DEVELOPMENT OF OPTICAL FIBER INSTRUMENTATION FOR USE IN SODIUM COOLED FAST REACTORS

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ABSTRACT

An optical frequency domain reflection interrogation system was used to measure frequency shift in single mode optical fibers as a function of temperature up to 700 ºC. A calibration function was developed to convert frequency shift to temperature. A method for encapsulating the optical fiber in a stainless steel sheath with inert cover gas for safe deployment of the sensors in sodium has been developed and tested. An optical fiber has been placed in the operational liquid sodium loop at the University of Wisconsin for testing of sensor applications.

Key Words: Optical Fiber, Liquid Sodium, Fiber Optics, Fast Reactor, Instrumentation

1 INTRODUCTION

1.1 Liquid Sodium Application

Improved instrumentation for alkali liquid metal systems is a key requirement in making the Sodium Fast Reactor a more economically viable energy source. This instrumentation should measure key features such as temperature, strain, velocity and liquid level.

Recent advancements in fiber optic sensors have allowed for quasi-continuous measurement of temperature and strain profiles of a system utilizing Swept-Wavelength Interferometry of Rayleigh backscattering with a resolution on the scale of millimeters [1] [2]. These high-resolution measurements allow for real-time thermal system monitoring and the ability to characterize thermal behavior in advanced liquid metal components such as electromagnetic pumps and compact heat exchangers.

A corollary to high frequency/resolution temperature measurements is the ability to determine local flow characteristics in the sodium such as velocity and turbulence with the use of cross correlation of the optical fiber temperature data [3]. Additionally, the liquid metal level may be determined by monitoring the differences in heat decay along the length of a submerged cylindrical cartridge heater after the heater is pulsed with power.

The sodium cooled reactor environment poses relatively difficult engineering challenges when attempting to implement instrumentation within the liquid sodium channels. Besides the up to 700 ºC temperatures, liquid sodium readily reacts and degrades most materials, including optical fiber coatings such as polyimide, acrylate, aluminum, gold, etc. Therefore it is necessary to determine the feasibility of utilizing optical fibers at these high temperatures, and to develop a method for dealing with the materials incompatibility of the optical fiber for safe in-sodium deployment.

1.2 Optical Fiber Sensor Theory

Utilizing Swept-Wavelength Interferometry the elastic Rayleigh backscattering behavior of photons due to local microscopic fluctuations of the glass core density can be monitored to produce nearly continuous temperature and strain measurements [4]. When these impurities undergo thermal or mechanical strain the frequency of the backscattered light will shift and this shift may be used to determine the thermomechanical state of the fiber at a continuous set of locations, or "gauges", along the fiber. .

This shift determination is done by utilizing Fourier-domain reflectometry, operating much like a Michelson interferometer with a wavelength swept laser source [5]. The test signal from the backscattered light through the fiber is collected with a photodiode and Fourier transformed from the time to frequency domain. This produces a pattern dependent on frequency, so that one may determine frequency shifts with respect to an unstrained reference state via cross correlation [6]. The particular optical interrogator used throughout these experiments was the Odisi-B from Luna Innovations, using a laser with 1550 nm central wavelength with 90 nm spectral range. This interrogator has a resolution as high as 1.25 mm gauge length, with a maximum scan frequency of 250 Hz, all over a length of up to 10 meters.

2 HIGH TEMPERATURE OPTICAL FIBER TESTING

2.1 Mechanism for Degradation of Fiber Coating

A single-mode optical fiber consists of three concentric components: the core, cladding and coating. The core and cladding act as the waveguide for the laser light, with the cladding having a slightly lower refractive index glass to provide total internal reflection to transport the light inside the core of the fiber. The outermost coating layer, typically composed of plastic, gives the otherwise fragile core and cladding increased mechanical strength and prevents moisture from diffusing into the glass.

Moisture is the primary mechanism for fiber degradation. When the fiber cladding is exposed to moisture it becomes susceptible to micro-cracks which develop on the surface of the cladding and propagate throughout the glass structure [7]. These flaws develop initially with the reaction of the water molecule and silicon oxide, where the water breaks one of the silicon to oxygen bonds, forming a weak hydrogen bond as seen in the following reaction schematic [8]:

$$\text{Si-O-Si} + \text{H}_2\text{O} \rightarrow \text{Si-O-H}\sim\text{H-O-Si}$$

This process is accelerated by environmental factors, especially high temperatures as in a 600ºC+ environment of a sodium cooled reactor. The change in crack length as a function of time is characterized by equation 1:

$$\dot{C} = AK_I^{\,n} \tag{1}$$

Where $\dot{C}$ is the rate of crack length growth, A is an environmental constant which is related to temperature and moisture content, K_I is a stress intensity factor based on the crack geometry and the applied stress, and n is the stress corrosion factor. The choice of optical fiber coating dictates this factor. Typical plastic coated silica fiber has a stress corrosion resistance factor of ~20, while more novel hermetically sealed carbon coated fibers have an n greater than 100 [8]. Thus this factor can be thought of as the ability of the fiber coating to prevent water-silica interaction in the waveguide of the optical fiber. At the time of this report carbon-polyimide coated hermetically sealed fibers are being acquired and only standard telecommunications grade polyimide and acrylate coated fibers have been tested.

2.2 Experimental Setup

A high temperature optical fiber test oven was constructed and is shown in figure 1. The oven was constructed from 45 cm of 2.54 cm diameter stainless steel tubing. Wall thickness of the oven was chosen to be relatively thick at 0.635 cm in order to reduce the sinusoidal temperature variation caused by the gaps between the heater tape wrapping. The 250 VAC heater tape was 90 cm long and 1.5 cm wide wrapped tightly and at an even spacing along the oven tube. The oven tube was wrapped with a layer of Kaowool and two layers of Pyrogel insulation. This oven tube was mounted vertically to a 60 cm length of 80/20 aluminum with the bottom tab mounted loosely to allow for thermal expansion of the oven tube. Notice 15 cm was left at the bottom of the oven before the mounting table to allow the termination fiber to exit the oven and wrap onto a spool at a large radius of curvature to prevent macro-bend losses in the fiber core.

The rightmost picture of figure 1 shows the end plate which was constructed to hold in place 8 test fibers and a 0.16 cm diameter thermocouple probe to acquire oven temperatures at the oven's center and provide the process variable for PID control of the heater. This end plate was mounted on either side of the oven and ensures the fibers remain isolated with respect to each other in the oven as this could cause unaccounted for strain in the spectral shift reflection readings. Additionally, the vertical orientation of the fiber testing oven ensures the fiber does not lay on the side of the oven as this could also cause unaccounted for strains at the oven tube, fiber coating interface.

Figure 1. Optical fiber high temperature testing oven. Shown without thermal insulation applied.

2.3 Results

2.3.1 Frequency Shift vs. Temperature

The previously described oven was used to acquire the spectral shift of Rayleigh backscatter in polyimide coated fiber as a function of oven temperature for temperatures up to 700 ^{o}C. This test was done to produce fit curves for high temperatures above 300 ^{o}C, outside of the range of the linear fit that Luna Innovations includes in their standard software package, as can be seen in figure 2 where the temperature offset is 100 ^{o}C+ at 500 ^{o}C [9]. The Luna linear fit as well as the fits found through experimentation and literature search can be found in table 1. A second order polynomial fit found by Wood et al. at The Ohio State University for acrylate coated fibers is shown in figure 2 and table 1 [10].

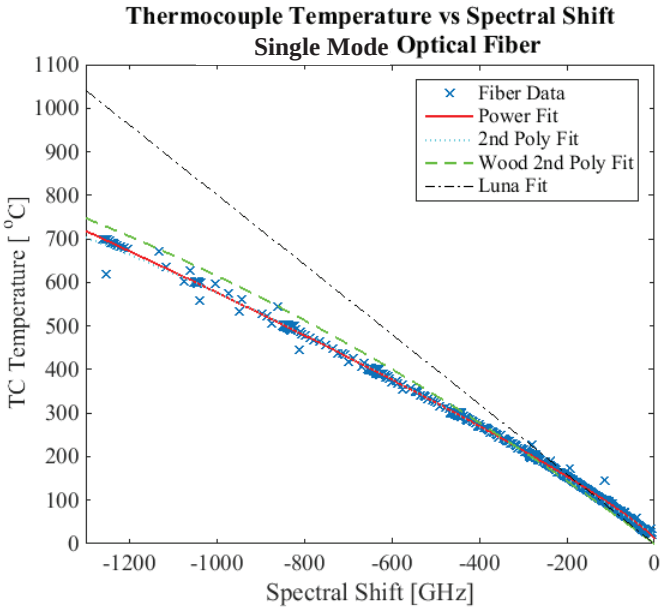

Figure 2. Thermocouple Temperature vs Spectral Shift, Polyimide Coated Fiber Data (Wood Fit from Acrylate Coated Fiber Data)

Table I. Frequency Shift to Temperature Conversion Functions

Name	*Equation*	*Ref.*
Luna Linear Fit	$T[°C] = -0.801\ S + 25$	[9]
Power Fit	$T[°C] = 1.558\ \lvert S\rvert^{0.8532} + 11.38$	-
2nd Polynomial Fit	$T[°C] = -(1.00 * 10^{-4})S^2 - 0.654\ S + 22.042$	-
Wood 2nd Polynomial Fit	$T[°C] = -(1.33 * 10^{-4})\ S^2 - 0.748\ S - 0.2290$	[10]

Note in figure 2 the polynomial fit by Wood for acrylate coated fiber shows relatively good agreement for the polyimide coated frequency shift to temperature data. A power fit was calculated and proved to match the spectral shift as a function of oven temperature with higher correlation than a 2nd order polynomial fit calculated for polyimide, both included in table 1. Note that there may be offset between the fit by Wood and those found in this paper due to different fiber manufacturers and/or manufacture date. This data was included simply to show a general agreement with high temperature spectral shift data from the literature.

2.3.2 High Temperature Oven Test Results

A series of high temperature oven tests were performed with polyimide and acrylate coated fibers. The results for the thermocouple and fiber temperature data fit with the power fit function of table 1 can be seen in figure 3. This test was run for 60 hours and ramped up to 700 °C maximum oven temperature with a polyimide coated fiber. A section of the data in figure 3 can be seen in figure 4 for the high temperature polyimide coated fiber test from 12-22 hours. As can be seen when the oven ramps up to 500°C there is a gradual drop in fiber temperature of around 15 °C, which corresponds to a shift in frequency towards the reference of 30 GHz. Given the temperature is steady according to the thermocouple data of figure 4, and this phenomenon has been seen at this temperature in other test runs, this shift is likely attributed to a cladding-coating interface interaction. This temperature is a point at which the polyimide readily decays as will be seen in the next section of this report. Therefore the complete decay of the polyimide coating induces a measureable mechanical strain on the optical fiber.

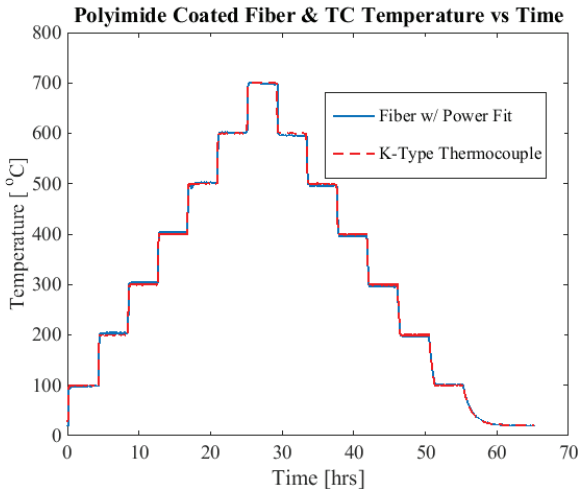

Figure 3. High temperature oven test of polyimide coated fiber.

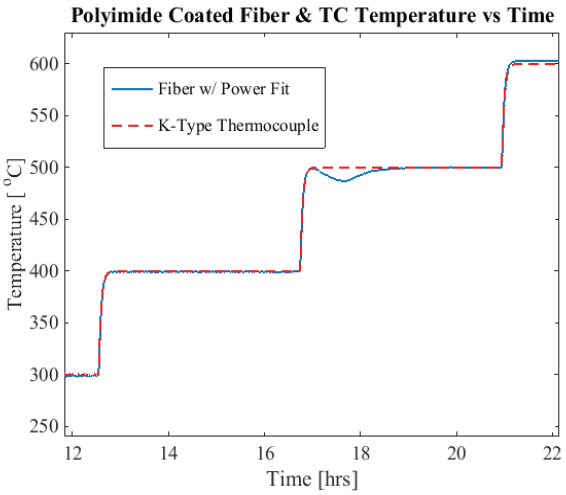

Figure 4. High temperature oven test of polyimide coated fiber.

A polyimide coated fiber was sealed in a stainless steel 1.6 mm diameter capillary tube and back filled with helium as described later in this report and tested in parallel with an identical fiber in a capillary tube without helium backfill. The fibers were subject to the oven temperature regime shown in figure 3 and the Rayleigh backscatter profile before and after tests are included in figures 5 and 6 for polyimide coated fibers in atmosphere and in helium, respectively. These Rayleigh backscatter profiles can be used as a diagnosis tool for optical fiber condition, showing amplitude of losses as a function of distance. The polyimide coated fiber in helium has a correlation coefficient of 0.95 for before and after oven exposure while the polyimide coated fiber in air has a lower correlation coefficient of 0.86. This result proves the superior behavior of the optical fiber when it is placed in an inert atmosphere.

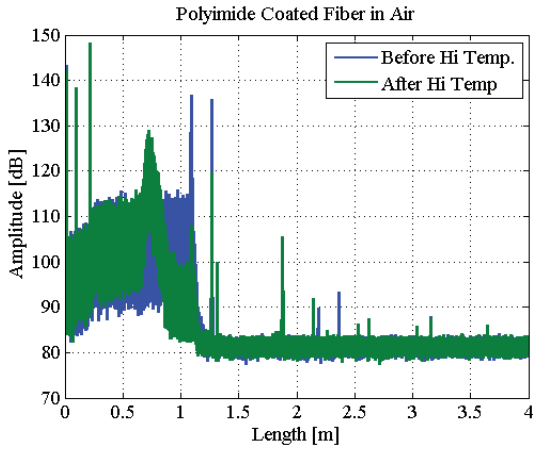

Figure 5. Rayleigh backscatter profile of polyimide coated fiber in air, before/after high temperature

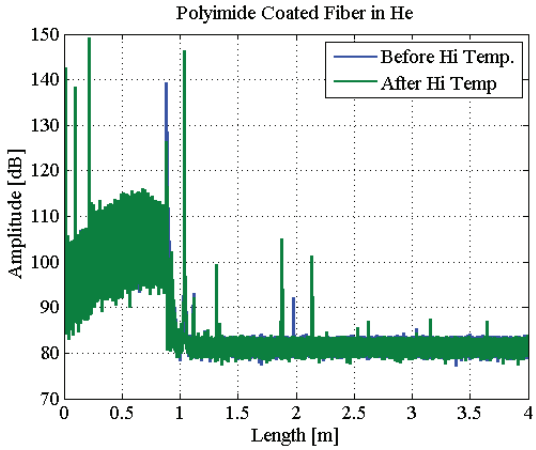

Figure 6. Rayleigh backscatter profile of polyimide coated fiber in helium, before/after high temperature

Figure 7 displays a weight loss percentage of polyimide film at a number of isothermal temperatures as a function of time [11]. Notice that at 600 °C there is a weight loss of 90% within 400 minutes. Therefore, for long time periods it may be necessary to utilize a hermetic carbon coating under the polyimide coating for long periods of exposure to high temperature to ensure that any residual moisture or contaminants released during the breakdown of the polyimide coating do not make their way into the cladding and core of the fiber.

During testing a significant amount of noise was present at the oven entrance and exit regions, as can be seen in the spectrum shift vs fiber position vs time plot included in figure 8. This noise is attributed to the very high temperature gradient seen in these regions, from room temperature to 500 ºC+ over a few centimeters. As described before, the optical interrogator creates gauge locations along the fiber and measures the spectral shift with respect to reference at each of these locations. As these gauges are on the millimeter scale it is assumed that the entire gauge is exposed to the same temperature/strain condition. However when sharp gradients exist and the spectral shift becomes non uniform over the length of the gauge this results in poor correlation peaks relative to the noise floor. According to applications engineers at Luna Innovations, the interrogator cannot distinguish between the shifted spectral peak and the noise floor and therefore picks a random peak which has a higher correlation—producing wild and random temperature fluctuations. This issue does not affect the spectral shift readings outside of the high gradient areas and is only present when there is a large temperature difference over relatively short distances.

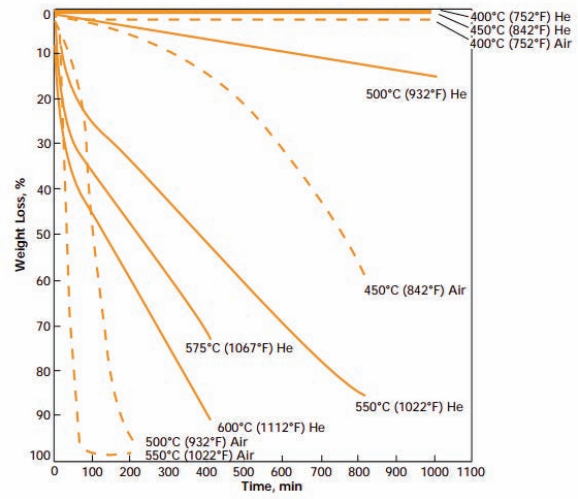

Figure 7. Isothermal Weight Loss of 25 µm Polyimide Film (DuPont) [10]

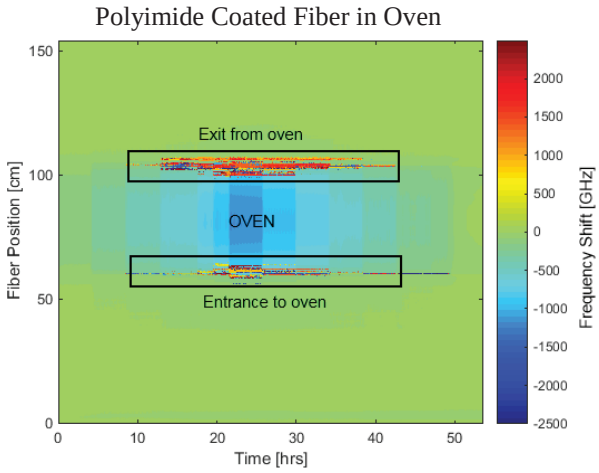

Figure 8. Temperature gradient induced noise in fiber at 700 ºC in oven

2.3.3 Coating Degradation

Acrylate and polyimide coated fibers were tested in the previously described oven for a range of temperatures up to 700 ºC. The acrylate coated fiber has a maximum temperature rating of 85 ºC and the polyimide coated fiber has a maximum rating of 300 ºC. Above these temperatures the plastic coating begins to carburize as can be seen in figure 9, showing acrylate and polyimide coated fibers after being placed in the oven for a temperature stair step up from 50 ºC to 550 ºC in 50 ºC increments each held for 1 hour. Notice the acrylate begins to disintegrate at 200 ºC while the polyimide begins to disintegrate at 350 ºC over this short time period. The breakdown of the fiber coating is a function of time as well as temperature so one would expect the coating to break down further over longer time periods.

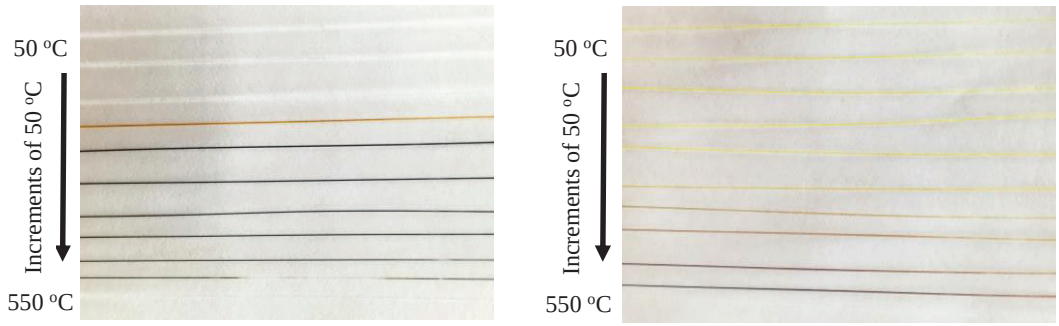

Figure 9. Acrylate (left) and Polyimide (right) coated fibers after exposure to oven ramping from 50-550 ºC, discrete steps of 50 ºC/hour.

Figures 10 and 11 show images acquired with an optical microscope of an acrylate coated fiber after exposure to 700 ºC over an 8 hour time period. Note that in figure 10 the 250 µm plastic coating has been vaporized to reveal the 125 µm silica cladding. Figure 11 shows the exposed silica cladding with clearly visible micro-cracks beginning to form at the surface.

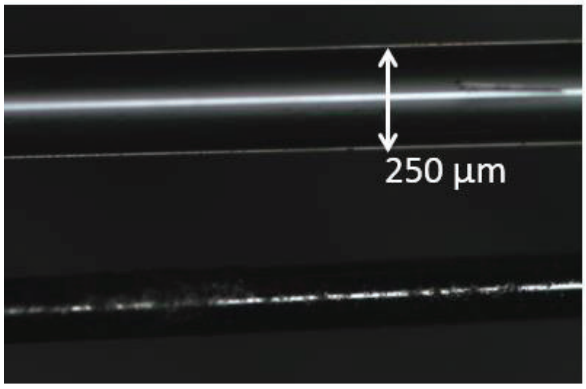

Figure 10. New acrylate coated fiber (top) versus acrylate coated fiber after exposure to 700 ºC (bottom). 10X image from optical microscope.

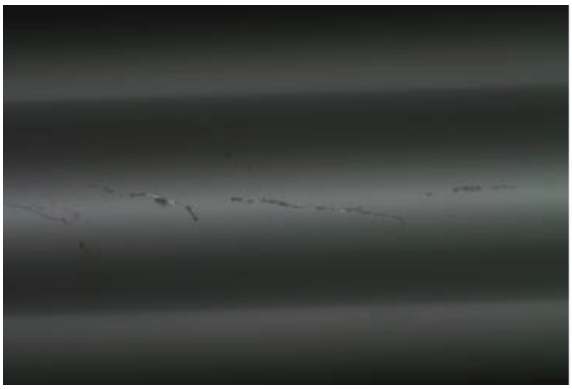

Figure 11. 8-hour furnace test at 700 ºC. 20X image from optical microscope.

2.3.4 Optical Fiber Manufacture for Sodium System Deployment

A protocol for optical fiber sensor manufacture has been developed through experimentation, consultation with fiber optic engineers at Luna Innovations and through literature search. Key elements for manufacture of the fiber include a lead-in, "vibration-correction", fiber region and a spliced on termination end. The lead-in fiber region should be at least 30 cm [12]. The termination end should be at least 20 cm. The termination end should be constructed with coreless optical fiber, in order to disperse the light from the fiber under test to prevent back reflections at the end of the termination fiber. A schematic which includes a properly constructed optical fiber with dimensions has been included in figure 12.

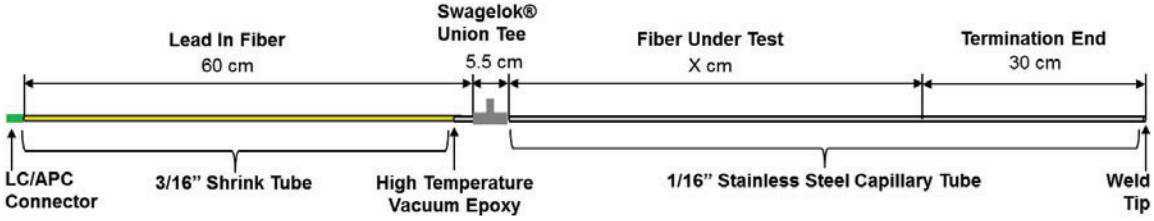

Figure 12. Optical fiber in stainless steel capillary tube.

In figure 12 is pictured a 1.6 mm diameter stainless steel capillary tube assembly to house the fiber for deployment in sodium. Note the Swagelok union-T connecting the two capillary tube segments—this allows for the backfilling of an inert gas such as helium to limit the amount of moisture and impurities in air in the fiber atmosphere. As seen in figure 7, the limiting of air with the backfilling of helium drastically reduces the weight loss percentage of a polyimide film at high temperature. At 450°C there seems to be a negligible weight loss of polyimide in a helium environment.

2.4 Sodium Loop Facility

A preliminary test of the optical fiber described in the previous section was tested in the expansion tank of the University of Wisconsin Dynamic Sodium Loop, shown in figure 13. The optical fiber temperature matched the expansion tank thermocouple temperature with high correlation throughout the 6 hour test and the method for sealing the fiber in capillary tube maintained its structural integrity throughout the test. This was a very preliminary test, future testing of the optical fiber will require disassembly of the main loop as any welding done to mount an optical fiber port will require the contaminants to be thoroughly cleaned with Oakite acid to remove any impurities that would contaminate the reactor grade sodium in the loop.

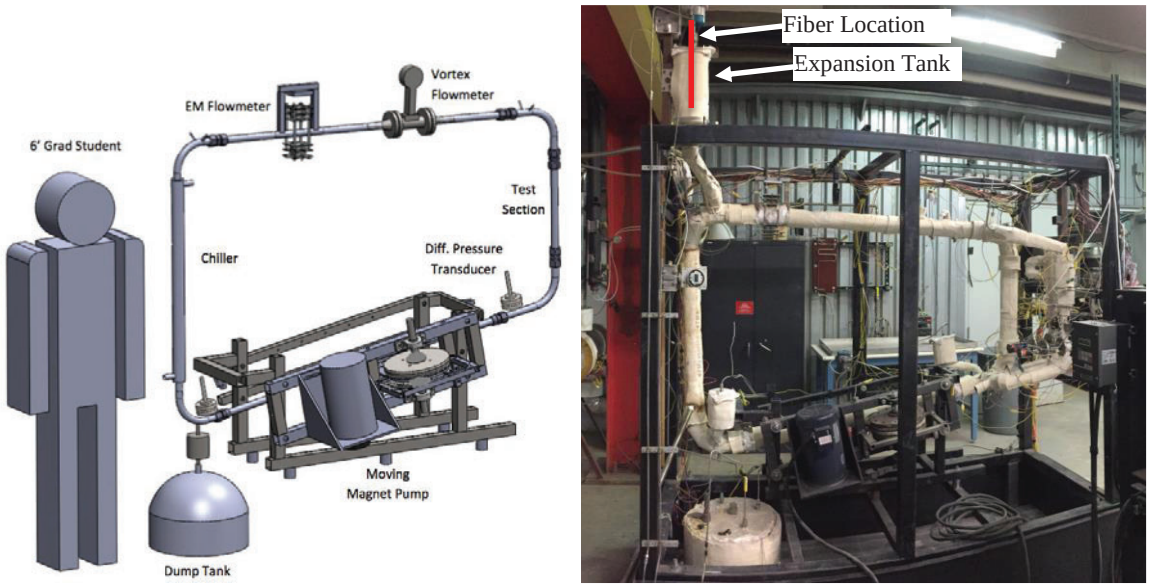

Figure 13. University of Wisconsin Dynamic Sodium Loop

Results for this preliminary optical fiber in sodium expansion tank can be seen in figures 14 and 15. Note the temperature was nearly constant throughout the entire submerged optical fiber so a single fiber gauge point in the middle of the sodium level was chosen for temperature measurement. The expansion tank was set to 250 ºC steady state, then cycled up to 300 ºC then back to 200 ºC at around 770 and 800 minutes, respectively, to monitor the temperature response of the fiber. At 600 minutes the tube leading to the expansion tank was cycled up to 270 ºC which can be seen as the sodium thermally conducts that heat to see a temperature response in the sodium above the tube at the internal fiber but not at the externally welded thermocouple. Notice in figure 15 one can see a slight time lag in the response to the cycling on and off of the heater being controlled via PID from the external welded on K-type thermocouple. Future tests will include an internal thermocouple mounted in close proximity to the fiber to ensure accurate temperature response validation of the optical fiber sensor.

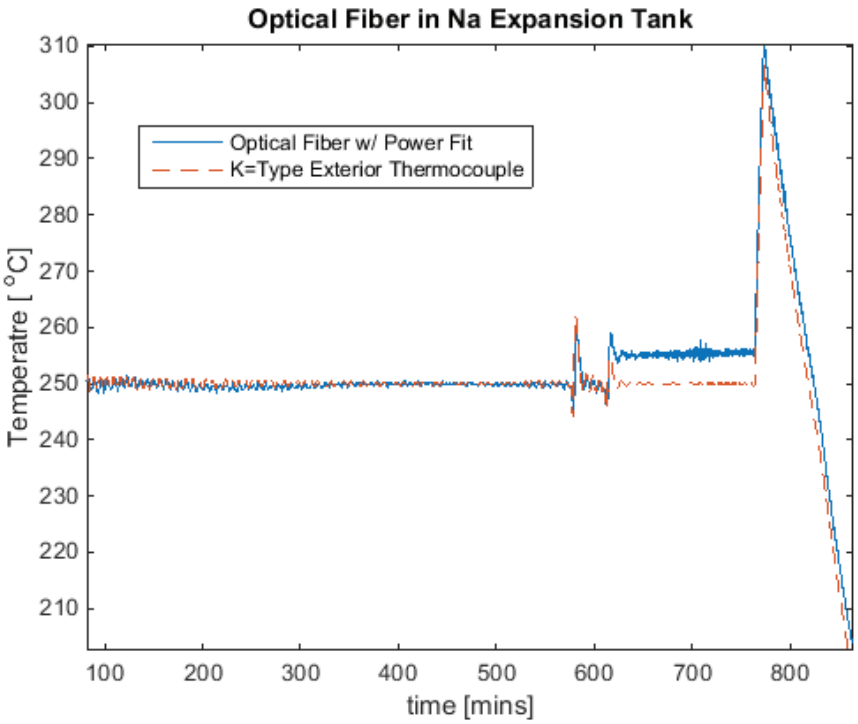

Figure 14. Preliminary Dynamic Sodium Loop optical fiber results, 100-850 minutes into run.

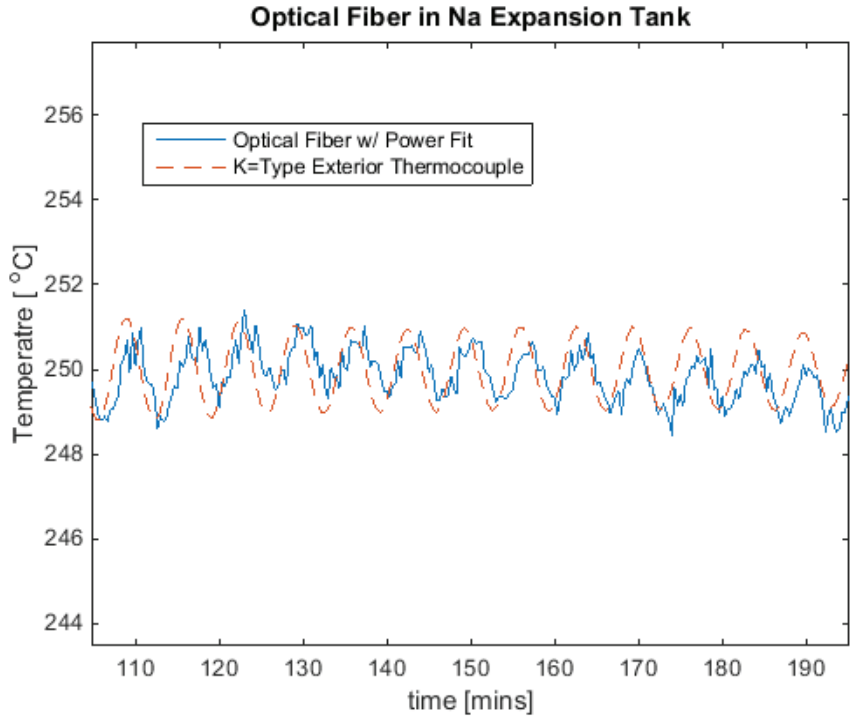

Figure 15. Preliminary Dynamic Sodium Loop optical fiber results, 105-195 minutes into run.

3 CONCLUSIONS

Optical fibers offer high resolution measurements of temperature over 10+ meters. The issues with fiber coating breakdown at high temperature were explored and a viable solution of backfilling a capillary tube with inert gas was tested and results proved favorable for this method of coating conservation. The authors are currently attempting to acquire hermetically sealed, carbon coated polyimide coated optical fiber, a specialty fiber which is difficult to come by. This fiber should further aid in reducing water from migrating into the optical waveguide, causing signal attenuation. A preliminary test of sodium loop polyimide coated optical fiber in-situ was performed and future testing in the University of Wisconsin sodium loop will be performed to assess the viability of utilizing optical fibers in sodium cooled reactor instrumentation.

4 ACKNOWLEDGMENTS

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