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MICROWAVE PROCESS CONTROL THROUGH A TRAVELING WAVE TUBE SOURCE

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ABSTRACT

A rapid feedback control system was designed to operate with a traveling wave tube amplifier for regulating the sintering temperature of tows and tubes in a single mode microwave cavity. The control system regulated the microwave frequency and power absorbed by the sample in order to maintain the sample temperature. Testing with NICALON tows and mullite tubes demonstrated that the control scheme worked well for stationary and slowly moving (<10mm/min) samples, but failed for fast moving samples. Difficulty with measuring sample temperatures was resolved by using a light sensor to measure the emitted light intensity and to gauge the relative degree of heating.

INTRODUCTION

Rapid feedback control with a variable frequency microwave source can provide practical process control over the heating of continuous ceramic filament tows, rods, and tubes in a single mode cavity. Process temperatures can be regulated despite large variations in dielectric loss and heating as a filament tow or rod moves through the microwave cavity. The rapid and independent control over microwave frequency and power level needed for process control was obtained from a traveling wave tube (TWT). Phase information from the microwave cavity can be used in a negative feedback loop to track the cavity frequency as it shifts due to changing dielectric properties of the load during heating [1,2]. By sampling the electric field level in the cavity, process temperatures should be controlled by regulating the microwave power absorbed in the heated tow or tube [1,2]. Absorbed power by the sample was chosen to be the controlled variable, rather than temperature, because of the problems in measuring the sample temperature [1-3]. This work examined the assumption that constant absorbed power under steady state heating will produce a constant temperature in the tow or tube. Examples of applied process control are described for microwave heating of NICALON tows and mullite tubes. The challenging tasks of process temperature measurement and verification of heating control in tows and tubes are discussed.

EXPERIMENTAL

A block diagram of the microwave system with the frequency and power controllers is shown in Figure 1. Diagrams of the controllers were described in earlier work [1,2]. The TWT amplifier had an output frequency range of 2.5 to 8.0 GHz and an output power of 0-300 Watts. The cavity RF signal and power absorbed by the cavity were measured by an electric field probe positioned at an electric field maximum. The forward power (RF_f) and cavity (RF_c) signals are RF signals used by the frequency controller to modulate the TWT output frequency. An independent frequency counter monitored the output frequency.

The power controller monitored four power levels in the system. The forward power (P_f) is produced by the TWT and transmitted towards the cavity. The reflected power (P_r) is returned from the cavity due to the non-ideal matching of the iris, cavity, and load. The cavity power (P_c)

is lost in the walls of the cavity due to its non-zero resistance. The absorbed power (P_a) is absorbed by the load in the cavity. The forward, reflected, and total cavity powers are measured directly by the controller, while the absorbed power is numerically derived. The difference of the forward and reflected power (P_f-P_r) is the total power in the cavity (P_c+P_a), either absorbed by the load or lost in the cavity walls. If P_c is subtracted from the difference of P_f - P_r, the remainder is the absorbed power P_a given by

$$P_a = P_f - P_r - P_c \qquad (1)$$

The control system measures P_f, P_r, and P_c, performs the above arithmetic, displays P_a, and controls it by modulating P_f. Independent power meters measured and recorded the three power levels for the tests. For the P_a reading to be accurate, the P_f, P_r, and P_c measurements must be calibrated.

First, a network analyzer was used to measure and calibrate the attenuation between the TWT input and the P_f, P_r, and P_c ports. By replacing the cavity with a well-matched load, P_c and P_r are nearly zero. Also, P_a equals P_f. The TWT power was swept, and the gain and offset of the control system P_f port were adjusted so that the displayed power corresponds to the power meter reading. To calibrate P_r, the load was replaced with a short which ensures that P_f equaled P_r and P_c was zero. The TWT power was again swept, and gain and offset of the control system P_r port were adjusted so that the displayed power remains zero. The final step was to calibrate P_c. By placing the cavity back into the system with no load, P_a should be zero. The cavity was excited at its resonant frequency and again the TWT power was swept while the gain and offset of the control system P_c port are adjusted so that the displayed power reading was zero. Thus with all three powers calibrated, the controller and its display were calibrated to read an accurate P_a.

The TE_{10n} single-mode cavity in Figure 1 was described in earlier work [1,2]. The test cavity was tuned to operate near 2.95 GHz. The cavity has two pairs of opposing circular ports, shown in Figure 2, positioned at an electric field maximum. Test samples were loaded vertically through the ports aligned with the transverse electric field in the cavity. A second pair of ports, perpendicular to the transverse electric field in Figure 2, provided for insertion of an Accufiber optical fiber thermometer (OFT) and for video recording of the heated sample. This local OFT lightpipe measured a mean temperature over the 4-5 mm sample length by line of sight. The angled port next to local OFT port in Figure 2 held a second global OFT sensor that viewed the entire 34 mm length of the heated sample in the cavity. The local OFT unit was a dual-wavelength sensor, measuring temperature at 800 nm and 950 nm [1-3]. The global OFT was a sensitive single-wavelength sensor, operating as a light meter over a 1-2 μm band to gauge the relative degree of heating.

The feedback controllers were tested by microwave heating stationary and moving test samples to observe the ability of the controllers to regulate the sample temperature and absorbed power. The sample length in the cavity was 34 mm long. The test samples included continuous NICALON tows (PVA sizing and 0.2 gm/m density) and thin-walled mullite tubes of two different diameters. The outer diameter and wall thickness for each tube were 1.6 mm x 0.2 mm and 4.5 mm x 0.8 mm.

RESULTS

Absorbed Power

Figure 3a shows the independently measured P_f, P_r, and P_c powers for a NICALON tow pulled at different speeds. The derived absorbed power P_a from Equation 1 is given in Figure 3b. While pulling at 8 mm/min, P_a was increased three times. Fluctuations in P_a occurred at faster pulling speeds in Figure 3b because the heated fraction of the tow length in the cavity was rapidly changing. The power controller also performed excellently for the mullite tubes at slow pull speeds (<10 mm/min). Our tests clearly demonstrated that the power controller operated as designed by maintaining P_a at a constant preset value. While pulling the 1.6 mm mullite tube at 40 mm/min, the controller automatically held P_a at a constant value, although greater than the preset one.

Microwave Frequency

Figure 4 gives the response of TWT output frequency and the frequency controller to stairstep changes in P_a for a stationary sample of 4.7 mm mullite tube. Decreases in P_a and sample temperature (not shown) produced increases in the cavity resonant frequency on the order of 0.2-0.5 MHz with probable decreases in the sample permittivity. Conversely, an increase in P_a and temperature yielded an decrease in the cavity resonant frequency. In general, the cavity resonant frequency with a stationary sample was constant under constant P_a for the test samples. However, pulling the sample or changing the pull speed produced a change in the resonant frequency. The frequency response in Figure 5 to a rapidly moving NICALON sample (also shown in Figure 3) was quite variable. The rapid frequency change reflected the large fluctuations in local temperature, also shown in Figure 5. From the video record of this sample, rapid changes in frequency occurred while the heated fraction of total tow length in the cavity was rapidly changing. In effect, the amount of tow sample heating was changing with time. Variation in the tow physical and dielectric properties for the moving tow could also contribute to the rapid change in the cavity frequency.

Temperature of a Stationary Sample

The temperature of a stationary sample can be regulated by the controllers for a well-behaved sample, as described in earlier work [1,2]. The temperature history of a ill-behaved stationary sample is shown in Figures 6 and 7. The dual-wavelength temperature from the local OFT for the 1.6 mm mullite tube in Figure 6 steadily approached a constant value near 960°C, while decreasing by ~100°C over 11 minutes under a constant P_a. The signal from the global light sensor in Figure 6 remained quite constant, indicating that the mean sample temperature was also constant. The video record for the sample showed that the sample heating was limited to a hot spot approximately 3-4 mm long. Also, the hot spot was slowly drifting to a position partially viewed by the local OFT, causing the measured drop in temperature.

A more extreme demonstration of the same phenomenon is given in Figure 7 for a 1.6 mm mullite tube. Prior to the temperature record shown, the hot spot on the tube was positioned below the field-of-view of the local OFT by pulling the tube through cavity in a downward direction. The temperature record in Figure 7 is for sample after stopping the tube motion. The local OFT indicates a large, rapid increase and then a large fall in the sample temperature. Signal from the global light sensor is relatively constant with a small initial increase leading to a small gradual drop. The video record shows that the hot spot on the tube rapidly drifted upward past the local OFT and settled at a position above the field-of-view of the local OFT. The temperature maximum corresponds to the hot spot passing directly in front of the local OFT.

The presence of hot spot heating and hot spot drifting was observed for all mullite samples tested in this work and in earlier work [2]. The NICALON tows did not demonstrate hot spot heating, but did clearly prefer to heat only on the upper half of the sample in the cavity.

This example of ill-behaved heating illustrates the problem of temperature measurement with a sensor, such as the Accufiber OFT, that views only a fraction of the sample in the microwave cavity. A global light sensor that views and measures the emitted light from the entire sample provides a better indicator of temperature control. The absorbed power P_a was selected as the potential control variable in this work precisely due to the extreme difficulty in measuring the sample temperature. The power controller tests indicate that controlling P_a can provide temperature regulation for stationary samples with different types of heating behavior.

Temperature of a Moving Sample

The temperature record for a NICALON tow sample, shown previously in Figures 3 and 5, is plotted in Figure 8 for the local OFT and the global light sensor. The local OFT temperature varied significantly at each of three different pull speeds (8, 18, and 39 mm/min). Because temperature from local OFT is negatively effected by rapid fluctuations in the heated tow fraction in the field-of-view, this measurement is not conclusive evidence against temperature control. The signal from the global light sensor in Figure 8 also varied significantly at the two greater pull speeds, indicating a lack of temperature control. At the slowest speed, the signal from global light sensor suggests that mean tow temperature was under control, recalling from Figure 3b that P_a was increased three times in the first half of the test at this speed.

The temperature record for a 4.6 mm mullite tube is shown in Figure 9 at a slow pull speed of 8 mm/min. At the start of the motion, the hot spot was located above the local OFT and then was rapidly pulled past the local OFT, coming to a steady position below the local OFT. This motion relative to the local OFT is consistent with the temperature curve. The oscillation in the temperature curve after 35 minutes was due to an oscillation in the position of the hot spot. The signal from the global light sensor in Figure 9 suggests that the mean sample temperature was well controlled once the hot spot had reached its steady position within the cavity.

CONCLUSIONS

The power controller performed, as designed, by holding the derived absorbed power P_a constant for stationary samples, slowly moving mullite tubes, and rapidly moving NICALON tows. The frequency controller rapidly adjusted the TWT output to track the cavity resonance frequency as the sample temperature changed. The mean sample temperature was regulated for stationary and slow moving (<10 mm/min) samples by controlling the absorbed power P_a. For faster moving samples, the mean temperature was found to fluctuate by 200° to 400°C over several seconds despite overt control of P_a.

Temperature measurements by an Accufiber OFT sighting only a fraction of the tow or tube in the cavity were strongly hindered by non-symmetric heating in a TE_{10n} cavity and by the difficulty to target the hottest portion of the sample. Samples frequently heat at hot spots (mullite tubes) or only on the upper half of the vertical sample (NICALON). To assist the OFT, a second

OFT (or a photodiode) was used to view the entire sample and to gauge the relative degree of heating by measuring the emitted light intensity.

ACKNOWLEDGMENTS

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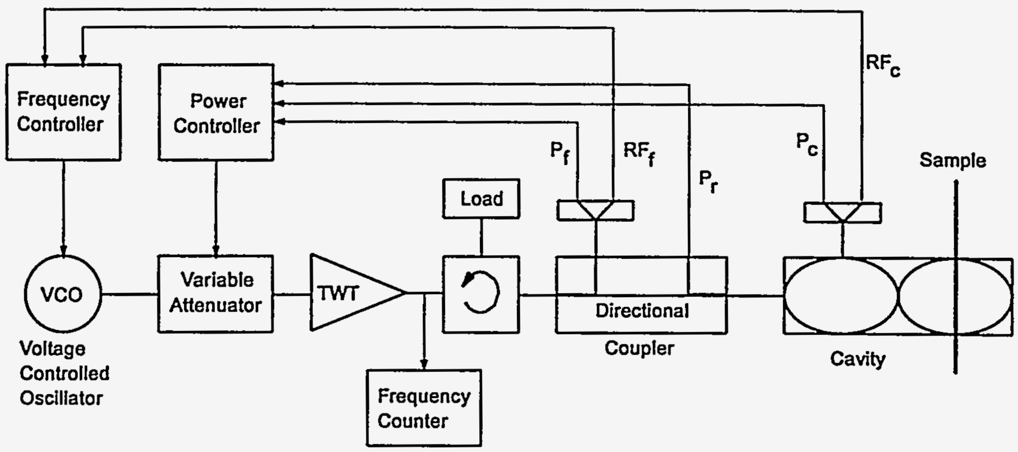

Figure 1. Schematic of microwave system with frequency and power controllers.

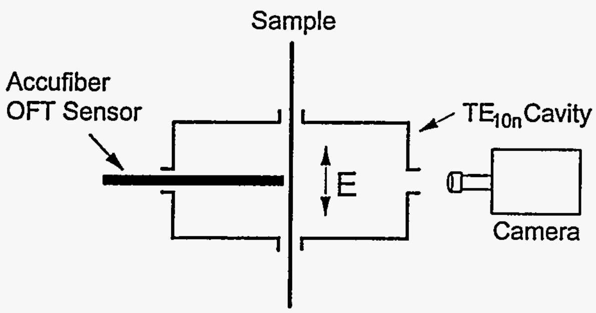

Figure 2a. Schematic cross-sectional view of the TE_{10n} cavity, showing sample position with OFT sensor and video camera.

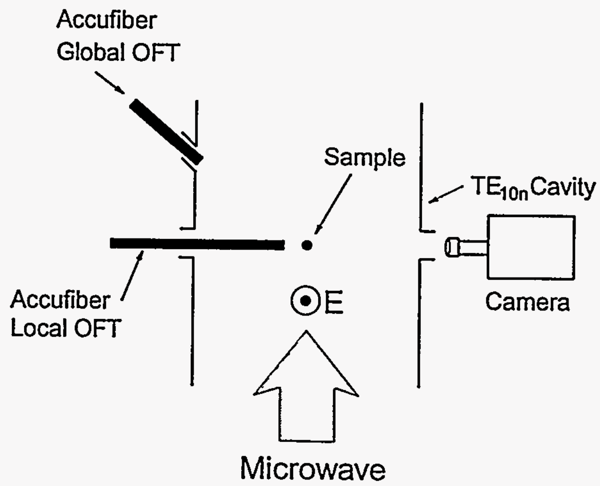

Figure 2b. Schematic top view of the TE_{10n} cavity, showing position of local and global OFT sensors.

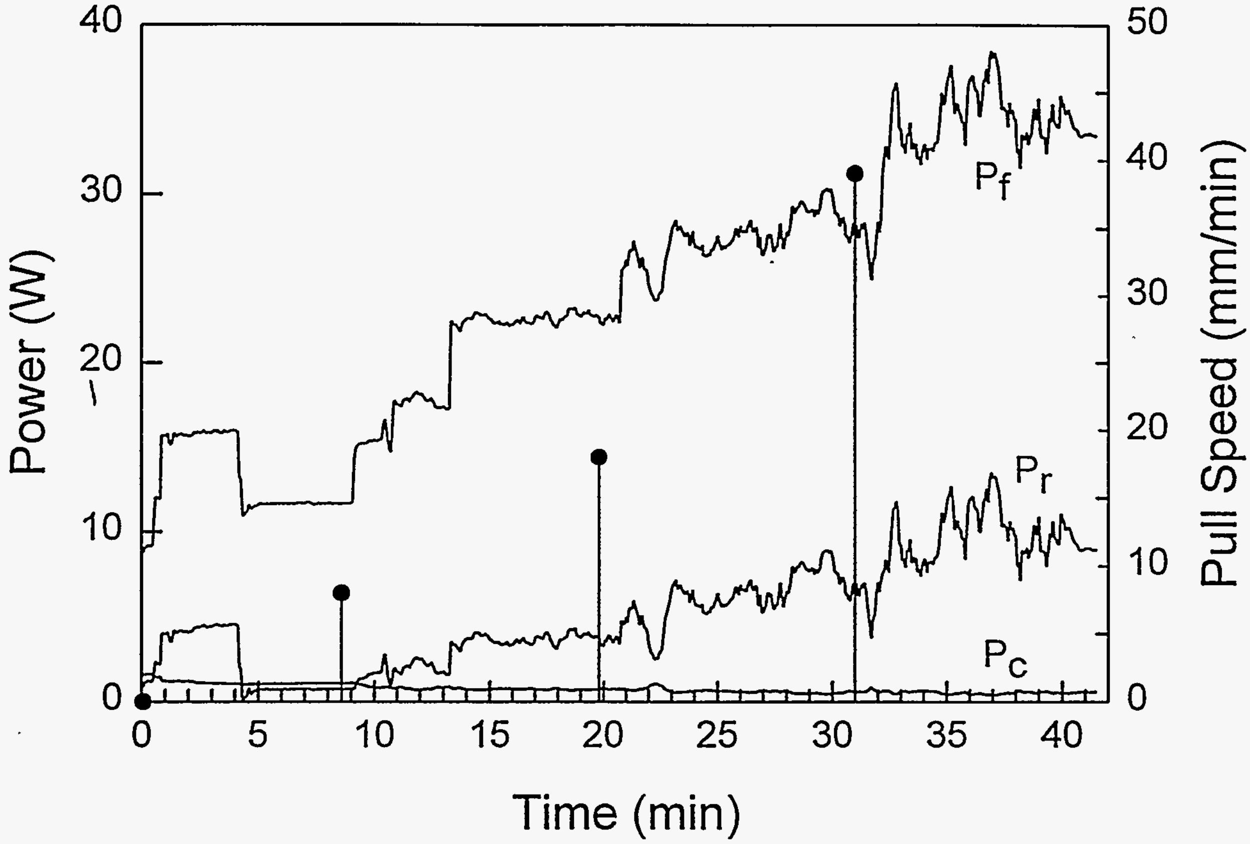

Figure 3a. Forward (P_f), reflected (P_r), and cavity (P_c) power levels used to heat a NICALON tow pulled up through the cavity at four different rates. Change in pull speed is marked by a vertical line from a filled circle denoting the new speed. Initially the tow is stationary.

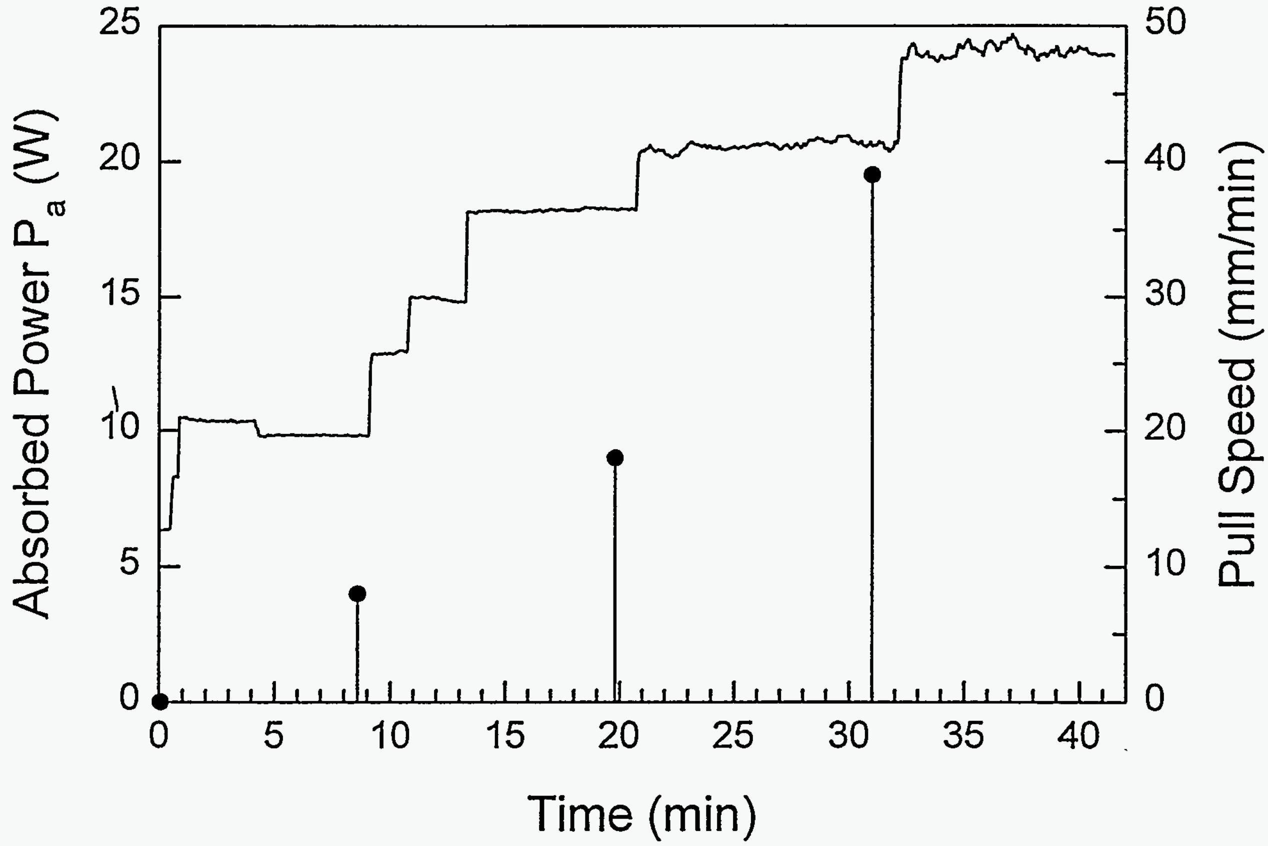

Figure 3b. Absorbed power P_a used to heat a NICALON tow pulled up through the cavity at four different rates. Change in pull speed is marked by a vertical line from a filled circle denoting the new speed. Initially the tow is stationary.

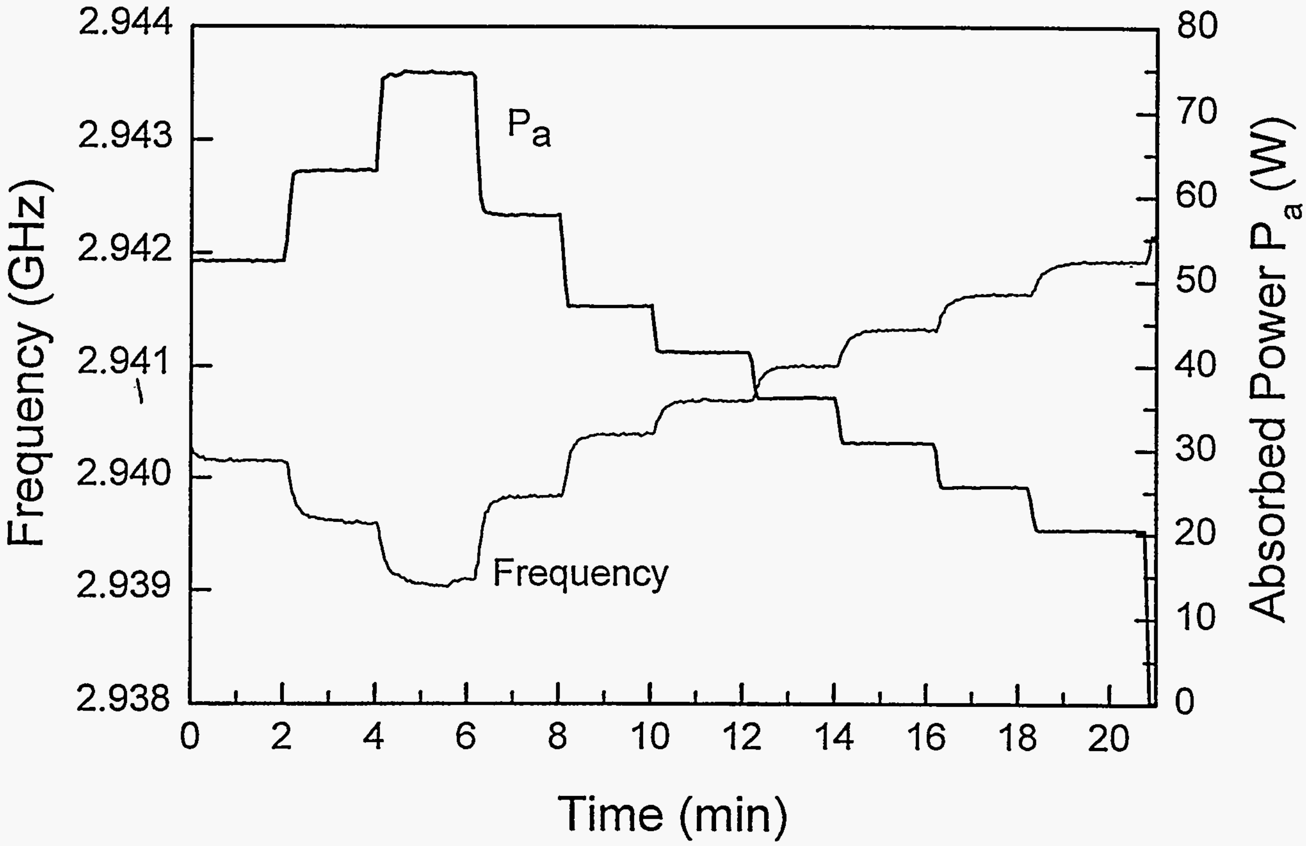

Figure 4. Microwave frequency and absorbed power P_a for a stationary mullite tube heated at different P_a values.

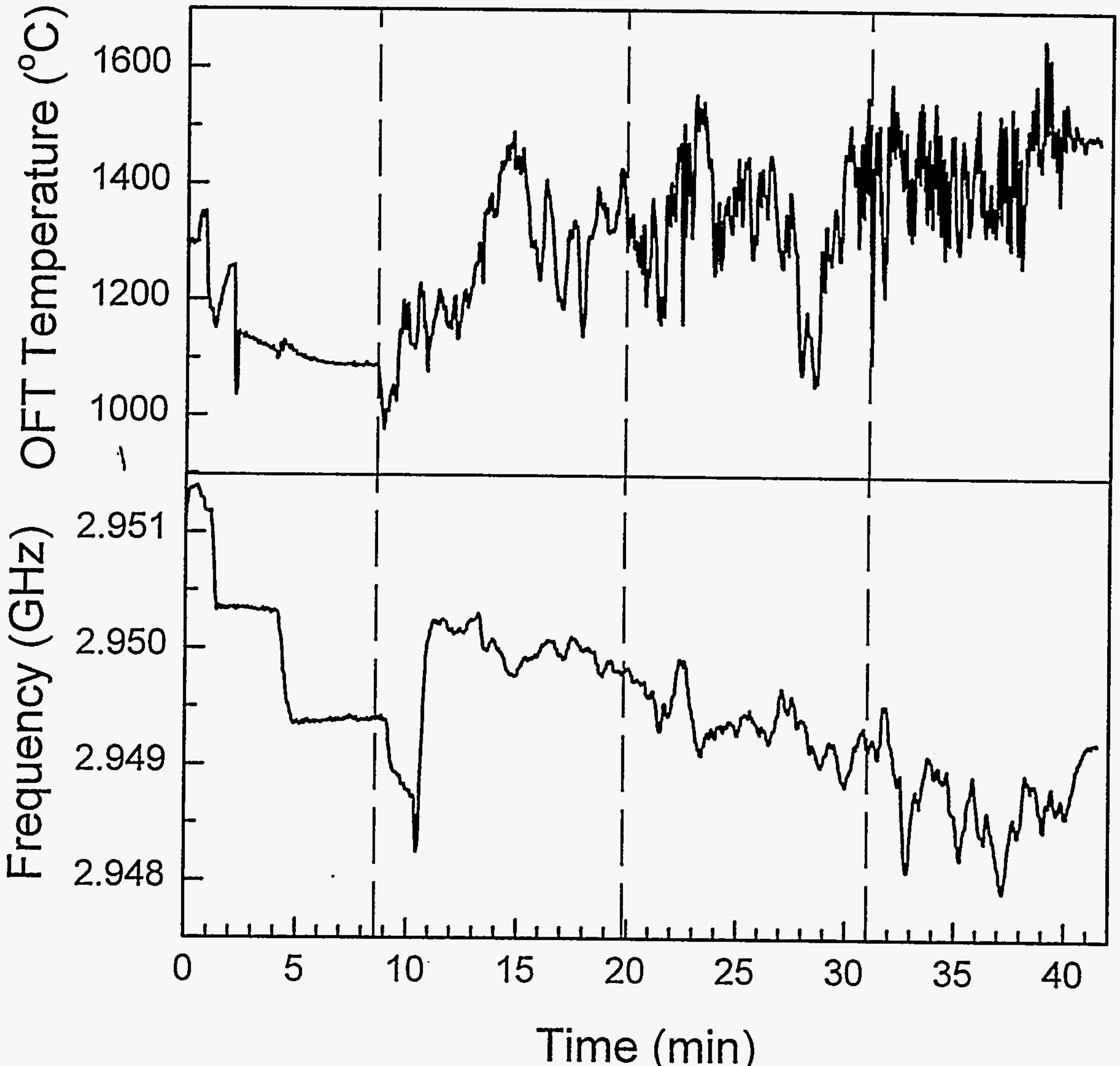

Figure 5. Sample temperature and microwave frequency for a NICALON tow pulled up through the cavity at three different speeds. The pull speed was initially zero, but was increased to 8, 18, and 39 mm/min at the first, second, and third vertical dashed line, respectively. The sample temperature was measured by the local OFT.

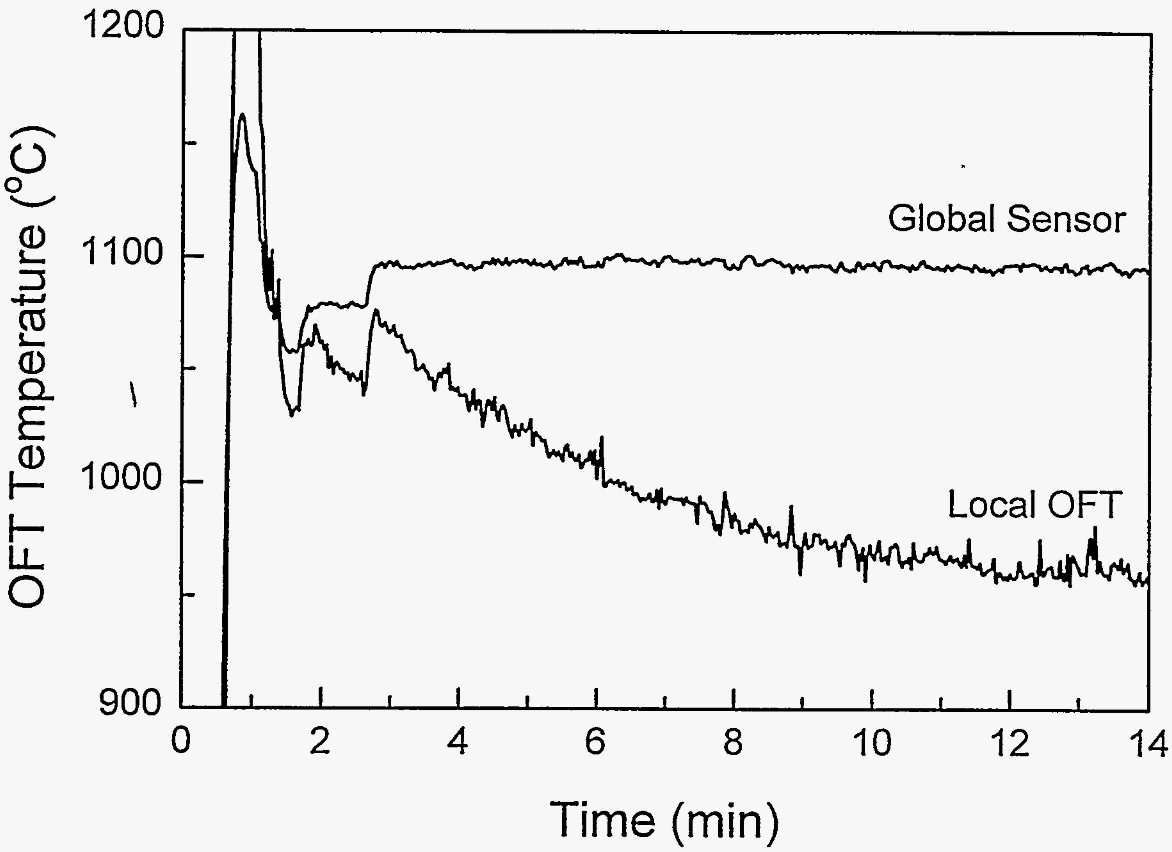

Figure 6. Signals from the local OFT and the global light sensor for a stationary 1.6 mm mullite tube. The global signal is plotted in arbitrary units.

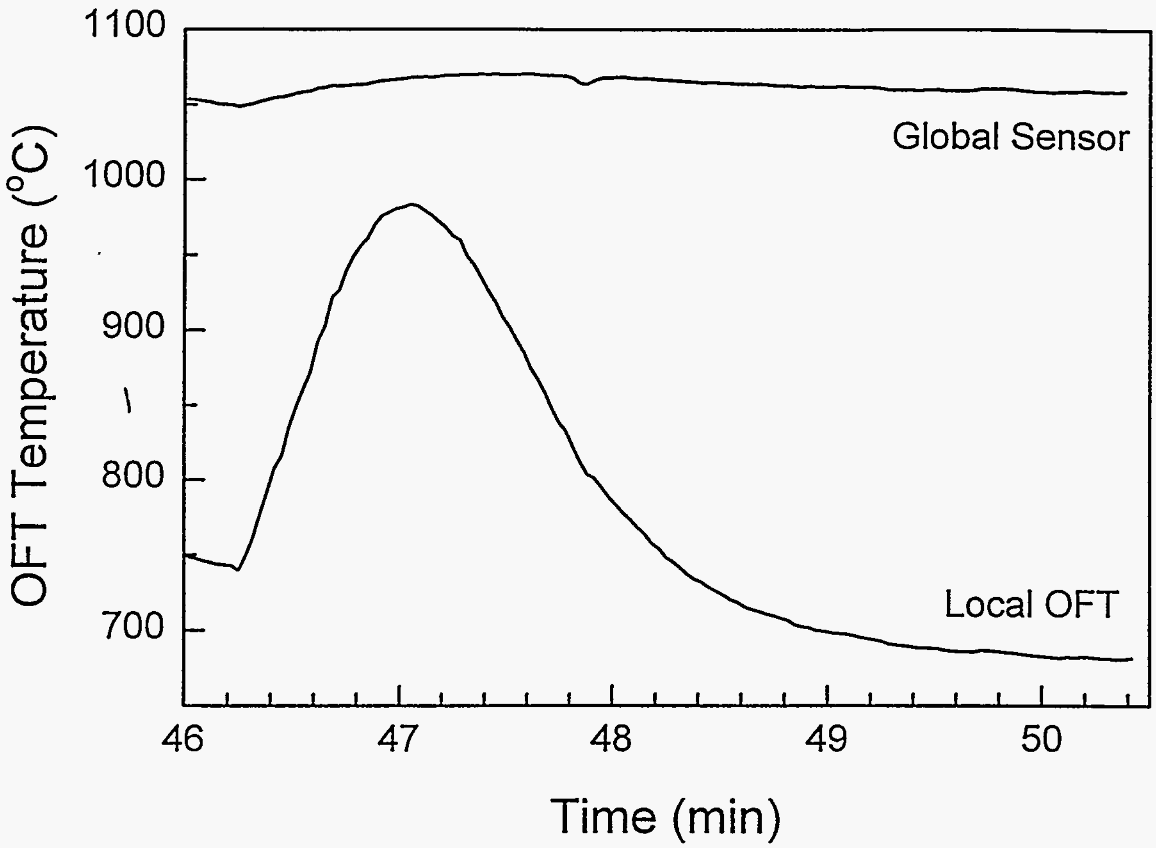

Figure 7. Signals from the local OFT and the global light sensor for a stationary 1.6 mm mullite tube. A hot spot migrated from bottom to top of the tube sample. The global signal is plotted in arbitrary units.

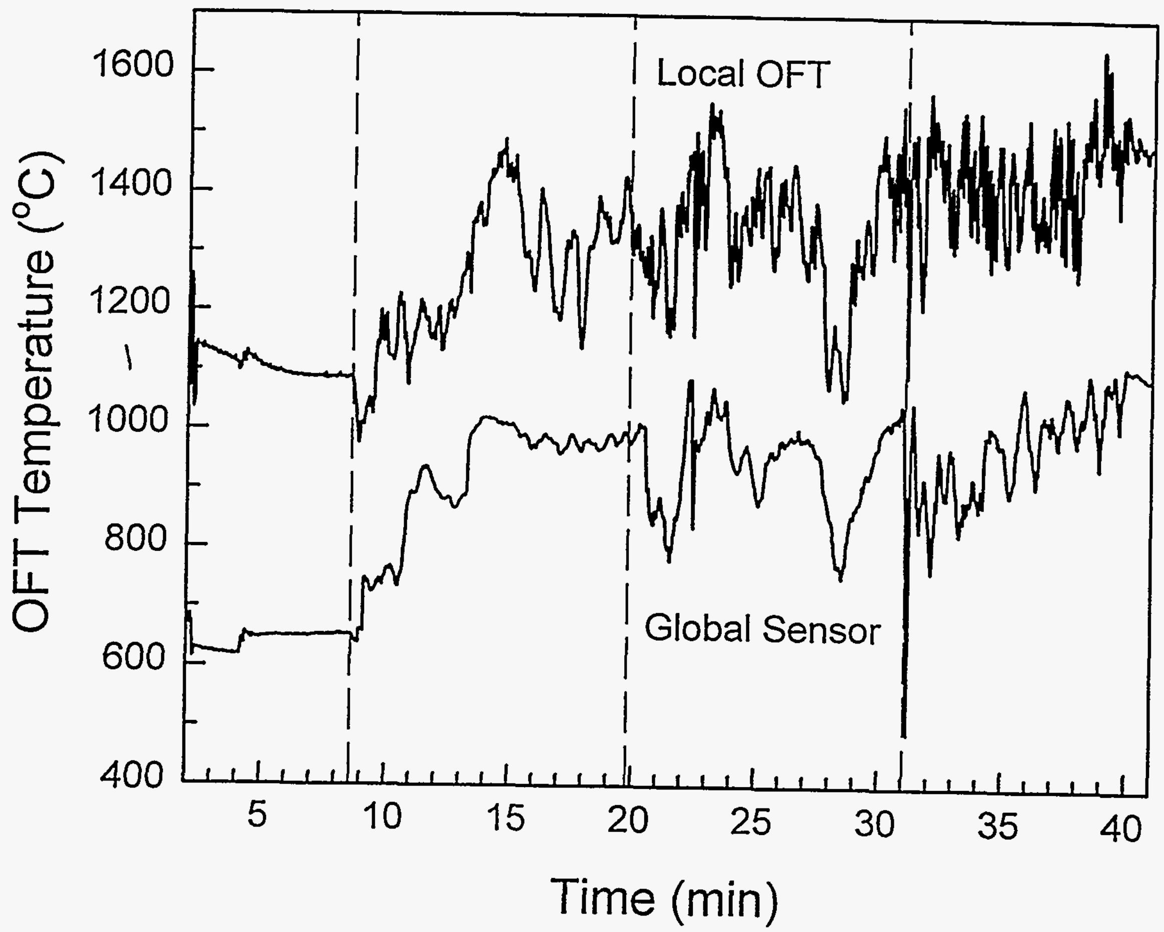

Figure 8. Signals from local OFT and the global light sensor for a NICALON tow pulled up through the cavity at three different speeds. The pull speed was initially zero, but was increased to 8, 18, and 39 mm/min at the first, second, and third vertical dashed line, respectively. The global signal in arbitrary units was shifted to avoid overlap with temperature curve.

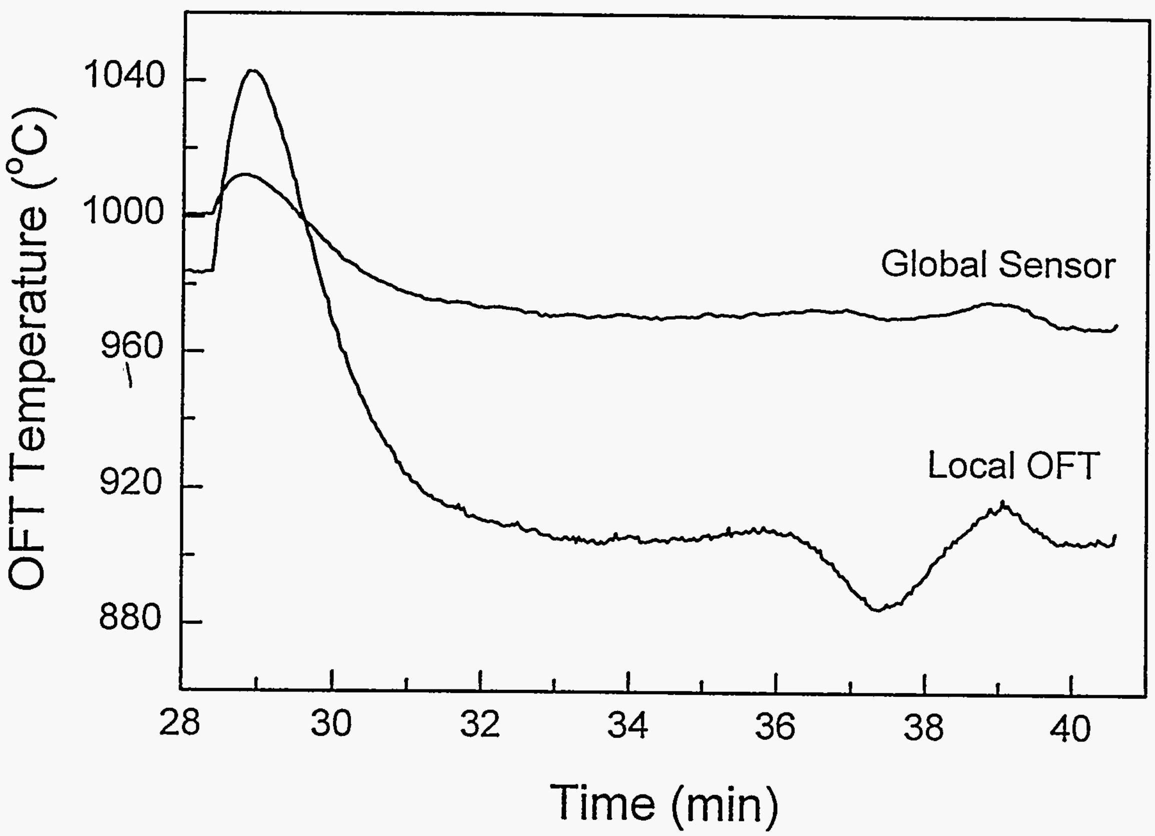

Figure 9. Signals from local OFT and global light sensor for a 4.6 mm mullite tube pulled down through the cavity at 8 mm/min. The global signal is plotted in arbitrary units.