Carbon Loaded Teflon (CLT): A Power Density meter for Biological Experiments Using Millimeter Waves

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The standard technique for measurement of millimeter wave fields utilizes an open-ended waveguide attached to a HP power meter. The alignment of the waveguide with the propagation (K) vector is critical to making accurate measurements. Using this technique, it is difficult and time consuming to make a detailed map of average incident power density over areas of biological interest and the spatial resolution of this instrument does not allow accurate measurements in non-uniform fields. For biological experiments, it is important to know the center field average incident power density and the distribution over the exposed area. Two 4 ft x 4 ft x 1/32 inch sheets of carbon loaded Teflon (CLT) (one 15% carbon and one 25% carbon) were procured and a series of tests to determine the usefulness of CLT in defining fields in the millimeter wavelength range was initiated. Since the CLT was to be used both in the laboratory, where the environment was well controlled, and in the field, where the environment could not be controlled, tests were made to determine effects of change in environmental conditions on ability to use CLT as a millimeter wave dosimeter. The empirical results of this study indicate CLT to be an effective dosimeter for biological experiments both in the laboratory and in the field.

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INTRODUCTION

Since the mid 1990's personnel at Brooks-City Base have conducted a series of experiments to determine the effects of millimeter waves on biological systems [Jauchem *et al*., 1999; Mason *et al*., 2001]. The exposure levels were determined by measuring the center field average incident power density with an open-ended waveguide or standard gain horn attached to a HP power meter [Shelton, 1991]. Beam size was estimated by exposing a piece of resistive cloth in the experimental exposure plane. The resistive cloth provided a good estimate of beam size but could not define beam uniformity due to the cloth's lack of uniformity and its rapid loss of heat, particularly in windy conditions. In an attempt to measure beam uniformity more precisely, two sheets of carbon loaded Teflon (CLT) (15% and 25% carbon) were procured and tested in an anechoic chamber at Brooks City-Base, Texas. CLT was chosen because of its excellent chemical stability and its ability to remain stable after exposure to high temperatures. This material coupled with a FLIR Model SC 3000 thermographic camera provided detail average incident power density

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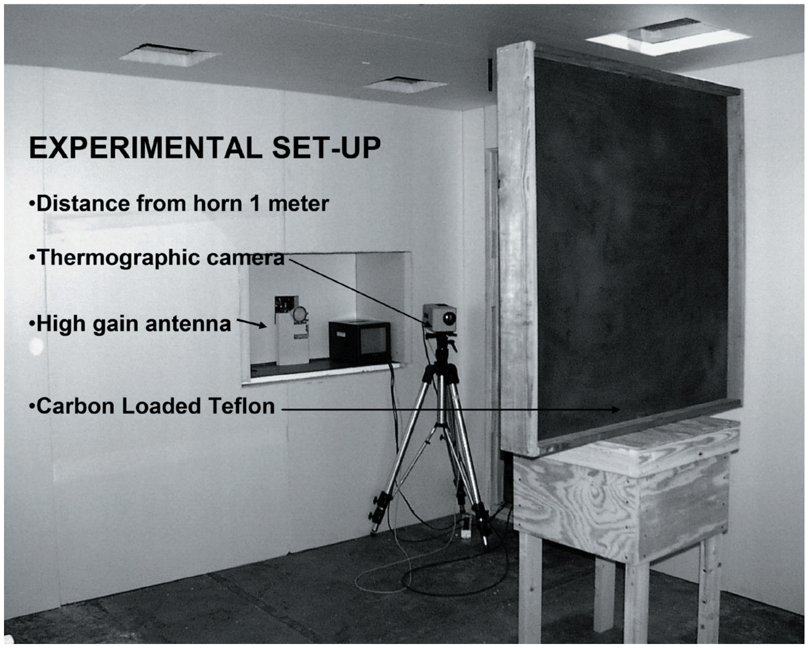

Figure 1. *Experimental set-up for testing the effectiveness of CLT as an average incident power density mapping tool.*

distribution information. A series of experiments yielded detail performance data concerning response of CLT as a function of environmental temperature, wind speed, humidity, and linearity of response with incident power density for 94-GHz exposures. Data were taken for 15% and 25% carbon material of 1/32 inch thickness. This material produced an excellent response for all test conditions.

METHODS

One 4 ft x 4 ft x 1/32 inch sheet of 15% carbon and one of 25% carbon CLT were procured from Boedeker Plastics Inc., Route 2, Box 5, Shiner, Texas 77984. Exposures to 94-GHz fields were made in an environmentally controlled anechoic chamber at 1 m from the high gain horn antenna. The average incident power density was determined by center beam measurements utilizing an open-ended waveguide attached to a HP Model W 8486A power head and a HP Model 437B power meter. The average incident power density was adjusted over the range of 0.1 to 7 W/cm^2 by adjusting the transmitter pulse repetition rate.

The experimental set-up for CLT measurements is shown in Figure 1. A FLIR Model SC 3000 thermographic camera was used to measure temperature changes in the CLT during exposures. All exposures for the environmental effects experiments were limited to 4.9 s except for the last experiment in the series; the FLIR camera was moved to the backside of the CLT and a 100-s exposure of 0.1 W/cm^2 was used. The FLIR measured the temperature at a rate of 60 measurements/s. A typical heating pattern is shown in Figure 2. Areas of interest of 2.5, 5, and 10 cm diameter are shown. For this experiment, the highest temperature in the 5 cm diameter area of interest was used for analysis. The temperature rate of change (°C/s) was calculated for the point of largest temperature change and was referenced to the center field average power density measured with the waveguide–HP power meter system that had been adjusted to detect the highest average incident power density. The response in terms of exposure and delta temperature (W/cm^2/°C/s) was calculated.

The standard exposure technique was to perform a 4.9 s exposure then move to an un-

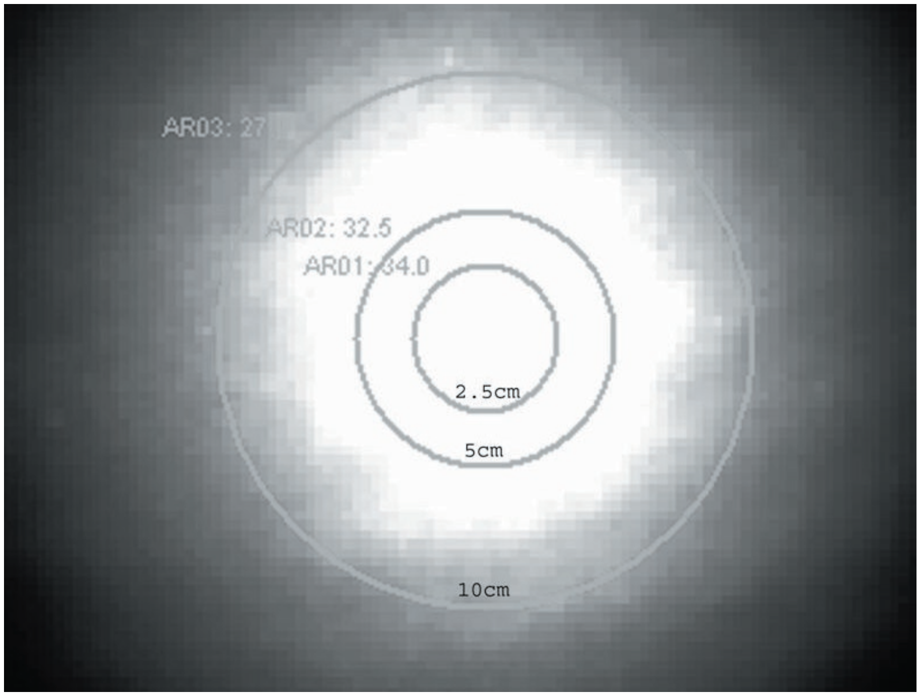

Figure 2. *A typical thermographic image taken for a 2.8 W/cm. 94-GHz exposure at a distance of 1 m from the transmitting antenna.*

exposed area for the next exposure. The CLT was moved ~ 25 cm and the FLIR camera was used to determine no overlap from the previous exposure. Three measurements were made for each exposure condition. These results were averaged for analysis. Several exposures were made by repeating the exposure without moving to an unexposed spot. In this case, the original exposure was compared with the mean of three additional exposures to the same spot.

Several experiments were performed to establish the usefulness of CLT as a field-measuring tool including: 1) The response to a 3 W/cm^2 average incident power density using the "moving to an unexposed spot method" to determine the effect of environmental temperature change from 22° and 32° C. 2) The response of the 15% and the 25% CLT to determine the effect of the amount of carbon in the Teflon suspension. 3) The 25% CLT was used to determine the effect of exposing the same spot. Delays between exposures of 1 and 3 minutes were used. 4) A Black & Decker Model BU2500 leaf blower was used to determine the effect of a 20 m/s wind incident at a 30° angle on the CLT sheet. Wind speed and environmental temperature and humidity were measured using a Kestrel Model K3000 pocket weather meter station. 5) Water was sprayed on the CLT to determine the effect of extreme humidity conditions. 6) Measurements were made with the thermographic camera on the unexposed (back) side of the CLT sheet while the front side of the CLT was exposed to a 0.1 W/cm^2 average incident power density for 100 s.

Curve Expert 1.3 (available at http://curveexpert.webhop.biz/) was used to fit the response data (W/cm^2/°C/s) to exposure time. Figure 3 shows a typical response for the 15% CLT. This curve fitting program fits the data to approximately 40 curves and presents this data with the fit having the highest r value (best fit) given first. This curve can be used for unknown exposures to calculate the response at a given time to determine the W/cm^2/°C/s factor. This factor when multiplied by the measured temperature change (°C/s) yields the average incident power density (W/cm^2) for definition of unknown fields.

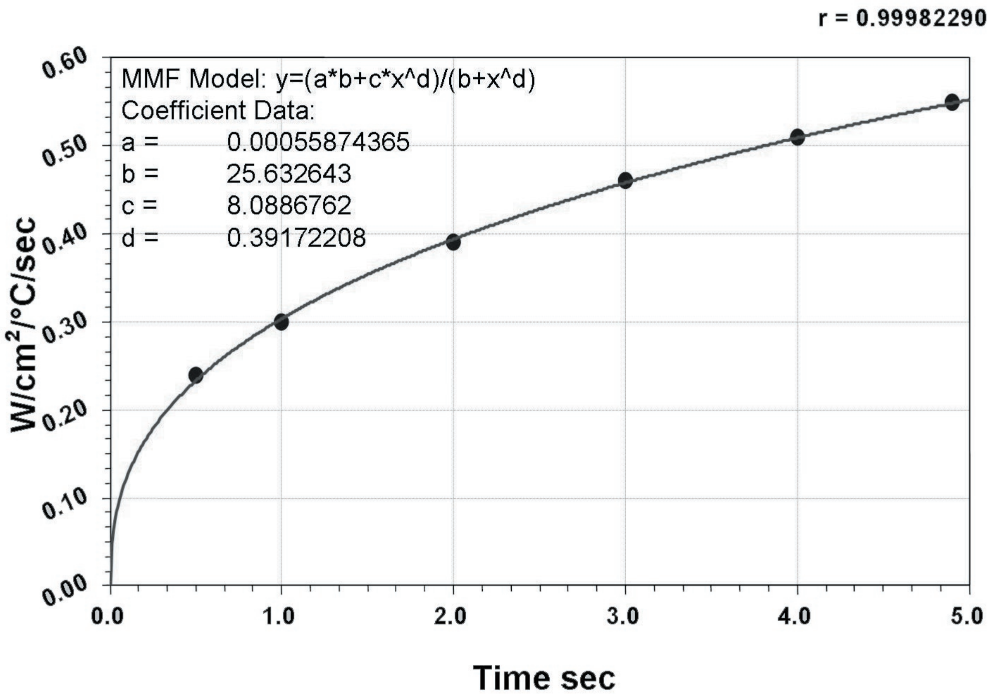

Figure 3. *Curve fit showing the response (W/cm²/°C/s) of 15% CLT as a function of time for 0 to 4.9 s exposures. These data were taken using an unexposed spot for each exposure and averaging three exposures.*

RESULTS

The 15% CLT was exposed to 3 W/cm², at 94 GHz, for 4.9 s at an environmental temperature of 22 °C and the delta T measured at 1 s intervals on three unexposed spots on the sheet. The chamber temperature was raised to 32 °C and the measurements repeated. The standard deviation expressed as a percentage of the mean, i.e. the coefficient of variation (COV) for three readings was generally in the 2 to 5% range for each point at 1 s or greater exposure time. The average delta temperatures at 22 °C were divided by the average delta temperatures at 32 °C. This ratio of 0.98 was within experimental accuracy. CLT response is not affected by environmental temperature over the 22 to 32 °C range.

The result of the comparison of 15% and 25% CLT response is shown in Figure 4. These measurements represent the average of 5 exposure levels between 0.5 and 7 W/cm². The greatest deviation occurred at the 0.5 s point where the response of the 25% CLT was 4% greater than the 15% CLT. This is considered to be within experimental accuracy indicating the amount of carbon in the CLT is not critical over the 15% to 25% range.

25% CLT was exposed to 3 W/cm² on a previously unexposed spot. After a delay of either 1 minute or 3 minutes, the same spot was exposed and the exposure repeated three more times. The mean heating rate (°C/s) of the three same spot readings was divided by the initial heating rate (°C/s) reading and the results plotted for 0.5, 1, 2, 3, 4, and, 4.9 s as shown in Figure 5. The COV for the three hot spot exposures for each of the 12 resulting points was generally 1% with a maximum COV of 3.7% indicating better repeatability than the cases where a previously unexposed spot was used each time where a 2 to 5% COV was observed. This slight difference could have been due to the change caused by repositioning in the unexposed spot data or the difference in uniformity in the CLT from one

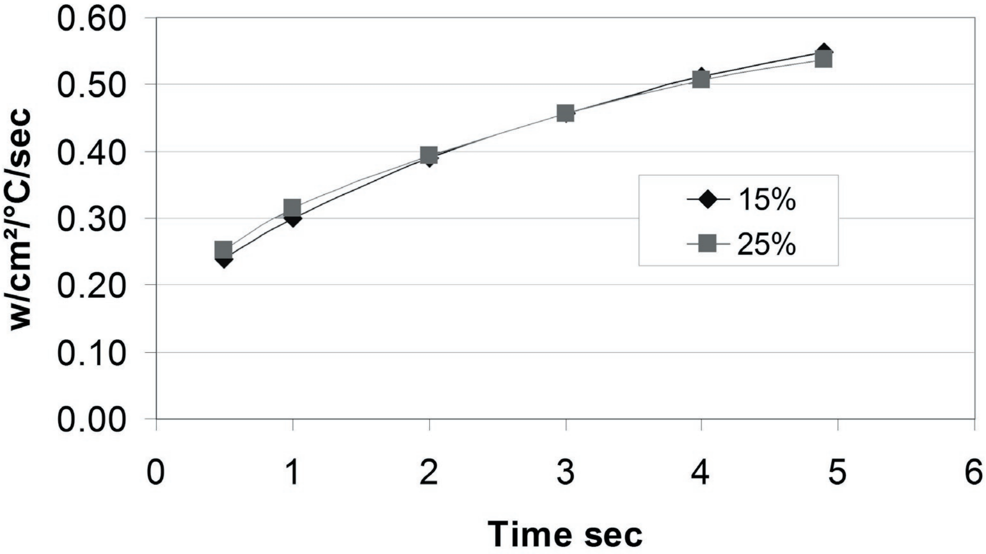

Figure 4. *Response curves for 15% and 25% CLT show no difference in response.*

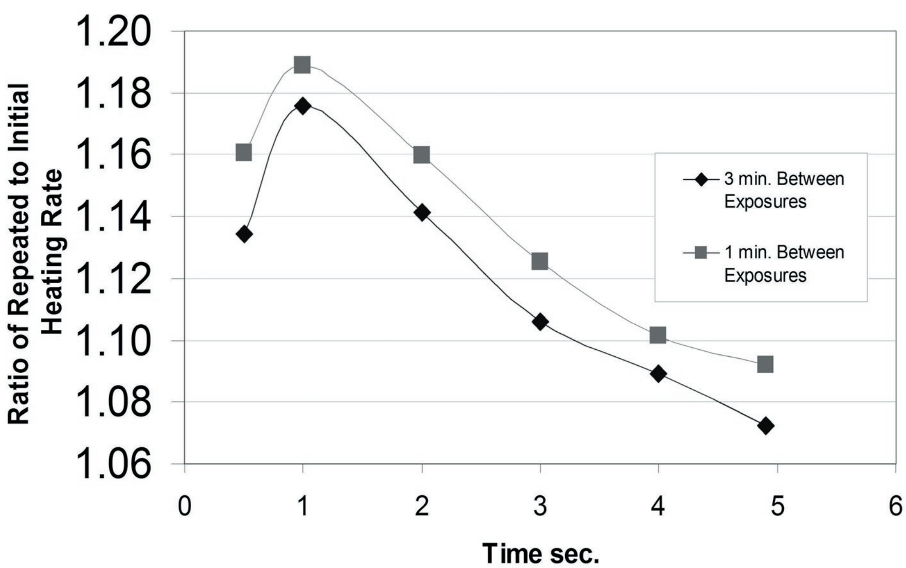

Figure 5*. Ratio of repeated heating rate to initial heating rate for 25% CLT exposed to 3 W/cm², 94 GHz. Note that the response at the 4.9 s mark had returned within 7% of baseline when 3 minute delay between exposures was used.*

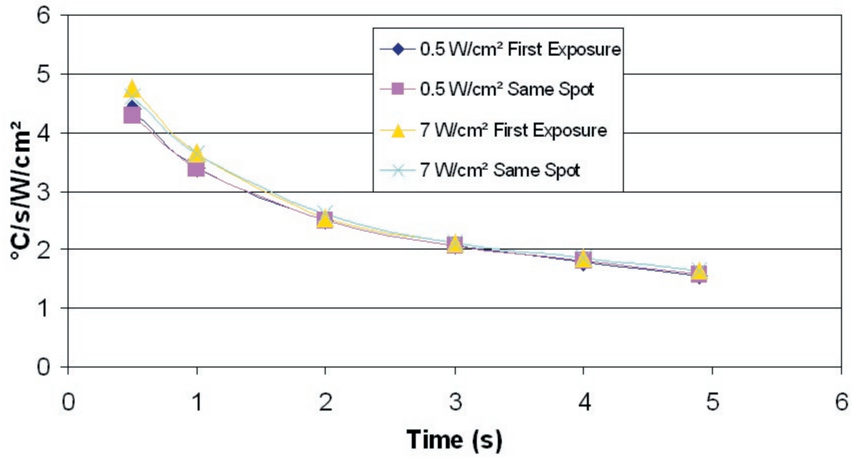

Figure 6. *Response of 15% CLT with a 20 m/s wind incident at 30°. The priming effect, measured with no wind, disappears in the 20 m/s wind.*

area of the CLT sheet to another. In any event, the difference was small with either technique producing good results. Accurate predictions of average incident power density without corrections could be made using the 4.9 s data if at least 3 minutes between exposures was maintained.

Figure 6 shows the heating rate °C/s for the first exposure and the average of subsequent exposures made at 1-minute intervals with a 20 m/s wind incident at 30° on the sheet of CLT. The heating rate (°C/s) was normalized to average incident power density so the 0.5 and 7 W/cm² data can be compared. The 0.5 and 7 W/cm² data agree within 4%. The first exposed spot response is within 2% of the mean of the repeated spot response for 0.5 through 4.9-s exposure times.

A dry spot was exposed to 3 W/cm². The sheet was then sprayed with water and another 3 W/cm² exposure made. After a 1 minute delay the CLT was sprayed again and the exposure was repeated until 3 wet spot measurements were accomplished. On visual inspection the CLT appeared to have stayed wet through each exposure. This procedure was repeated after the CLT was completely dry and the average of the two dry heating rates was divided by the mean of the two same wet spot heating rates (°C/s). Through 2 s of exposure time the dry to wet ratio was approximately 0.8 returning to 1.0 at the 4.9 s exposure point. Another experiment was preformed in which the wet CLT was moved to an unexposed region for each exposure until three sets of data were obtained. The sheet of CLT was sprayed with water after each exposure. For this condition, the dry to wet ratio stayed fairly constant at 0.8. The CLT with water produced a faster heating rate than the dry CLT. The results of these two experiments are shown in Figure 7.

Figure 8 shows the results when the camera viewed the back of a 1/32 in piece of CLT. The plot shows actual temperature increase as a function of time for a 0.1 W/cm² exposure. There was no difference in the response of 15 and 25% CLT when viewed from the backside of the CLT sheet. When 1.5 °C was subtracted from the front side 15% CLT sheet temperature measurements, the results fall on top of the backside data for all exposures greater than 10 s.

DISCUSSION

Standard techniques of measuring average

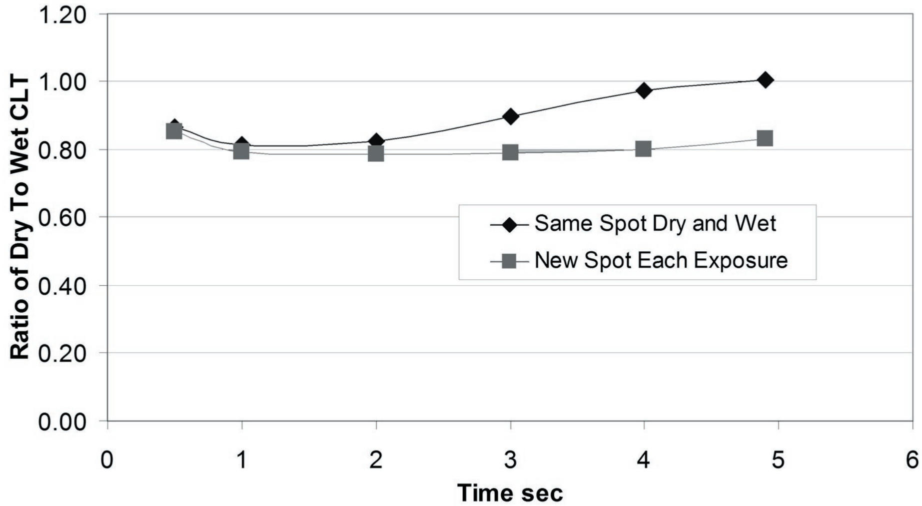

Figure 7. *Comparison of the response of wet CLT to dry CLT for 3 W/cm², 94-GHz exposures. The CLT was sprayed with water after each exposure. The exposure to the same spot returned to baseline at 4.9 s of exposure.*

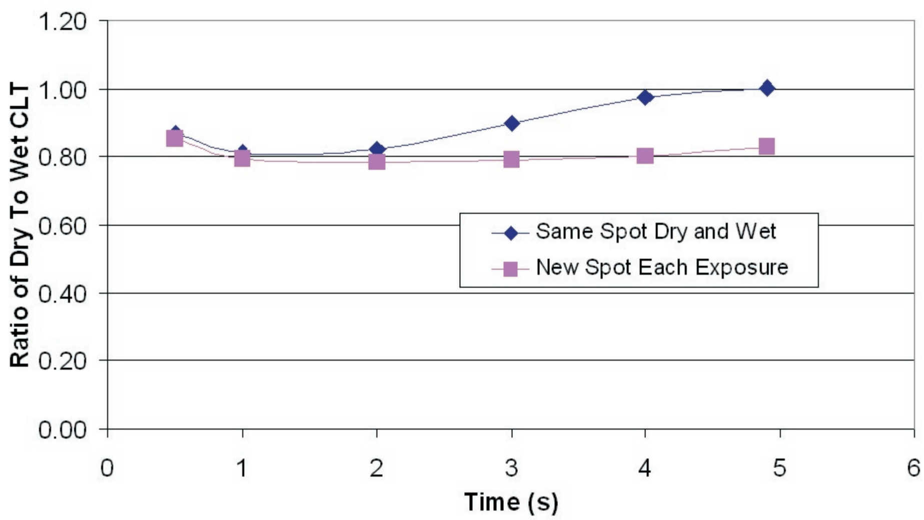

Figure 8. *Heating rate measurements from the back of a 1/32 inch piece of 15% CLT were identical to the front for exposures between 10 and 70 s to 0.1 W/cm², 94 GHz.*

incident power density patterns at millimeter wavelengths, using a standard gain antenna or an open-ended waveguide attached to a power meter, are complex and slow. The power meter method is used as the standard for measuring the center field (maximum) average incident power density. To expedite average incident power density distribution measurements, the technique of measuring the heating pattern on carbon loaded Teflon CLT using a thermographic camera resulted in quick and accurate temperature measurements that can easily be converted to average incident power density utilizing Microsoft Excel. Measurements were made at 0.017 s intervals for 7 W/cm² exposures on the edge of the heating pattern at approximately 10% and 20% of the center field heating rate to determine if heat flow from the center to the edge of the beam distorted the heating pattern. When power was terminated, the temperature on the edge of the beam began to decrease within 0.02 s indicating minimal heat flow from the center to the edge of the CLT. Measurements using a piece of CLT left outdoors and exposed to the elements for over two years yielded the same power density determination, within experimental variation, as CLT stored in the laboratory. CLT was chosen for its excellent mechanical, chemical and high temperature stability properties.

This study investigated the suitability of CLT as a dosimeter for both laboratory and field use. Test results showed that the 15% and 25% CLT exhibited results within statistical variation for all test conditions. The largest difference was detected at the 0.5 s point where the response of the 25% CLT was 4% greater than the 15% CLT. Using exposure times between 1 and 4.9 s and moving to an unexposed spot for each exposure, the COV for three readings ranged from 2 to 5%. This is within the experimental accuracy of the power meter standard measurement. No difference in heating rate was observed for ambient temperatures between 22 and 31 °C.

The heating rate is nonlinear, though quite repeatable, over the first 5 s of exposure. When the same spot as the first exposure is exposed, an even higher heating rate is observed in the first 5 s of exposure (Figure 5). The CLT responds as if the first exposure primed the spot (i.e., a 19% higher temperature at 1 s exposure if the exposure is repeated after 1 minute). This effect is time dependent returning to near baseline for time between exposures of greater than 3 minutes for the 4.9 s exposure point. The greatest accuracy of average incident power density determination will be obtained from delta temperatures over a 4.9 s or greater exposure time. In a no-wind situation such as the laboratory, same spot data should be taken at exposure times exceeding 4.9 s and the delay between exposures should be greater than 3 minutes, otherwise time corrections must be made.

When a 20 m/s wind was incident at 30°, the initial spot and the repeat spot data were within the experimental limits. The priming effect noted for no wind disappeared with the 20 m/s wind. This indicates an improvement in the capability of CLT to accurately determine average incident power density in windy conditions if the same spot is exposed.

Water was sprayed on the sheet of CLT after the dry spot exposure and a series of exposures made at 1 minute intervals. The 1 and 2 s data deviated by 20% from dry data but returned to the same level as the dry data in the 5th second of exposure. Observation of the material after each exposure indicated this phenomenon was not due to the evaporation of water from the surface of the sheet, as might be expected. For the wet CLT moved to an unexposed spot for each exposure, a constant 20% error was observed (Figure 7). This data indicates if the wet material is moved between each exposure a 20% correction must be made. If the same spot is used for a 5 s exposure, with 1 minute between exposures, the data in Figure 7 indicates that no correction is necessary when compared to the dry spot data.

After 10 s of exposure, the rate of temperature rise was the same for the IR camera measurements on the front and back of the CLT. Over 10 to 70 s, for 0.1 W/cm^2, the rate of temperature increase was linear. No difference was observed for the 15% CLT as compared with the 25% CLT. CLT can be used to measure average incident power density with the IR camera on the back side, but it requires calibration for delta Ts in the 10 to 70 s exposure time range.

CLT has proven to be an effective and efficient tool for measuring average incident power density patterns both in the laboratory and the field. There was no statistically significant difference in any test in the response of the 15% CLT as compared with the 25% CLT. Some of the observed phenomena such as the apparent priming effect observed for multiple exposures made to the same spot require further study to understand the mechanism. Detail average incident power density maps can be made in a very short time period. For biological studies, a CLT exposure prior to each animal exposure assures consistent results. CLT continues to be used in our laboratory and in the field as an effective average incident power density meter for millimeter wave exposures.

DISCLAIMER

The views and opinions in this paper are those of the authors and are not to be construed as official policy of the U. S. Air Force or of the U. S. Department of Defense.

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