TESTING OF A FIBER OPTIC WEAR, EROSION AND REGRESSION SENSOR

Valentin Korman
K Sciences GP, LLC, Huntsville, AL 35805

Kurt A. Polzin
NASA - Marshall Space Flight Center, Huntsville, AL 35812

ABSTRACT

The nature of the physical processes and harsh environments associated with erosion and wear in propulsion environments makes their measurement and real-time rate quantification difficult. A fiber optic sensor capable of determining the wear (regression, erosion, ablation) associated with these environments has been developed and tested in a number of different applications to validate the technique. The sensor consists of two fiber optics that have differing attenuation coefficients and transmit light to detectors. The ratio of the two measured intensities can be correlated to the lengths of the fiber optic lines, and if the fibers and the host parent material in which they are embedded wear at the same rate the remaining length of fiber provides a real-time measure of the wear process. Testing in several disparate situations has been performed, with the data exhibiting excellent qualitative agreement with the theoretical description of the process and when a separate calibrated regression measurement is available good quantitative agreement is obtained as well. The light collected by the fibers can also be used to optically obtain the spectra and measure the internal temperature of the wear layer.

INTRODUCTION

Harsh environments, by their very nature, adversely affect materials commonly associated with propulsion systems. These materials may be subject to high temperature, high energy particle impingement, exposure to ionized gases, or surface-to-surface frictional interaction. These different environments can all wear the exposed surface in some manner (erosion, regression, etc). In propulsion applications quantification of the wearing processes and rates is critical to propulsion component development and qualification, but it can be difficult to experimentally quantify these wearing mechanisms.

Wear metrics (including regression and erosion rates) are typically based on numerical models [1]. Few sensing devices or methods are capable of performing intrinsic wear measurements, particularly in real-time and *in situ*. Commonly, non-real-time extrinsic methods are instead used to measure wear, with most of these involving interruption of a test to permit physical measurements using more traditional methods [2]. Available real-time measurement methods rely on either surface profiling (e.g. laser profilometers) [3] or eroding 'sensors' which are capable of monitoring the temperature within a wearing environment but do not themselves have the same *in situ* response to the actual wear mechanisms affecting the material under test [4-5].

Recently, a fiber optic sensor was presented that is capable of measuring real-time *in situ* regression, erosion and wear in a variety of materials under numerous conditions [6]. The Regression, Erosion and Ablation Sensor Technology (REAST) [7] was initially developed to perform real-time measurement of the regression of solid rocket propellants, but it has since been demonstrated in a wide range of applications, including but not exclusively limited to propulsion. In this paper, we briefly review the REAST sensing technique and then present wear data obtained for many different applications in a number of different environments demonstrating the wide applicability of the method.

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SENSING PRINCIPLE

Fundamental to the operation of the fiber optic wear sensor is the transmission of light through an attenuating waveguide (e.g. optical fiber) as described mathematically by Beer's law [8] and shown schematically in Fig. 1. The attenuation coefficient, α, carries units of loss per unit length (e.g. dB/cm) and is an intrinsic property of the particular waveguide material. For high quality fiber optic glasses attenuation values are on order of a single dB/km. The attenuation of the fiber may be altered by a variety of methods to achieve values as high as 10 dB/mm. The REAST sensor, shown schematically in Fig. 2, is formed using two optical fibers with differing attenuation coefficients. The fibers are embedded in a parent material and both it and the fibers are worn or eroded over time by the same process. In the simplest case, the thermal environment responsible for the wear mechanism also provides the light collected by the sensor.

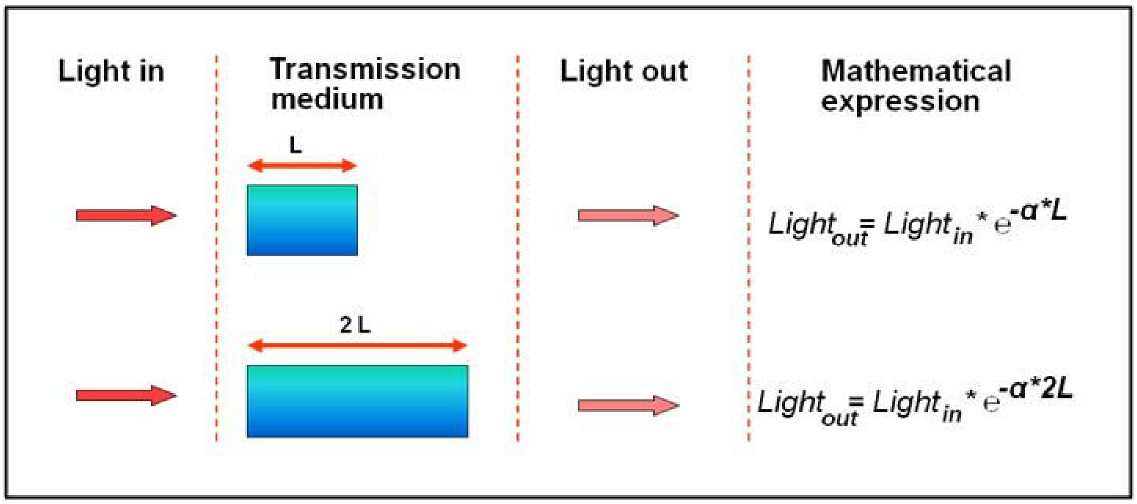

Figure 1 – Schematic description of Beer's law governing light propagation through a waveguide of given an attenuation α and length *L* [8].

In the limit where the cross-sectional area of the fiber is small compared to the exposed surface of the host material, we can assume that the amplitude of the light collected from the wearing process is equal for the two fibers. This permits algebraic manipulation to solve the equations shown in Fig. 2 for length. Here length refers to the fiber length, which will provide a measure of the host material wear rate if the two wear at the same rate. In practice, the tips of the two sensing fibers need to have differing attenuation coefficients only over the distance of expected wearing. The probes are typically formed from fusion splicing the attenuating regions upon a length of standard low-loss optical fiber. The low-loss fibers act as light conduits permitting the detector electronics to be located away from the wearing zone.

Detection of the optical signal is done through photoelectric conversion within a photodiode. Silicon photodiodes have shown a sufficient response when the temperatures at the wearing layer surpass 350 ^{o}C. For cooler wear processes, two alternative options have been demonstrated. A photodiode sensitive to longer wavelengths (and thereby cooler blackbody temperatures) may be used for detection if the temperature isn't too cool. Alternatively, a third fiber may be embedded into the parent material to backward propagate an exterior source of light (provided by a light emitting diode, laser, etc) that can be re-collected by the fibers comprising the sensor.

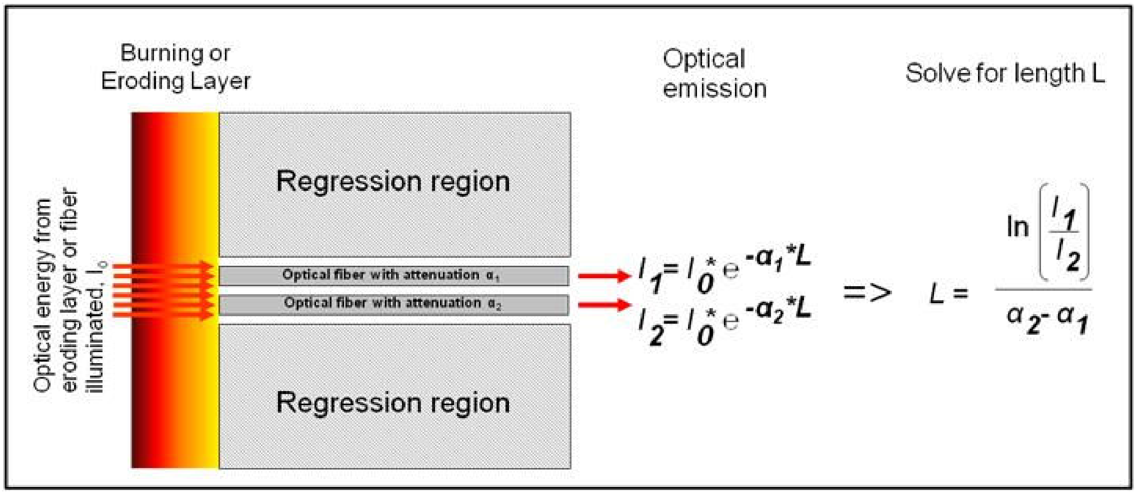

Figure 2 – Operational schematic of the fiber optic wear sensor.

RESULTS AND DISCUSSION

The REAST sensor was originally developed to monitor the propellant regression within a solid rocket motor. Tests were conducted on various small-scale rocket motors or in "motor-like" environments. These included tests on perchlorate-based road flares (2800 °C) and Estes-brand model rocket motors. In both these tests the fibers were introduced longitudinally into the components to monitor the regression of the propellant rate. The data obtained using the flare are presented in Fig. 3. These data exhibited reasonable agreement with the highly unstable burning rate of the flare, which was observed to chugs, crackle and pop as it burned. Unlike the longer-lasting flare, the Estes rocket motor burned very quickly and in a more stable manner as demonstrated in the data presented in Fig 4.

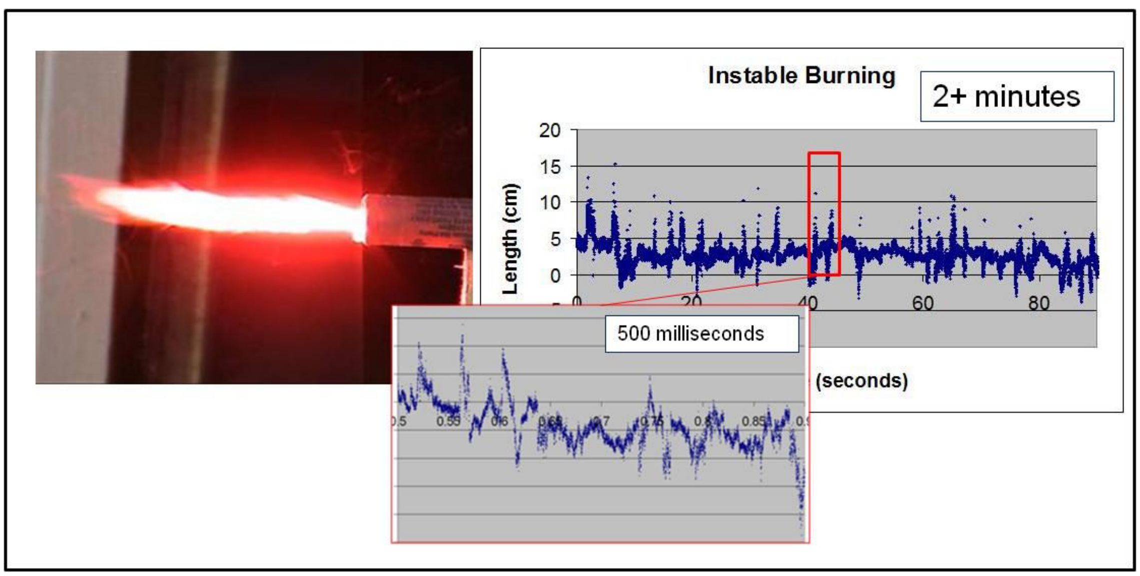

Figure 3 – Length sensing on a road flare. Burn instabilities are shown on a faster timescale.

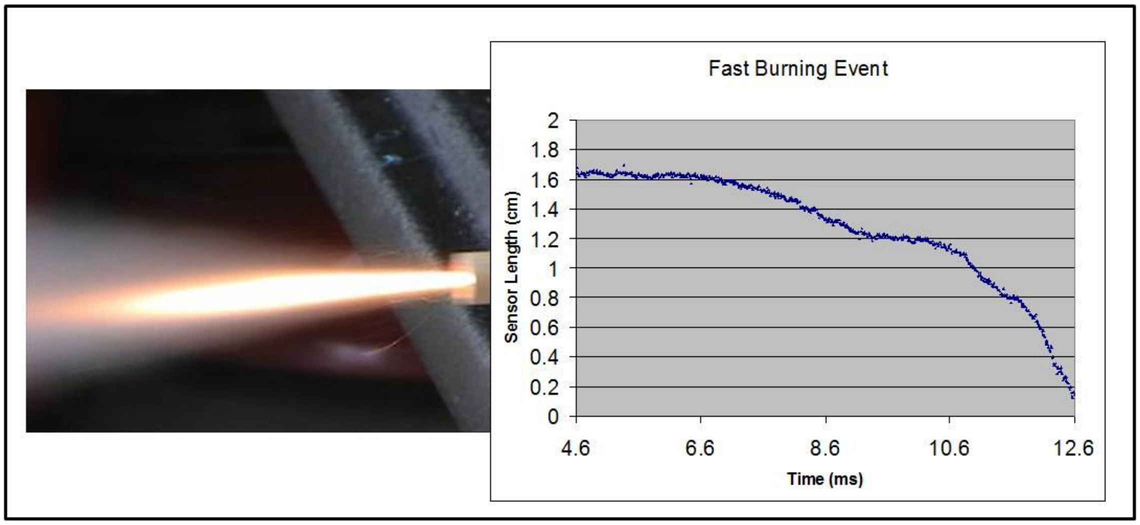

Figure 4 – Regression in fast burning Estes-brand rocket motor.

In addition to the regression measurements in combustion applications, testing was performed using a fluted-end cutter on an automated milling machine to slowly cut away an aluminum substrate that was instrumented with a REAST sensor.. The wearing process closely resembles a fracturing or chipping mechanism. The use of the mill, with its computer controller, permitted real-time feedback of the length eroded as the cutting tool was advanced into the substrate. In this application, the temperature is relatively low so an additional fiber was used in the sensor to propagate light from a white light LED source in the manner described in the previous section. The test setup and data obtained for two separate measurements of the cutting process are shown Fig. 5. The ‘cleaner’ test data were acquired in between passes of the cutter. The aluminum test article was capped by an aluminum cap for these data creating a simulated “target” for the emitted LED signal. The ‘coarser’ or noisier raw data plot was obtained real-time during the cutting operation.. During the cutting operation, it was discovered that the sensor scavenged light from the facility overhead lighting (fluorescent lights), providing a means to perform the measurement real-time. Of particular note is the improvement in the signal-to-noise as the fiber is worn. When the probe is longest, the difference in the two signals transmitted by the sensing fibers is greatest and the amount of noise in the ratio of the two intensities is greatest. This noise decreases as the probe shortens and the difference in the two signals decreases.

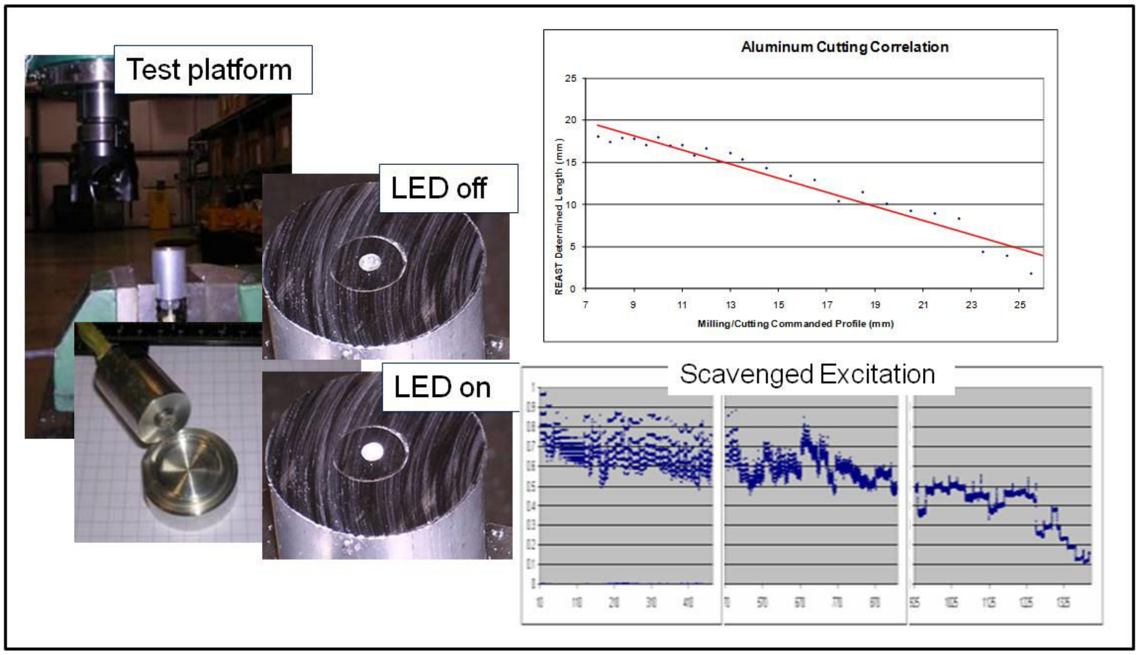

Figure 5 – Wear simulated by the cutting of an aluminum substrate.

Testing was also carried out through metal-to-metal high temperature friction-type erosion. A thermally isolated relatively hard stainless steel alloy (type 316) was held by the rotating part of a machine lathe. While rotating, a softer (type 304) stainless steel test article with an embedded wear sensor was forced into the rotating part. The position of the probe relative to the harder wearing drum was monitored using a position gauge. During testing a molten zone was quickly formed as well as spallation of the softer alloy onto the harder. The formation of the melt zone of the 304 alloy signifies a temperature exceeding 1400 ^{o}C [9]. The test fixture and resulting wear measurements are presented in Fig. 6.

The REAST sensor has been tested at NASA Marshall Space Flight Center's Hyperthermal Test Facility. An arc-heated nitrogen flow is passed through a throat generally comprised of graphite. For wear sensor testing, the contoured graphite 'shoe' was modified so samples of differing materials would compromise the outer wall of the throat, ablating over time as she hot arc-heated gas passed through the system. Results obtained for an ethylene propylene diene Monomer (EPDM) rubber sample are presented in Fig. 7.

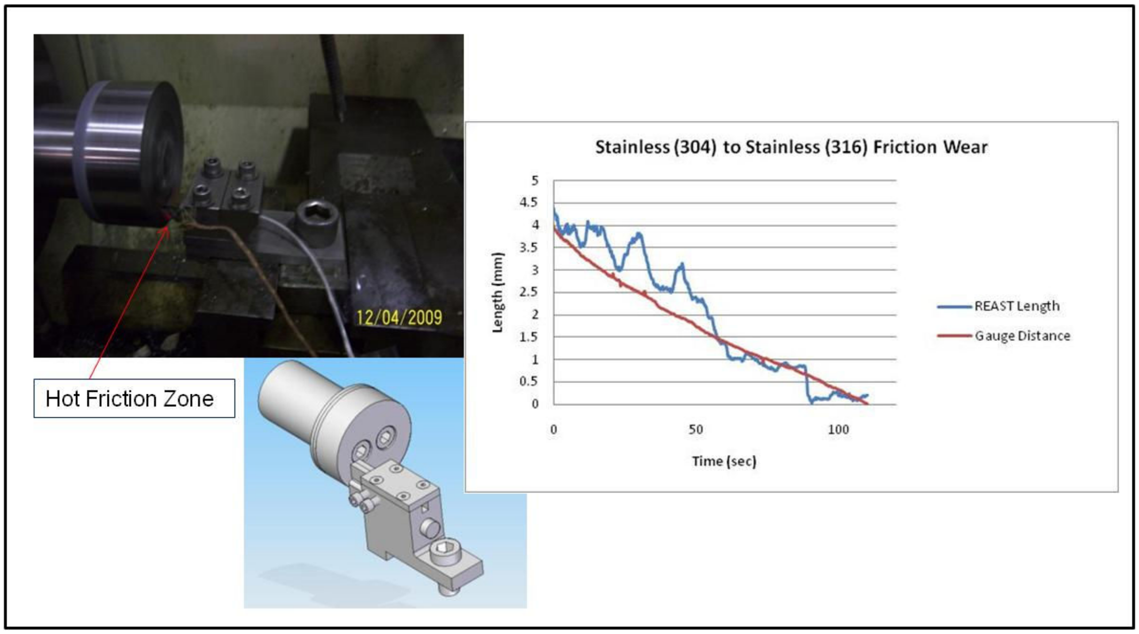

Figure 6 – Stainless steel alloy friction wear (304 stainless melting against 316 stainless).

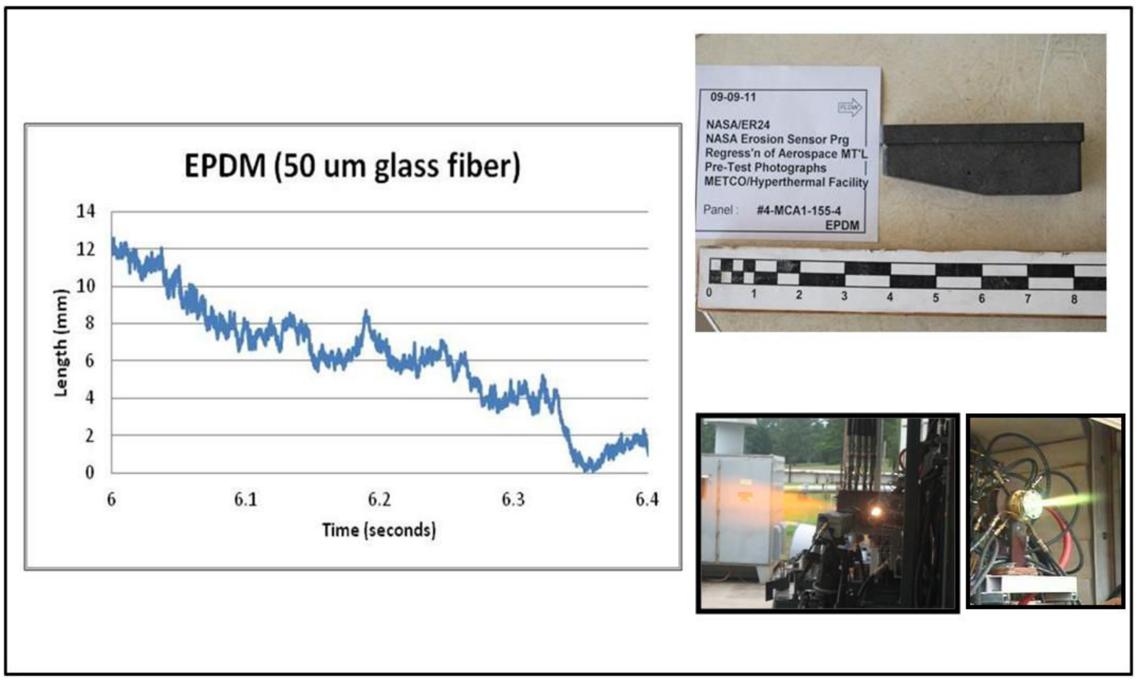

Figure 7 – Current results from EPDM erosion in NASA MSFC's Hyperthermal Test Facility, shown in the lower right part of the figure.

In addition to the regression, erosion and wear data presented here, the sensor has also demonstrated the capability of capturing optical spectra permitting the optical measurement of temperature at the wearing interface. As seen in Fig. 2, both fibers are in physical contact with the wearing layer, providing a window on the wearing event. By splitting the optical signal and measuring the spectrum using a spectrometer a black or gray body temperature may be determined. The visible optical spectrum from the *interior* of a road flare obtained during the burning process is presented in Fig. 8. For a set of fixed conditions (e.g., thermal layer is closely-coupled to the fiber) the intensity of the light for an integrated waveband, such as that of a photodiode, will be proportional to temperature to the fourth power. Two approaches may be taken. One, a blackbody or graybody temperature approximation using estimates of the emissivity as a function of temperature and wavelength. Similarly the thermal response of the probe to the wear physics can be calibrated using some other method and then assumed to be similar in the application of interest. The light transmission response as a function of temperature is shown Fig. 9 where the optical fiber was responding to a calibration thermal oven. Initial data were used to create a 'fit' function for the particular scenario of a fiber pointed at the interior of a ceramic oven. A thermocouple located inside the oven was used as the calibration benchmark source. As expected the fit function to calibrate the output of the fiber had the form of temperature to the fourth power. The test was repeated in the oven using the derived calibration function, and highly accurate results were obtained.

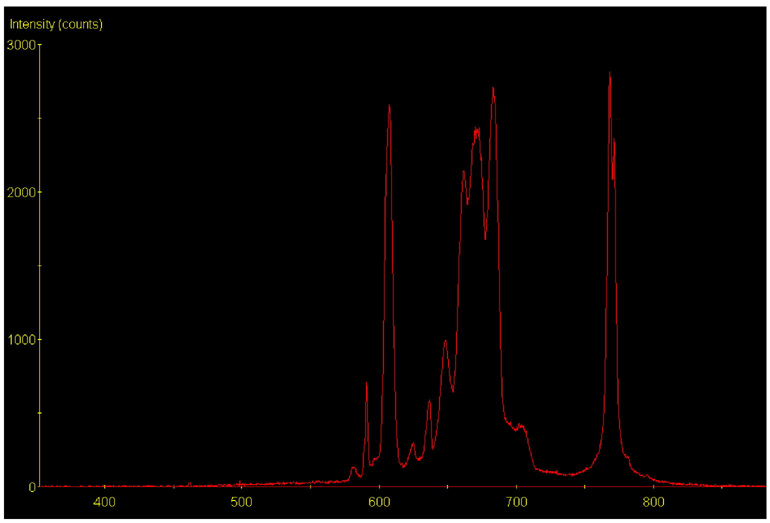

Figure 8 – Optical spectrum from the (internal) burning layer in a road flare.

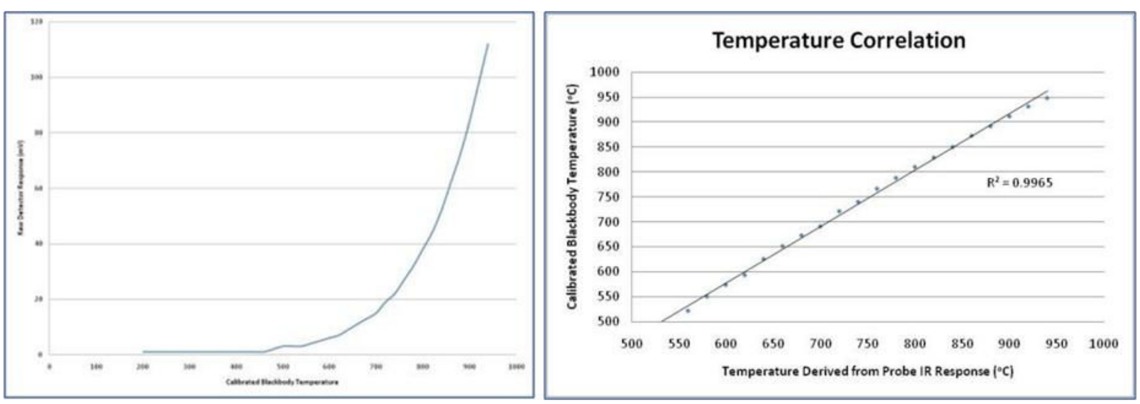

Figure 9 – Raw optical signal versus temperature obtained using a thermal calibration source (left) and the fit function for that particular system derived from the raw data (right).

SUMMARY AND CONCLUSIONS

The REAST sensor operates using two fibers of different attenuation constants, with Beer's law providing the link between the ratio of light intensity transmitted by each fiber and the remaining length of fiber. This measurement technology has been demonstrated to a variety of wearing conditions and environments. The embedded fiber sensor provides a reliable measure of length and when properly matched and embedded in a host material can provide real-time *in situ* measurement of regression, burning, erosion, ablation or wear of that material. Additionally, the optical signals may be repurposed to obtain optical spectra of the wearing layer and, with calibration, the internal temperature of the wearing layer can be found.

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