# Distributed Fiber Optic Temperature Sensing

Sensuron, LLC
+1 512-827-2040
info@sensuron.con
www.sensuron.com

# Table of Contents

# 1 Introduction

Temperature is the most measured physical parameter in the world. For many industrial and commercial processes, temperature monitoring is essential to ensure operational safety and efficacy. Conventional electric temperature sensors prevalent throughout industry can perform adequately if they are replaced often and are effectively shielded from EMI. However, they all suffer from the same inherent limitation: they can only measure temperature at a single point or location. In practice, these sensors are often deployed at only a handful of locations and thus the overall temperature distribution remains unknown.

Sensuron's Fiber Optic Sensing System (FOSS) technology offers an alternative method to measure temperature. In contrast to conventional temperature sensors, Sensuron interrogators acquire continuous temperature profiles along the entire length of an optical fiber with millimeter spatial resolution. The temperature at thousands of sensing points can be monitored using just a single lead cable. Processes that rely on temperature sensors to maintain ambient temperature uniformity or to detect hot spots stand to benefit considerably from understanding the overall temperature distribution. The intent of this document is to present fundamentally how to perform distributed temperature sensing with the Sensuron technology and demonstrate achievable accuracies with empirical results. If the reader is unfamiliar to the underlying principles behind fiber optics and the Sensuron interrogators, our white paper on Fiber Optic Sensing Fundamentals is a recommended precursor to this document.

# 2 Fiber Temperature Sensitivity

The two direct measurements of all Sensuron interrogators are mechanical strain ($\epsilon$) and temperature ($T$). This is due to the inherent sensitivity of the Bragg wavelength ($\lambda_b$), as seen below in the well-known Bragg equation.

$$\frac{\Delta\lambda_B}{\lambda_B} = \kappa\epsilon + \Delta T(\alpha + \eta) \tag{1}$$

The temperature sensitivity stems from two phenomena, changes in the core refractive index with respect to temperature and thermally induced strain. In equation (1), the temperature dependency of the refractive index is described by the thermo-optic coefficient ($\eta$). $\alpha$ is the coefficient of thermal expansion of pure silica, relating the thermally induced expansion/contraction of the Fiber Bragg Grating (FBG) to shifts in the reflected Bragg wavelength. The acquired strain data is always the apparent strain ($\epsilon_{app}$) which includes effects due to mechanical strain ($\epsilon_{mech}$) and temperature ($\epsilon_T$).

$$\epsilon_{app} = \epsilon_{mech} + \epsilon_T \tag{2}$$

The fundamental objective behind fiber optic temperature sensing is successfully minimizing the mechanical strain component, such that the measured apparent strain is only comprised of effects due to temperature.

$$\epsilon_{app} = \epsilon_T \tag{3}$$

If fiber is effectively isolated from mechanical strain, equation (1) reduces to the following:

$$\frac{\Delta\lambda_B}{\lambda_B} = \Delta T(\alpha + \eta) \tag{4}$$

Note that equation (4) only describes the first-order sensitivity of the Bragg wavelength to temperature, thus, it is only valid within the linear range. The temperature sensitivity becomes nonlinear over an extended range due to coating effects and the nonlinear nature of the thermo-optic effect. Regardless of the temperature range, a calibration is required to accurately characterize the FBG response to temperature changes. If only a linear calibration is required, equation (5) is used to correlate the measured apparent strain ($\epsilon_{app}$) to temperature:

$$T(\epsilon) = C_1\epsilon + T_0 \tag{5}$$

where $T_0$ is the temperature at measurement start. For extended ranges, equation (6) represents the general form of the calibration.

$$T(\epsilon) = C_n\epsilon^n + C_{n-1}\epsilon^{n-1} + \ldots + C_2\epsilon^2 + C_1\epsilon + T_0 \tag{6}$$

## 3 Coating Effects

Optical fiber must be coated to reduce its fragility and to allow it to be handled without breaking. The coating material is also critical to fiber's performance as a sensor. Stiff polymer coatings, such as polyimide and Ormocer, are widely used for strain sensing applications due to their excellent strain transfer properties across a wide operational temperature range. However, like all polymers, these coatings are hygroscopic in nature and will expand volumetrically as they absorb moisture from the air. Consequently, the expansion of the coating due to changes in humidity transfers a small amount of strain into the fiber optic core, resulting in an additional humidity dependent hysteresis. Since relative humidity (RH) is intrinsically dependent on the ambient temperature, this effect is undesirable for temperature sensing and limits the accuracy of the sensor.

Although a stiff coating is essential for strain sensing, a much softer coating material such as Ormocer-T is ideal for temperature sensing. Ormocer-T is equally susceptible to changes in RH as Ormocer, but the soft nature of the coating greatly reduces the humidity sensitivity of the fiber. At temperatures above approximately 50°C, Ormocer-T becomes so soft that essentially no coating induced strain transfers to the core. Ormocer-T coated fiber is recommended for temperature sensing up to 200 °C. The difference in performance of Ormocer-T compared to a stiff coating such as Ormocer largely depends on the humidity variation within the operating environment.

# 4 Sensor Preparation

Prior to using a Sensuron interrogator to perform distributed temperature sensing, the fiber must be properly conditioned and configured. The preparation steps discussed in this section are critical to optimizing the accuracy and repeatability of the measurement.

## 4.1 Thermal Conditioning

To achieve a stable thermal response, fiber must first be preconditioned to the temperature range that it is expected to operate in. At a minimum, it is recommended that a single preconditioning cycle is performed where the fiber is subjected to the maximum and minimum operating temperatures for a few hours. The conditioning cycle primarily serves to "anneal" the coating to release residual strains induced by manufacturing. If this step is bypassed, each sensor will exhibit a large hysteresis during the initial cycle compared to all subsequent cycles, which can lead to an erroneous measurement. The illustration below is provided to demonstrate the amount of hysteresis that can be present during the initial cycle.

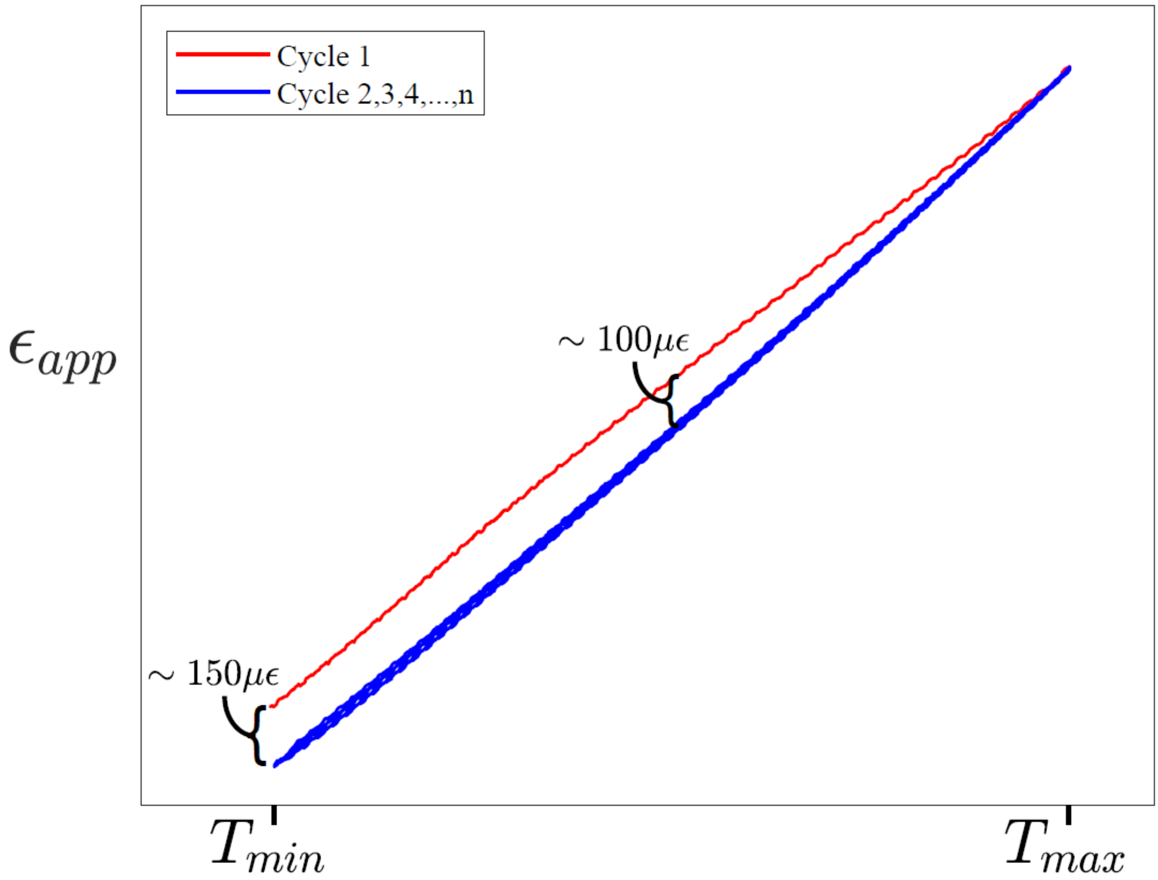



**Figure 1:** The thermal response of the fiber during the initial ramp up will deviate significantly from all subsequent cycles due to relaxation of residual strains in the fiber.

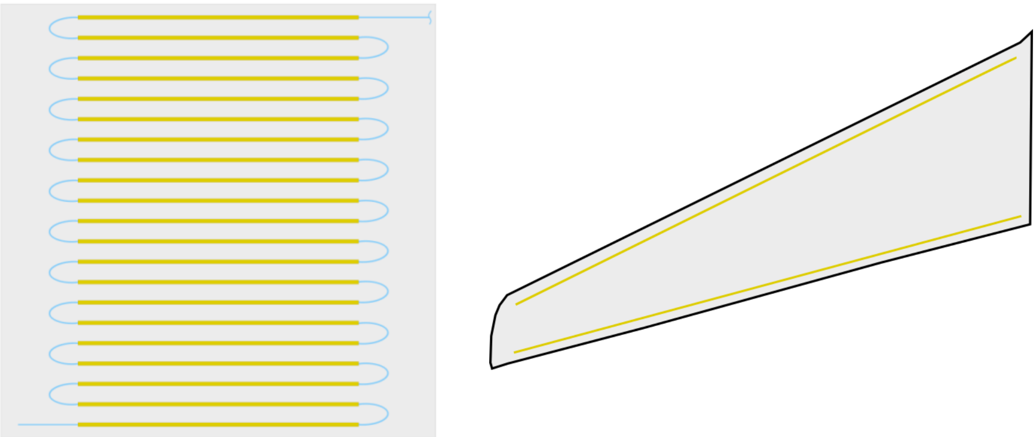
## 4.2 Packaging Considerations

The importance of keeping the optical fiber completely isolated from mechanical strain when performing distributed temperature sensing cannot be overstated. This is typically accomplished by packaging the fiber inside a small tube or capillary. The capillary is adhered to the substrate while the fiber housed inside floats freely. As long as friction effects are small, the measured apparent strain only includes effects due to temperature and a repeatable calibration curve can be generated (Eq. 6).

The overall performance of a distributed fiber optic temperature sensor largely depends on the packaging and installation configuration. Ideally, the packaging material is small in size and highly conductive to minimize thermal resistance through the tube wall. The most important consideration, however, is ensuring the fiber remains isolated from mechanical strain throughout the entirety of the temperature range. As the ambient temperature changes near the packaged sensor, the fiber and capillary material undergo thermal expansion/contraction. If there is a large contrast between the amount of thermal expansions/contraction induced in the fiber and the capillary material, friction effects become more significant. Ideally, the capillary material has a CTE similar to that of silica glass ($0.55 \times 10^{-6}$/°C) so that the fiber and packaging materials expand/contract similar amounts. One should be mindful that if the packaged sensor is bonded to a substrate with a mismatched CTE, it will be forced to undergo the same expansion/contraction as the substrate. Regardless, friction effects can be mitigated if proper installation procedures are followed.

## 4.3 Installation Considerations

Depending on how the fiber is packaged and installed, the thermal expansion/contraction of the capillary material can induce mechanical strain within the fiber via friction effects, resulting in an incorrect temperature measurement. The installation configurations shown in Figure 2 demonstrate how to mitigate friction effects.



(a) (b)

**Figure 2:** (a) The general installation strategy for complex layouts that require turns and bends. Only the straight segments of fiber are housed inside a tubing while the fiber bends remain free. If no turns or bends are required, the entire length of fiber may be packaged, as illustrated in (b).

If many turns and bends are required within the installation configuration to achieve the desired spatial coverage, it is recommended that only the straight portions of fiber are packaged or housed inside a tube. This installation strategy is illustrated in Figure 2(a). Due to thermal expansion of the tubing material, a significant amount of friction induced strain can build up within the fiber if the fiber bends are also packaged. If the installation layout follows the general concept demonstrated in Figure 2(a), undesirable friction effects are minimized. If the installation layout does not require any turns or bends, the entire length of fiber may be packaged, as illustrated in Figure 2(b).

Depending on several factors, it is possible to package the entire fiber even if the installation requires turns and bends. Such factors include the length of the fiber, number of turns required, bend radius of each turn, capillary material, inner diameter of the capillary, and temperature range. Generally, only a few turns will be able to be accommodated. All installation configurations should be validated before use.

# 5 Calibration

The overall accuracy of a fiber optic temperature sensor is also highly dependent on the quality of the calibration. The two primary devices employed as reference temperature sensors during calibration are thermocouples and resistance temperature detectors (RTDs). Both devices can be used effectively, however, calibrating with thermocouples is typically less cumbersome because you are able to measure the temperature at a highly localized point. As illustrated in Figure 3, thermocouples can be adhered to the outside of a packaged temperature sensor to monitor the local ambient temperature at a single fiber optic sensor location.

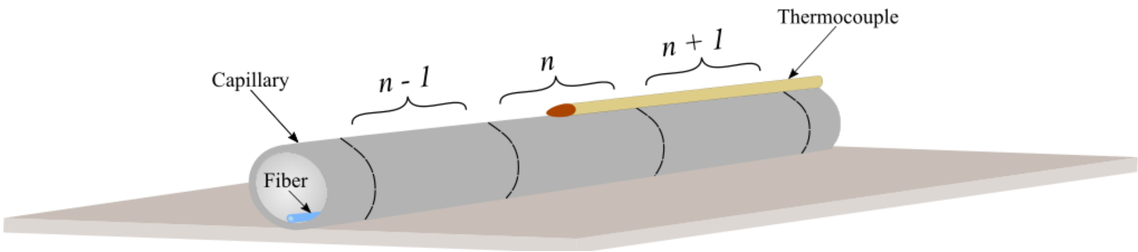



**Figure 3:** A thermocouple is positioned at fiber optic sensor $\boldsymbol{n}$ to monitor the local ambient temperature. The thermocouple data and measured apparent strain at sensor $\boldsymbol{n}$ are correlated to generate a polynomial calibration curve. For optimal calibrations, thermal paste or heat conductive tape should be used at the thermocouple interface.

The thermocouple output can be easily correlated to the output of the fiber optic sensor to generate the calibration curve. Calibration should always be performed across the entire temperature range that the fiber optic sensor will operate in. Due to their superior accuracy and repeatability compared to other types, Type T thermocouples are optimum for temperature ranges within -200°C to 200°C. The order of the polynomial function (Eq. 6) required to accurately map the apparent strain data to temperature will depend on the temperature range.

For Ormocer-T coated fiber (Figure 4), a linear calibration is sufficient within the range 25°C to 90°C, with higher order polynomials required for extended ranges.

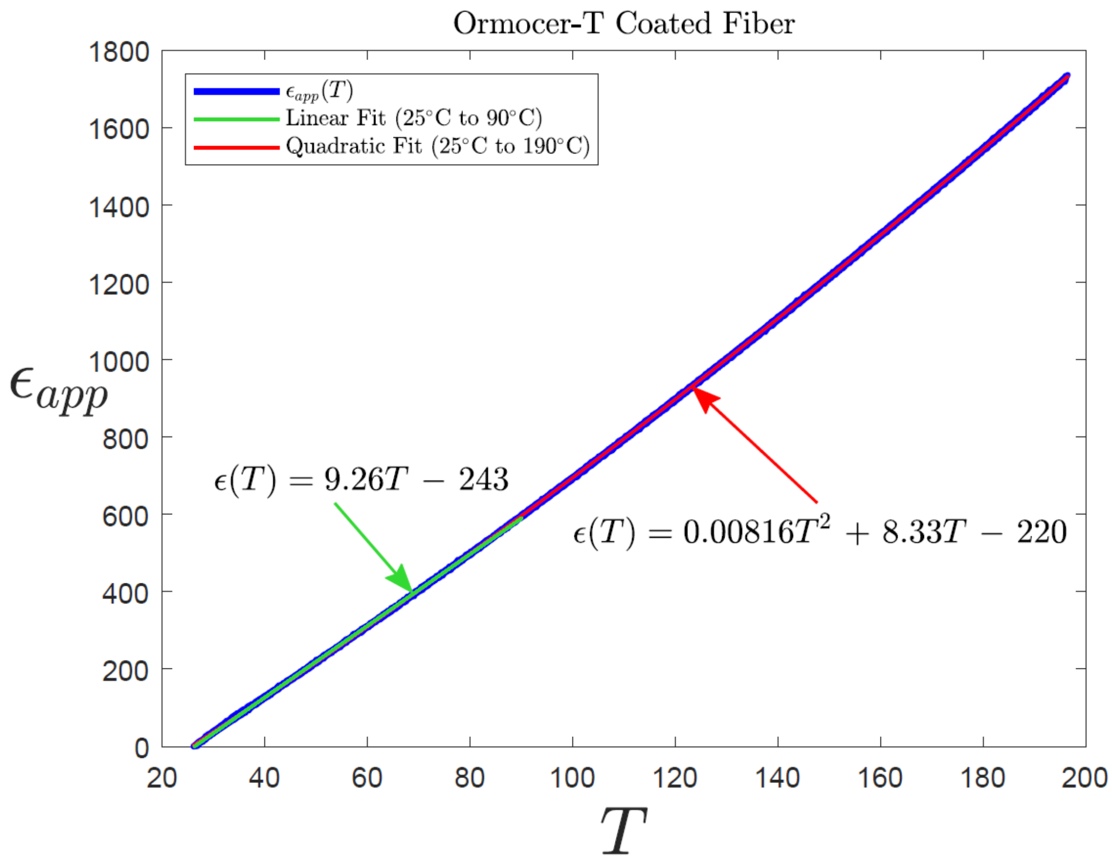



**Figure 4:** The temperature sensitivity of Ormocer-T coated fiber is shown. The sensitivity is effectively linear from 25°C to 90°C at approximately 9.2με/°C. Beyond 90°C, a higher order polynomial calibration is required as the sensitivity becomes nonlinear.

## 6 Empirical Results

The procedures discussed in Sections 3 through 5 are carried out to assess the feasible accuracies that can be obtained using a Sensuron Summit interrogator and Ormocer-T coated fiber. For this preliminary study, the temperature range to be investigated is 25°C to 190°C using a sensor length of 2.5m.

### 6.1 Sensor Preparation

The fiber is annealed at 200°C for 6 hours to stabilize the thermal response prior to use. For all experiments, the maximum operating temperature is limited to 190°C to safely operate below the annealing temperature.

### 6.2 Test Fixtures

Two test fixtures are utilized: one for calibration (aluminum beam fixture) and one to perform an accuracy assessment (aluminum plate fixture).

### 6.2.1 Aluminum Beam Fixture

Approximately 0.25m of fiber is installed on the top surface of a short aluminum beam (6061-T6511) using square brass tubing (3/32”). This fixture is utilized to acquire calibration data to characterize the temperature sensitivity of this specific batch of fiber. The generated calibration equations are used to assess the accuracy of the sensor shown in Figure 6.

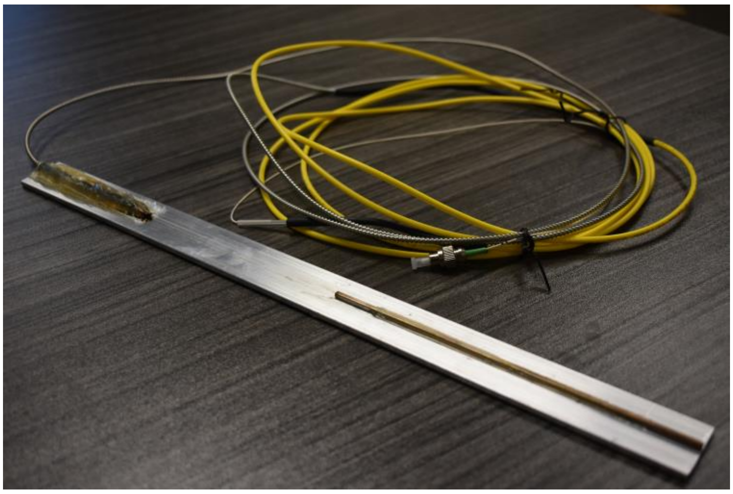


**Figure 5:** A short length (0.25m) of Ormocer-T fiber is used for calibration**.**

### 6.2.2 Aluminum Plate Fixture

2.5m of fiber is installed on the top surface of an aluminum plate (2024-T3) and packaged in square brass tubing (3/32”). Due to its robustness and high thermal conductivity, brass square tubing is used, but there is significant flexibility in choosing the capillary material and geometry. As shown in Figure 6, several small bends and turns are included in the installation pattern.

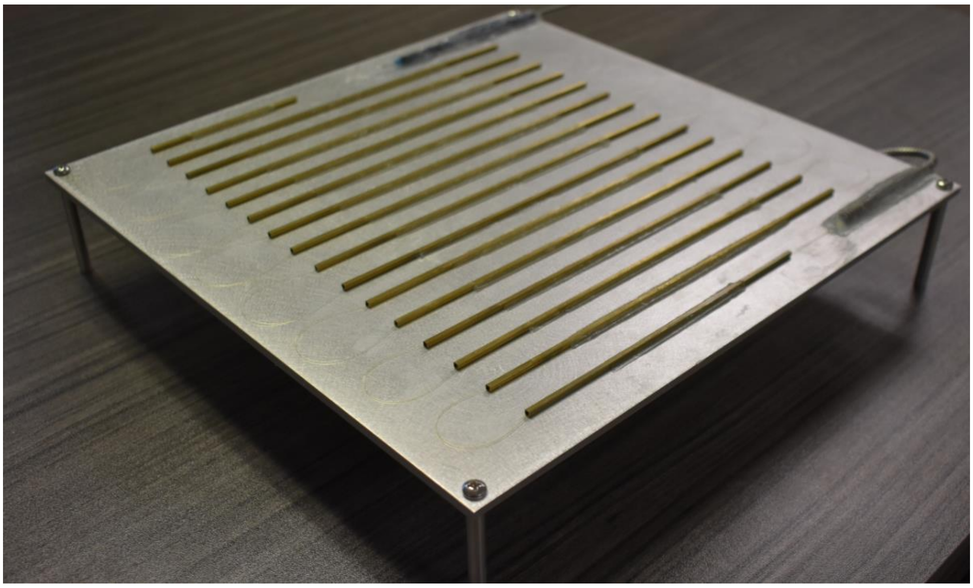


**Figure 6:** Several short segments of brass are utilized to achieve the desired spatial coverage. Depending on the chosen operational spatial resolution, the 2.5 m sensor length is comprised of between 100 and 1600 temperature sensors.

## 6.3 Calibration

Throughout all experiments, Type T Thermocouples (PFA insulated, 30 gauge) are utilized as the reference temperature sensors. National Instruments hardware used to record the thermocouple measurements includes a cDAQ-9185 Chassis and two NI-9212 thermocouple modules. To generate a calibration, a single thermocouple is placed at an arbitrary fiber optic (FO) sensor location along the short beam test fixture.

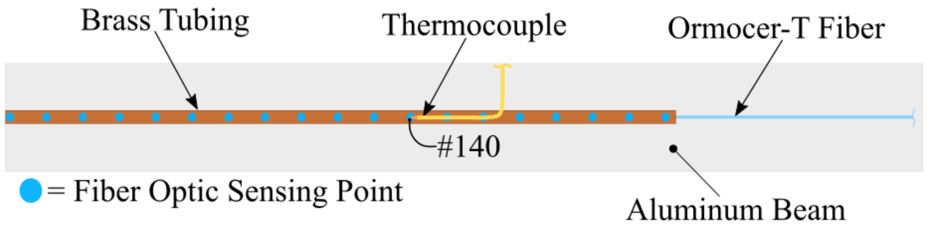



**Figure 7:** The corresponding fiber optic (FO) sensor number (#140) is identified and recorded. Thermal paste is used at the thermocouple interface to minimize the temperature difference between the thermocouple and fiber optic sensor.

The corresponding fiber optic sensor is identified (#140) by using a localized heat source to stimulate the sensor. The sensor number corresponds to the X-axis location of the sensor in the RTS Client software visualizer window. Data is recorded for three complete temperature cycles (25°C to 190°C) to evaluate the calibration behavior of the fiber. To minimize thermal gradients inside the thermal chamber, the temperature cycle profile included a ramp rate of 2°C/min and 30 min dwell periods at the extreme temperatures. Synchronization of the thermocouple data and fiber optic sensor data is performed using LABVIEW. The recorded calibration data is shown in Figure 8.

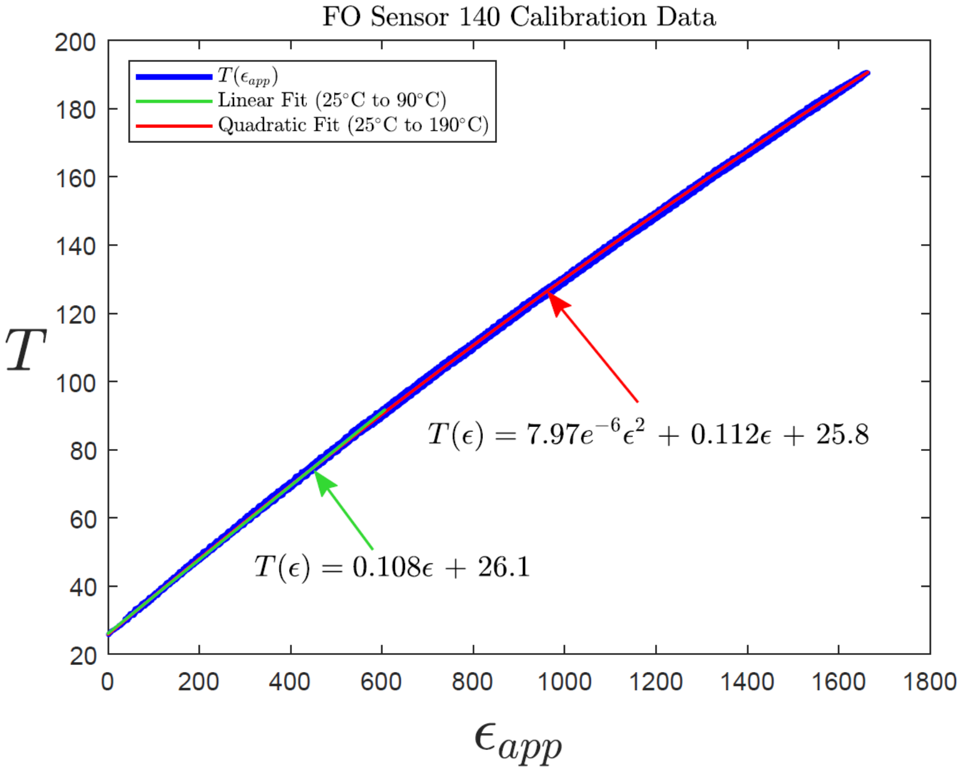



**Figure 8:** The linear and quadratic calibration equations are shown. For this temperature range (25°C to 190°C), higher order calibration equations are required for optimal performance.

To assess the performance of the 2.5m fiber installed on the aluminum plate fixture, linear (Eq. 7) and 4th order (Eq. 8) polynomial functions are generated from the data set plotted in Figure 8 (p. 10). The linear calibration is only valid from 25°C to 90°C while the quartic calibration is valid from 25°C to 190°C.

$$T_{linear}(\epsilon) = 0.1082\epsilon + 26.12° \quad (7)$$

$$T(\epsilon) = 1.235^{-12}\epsilon^4 - 2.893^{-9}\epsilon^3 - 6.355^{-6}\epsilon^2 + 0.1121\epsilon + 25.85° \quad (8)$$

## 6.4 Accuracy Assessment

To perform a comprehensive accuracy evaluation of the 2.5m fiber, a total of 9 thermocouples (TCs) are placed at arbitrary fiber optic sensor locations on the aluminum plate test fixture. For this evaluation, the interrogator is operated using 12.7 mm spatial resolution. The locations of the 9 thermocouples are illustrated in Figure 9.

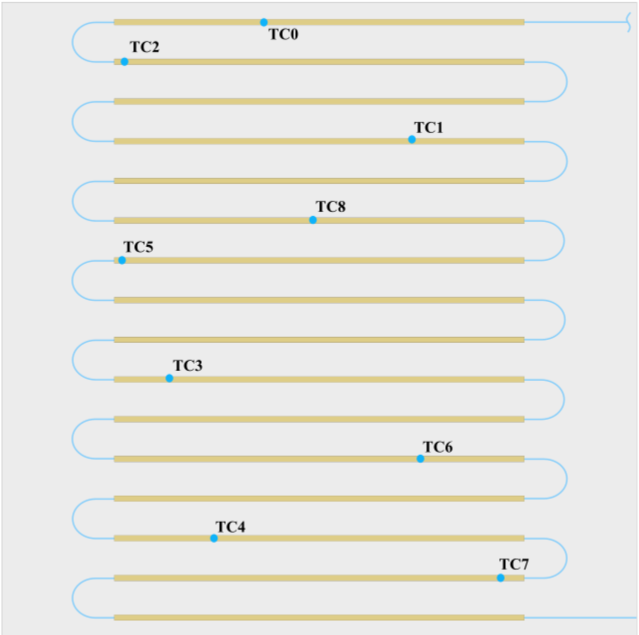



**Table 1**

| TC# | FO Sensor # |
|---|---|
| TC0 | 173 |
| TC1 | 196 |
| TC2 | 178 |
| TC3 | 233 |
| TC4 | 262 |
| TC5 | 221 |
| TC6 | 256 |
| TC7 | 275 |
| TC8 | 215 |

**Figure 9:** The locations of the 9 thermocouples are shown. At each thermocouple location, the corresponding fiber optic (FO) sensor number is identified and recorded in Table 1. Thermal paste is used at each thermocouple interface to minimize the temperature difference between the thermocouple and fiber optic sensor.

Data is acquired from each thermocouple and fiber optic sensor following the same procedures and temperature profile described on page 10. At each thermocouple location, the corresponding fiber optic sensor is identified (Table 1) using a localized heat source. Two complete temperature cycles (25°C to 190°C) were completed using a ramp rate of 2°C/min and dwell periods of 30 minutes at the extreme temperatures. Using equations (7) and (8), the temperature at each of the 9 FO sensor locations is measured throughout the 14-hour test. Residuals between each FO sensor and corresponding thermocouple are calculated using both the linear and quartic calibration equations (Figure 9).

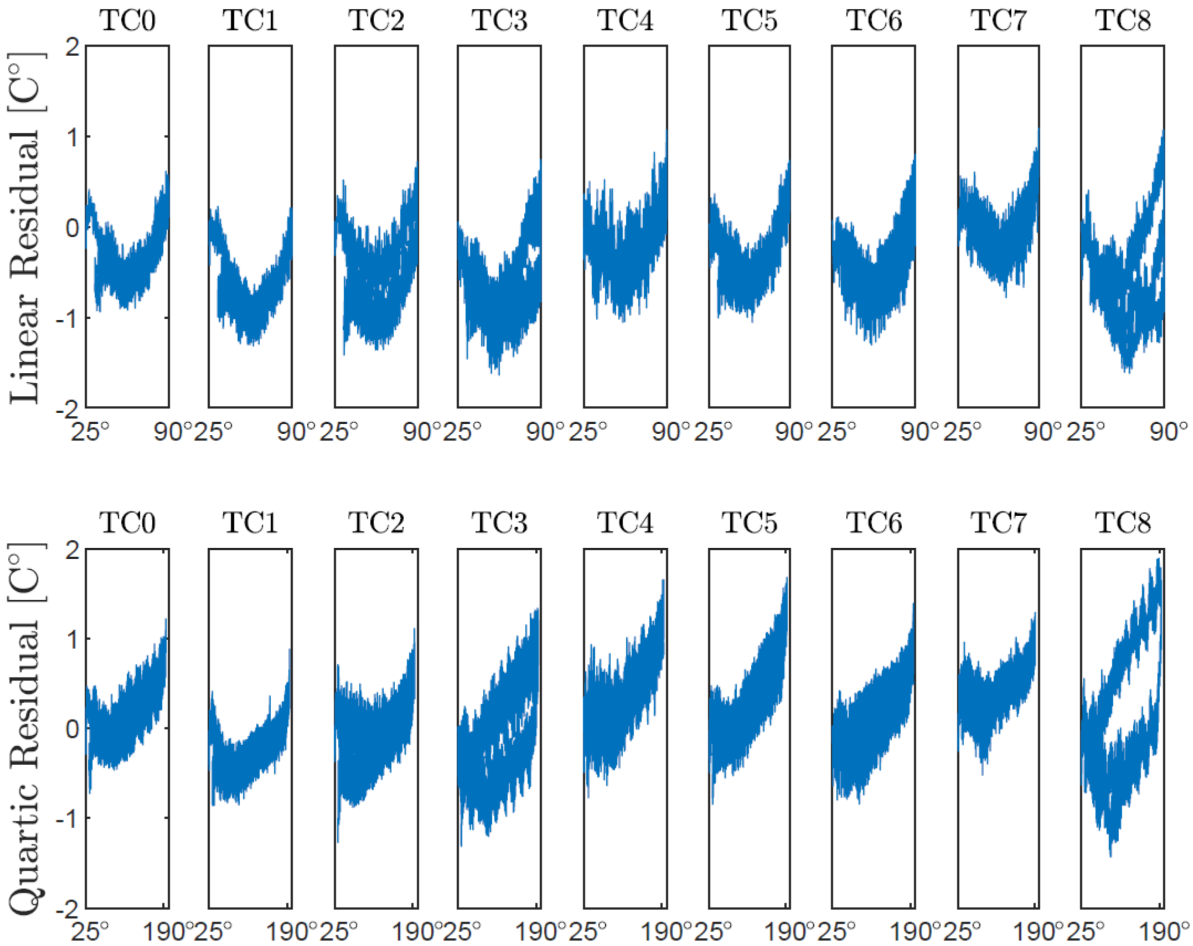



**Figure 9:** Residuals from linear and quartic fits over the ranges 25°C – 90°C and 25°C – 190°C, respectively.

Evaluating the linear range of 25°C to 90°C, the FO sensor located at TC3 (FO Sensor #233) registered the largest single point residual of 1.64°C. Over the full range of 25°C to 190°C, FO Sensor #215 (located at TC8) registered the largest single point residual of 1.89°C. The average residual across all 9 thermocouples for the linear and full temperature ranges is 0.50°C and 0.38°C, respectively. These results are summarized below in Table 2.

**Table 2**

| | Linear (25°C - 90°C) | Quartic (25°C - 190°C) |
|---|---|---|
| Max Residual | **1.64°C (TC3)** | **1.89 °C (TC8)** |
| Average Residual (Across All TC's) | **0.50°C** | **0.38°C** |

# 7 Technology Benefits

Sensuron's fiber optic sensing technology provides a new level of insight into surface and ambient temperature distributions, allowing users to thermally map areas of interest in real-time with a spatial resolution as low as 1.6 mm. This level of data granularity is impractical to achieve using traditional single point temperature sensors. Due to its small size, chemical inertness, and immunity to electromagnetic interference, optical fiber can be installed in environments that alternative sensors cannot operate in. Processes that rely on maintaining temperature uniformity such as the curing of composite parts or thermal management of battery packs stand to benefit greatly from these capabilities.

In the rocket industry, adequate thermal insulation is critical to the survivability of the rocket and overall mission success. Distributed temperature sensing can be utilized to optimize the thermal insulation design and reduce weight. Other applications include optimizing the performance and effectiveness of heat exchangers, such as a radiator, by thermally mapping the path of the working fluid. Due to the continuous nature of the measurement, temperature gradient distributions are fully captured, providing engineers significantly greater insight into the underlying physics of their device.

A vast majority of applications that currently employ traditional single point temperature sensors, such as thermocouples, would benefit from having thousands of additional measurement points. The primary reasons that thermocouples are currently deployed in limited quantities is the installation time associated with each sensor, the cumbersome wire bundles, and the associated weight penalty. Sensuron's fiber optic sensing technology overcomes all three of these issues, enabling engineers to capture information that would otherwise be impractical to gather.

# 8 Summary

The underlying physics and fundamental preparation steps involved in successfully performing distributed fiber optic temperature sensing with the Sensuron technology are discussed. Using Type T Thermocouples, residuals below 2°C are demonstrated for a 2.5m optical fiber comprised of approximately 200 temperature sensors. Within the range 25°C to 190°. the maximum and average residual across nine arbitrary fiber optic sensors are 1.89°C and 0.38°C, respectively.

For more information, please contact info@sensuron.com