diaphragm thickness, which changes over time due to corrosion. This work describes the fabrication and initial external pressure testing of a sensor made of aluminum. The cavity length follows the applied pressure, indicating that the proposed sensor concept is viable. However, there are clear issues with reliability that could be improved with a modified interrogation technique. Future testing will focus on improving the measurement reliability, embedding in nickel alloys relevant to MSRs, and testing the nickel-based sensor during exposure to high-temperature molten salt.

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REFERENCES

1. M. W. ROSENTHAL, P. R. KASTEN, and R. B. BRIGGS, "Molten-Salt Reactors—History, Status, and Potential," *Nuclear Applications and Technology,* **8**, 107–117 (1970).
2. D. BROUILLETTE. *DOE: There's a Definite Need for a Fast Test Reactor*. 2019 [accessed 2019 May, 28]; Available from: https://www.energy.gov/ne/articles/doe-theres-definite-need-fast-test-reactor.
3. K. KORSAH et al., "Assessment of sensor technologies for advanced reactors," ORNL/TM-2016/337 R1, Oak Ridge National Laboratory (2017).
4. D. E. HOLCOMB et al., "Development of an in-situ corrosion monitor for molten salt reactors," in 11th Nuclear Plant Instrumentation, Control and *Human-Machine Interface Technologies 2019*. 2019: Orlando, FL.
5. G. CHEYMOL et al., "High Level Gamma and Neutron Irradiation of Silica Optical Fibers in CEA OSIRIS Nuclear Reactor," *IEEE Transactions on Nuclear Science,* **55**, 2252–2258 (2008).
6. C. M. PETRIE et al., "Reactor radiation-induced attenuation in fused silica optical fibers heated up to 1000 °C," *Journal of Non-Crystalline Solids,* **409**, 88–94 (2015).
7. C. PETRIE et al., "Embedded metallized optical fibers for high temperature applications," *Smart Materials and Structures* (2019).
8. C. M. PETRIE et al., "High-temperature strain monitoring of stainless steel using fiber optics embedded in ultrasonically consolidated nickel layers," *Smart Materials and Structures,* (under review).
9. Y. LIU et al., "Digital phase demodulation for low-coherence interferometry-based fiber-optic sensors," *Optics Communications,* **411**, 27–32 (2018).
10. Y. HUANG et al., "An extrinsic Fabry–Perot interferometer-based large strain sensor with high resolution," *Measurement science and technology,* **21**, 105308 (2010).