

Measuring Background Convectivity

Randy Cox, Roland Fuentes
Teledyne Brown Engineering
Huntsville, AL 35807

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1.0 ABSTRACT

We have developed an instrument to measure the relative or absolute values of convection in some environment. The device eliminates or reduces the radiation and conduction effects between the itself and its environment so that essentially all of the heat lost by the it is lost by convection. When correlated with environmental data collected simultaneously with the measurements of the device performance, a coefficient of convection may be computed and displayed in real time. This coefficient is important in the understanding of natural heat transfer process in the environment, and how man-made objects subjected to that environment by react. In particular, we use the meter to help us determine the contribution of convection to the overall thermal balance of camouflage designed for military use. Herein, we describe in detail the device, its operating principles, and how the data it yields is used for better understanding of thermal signatures and the design of thermal camouflage.

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2.0 INTRODUCTION

Heat can be transported by three mechanisms: radiation, conduction, and convection. Radiation relies on the emission of electromagnetic energy from some relatively warm body and the absorption of that emitted energy by some cooler body. Conduction relies on the physical contact of the warm body to the cold by direct transfer of the vibrational energy of the bodies' molecules. Convection relies on the movement of some fluid (either liquid or gas) between the warmer body and cooler body to transfer the energy from one to the other.

Convection can be segregated into two types: natural and forced. In natural convection, heat from the a warm surface warms the immediate volumes of fluid surrounding the surface. This heated volume of fluid becomes buoyant – due to a change in density induced by the warming of the volume – and is transported away from the warm surface. Cooler fluid moves in to replace the warm, buoyant fluid, which is in turn warmed, made buoyant, and itself replaced by yet another portion of cooler fluid – thus establishing a convection loop – which is the continuous fluid movement created by the warming of the fluid by the surface. The rate of natural convection is dependent upon many factors, such as: surface/fluid temperature differential; surface area, and surface orientation.

In forced convection, the fluid warmed and made buoyant by the warm surface is replaced with cooler fluid by the mass flow of the fluid due to some external energy input – such as a fan or blower. In this case, the rate of convection is dependent almost solely on the mass flow rate of the fluid.

Our convection meter presents a device of well-defined shape and orientation which is heated to and maintained at some known set-point temperature. The power required to maintain this set-point is monitored. These data, when correlated with environmental data such as air temperature, humidity, solar insolation, and wind speed, allow the computation of coefficients of convection in both natural and forced convection regimes.

3.0 DESCRIPTION OF THE DEVICE

Please refer to figure 1 to locate the particulars of the convection meter as they are described. The meter consists of a hollow, polished aluminum cylinder (1) that is mounted in vertically on a tripod (4). Bonded to the inside surface of the cylinder are multiple thin-film heating elements. Attached to the outside surface of the cylinder are temperature sensors (5) – one for each element. The cylinder is plugged on its highest end (2) so that airflow may not cool the interior surface. A bottom plug (3) is provided to prevent airflow and serves as a mounting device to attach the cylinder to the tripod.

Figure 2 is a cutaway view of the device. This figure illustrates the attachment of the thin film heating elements (6) to the inside of the cylinder (1). Wires carrying electrical power to these heaters (7) are arranged through the hollow core of the device, along with signal leads (8) for the temperature sensors (5). All leads and wires are consolidated into a single cable (9) for attachment to the controlling electronics (10).

The aluminum cylinder is a two-piece shell formed by cutting a length of aluminum tubing in half lengthwise. The shells are then attached to the upper and lower plugs by means of screws. The shell is drilled through at each place a temperature sensor is attached to the outer surface – providing space for the sensor's signal leads to be fed through to the inside of the hollow cylinder.

The outside surface of the aluminum cylinder is polished to a high sheen to reduce radiant heat exchange between the cylinder and the environment. This cylinder is made of thin aluminum to minimize the thermal lag between thermal event (such as the onset of wind or the turn-on of heaters) and temperature change of the aluminum.

The controlling electronics sense the surface temperature of the cylinder, compare it to some set point, then adjusts the power fed to the heaters accordingly to maintain the set point. There are eight or more heater/sensor combinations. Each heater has its own independent temperature sensor associated with it.

The convection meter is built in the form of a vertical cylinder because this shape and orientation reduces the variables involved in computation of the coefficient of convection. Empirical values for vertical cylinders may be found in heat transfer literature. The wind resistance and air flow around cylinders is also well documented in various engineering references. Therefore, one may calculate the expected coefficient of

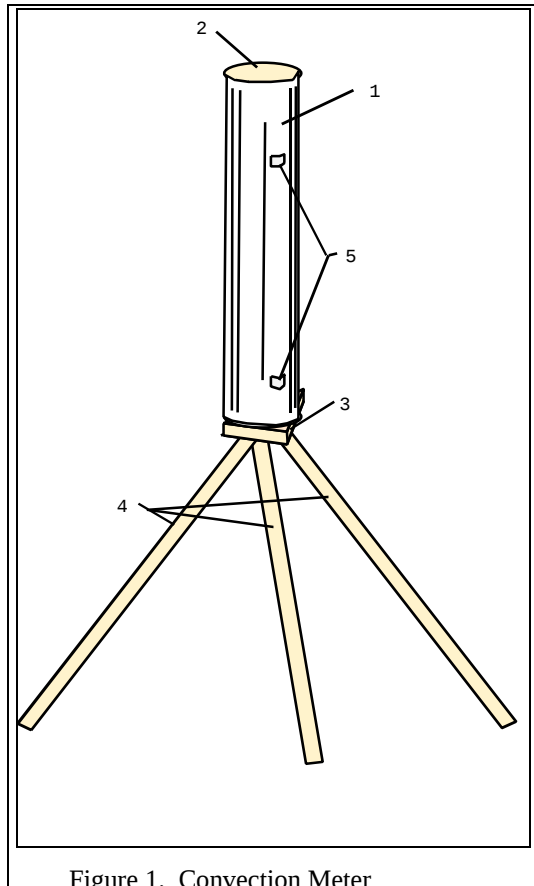


Figure 1. Convection Meter

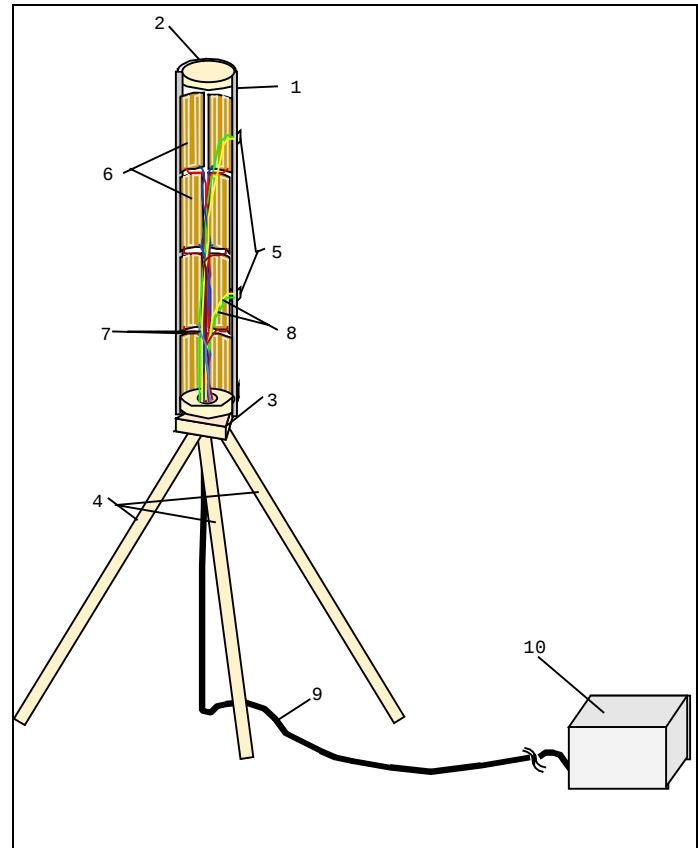


Figure 2. Inside of the Convection Meter

convection for the meter, then correlate the results of those calculations with experimental data taken from its operation.

The coefficient of convection for a vertical surface in air is approximately $10 \text{ W/m}^2\text{-K}$. The actual heat transfer due to convection is given by:

$$q_c = \bar{h}_c A \Delta T$$

If the surface area of our device is approximately 0.5 square meters, the air temperature is 300 Kelvin, and we maintain our meter's temperature at 310 Kelvin, then the heat flow due to convection is approximately 500 Watts.

Now, the radiant heat transfer is given by:

$$q_r = \epsilon \sigma A \Delta T^4$$

where ϵ is the emissivity of the surface, σ is the Stefan-Boltzman constant ($5.67 \times 10^{-8} \text{ W/m}^2\text{-K}^4$), A is the heat-emitting area, and ΔT is the temperature difference between background and emitting surface. A polished aluminum surface exhibits an emissivity of around 0.08 in the thermal part of the electromagnetic spectrum (3-5 m band). The radiant heat emitted by our device, then, for the same environment for which we calculated the convective heat loss given above, is approximately 14.6 Watts. Therefore, the radiant heat loss for our device is approximately three percent of the convective heat loss for a typical environmental scenario. If the surface of the convection meter was a high emissivity surface its radiant loss would be over 100 Watts

– a significant fraction of the convective loss. Therefore, the low emissivity of keeps the radiant term small with respect to convection.

The electronics monitor the power input to the heaters. This is used to determine the heat required to maintain the cylinder set point temperature in all weather conditions. This data is monitored and recorded via a laptop computer connected to the device's electronics by an RS-232 serial port.

The laptop computer also monitors the apparent temperature indicated by an imaging infrared camera. This camera (such as the Inframetrics Infracam) has the capability to display the apparent temperature (as determined by the camera-perceived emission of thermal energy) of some point or area in the camera field of view. This apparent temperature is available on the camera's serial data port.

A weather station recording the ambient air temperature, the barometric pressure, wind speed, wind direction, solar insolation, and relative humidity is also monitored by the laptop concurrently with the monitoring and recording of device data and infrared camera data.

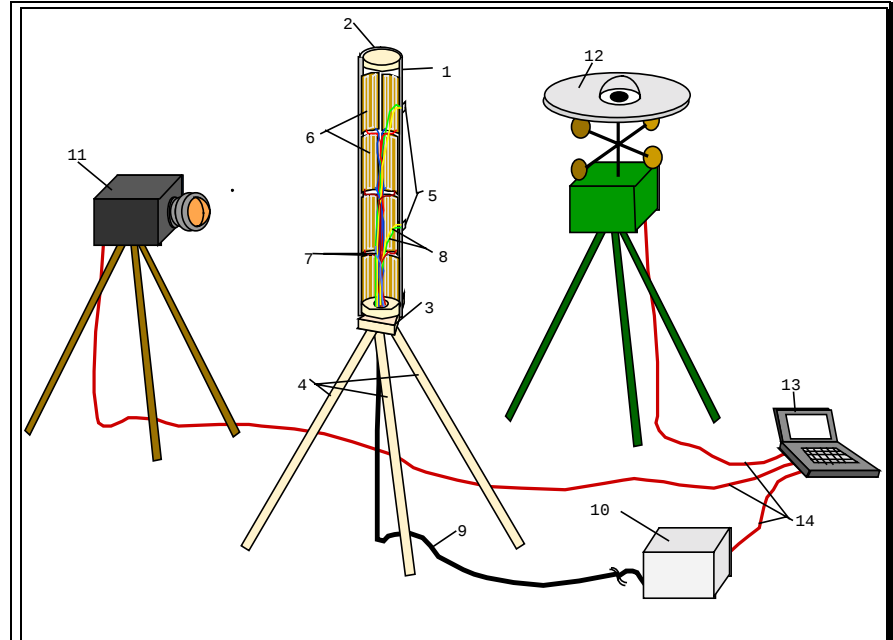


Figure 3. Data Collection Equipment

Figure 3 illustrates how the meter is used in conjunction with a weather station (12) and infrared camera. (11). The laptop computer (13) is connected to the convection meter by means of serial data lines (14) running from station, camera, and the meters controlling electronics (10). The laptop records data from all items continually, and records them on disk for later retrieval and analysis.

The coefficient of convection may be derived from this data and the physical constants of the device. The convection equation given previously When all data are reduced and plotted, one may correlate the apparent temperature of objects imaged by the thermal camera to environmental effects, and separate the influence of radiant heat transfer with that of convection. Figure 4 is an illustration of such a correlation plot, in which the ambient air temperature (blue) is plotted with wind speed (green), solar insolation (brown), convective heat loss (red), and the apparent temperature of tree leaves (black) as indicated by a thermal imager. In this figure, the data plotted was taken overnight from approximately 6:00 PM to 9:00 AM. Notice the large increase in solar insolation as the sun rises. The indicated apparent temperature of the tree increases drastically about 7:00 AM as the sun rises behind the imaged tree – showing that the increase in apparent temperature is due to the sun's radiance filtering through the leaves, and not to any physical may be rewritten as:

$$h_c = \frac{q_c}{A\Delta T}$$

4.0 COLLECTION AND REDUCTION OF CONVECTION DATA

Our convection meter measures q_c directly. We know from the controlling electronics the temperature of the device, and from the weather station we know the ambient air temperature. These two temperatures allow us to determine DT ($T_{\text{meter}} - T_{\text{ambient}}$). We know the area of the meter because we designed and built it (0.5 sq meters). The plot shown in figure 5 illustrates the results of using the data from figure 4 to calculate the coefficient of convection from the rewritten convection equation.

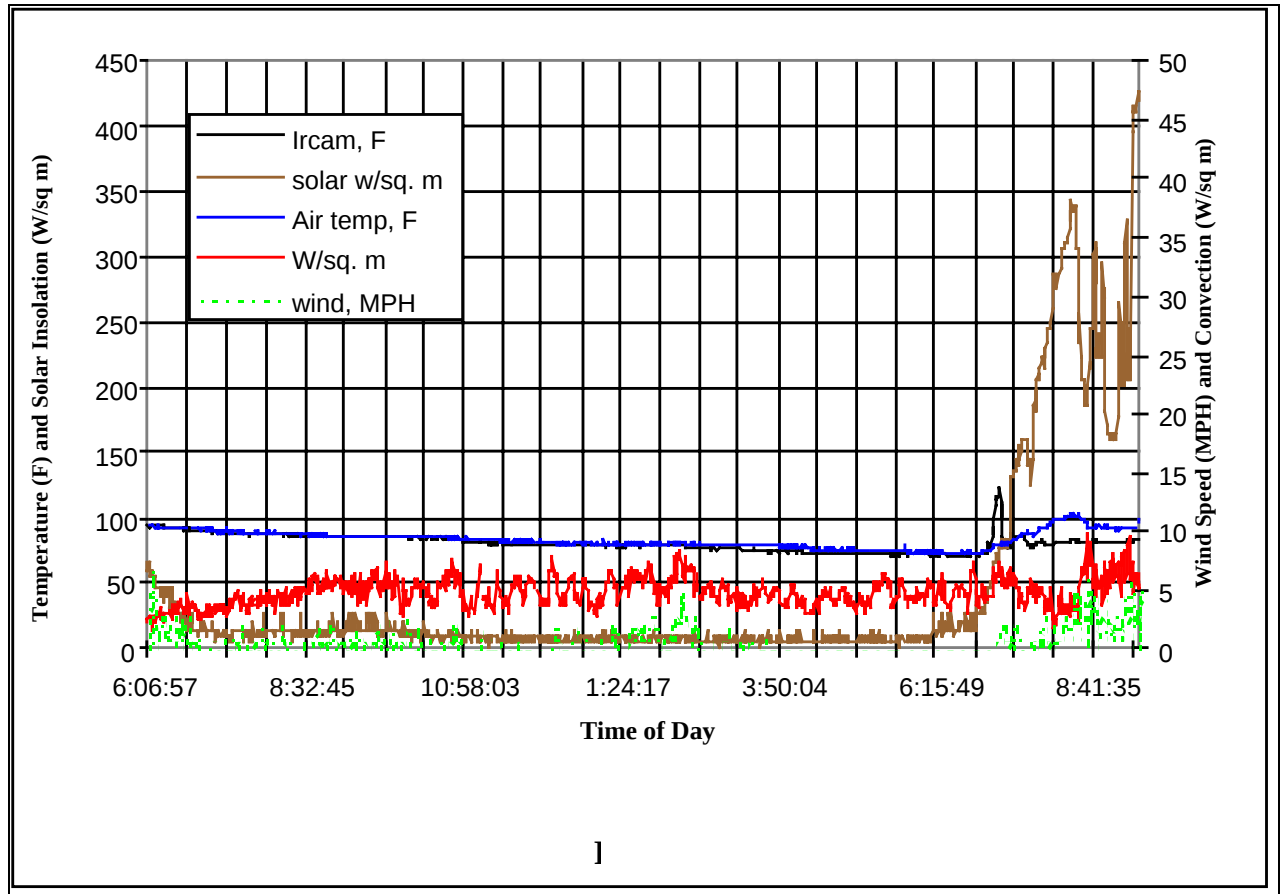


Figure 4. Meter Correlation Data Plotted versus Environmental Parameters

Figure 5 illustrates the effect of wind speed on the coefficient of convection. The minimum coefficient of convection is held in this figure as 1.0. Figure 6 is, perhaps, a bit more informative. In this plot, we show the indicated difference between the apparent temperature of the tree as measured by the thermal camera and the ambient air temperature – as measured with a thermocouple. This difference is labeled temp delta in figure 6. These are plotted with the measured wind speed and the calculated coefficient of convection.

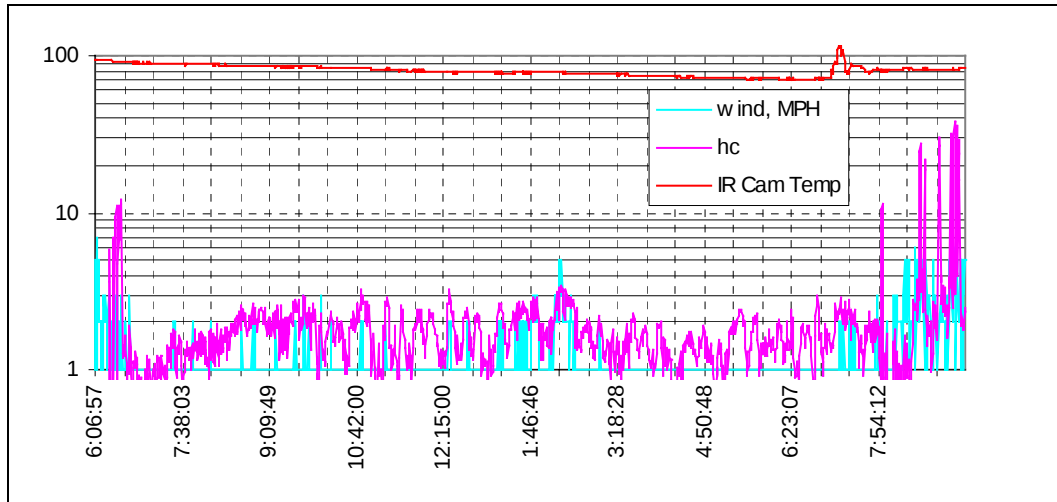


Figure 5. Coefficient of Convection Plotted with Wind Speed and Apparent Temperature

Figure 6 indicates that there is a measurable effect on the apparent temperature by convection. When the wind stops, the temperature difference increases. When it picks up, the temperature difference decreases. This implies that at low convection values, radiant effects between object and background manifest themselves, but convective effects dominate the apparent temperature

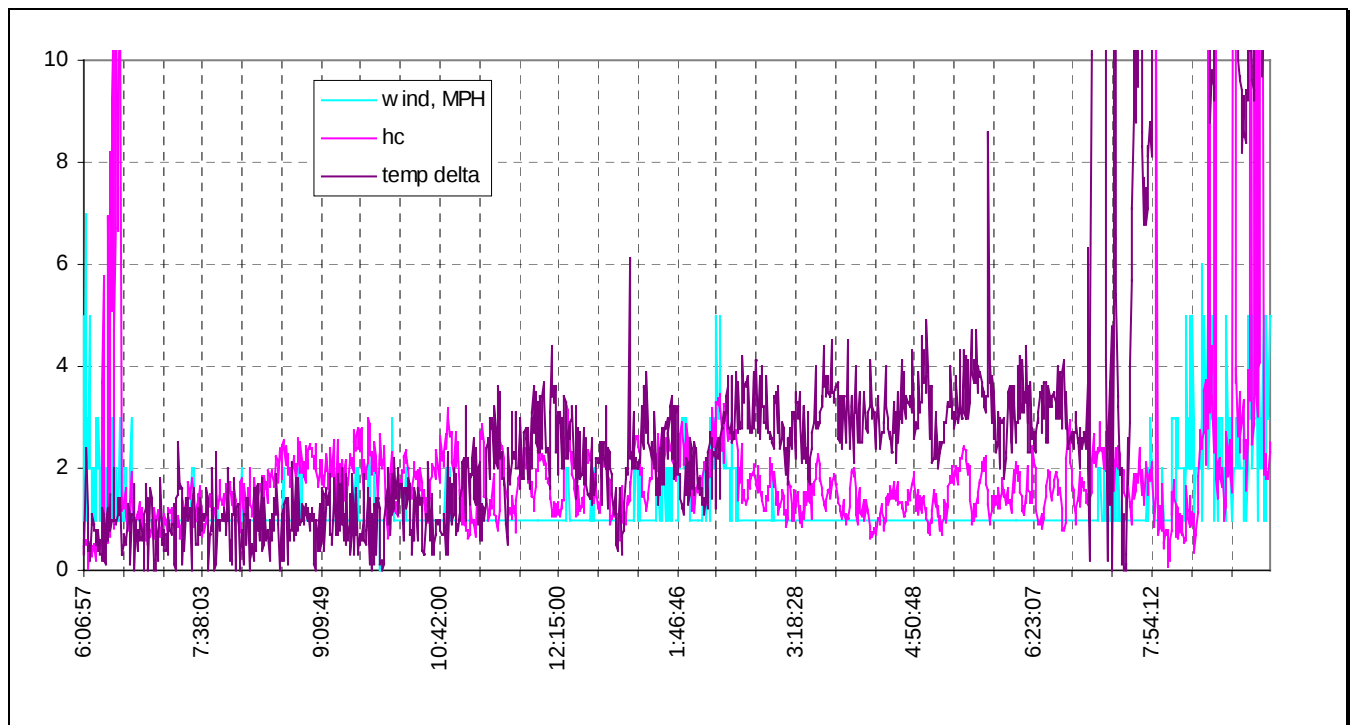


Figure 6. Difference between Air Temperature and Apparent Temperature

Consider that the power received from some body by an infrared sensor is a function of the physical temperature of the body, its emissivity, its reflectivity, and the apparent temperature of the background in which it lies. One notation showing such a relationship is:

$$E_b = \sigma(\gamma T_{bkg}^4 + \epsilon T_{physical}^4)$$

where γ is the objects thermal reflectivity, ϵ is its emissivity, and σ is the Stefan Boltzman constant. Figure 7 is a plot of this relationship for a object whose physical temperature is 40 C and whose background temperature is 25 C. Remember, the relationship between emissivity and reflectivity is:

$$\epsilon = 1 - \gamma$$

so, figure 7 just uses emissivity for its coordinate.

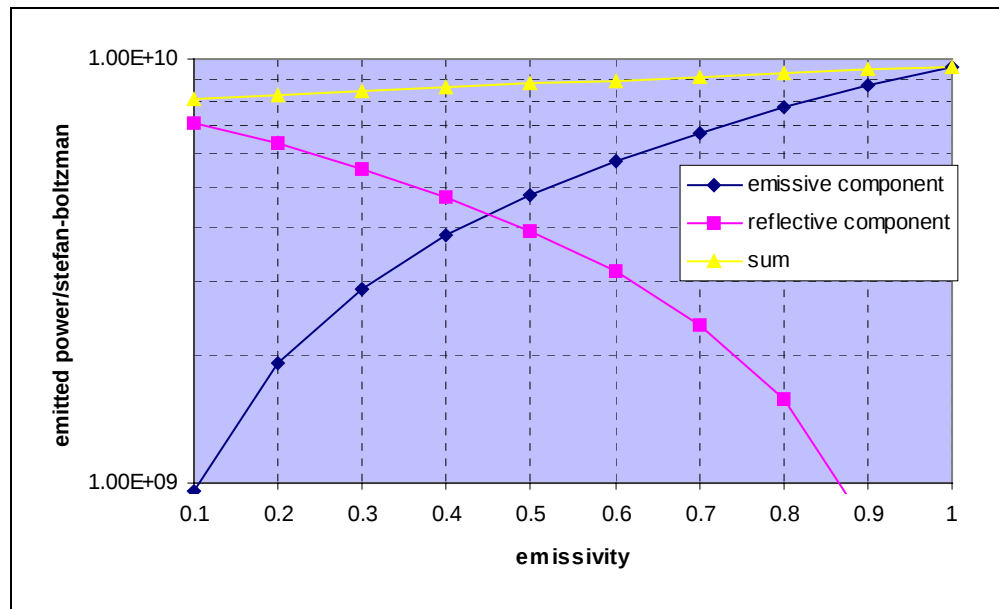


Figure 7. Reflective and Emissive components of the Apparent Radiant Power of some Background-Embedded Object

Like mister natural said, “what does this mean?”.... Well, let’s add one more figure, Figure 8, which is the same plot, except the background temperature is -40 C. Such a case might represent viewing an object that has a clear, cold sky overhead.

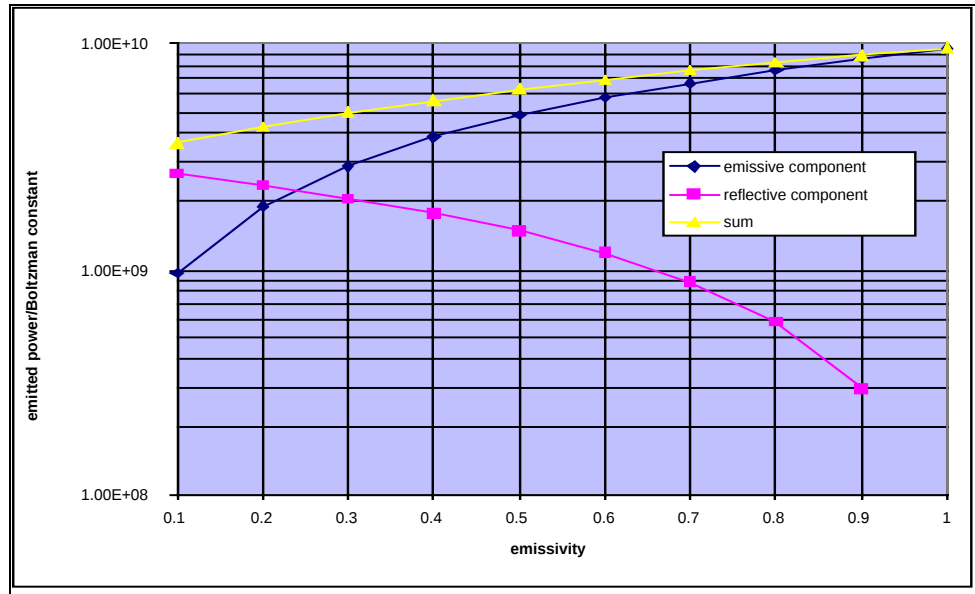


Figure 8. Reflective and Emissive components for 40 C Object with a -40 C Background

The point of these plots in figures 7 and 8 is that only at fairly high reflectivities (higher than 55% and 75%, respectively) does the reflective component of the object dominate the apparent temperature perceived by some thermal imager. At lower reflectivities the apparent temperature is governed primarily by the physical temperature of the object which - in the absence of conduction - is dominated by convective heat transfer. *That* is why we need to monitor the convection and correlate it with the apparent temperature of our object.

5.0 CONCLUSION AND FUTURE WORK

We conclude that we can reliably measure the natural and forced convection in the atmosphere in a manner conducive to correlating the convection with atmospheric processes. In addition, we have established a method to correlate the convection with the apparent temperature of objects.

In FY '99, we intend to continue taking data in over a variety of weather conditions to build a data base of typical environmental convectivities. We also plan to use our convection meter as a device to determine the convective merits of camouflage designs. To this end, we are developing a new radiant calibration standard, which we will be using as the apparent temperature source maintained in the thermal camera field of view while convection data is taken.