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TECHNIQUES AND ANALYSIS OF THERMAL INFRARED CAMOUFLAGE IN FOLIATED BACKGROUNDS

REPORT

for

U. S. Army
Mobility Equipment
Research and
Development Command
Fort Belvoir, Virginia

Contract No. DAAG53-76-C-0134

Final Report

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TECHNIQUES AND ANALYSIS OF THERMAL INFRARED CAMOUFLAGE IN FOLIATED BACKGROUNDS.

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PREFACE

This report covers work accomplished under contract DAAG53-76-C-0134. The contract was for the survey and analysis accomplished and did not include any other sub-tasks.

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TECHNIQUES AND ANALYSIS OF THERMAL INFRARED CAMOUFLAGE IN FOLIATED BACKGROUNDS

FINAL REPORT

6 April 1976 Through 6 January 1977

(micrometers

I. INTRODUCTION

The objective of this effort was to investigate thermal infrared ($3-5\ \mu$ and $8-14\ \mu$) camouflage measures for military targets in foliated backgrounds. Common lightweight materials were considered as the possible emulators of the foliated backgrounds. These materials were considered to be cloth like material with very low thermal inertia.

Since the thermal infrared camouflage problem exists throughout the day, the infrared signature was considered for the emulator and the foliage during the entire day. Both analytical and experimental evaluation of the foliage signature and analytical evaluation of a proposed emulator were examined.

Successful evaluation of the thermal infrared signature of foliage for a 24 hour period depends upon the modeling of the energy exchange mechanism of the foliage. The energy exchange of foliage, in general terms, cannot be modeled successfully because of the many independent variables, however the energy exchange for an individual element of the foliage, such as a single leaf, may be modeled. If camouflage materials are produced which emulate the infrared signature of an individual leaf and if these materials are properly distributed on netting, the emulation of background foliage should be possible. For this reason, the major thrust of this effort was toward the modeling of an individual leaf rather than a gross foliage background.

Both a leaf and the leaf emulator, or camouflage material, exist in an environment which exchanges energy with them by two basic mechanisms, convection and radiation. The convection mechanism is controlled by the external flow field, wind velocity and turbulence, and by the physical dimensions of the object. These mechanisms have been extensively investigated and are reported in many standard texts and references, however, the results for the specific case of leaves was reported by Parkhurst, et al. in reference 1.

In the case of radiation energy exchange, the leaf environment is logically divided into two broad radiant energy wavelength regions. These are the thermal, wavelengths of about 2.5 micrometers to 20 micrometers, and the solar, wavelength of about 0.3 micrometers to 2.5 micrometers, regions. Both environments have been extensively investigated and may be modeled under specific meteorological conditions. However, with the very large number of meteorological and other environmental variables possible, modeling must be accomplished with average conditions. These average conditions, while useful for comparison of IR signatures from camouflage materials and leaves, may never be duplicated by natural conditions.

II. THERMAL MODEL FOR LEAF

Basic Considerations

The transient thermal response of a leaf is governed by the energy exchange with the environment at the leaf boundaries and the thermal capacitance of a leaf. By considering a typical leaf thickness, the rate of response or time constant is of the order of 300 seconds [2]. Since the time periods of interest in this study are much longer, the leaf was modeled assuming steady state occurs in each time period. With this basic assumption the model becomes simplified in that the environmental input may be equated to the leaf energy loss to determine the leaf temperature.

Environmental Conditions

Convective Environment: The convective environment for a leaf consists of the air temperature and velocity. Since both of these are meteorological quantities the approach taken was to assume a typical variation for diurnal temperature variation and a constant air velocity. The air temperature was specified over the twenty four hour period by the ASHRAE recommended procedure [3]. Maximum and minimum temperatures were chosen for the type season of interest.

Wind velocity was considered constant at a value input into the program. Values from 6.7 m/s (15 mph) to calm were examined.

Radiation Solar Environment: The solar energy incident upon a leaf was determined using the ASHRAE method to determine the intensity of the direct solar beam and the diffuse or scattered component [3]. The solar declination for any day was used as a program input. From this information and the leaf direction parameters, i.e. the angle of tilt and the azimuth angle, the solar energy incident on the leaf upper surface was evaluated. Reflected solar radiation was assumed to be negligible.

Longwave Radiation Environment: Longwave radiant energy impinges on the leaf from three sources. First, from the warm humid atmosphere; second from the ground below the leaf; third from any object in view of the leaf. The radiant energy originating in the atmosphere is a function of the atmospheric dry bulb temperature and the moisture content. This radiant flux is approximated by several authors using an equation of the form: [4]

$$q''_{atm} = \sigma T_a^4 (A + B\sqrt{e}) \qquad 1$$

in which

q''_{atm} is the radiant flux in cal./cm^2/min.

T_a is the absolute air temperature in °K

e is vapor pressure of the water in the air in millibars

σ is the Stefan Beltzmann Radiation constant

A and B are constants varying from author to author in [illegible] approximate ranges of $\underline{0.4} \leq A \leq \underline{0.75}$, $\underline{0.047} \leq B \leq \underline{0.08}$

The long wavelength energy flux on the leaf from the ground is given by:

$$q''_{gr} = \epsilon_{gr} \sigma T^4_{gr} F_{\ell - g} \qquad 2$$

in which,

q''_{gr} is the radiant flux in cal./cm^2/min.

T_{gr} is the absolute temperature of the ground,

ϵ_{gr} is the long wavelength emittance of the ground i.e., $\epsilon_{gr}(T_{gr})$,

$F_{\ell - g}$ is the fraction of the ground seen by the leaf, i.e. one for the bottom of a horizontal leaf, ½ for one side of a vertical leaf, etc.

The third component of the long wavelength radiant energy is a variable dependent upon the individual case studied. For the purpose of this work, this term was assumed to be negligible. This assumption was made on the basis that an emulator would react to surrounds exactly like the leaf if the emulator reacts to the simplified surrounds like the leaf.

In order to evaluate radiant input to the leaf from the ground, the ground temperature must be determined. Modeling of the ground to obtain this temperature requires a transient model. In this case the ground was modeled as a semi-infinite slab with constant thermal properties. Properties used were obtained from reference 5. One of the most uncertain variables in this sub-analysis was the convective heat transfer from the ground surface to the air. This was finally obtained from reference 6 using reasonable vegetation heights. The expression used was

$$h = (C_f/2) \rho C_p (P_r)^{-2/3} U \qquad 3$$

Budyko [7] presents results of a study of drag caused by vegetation on the earth's surface and proposes a drag coefficient as follows:

$$C_f/2 = [2.5 \ln(\gamma/Z_o) + 5]^{-2} \qquad 4$$

in which:

h is the convective coefficient in cal./cm^2/min. - °C

C_f is the drag coefficient depending upon surface roughness,

ρ is the density of air g/cm^3,

C_p is the specific heat of air cal/gm- °C,

P_r is the Prandtl number of air,

U is the wind velocity cm/min,

γ is the height of wind velocity measurement assumed to be 76 cm,

Z_o is the height of vegetation in cm.

Leaf Energy Balance:

Radiant Input: The radiant energy input to a leaf was divided into the two parts, solar energy input and long wavelength energy input. The solar normal or beam intensity was obtained from: [3]

$$q''_{SN} = A/\exp(\beta/\sin a) \qquad 5$$

in which

q''_{SN} is the normal solar intensity w/m^2

a is the solar altitude in degrees

A is the apparent solar irradiation at air mass=0

β is the atmospheric extinction coefficient

The actual energy incident on the leaf consists of the solar beam radiation projected on the leaf surface plus the scattered solar energy. Scattered solar flux was determined from: [3]

$$q''_{SD} = Cq''_{SN}F_{\ell-s} \qquad 6$$

in which

q''_{SD} is the diffuse or scattered solar irradiation,

q''_{SN} is defined in equation 5

C is a constant which depends on atmospheric dust. moisture, and air mass,

$F_{\ell-s}$ is the fraction of the sky seen by the leaf, configuration factor from the leaf to the sky.

These two energy fluxes were assumed to be incident on the leaf upper surface and the energy input was taken to be their sum multiplied by the solar absorptance of the leaf upper surface.

$$q''_{TOT} = (q''_{SD} + q''_{SN})\, \alpha_{s\ell u} \qquad 7$$

Values for the solar absorptance of leaves are available in many sources but the values used were from Birkebak and Birkebak.[8]

Long wavelength energy input to the leaf from the air (q''_{atm}) and the ground (q''_{gr}) as given in equations 1 and 2 were treated as follows. The energy input from the atmosphere was assumed to be the same for both the upper and lower surfaces of the leaf and the ground energy input was assumed to be to the leaf lower surface only. Thus the total energy input per unit area of leaf was $\alpha_{tu} q''_{atm} + \alpha_{t\ell} q''_{atm} + \alpha_{t\ell} q''_{gr}$ where α_{tu} is the long wavelength absorptance of the leaf upper surface and $\alpha_{t\ell}$ is the long wavelength absorptance of the leaf lower surface.

Convective Energy Input: The convective energy input was evaluated from the standard convective heat transfer expression

$$q''_{conv} = h_c (T_{atm} - T_{leaf}) \qquad 8$$

in which

q''_{conv} is the convective heat flux in cal. /min. -cm^2

h_c is the convective heat transfer coefficient in cal/min-cm^2-°C

T_{atm} is the atmospheric temperature in °C

T_{leaf} is the leaf temperature in °C

Values of h_c were obtained using the procedures of reference 1. These are based on standard equations for free and forced convection and therefore require the evaluation of the following dimensionless parameters:

(1) The average Nusselt Number

$$\overline{Nu} = h_c L/k. \qquad 9$$

(2) The Reynolds Number

$$Re_L = U\rho L/\mu \qquad 10$$

(3) The Grashof Number

$$Gr_L = \beta g \rho^2 L \Delta t/\mu^2: \qquad 11$$

in which

L is the effective leaf dimension in cm

U is the wind velocity in cm/min

g is the acceleration of gravity in cm/min^2

k is the thermal conductivity of air in cal. /cm-min-°C

β is the temperature coefficient of volume expansion in cm^{-1}

μ is the absolute viscosity of air in gm/cm-min

ρ is the density of air in gm/cm^3

The standard correlations using the dimensionless parameters are

(1) For free convection from vertical plates

$$\overline{Nu} = 0.480\, Gr_L^{\frac{1}{4}} \qquad 12$$

(2) For free convection from the upper surface of a horizontal plate warmer than air or to the lower surface of such a plate cooler than air:

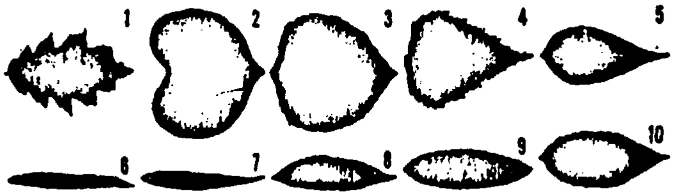
$$\overline{Nu} = 0.497\, Gr_L^{\frac{1}{4}} \qquad 13$$

(3) For free convection from the lower surface of a warmer than air horizontal plate or to the upper surface of a cooler than air horizontal plate:

$$\overline{Nu} = 0.249\, Gr_L^{\frac{1}{4}} \qquad 14$$

(4) For forced convection to or from a plate having a uniform temperature:

$$\overline{Nu} = 0.595\, Re_L^{\frac{1}{2}} \qquad 15$$



LEAF	1	2	3	4	5	6	7	8	9	10
X FORC.	.378	.594	.505	.407	.448	.681	.501	.508	.647	.471
X FREE	.465	.695	.610	.495	.526	.715	.577	.581	.697	.572
X TURB.	.480	.711	.628	.511	.541	.721	.591	.595	.705	.589
L FORC.	•	.811	.649	.487	.555	•	•	.612	.718	.636
L FREE	•	.828	.672	.529	.576	•	•	.643	.737	.657
L TURB.	•	.831	.677	.537	.580	•	•	.648	.740	.661

Fig. 1. Values of R for ten real leaves. X = flow perpendicular to stem; L = flow parallel to stem; FORC. = forced convection in laminar flow; FREE = free convection in laminar flow; TURB. = forced convection in turbulent flow. (Reproduced from Ref. 1.)

A decision as to whether the flow field was strong enough to cause forced convection was made by comparing the values of Gr_L and $(Re_L)^2$. If $(Re_L)^2$ was larger than Gr_L the forced convection equation was used. Values of L for use in these expressions were obtained from $L = RL_{max}$ in which R was obtained from figure 1 and L_{max} was the average maximum dimension of the leaf under consideration.

Transpiration Energy Loss: The energy loss from a leaf by transpiration of the leaf moisture was extensively studied by several authors. In this work, the results and methods presented by Gates in references 9 and 10 were used. The expression for transpiration energy loss is

$$q''_e = \left[\frac{\rho_g(T_\ell) - \varphi\rho_g(T_a)}{r_\ell + r_a}\right] h_{fg} \qquad 16$$

in which

q''_e is the transpiration energy flux in cal./cm^2-min.

$\rho_g(T_\ell)$ is the density of saturated water vapor at the leaf temperature in gm/cm^3,

$\rho_g(T_a)$ is the density of saturated water vapor at the air temperature in gm/cm^3,

h_{fg} is the latent heat of vaporization of water at the leaf temperature

φ is the relative humidity of the air,

r_ℓ is the internal leaf diffusion resistance in min/cm

r_a is the boundary layer resistance given by equation 17.

$$r_a = k_2 \frac{W^{0.20} L^{0.35}}{U^{0.55}} \qquad 17$$

in which

W is the leaf dimension transverse to the wind in cm,

L is the leaf dimension in the direction of the wind in cm,

U is the wind velocity in cm/min

k_2 is the dimensional constant of 0.247 cm/min.$^{1.55}$

Values for the internal diffusion leaf resistance are presented by Gates for several common leaves. These values are presented as constants although it is known that water stress or high environmental temperatures cause these resistances to change. In this work constant leaf resistance values were assumed.

Leaf Radiant Energy Loss: The radiant energy loss of the leaf was calculated assuming the upper and lower surfaces had the same emittance. This results in

$$q''_r = 2\epsilon\sigma T_\ell^4 \qquad 18$$

in which

q''_r is the radiant loss per unit area of leaf in cal./cm^2-min

ϵ is the emittance of the leaf at the leaf temperature

T_ℓ is the absolute leaf temperature in °K

The leaf was assumed to have negligible thermal mass, therefore, the sum of the energy gain was set equal to the energy loss to calculate the leaf temperature.

Leaf Radiance in the 3-5 and 8-14 Micrometer Wavelength Region

3-5 Micrometer Wavelength Region: The radiant flux from a leaf in the 3-5 micrometer wavelength range was assumed to consist of three components. These components were; (1) energy emitted as a function of the leaf temperature; (2) energy reflected off the leaf upper surface from incident solar energy and, (3) solar energy reflected off of the ground and transmitted through the leaf. The components were calculated as follows:

$$R_{3-5}(\text{Thermal}) = \epsilon \sigma F_1 T_\ell^4 \qquad 19$$

where

R_{3-5}(Thermal) is the first component cal. /cm^2 /min.

ϵ is the leaf emittance

T_ℓ is the leaf temperature, °K

F_1 is the fraction of energy radiated between 3 and 5 micrometers by a Plankian radiator.

$$R_{3-5}(\text{Solar}) = \rho_{su} F_2 G_s \cos\theta \qquad 20$$

where

R_{3-5}(Solar) is the second component, cal. /cm^2/min.

ρ_{su} is the solar reflectance of the leaf upper surface

F_2 is the fraction of the solar insolation which is in the 3-5 micrometer wavelength range

G_s is the solar insolation in the 3-5 micrometer range, cal. /cm^2/min.

θ is the zenith angle

$R_{3-5}(\text{Solar Reflected}) = \tau_{\ell}\,\rho_{SG}\,F_2 G_s \cos\theta$ 21

where

R_{3-5}(Solar Reflected) is the third component, cal./cm^2/min.

τ_{ℓ} is the leaf transmittance.

The sum of these three would be the energy flux at the leaf surface which would be detected by a 3-5 micrometer wavelength energy sensor system.

8-14 Micrometer Wavelength Region: The radiant flux from the leaf in the 8-14 micrometer wavelength range was assumed to be from the same three components as used in the 3-5 micrometer wavelength range. In calculating the values, the only change in equations 19, 20, and 21 are the fractions F_1 and F_2. Thus the same equations were used with different values for these fractions.

III. EXPERIMENTAL VERIFICATION OF THERMAL MODEL

Experimental Procedure: In order to test the validity of the thermal model used, an experiment was designed and run. This consisted of instrumenting leaves on two living trees, measuring the leaf temperature and the environmental conditions for the leaves.

Leaf Measurements: A nearly horizontal leaf on a common burr oak (Quercus Macrocarpa), a vertical leaf on a silver maple (Acer Saccharnum) and a horizontal leaf on the silver maple were instrumented. In order to minimize the effect of the measurement probes, small gage (40 gage) thermocouples were installed on the lower surface of the leaves. These thermocouples were shielded from direct solar insolation by being on the lower leaf surface and were in contact with the leaf for about 2 cm which should reduce thermocouple conduction effects. Temperatures were continuously recorded on a 12 point Leeds and Northrup Speedomax W recorder. As a check on the measured temperatures, total radiation pyrometric temperatures were measured with a Barnes PRT-10 radiometer.

Ground Temperature Measurement: Ground temperatures at depths of 5 and 6.4 cm were made using 24 gage thermocouples. Surface temperature could not be measured directly, due to short grass on the surface, therefore, the radiometric temperature was measured with the Barnes PRT-10 radiometer. Actual ground temperatures were estimated from the radiometric measurement by assuming a ground emittance consistent with the actual ground surface.

Environmental Conditions: The environmental variables needed for this study were dry bulb air temperature, wet bulb air temperature, wind velocity and solar insolation. Dry bulb temperatures were measured continuously using a shielded thermocouple and wet bulb temperature was measured each 30 minutes using a hand sling psychrometer. Wind velocity was measured at 1.1 meters above the ground using a ball and cup anemometer. Solar insolation was measured continuously using an Eppley 8-48 black and white pyranometer. Experimental data is summarized in Table I.

TABLE I
Experimental Data

Date: 3 September, 1976 Time: 1300 - 2330

ata int	Local Time	Local Solar Time	Camouflage Material Temperature	Maple Leaf Temperature		Oak Leaf Temperature		Ground Temperature			Air Temperature		Relative Humidity	Solar Flux (cal/cm^2/min)	Wind Speed (cm/min)	Comments
				TC	RAD2	TC	RAD2	2" Deep	Ground Surface Temp.	RAD2	Dry Bulb	Wet Bulb				
1	1300	11.60	--	38	38	37	38	30	51.43	43	31.7	23.3	.49	1.22	16551	clear
2	1330	12.10	--	39	40	38	41	31	57.59	49	33	23	.43	1.27	7590	clear
3	1400	12.60	--	43	44	43	44	31	57.59	49	33.9	22.8	.42	1.27	0	clear
4	1430	13.10	42	40	41	39	40	32	53.45	45	36.4	23.3	.34	1.22	0	clear
5	1500	13.60	45	39	40	36.5	41	32	55.54	47	35	23	.37	1.12	0	clear
6	1530	14.10	36	32.9	36	32.6	35	32.8	45.27	37	33.9	22.5	.38	0.31	8748	cloudy
7	1600	14.60	34	32.3	33.5	31.4	33	31.5	42.71	34.5	35	22.2	.33	0.23	0	cloudy
8	1630	15.10	36	39	34.0	36.5	38	31.5	46.30	38	33.6	23.0	.41	0.88	9845	clear
9	1700	15.60	40.5	40	36.0	38.0	36	32	47.84	39.5	33.3	22.8	.40	0.75	0	clear
10	1730	16.10	34	31.8	34.0	31.5	32	32	42.19	34	32.8	22.8	.43	0.19	14844	cloudy
11	1800	16.60	32	36	32.0	33	31	31	40.14	32	32.5	22.6	.44	0.45	13960	clear
12	1830	17.10	31	31	33.0	31	32	30	40.14	32	31.1	22.2	.47	0.30	8352	clear
13	1900	17.60	28	31	31.0	30	30	29.5	37.06	29	30.0	21.7	.48	0.16	14021	clear
14	1930	18.10	28	31.5	30.0	30.5	30	30	36.03	28	28.9	21.7	.54	0.04	8677	clear
15	2000	18.60	26	--	30.0	30	28	30	33.98	26	27.8	21.7	.59	0	15362	clear
16	2030	19.10	26	--	32.0	29	28	30.5	36.03	28	26.7	21.1	.62	0	8687	clear
17	2100	19.60	24	29	28	28	28	30	31.93	24	26.1	21.1	.64	0	13411	clear
18	2130	20.10	24	29.5	28	29.5	26	31	31.93	24	26.1	21.1	.64	0	9906	clear
19	2200	20.60	22	30	27	28	26	30	31.93	24	25.6	21.1	.68	0	11217	clear
20	2230	21.10	22	27	26	27	26	29	30.90	23	25.0	20.8	.68	0	11278	clear
21	2300	21.60	22	26	26	26	25	28.5	30.90	23	24.4	20.6	.71	0	8047	clear
22	2330	22.10	21	26	24	25	24	28.5	29.87	22	23.6	20.0	.72	0	11156	clear

Date: 4 September, 1976 Time: 0000 - 1130

Data Point	Local Time	Local Solar Time	Camouflage Material Temperature	Maple Leaf Temperature		Oak Leaf Temperature		Ground Temperature			Air Temperature		Relative Humidity	Solar Flux (cal/cm²/min)	Wind Speed (cm/min)	Comments
				TC	RAD2	TC	RAD2	2" Deep	Ground Surface Temp.	RAD2	Dry Bulb	Wet Bulb				
23	0000	22.60	19	25.5	24	25.5	23	28	28.85	21	22.8	20.3	.80	0	8230	clear
24	0030	23.10	21	24.0	23	24	23	28	28.85	21	22.2	20.3	.84	0	6431	clear
25	0100	23.60	20	24	23	24	22	28	27.82	20	21.7	20.6	.90	0	7376	clear
26	0130	0.10	18	24	22	24	22	28	27.82	20	21.7	20.6	.90	0	7711	clear
27	0200	0.60	18	23.5	22	23.5	22	27	27.82	20	21.7	20.6	.90	0	7772	clear
28	0230	1.10	18	23.5	22	23.5	21	27	27.82	20	20.6	20.6	1.00	0	4938	clear
29	0300	1.60	18	23.5	22	23.5	22	27.5	27.82	20	20.8	20.6	.98	0	6370	clear
30	0330	2.10	18	23	22	23	22	27	27.82	20	20.6	20.6	1.00	0	0	clear
31	0400	2.60	19	23.5	22	23	22	27	28.85	21	20.8	20.8	1.00	0	8839	clear
32	0430	3.10	18	23.5	22	22.5	22	27	28,85	21	20.8	20.8	1.00	0	7803	clear
33	0500	3.60	18	23	21	20	21	27	26.79	19	20.6	29.8	1.00	0	7163	clear
34	0530	4.10	17	15	20	23	21	26.5	26.79	19	20.6	20.8	1.00	0	3566	clear
35	0600	4.60	20	23	20	--	20	26.9	26.79	19	20.0	20.6	1.00	0	3170	clear
36	0630	5.10	20	22.9	19.5	--	19.5	26.8	25.77	18	20.0	20.3	1.00	0	2774	clear
37	0700	5.60	20	22.4	21	--	20	26.5	26.26	18.5	20.0	20.4	1.00	.03	3200	clear
38	0730	6.10	20	23	20.5	--	20	26.7	26.79	19	20.3	20.6	1.00	.06	2987	clear
39	0800	6.60	21	24	22	--	20.5	26.8	29.87	22	21.1	21.1	1.00	.15	5669	clear
40	0830	7.10	24	26	24	--	22	26.2	33.98	26	22.2	22.2	1.00	.28	11156	clear
41	0900	7.60	30	27.5	27	26.8	27	27	36.03	28	25.0	22.8	.84	.44	5791	clear
42	0930	8.10	30	30.4	28	30.2	28	27.6	38.60	30.5	26.4	23.3	.80	.61	7650	clear
43	1000	8.60	30	30	28	31	29	28	41.17	33	27.2	23.6	.74	.74	19521	clear
44	1030	9.10	32	30	--	32.2	--	27.3	43.22	35	28.3	23.9	.70	.85	18867	clear
45	1100	9.60	37	31.9	--	35	--	28.2	44.76	36.5	30.0	24.4	.64	.95	16250	clear
46	1130	10.10	42	37.4	--	38.9	--	28.4	50.41	42	31.7	24.7	.58	1.06	0	clear

Date: 4 September 1976 Time: 1200-2330

Data Point	Local Time	Local Solar Time	Camouflage Material Temperature	Maple Leaf Temperature			Oak Leaf Temperature			Ground Temperature			Air Temperature		Relative Humidity	Solar Flux (cal/cm^2/min)	Wind Speed (cm/min)	Comments
				TC	RAD2		TC	RAD2		2" Deep	Ground Surface Temp.	RAD2	Dry Bulb	Wet Bulb				
					T	B		T	B									
47	1200	10.60	40	36	35	35	39.8	38	37.5	30	49.89	41.5	34.4	25	.47	1.13	16253	T&B=Top & Bottom radiometer readings
48	1230	11.10	40	36.2	36	35.5	40	38	35	30.8	53.49	45	34.4	25	.47	1.18	9708	
49	1300	11.60	42	39	38	38	41	40	39	31.5	54.51	46	36.7	23.9	.35	1.22	12979	
50	1330	12.10	42	41	39	39	43	41	43	32.3	55.54	47	36.7	23.9	.35	1.23	16250	clear
51	1400	12.60	43	41	41	41	42.5	42	42	32.8	54.51	46	38.9	25	.33	1.21	19521	cloudy
52	1430	13.10	42	41.7	41	41	43.8	42	42	34	54.51	46	37.2	23.3	.32	1.23	13634	clear
53	1500	13.60	45	40.5	42	42	43	42	42	33.7	54.51	46	37.2	23.9	.34	1.18	16250	clear
54	1530	14.10	43	39.3	41	40	39.5	40	40	32.6	52.46	44	36.1	23.3	.34	1.09	19521	clear
55	1600	14.60	41	41	40	40	39	38	38	33	51.43	43	36.9	25.0	.38	1.01	19521	clear
56	1630	15.10	42	41.5	41.5	41	38.6	38	38	33	51.43	43	36.1	23.9	.37	.84	12979	clear
57	1700	15.60	41	37.5	38	40	37	38	38	32.5	50.41	42	36.1	23.3	.35	.71	19521	clear
58	1730	16.10	40	37.5	40	42	35	40	39	33	48.35	40	36.1	22.2	.30	.29	18213	clear to cloudy
59	1800	16.60	39	37.5	40	40	34	39	39	31	48.35	40	35.0	22.8	.35	.35	17559	clear
60	1830	17.10	36	38	38	38	34	36	36	32	44.25	36	34.4	23.3	.39	.34	19521	clear
61	1900	17.60	33	36.5	36	36	33.5	35	35	32	42.19	34	33.3	23.3	.43	.18	19521	clear
62	1930	18.10	31	32.3	32	32	32.2	32	31	31.4	38.09	30	30.8	22.8	.51	.03	19521	clear
63	2000	18.60	30	32.0	32	32	31	31	31	31	36.03	28	28.9	22.2	.57	0	12979	clear
64	2030	19.10	27	29.4	29.5	29	30	29	28	30.8	33.98	26	27.8	21.7	.59	0	9708	clear
65	2100	19.60	28	29.5	30	29	30	29	29	30.5	34.49	26.5	27.8	21.7	.59	0	9708	clear
66	2130	20.10	28	29.1	28	28	29.3	27	26	30.8	32.95	25	27.6	21.7	.59	0	9708	clear
67	2200	20.60	28	28.5	27	27.5	29.2	27	27	30.3	31.93	24	27.2	21.4	.60	0	11671	clear
68	2230	21.10	26	27.9	27	27	27.5	24	25	30	31.93	24	26.1	21.1	.64	0	9054	clear
69	2300	21.60	26	28.1	26	26	28.5	25	25	30.3	30.90	23	26.1	21.1	.64	0	9708	clear
70	2330	22.10	26	26.4	26	26	26.8	25	25	28.5	31.41	23.5	26.4	21.1	.63	0	7092	clear

Date: 5 September 1976 Time: 0000 - 1130

Data Point	Local Time	Local Solar Time	Camouflage Material Temperature	Maple Leaf Temperature			Oak Leaf Temperature			Ground Temperature			Air Temperature		Relative Humidity	Solar Flux (cal/cm²/min)	Wind Speed (cm/min)	Comments
				TC	RAD2		TC	RAD2		2" Deep	Ground Surface Temp.	RAD2	Dry Bulb	Wet Bulb				
					T	B		T	B									
71	0000	22.60	26	26.2	25	26	26.5	25	24	29	30.39	22.5	25.0	20.8	.69	0	0	clear
72	0030	23.10	22	27	25	25	27	26	27	29	30.90	23	23.9	20.8	.77	0	0	clear
73	0100	23.60	20	27	25	25	26.8	24	25	29	29.87	22	23.3	20.8	.80	0	8400	clear
74	0130	0.10	21	25.8	24	24	27	23	24	30	28.85	21	22.5	20.6	.85	0	0	clear
75	0200	0.60	19	26	23	23	26.5	23	23	29.5	27.82	20	21.7	20.6	.90	0	0	clear
76	0230	1.10	18	26	23	23	26.3	22	22	29.8	27.82	20	21.7	20.6	.90	0	0	clear
77	0300	1.60	18	25.5	22	22	26	21	22	29.5	26.79	19	21.4	20.3	.97	0	0	clear
78	0330	2.10	19	26.5	22	22	26	23	24	29.5	27.82	20	21.9	20.3	.88	0	0	clear
79	0400	2.60	18	25.5	22	22	26	22	22	29	26.79	19	21.1	20.3	.93	0	0	clear
80	0430	3.10	17	24.8	21	21	26	21	22	29	26.79	19	20.6	20	.95	0	0	clear
81	0500	3.60	16	24	22	22	25	22	21	29	25.77	18	20.0	20.0	1.00	0	0	clear
82	0530	4.10	17	26	22	22	25	21	22	29	27.82	20	20.5	20.0	.97	0	0	clear
83	0600	4.60	16	24	21	21	24	21	20	28.5	26.79	19	20	19.4	.95	0	0	clear
84	0630	5.10	15	23	19	18	23.5	19	18	28.6	24.74	17	19.4	19.4	1.00	0	0	clear
85	0700	5.60	15	23	19	19	23.5	19	18	28.5	24.74	17	19.2	19.4	1.00	0	0	clear
86	0730	6.10	16	23	20	20	23.5	20	20	28.5	25.77	18	19.7	19.4	.98	.03	0	clear
87	0800	6.60	19	26.5	22	22	25	21	21	29	29.87	22	22.7	20.6	.82	.16	0	clear
88	0830	7.10	22	27	25	25	26.5	23	22	28	32.95	25	24.4	21.1	.75	.32	0	clear
89	0900	7.60	26	26	26	26	28	26	26	27	36.03	28	26.7	22.2	.68	.43	0	clear
90	0930	8.10	31	29	27	28	30	28	28	27	40.14	32	27.5	22.8	.67	.58	0	clear
91	1000	8.60	36	31	32	31	31.5	31	32	25.5	44.25	36	28.9	23.9	.66	.73	10363	clear
92	1030	9.10	36	34	32	33	35	32	32	28.5	46.30	38	30.6	23.9	.57	.87	12979	clear
93	1100	9.60	38	37	34	35	39.5	37	37	29	50.41	42	31.7	23.9	.54	.95	0	clear
94	1130	10.10	40	36	34	34	38	36	37	30	51.43	43	32.8	23.9	.48	1.04	12979	clear

Date: 5 September 1976 Time: 1200 - 2330

Data Point	Local Time	Local Solar Time	Camouflage Material Temperature	Maple Leaf Temperature			Oak Leaf Temperature			Ground Temperature			Air Temperature		Relative Humidity	Solar Flux (cal/cm²/min)	Wind Speed (cm/min)	Comments
				TC	RAD2		TC	RAD2		3.5" Deep	Ground Surface Temp.	RAD2	Dry Bulb	Wet Bulb				
					T	B		T	B									GT-TC
95	1200	10.60	39	39.5	36	36	40	38	38	31.0	53.49	45	33.9	23.9	.44	1.13	12979	depth-3.5"
96	1230	11.10	42	37	35	35	40.5	37	37	30.6	55.03	46.5	34.4	22.2	.37	1.17	19521	clear
97	1300	11.60	45	42.5	38	38.5	43	41	42	31	55.03	46.5	35	22.2	.33	1.19	0	clear
98	1330	12.10	40	40	37	38.5	42	39	39	32.5	55.54	47	34.4	22.8	.37	1.21	19521	clear
99	1400	12.60	45	43.5	39	39	42	40	40	32	54.51	46	35	22.2	.33	1.19	0	clear
100	1430	13.10	--	43.5	41	41	43.5	41	40	33	54.51	46	35	21.7	.31	1.17	12979	clear
101	1500	13.60	[illegible]	43	39	39	41	38	38	32.5	52.46	44	35.3	22.2	.35	1.12	12979	clear
102	1530	14.10	44	44.5	40	40	43.5	40	40	32	53.49	45	35	21.9	.32	1.00	0	clear
103	1600	14.60	40	38.5	36	35	39	36	36	31.7	50.41	42	35	21.9	.32	.93	19521	clear-horiz. maple leaf
104	1630	15.10	40	38	38	38	38	38	38	32	50.41	42	34.4	22.2	.35	.80	19521	clear
105	1700	15.60	39	37.2	36	36	36.9	36	35	32.2	47.33	39	34.4	21.7	.33	.70	22792	clear
106	1730	16.10	40	37.1	35	36	36.7	35	34	32	45.27	37	34.4	21.7	.33	.56	19521	clear
107	1800	16.60	36	35	34	34	35	34	33	31.5	43.22	35	33.6	21.7	.35	.43	19521	clear
108	1830	17.10	34	33	33	34	34	33	34	31.3	42.19	34	33.3	21.7	.37	.27	22792	clear
109	1900	17.60	31	31	33	33	31	32	31	30.5	40.14	32	31.7	21.7	.42	.12	26063	clear
110	1930	18.10	26	30	29	29	29.2	28	28	30.8	36.03	28	28.6	21.7	.55	.03	18213	clear
111	2000	18.60	26	29.5	28	28	29	28	26	31	33.98	26	27.2	21.1	.58	0	19521	clear
112	2030	19.10	26	29	28	28	29	27	27	31.2	33.98	26	26.1	20.6	.62	0	28026	clear
113	2100	19.60	23	28	25	25	28	25	25	30.8	30.90	23	25.0	20.3	.65	0	15596	clear
114	2130	20.10	22	27.5	25	26	27.4	25	25	30.7	30.90	23	24.4	19.7	.65	0	14942	clear
115	2200	20.60	22	26.7	24	24	27	24	24	30.5	29.87	22	24.4	19.4	.64	0	0	clear
116	2230	21.10	21	26.8	24	24	27	24	24	30	29.87	22	23.6	18.9	.65	0	12325	clear
117	2300	21.60	20	26.4	24	24	26.2	23	23	30	29.87	22	23.3	18.6	.65	0	11017	clear
118	2330	22.10	19	25	22	22	26	22	21	30	26.79	19	21.7	18.3	.74	0	0	clear

Date: 6 September 1976 Time: 0000 - 1130

Data Point	Local Time	Local Solar Time	Camouflage Material Temperature	Maple Leaf Temperature			Oak Leaf Temperature			Ground Temperature			Air Temperature		Relative Humidity	Solar Flux (cal/cm^2/min)	Wind Speed (cm/min)	Comments
				TC	RAD2		TC	RAD2		3.5" Deep	Ground Surface Temp.	RAD2	Dry Bulb	Wet Bulb				
					T	B		T	B									
119	0000	22.60	18	25	22	22	25.2	23	22	29.5	27.82	20	21.7	18.3	.74	0	9708	clear
120	0030	23.10	20	24.5	22	22	25	22	22	29.2	27.82	20	21.1	18.1	.75	0	0	clear
121	0100	23.60	20	24	22	23	25	22	22	29.2	26.79	19	20.3	17.8	.78	0	0	clear
122	0130	0.10	16	22.8	20	20	23.5	20	20	29	25.77	18	20.0	17.8	.80	0	0	clear
123	0200	0.60	17	23	20	20	23	20	20	29	25.77	18	19.7	17.2	.78	0	0	clear
124	0230	1.10	17	22.6	18	18	23.6	18	18	29	23.71	16	18.9	17.2	.85	0	0	clear
125	0300	1.60	16	21.9	18	18	22.6	18	18	29	23.71	16	19.4	17.2	.80	0	0	clear
126	0330	2.10	15	21.2	18	18	24	18	18	28.8	23.71	16	17.8	16.7	.90	0	0	clear
127	0400	2.60	15	20.8	17	17	21.1	17	17	28.8	22.69	15	17.5	15.7	.92	0	0	clear
128	0430	3.10	14	20.5	15.5	15	21.5	17	17	28.7	22.69	15	17.8	16.7	.89	0	0	clear
129	0500	3.60	14	20.5	16	16	21.1	16	16	28.4	22.17	14.5	16.9	16.4	.94	0	0	clear
130	0530	4.10	14	21.1	16	16	21.8	16	16	28.2	22.69	15	16.7	16.4	.97	0	0	clear
131	0600	4.60	12	19	14	14	20.8	15	15	27.9	21.66	14	16.7	16.1	.94	0	0	clear
132	0630	5.10	14	20	15	15	20.6	15	15	27.5	21.66	14	16.7	16.1	.94	0	0	clear
133	0700	5.60	13	19.9	14	14.5	21	15	15	27.8	21.66	14	16.7	16.1	.94	0	0	clear
134	0730	6.10	14	20.3	14	14	21	14	14	27.6	21.66	14	17.2	16.1	.89	.03	0	clear
135	0800	6.60	20	22.9	17.5	17.5	22.3	17	17	28	25.77	18	19.4	17.2	.80	.14	0	clear
136	0830	7.10	25	24.7	20	20	22.8	18	18	27	29.87	22	20.8	17.8	.75	.28	0	clear
137	0900	7.60	31	25.9	21.5	22	25	21	21	25.9	32.95	25	23.9	18.9	.63	.42	0	clear
138	0930	8.10	32	26.8	24.5	25	25.5	24	24	23.9	34.49	26.5	26.1	19.4	.54	.56	12979	clear
139	1000	8.60	34	27.2	25.5	26	26	26.5	26	22.5	39.11	31	27.8	20.3	.51	.70	12979	clear
140	1030	9.10	40	29.5	30	32	28.5	30	31	22.8	45.27	37	30.6	21.4	.45	.82	16250	clear
141	1100	9.60	50	33.8	34	35	32	35	36	26.5	52.46	44	30	21.7	.48	.93	9708	clear
142	1130	10.10	42	35.5	37	38	35	36	37	28	53.49	45	30.6	22.2	.49	1.04	10363	clear

Date: 6 September 1976 Time: 1200 - 2330

Data Point	Local Time	Local Solar Time	Camouflage Material Temperature	Maple Leaf Temperature			Oak Leaf Temperature			Ground Temperature			Air Temperature		Relative Humidity	Solar Flux (cal/cm^2/min)	Wind Speed (cm/min)	Comments
				TC	RAD2		TC	RAD2		3.5" Deep	Ground Surface Temp.	RAD2	Dry Bulb	Wet Bulb				
					T	B		T	B									
143	1200	10.60	44	37.2	35	36	35	38	39	29	53.49	45	32.2	22.8	.45	1.12	18213	clear
144	1230	11.10	47	38	38	39	37	38	40	30	56.57	48	31.9	22.5	.44	1.16	16250	clear
145	1300	11.60	43	37	40	39	38.8	40	39	30.7	57.59	49	33.9	21.9	.35	1.19	12979	clear
146	1330	12.10	48	37.8	37	38	39	40	39	31	55.54	47	33.9	22.8	.38	1.12	14288	clear
147	1400	12.60	43	39	39	39	39	37	37	32	55.54	47	33.9	22.2	.36	1.17	8400	clear
148	1430	13.10	45	38.3	39	39	36.9	38	40	32	55.54	47	33.3	22	.40	1.14	11671	clear
149	1500	13.60	38	36.8	36	34	36	35	36	32	52.46	44	32.8	22.8	.43	1.08	14288	clear
150	1530	14.10	38	36.5	35	35	38	35	34	32	50.41	42	33.6	22.2	.39	1.03	--	clear
151	1600	14.60	36	35.7	34	34	36.6	34	34	31.5	48.35	40	33.3	21.7	.36	.93	0	clear
152	1630	15.10	36	36.0	34	34	35	34	34	--	50.41	42	33	21.1	.35	.82	12802	clear
153	1700	15.60	40	36.0	36	36	35	35	35	31	46.30	38	32.8	21.1	.36	.70	16459	clear
154	1730	16.10	40	34.6	34	34.5	34.5	34	34	31.6	44.25	36	32.8	21.4	.37	.58	19521	clear
155	1800	16.60	38	33	33	33	34.1	33	32	32.7	42.19	34	32.2	21.4	.38	.43	16250	clear
156	1830	17.10	35	32	33	33	32.8	32	31	31.2	41.17	33	31.1	21.7	.44	.29	12979	clear
157	1900	17.60	31	30.6	30	30	31.3	30	30	30.6	37.06	29	30.6	21.7	.46	.13	8400	clear
158	1930	18.10	28	29.9	28	28	30.4	28	28	30.2	35.01	27	28.9	21.1	.50	.01	9708	clear
159	2000	18.60	27	29.5	28	28	30	28	27.5	31	32.95	25	27.4	19.7	.49	0	12979	clear
160	2030	19.10	24	29	26	26	29.4	25	25	31.5	29.87	22	26.9	19.4	.50	0	0	clear
161	2100	19.60	22	27	24	24	28.1	25	25	31	27.82	20	23.6	19.4	.69	0	0	clear
162	2130	20.10	20	26.2	23	24	26.7	22	22	30.5	27.82	20	22.8	18.9	.70	0	8400	clear
163	2200	20.60	20	26	24	24	26.9	23	23	30.5	26.79	19	23.6	18.3	.60	0	0	clear
164	2230	21.10	19	26	22	21	26.5	22	22	30.5	25.77	18	22.8	18.3	.65	0	0	clear
165	2300	21.60	18	24.9	21	21	25.8	21	20	30	25.77	18	20.6	17.8	.76	0	0	clear
166	2330	22.10	18	24.2	20	21	25.8	21	20	30	25.77	18	20.3	17.5	.77	0	0	clear

Date: 7 September 1976 Time: 0000

Data Point	Local Time	Local Solar Time	Camouflage Material Temperature	Maple Leaf Temperature			Oak Leaf Temperature			Ground Temperature			Air Temperature		Relative Humidity	Solar Flux ($cal/cm^2/min$)	Wind Speed (cm/min)	Comments
				TC	RAD2		TC	RAD2		3.5" Deep	Ground Surface Temp.	RAD2	Dry Bulb	Wet Bulb				
					T	B		T	B									
167	0000	22.60	15	22.9	18	19	24	20	19	--	22.69	15	20	17.5	.82	0	0	clear

Results of Experimental Verification

The thermal model was used to calculate the leaf temperatures and ground temperature for the 72 hour experimental period. Measured values of air temperature, relative humidity, wind speed, and solar insolation on a horizontal plane were used at one half hour intervals to calculate leaf and ground temperatures. The calculated values of leaf and ground temperatures and the experimental values are shown in figures 2 through 7. Each figure is for one full days data, i.e., for the entire diurnal cycle. The figures are in pairs, that is figure 2 and 3 are for 4 September 1976, figure 4 and 5 for 5 September 1976, figures 6 and 7 for 6 September 1976. The leaf temperature measured and calculated are shown on figures 2, 4, and 6. Calculated and measured ground temperatures along with measured air temperatures are shown in figures 3, 5, and 7.

In order to assess the accuracy of the thermal model, the errors were statistically examined. This analysis indicated the mean error, i.e., the measured leaf temperature minus the calculated leaf temperature to be 0.21 degrees Celsius with a standard deviation of the errors of 4.00 degrees. From this information the leaf temperature calculated has a mean error with 95% confidence of -0.46 or +0.89° Celsius.

IV. CAMOUFLAGE MATERIAL REQUIREMENT

Leaf Temperature Emulator: The thermal model prepared was used to determine the necessary properties of a material which would emulate leaves thermal response during one day. A study of the leaf response and characteristics indicated that an emulator could be produced if the material

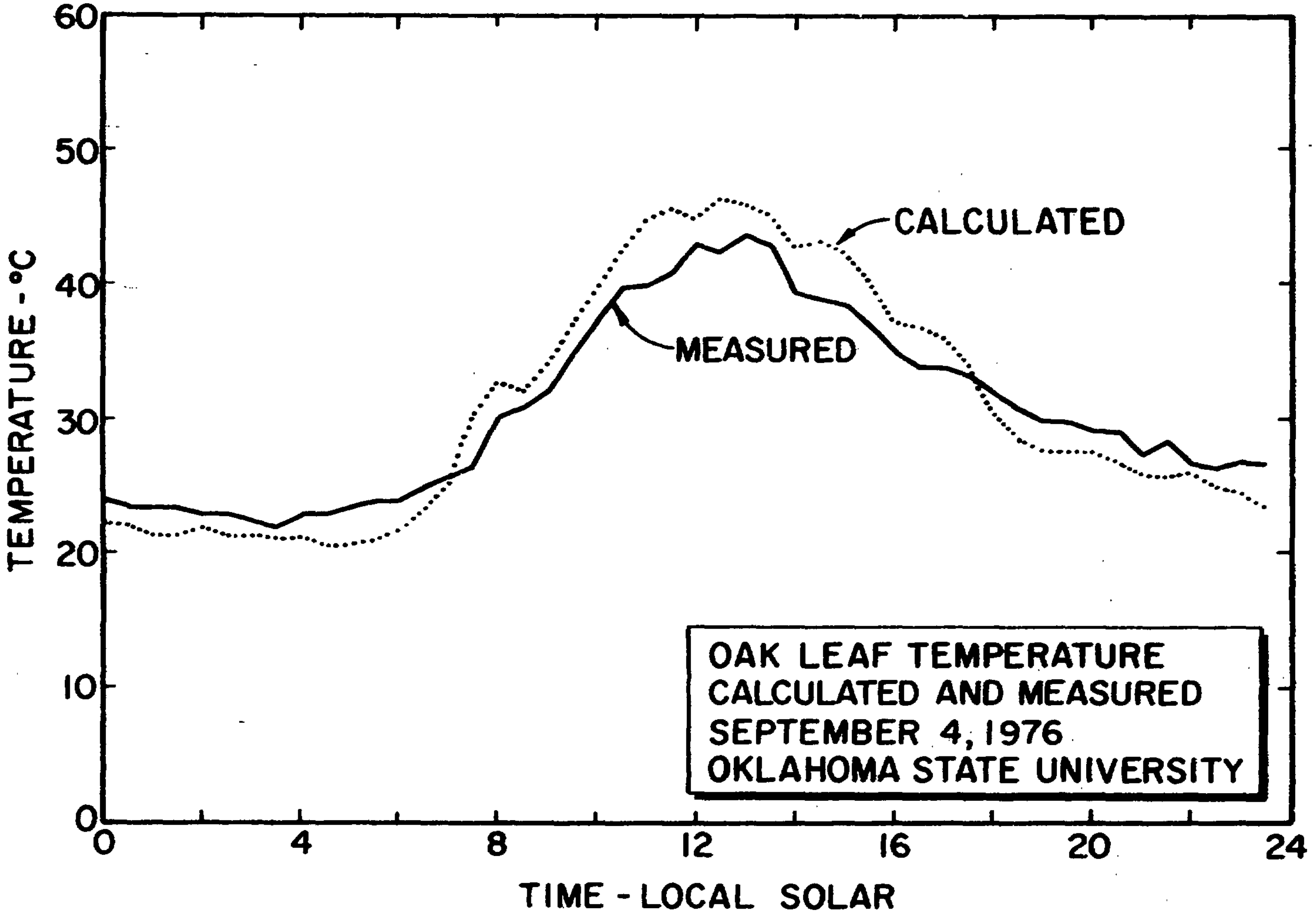

60
50
40
30
20
10
0
TEMPERATURE - °C
0
4
8
12
16
20
24
TIME - LOCAL SOLAR
CALCULATED
MEASURED
OAK LEAF TEMPERATURE
CALCULATED AND MEASURED
SEPTEMBER 4, 1976
OKLAHOMA STATE UNIVERSITY

Figure 2

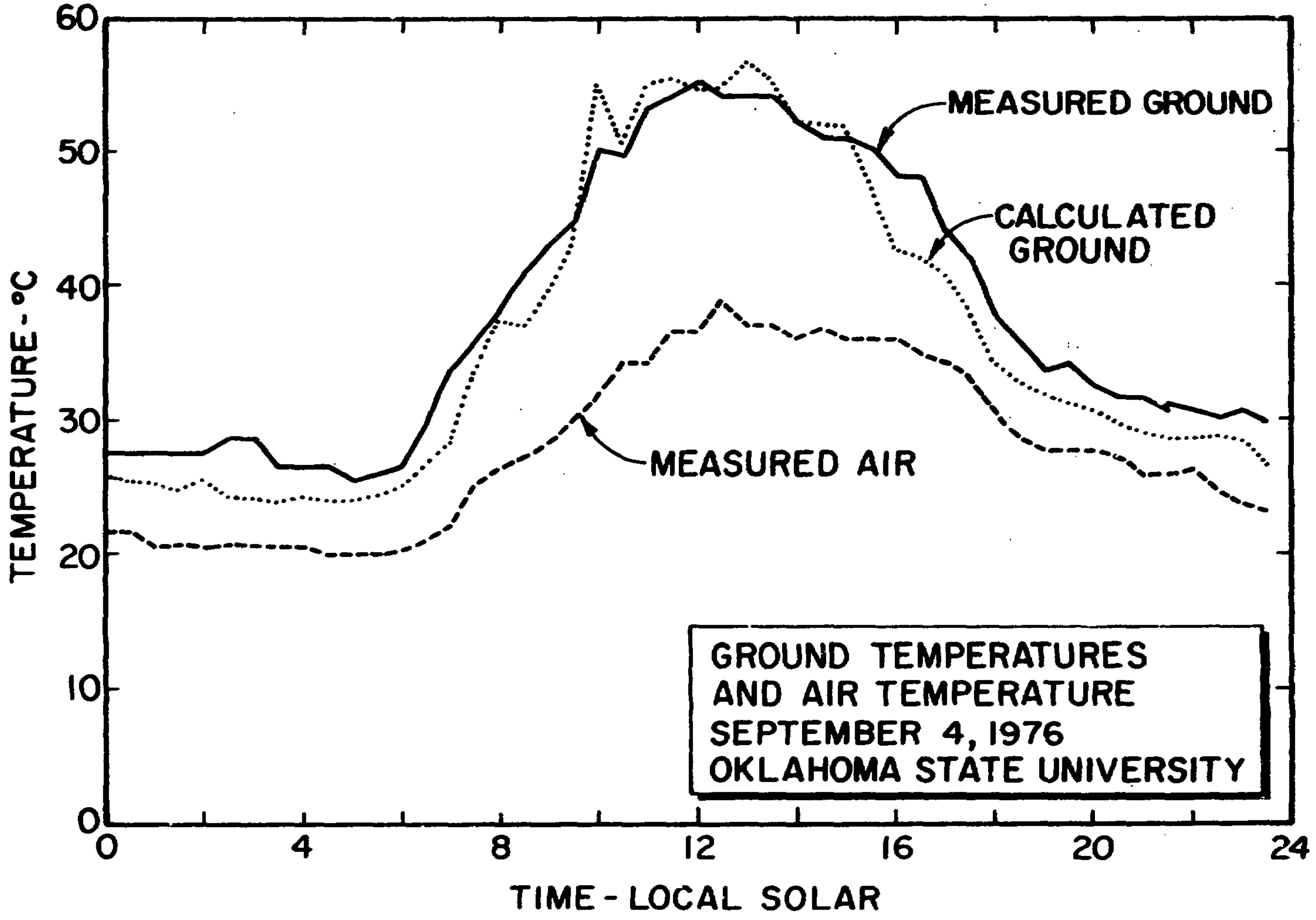

60
50
40
30
20
10
0
TEMPERATURE - °C
0
4
8
12
16
20
24
TIME - LOCAL SOLAR
MEASURED GROUND
CALCULATED GROUND
MEASURED AIR
GROUND TEMPERATURES
AND AIR TEMPERATURE
SEPTEMBER 4, 1976
OKLAHOMA STATE UNIVERSITY

Figure 3

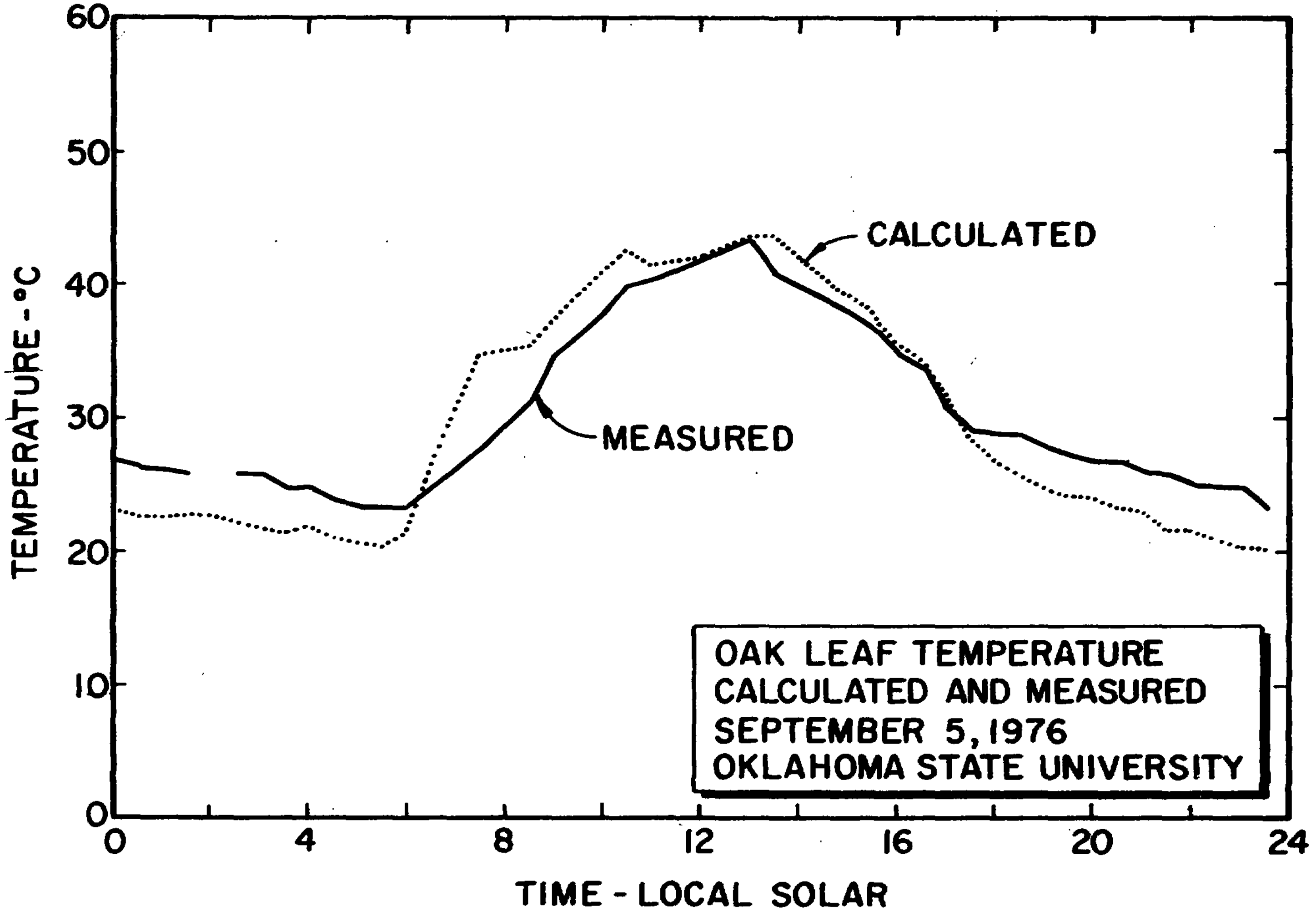

60
50
40
30
20
10
0
TEMPERATURE - °C
0
4
8
12
16
20
24
TIME - LOCAL SOLAR
CALCULATED
MEASURED
OAK LEAF TEMPERATURE
CALCULATED AND MEASURED
SEPTEMBER 5, 1976
OKLAHOMA STATE UNIVERSITY

Figure 4

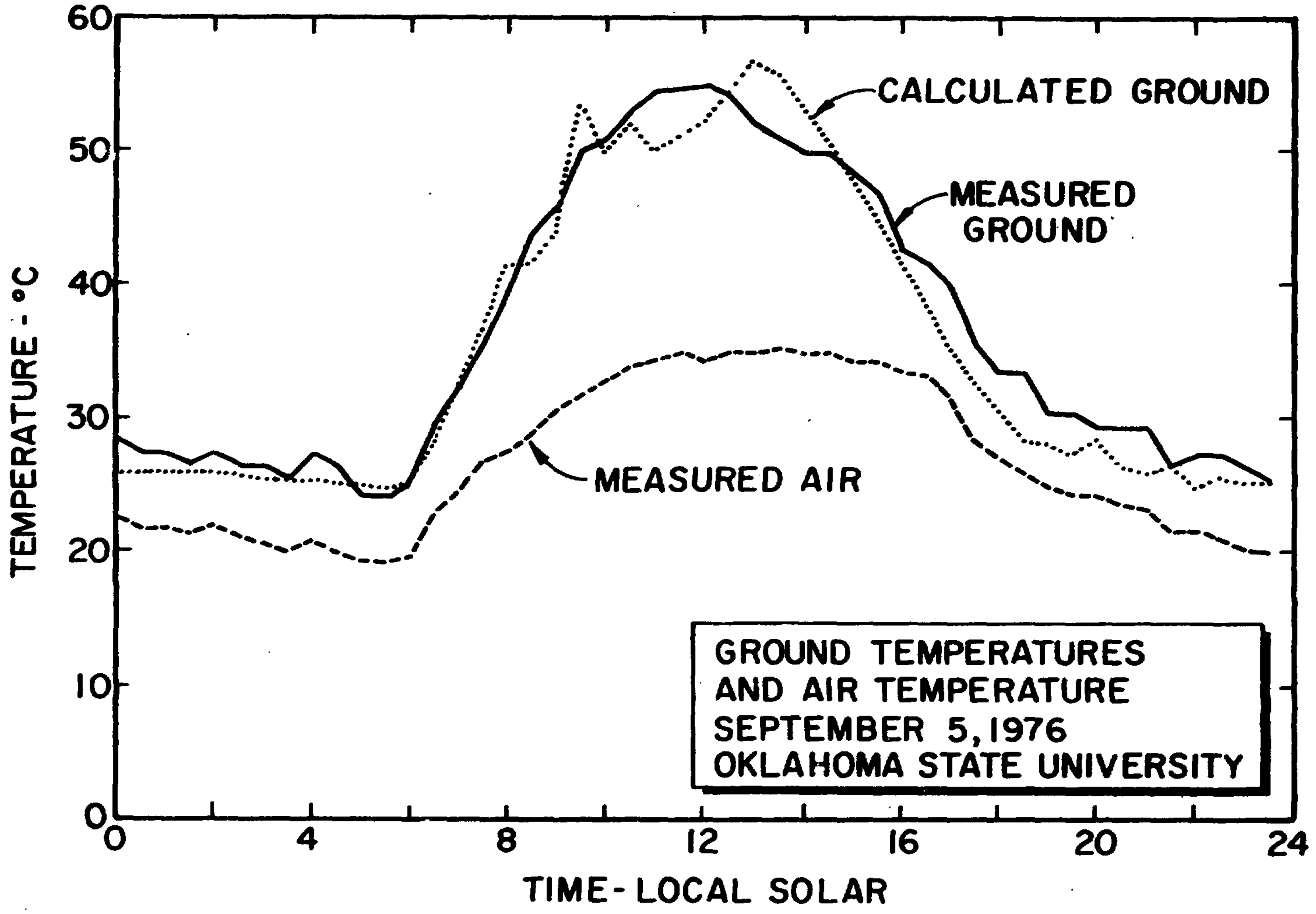

60
50
40
30
20
10
0
TEMPERATURE - °C
0
4
8
12
16
20
24
TIME- LOCAL SOLAR
CALCULATED GROUND
MEASURED GROUND
MEASURED AIR
GROUND TEMPERATURES
AND AIR TEMPERATURE
SEPTEMBER 5, 1976
OKLAHOMA STATE UNIVERSITY

Figure 5

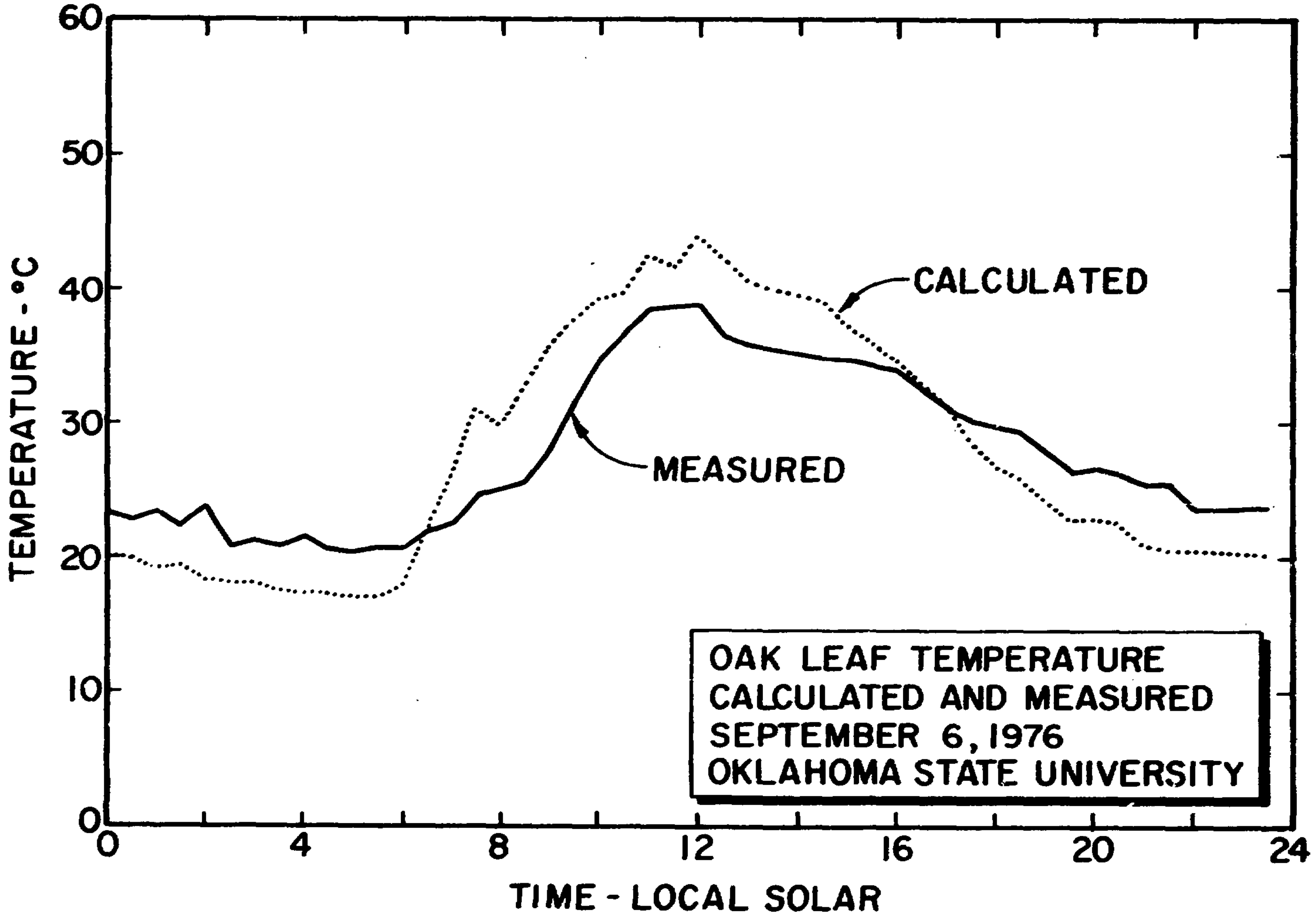

TEMPERATURE - °C
60
50
40
30
20
10
0
0
4
8
12
16
20
24
TIME - LOCAL SOLAR
CALCULATED
MEASURED
OAK LEAF TEMPERATURE
CALCULATED AND MEASURED
SEPTEMBER 6, 1976
OKLAHOMA STATE UNIVERSITY

Figure 6

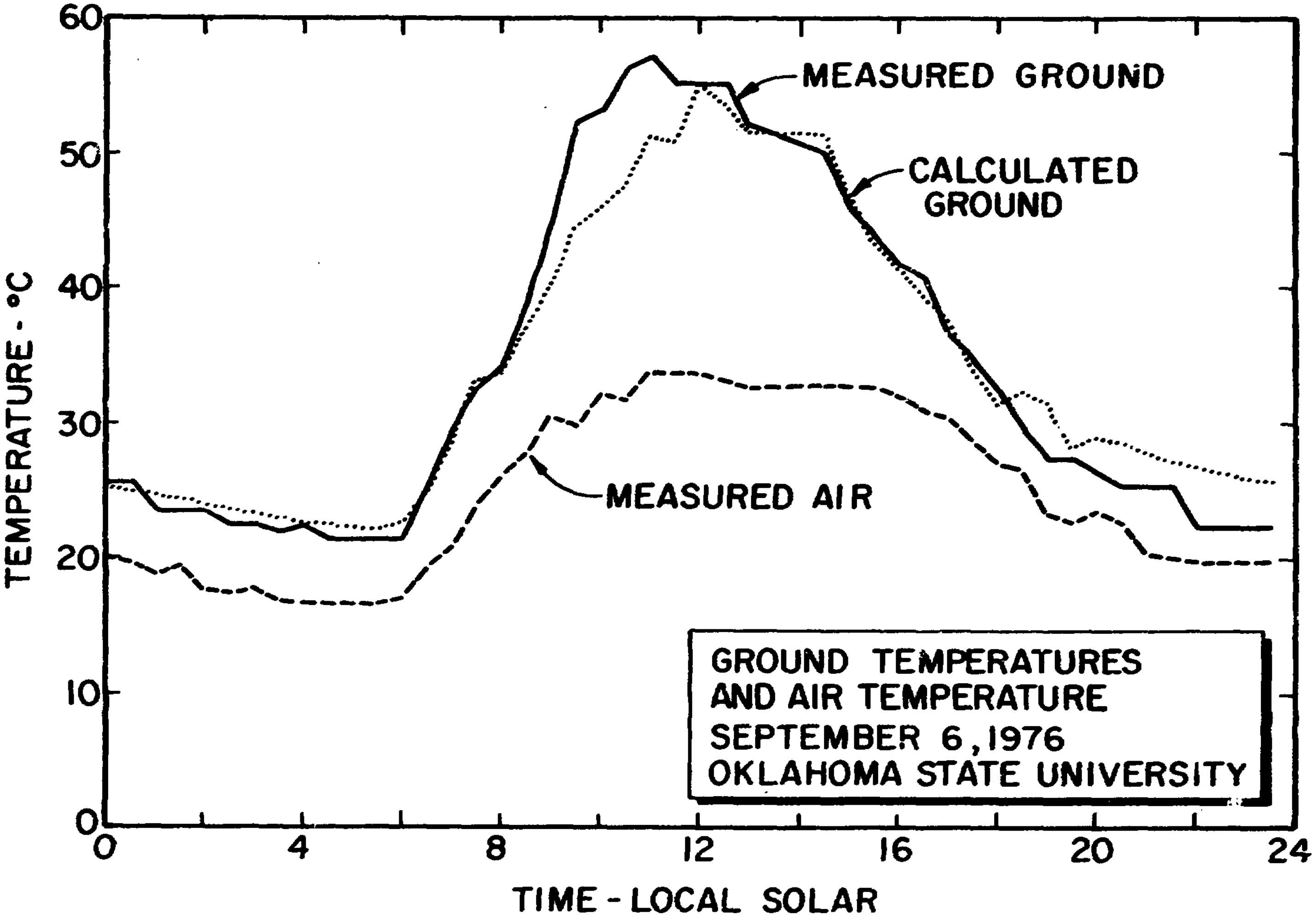

MEASURED GROUND
CALCULATED GROUND
MEASURED AIR
GROUND TEMPERATURES
AND AIR TEMPERATURE
SEPTEMBER 6, 1976
OKLAHOMA STATE UNIVERSITY
TEMPERATURE - °C
60
50
40
30
20
10
0
0
4
8
12
16
20
24
TIME - LOCAL SOLAR

Figure 7

emittance and reflectance could be controlled. As an example of this figure 8 shows the thermal response, as predicted from the thermal model, for a maple leaf, an aspen leaf, and a material designed to emulate the maple leaf. This material would be a material with low thermal mass, clothlike, with solar absorptance of 0.47 and long wavelength emittance of 0.95. As can be seen from figure 7, this material would satisfactorily emulate the diurnal temperatures of maple leaves but would not emulate the diurnal temperatures of aspen leaves. This is because the transpiration rate for an aspen leaf is greater than the transpiration rate of a maple leaf. An emulator for the aspen would have different properties which could be found using the thermal model presented.

Camouflage Material Detectability: In order to assess the detectability of the leaf emulator with a maple leaf background, the total radiant energy leaving the emulator and the leaf were evaluated for the 3-5 micrometer and 8-14 micrometer wavelength bands. These values are plotted in figures 9 and 10. Within the accuracy of the model, the leaf radiance and the emulator material are identical. This indicates that the camouflage role of the material would be well fulfilled in the 3-5 and 8-14 micrometer wavelength ranges.

Visual Camouflage Problem: The solar absorptance of the camouflage material which was used to obtain the results shown was 0.47. The solar absorptance of a material is a function of the spectral reflectance over the wavelength range in which the suns energy reaches the earths surface.

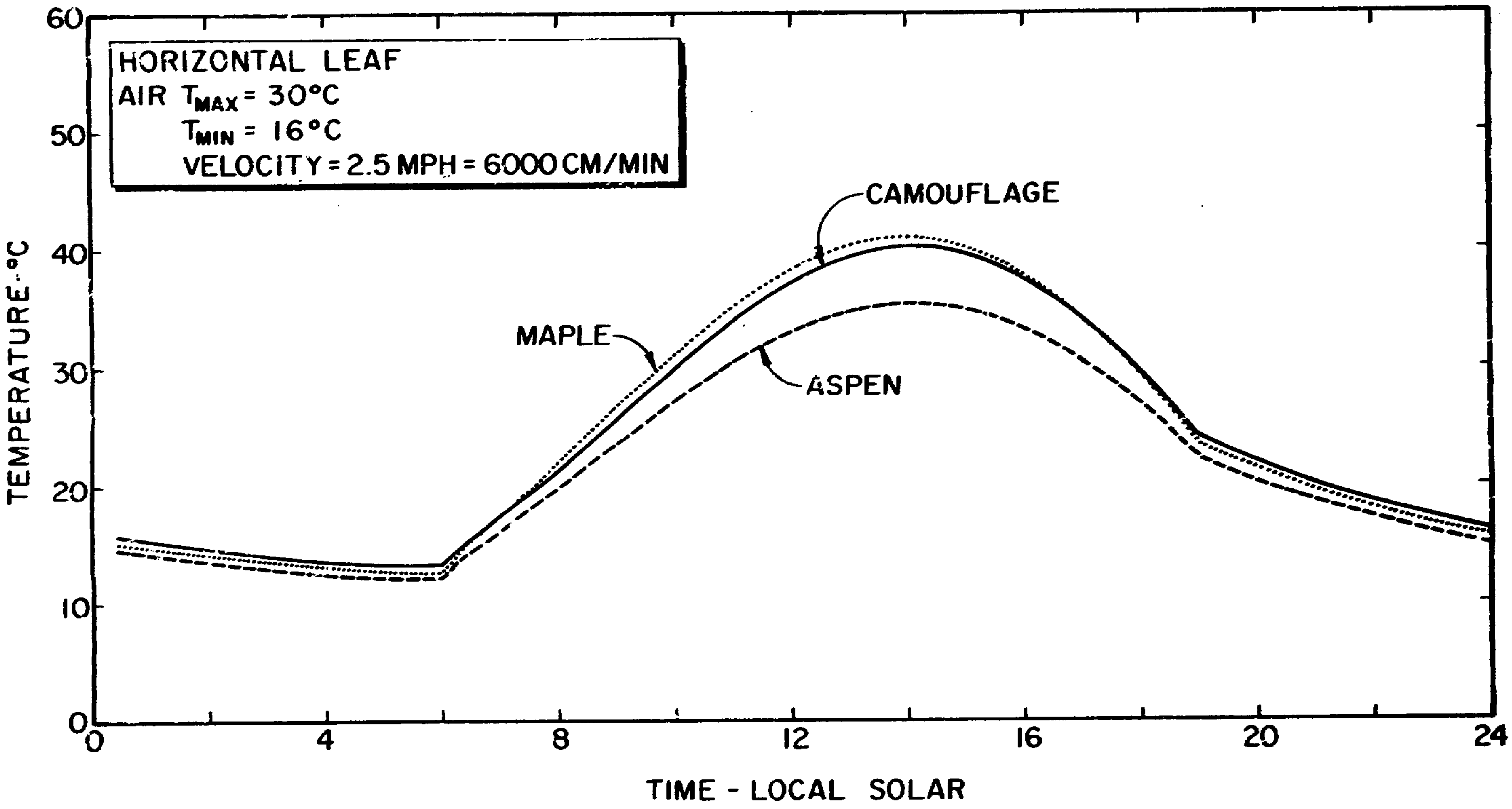

HORIZONTAL LEAF
AIR T_{MAX} = 30°C
T_{MIN} = 16°C
VELOCITY = 2.5 MPH = 6000 CM/MIN
CAMOUFLAGE
MAPLE
ASPEN
TEMPERATURE-°C
0
10
20
30
40
50
60
0
4
8
12
16
20
24
TIME - LOCAL SOLAR

Figure 8

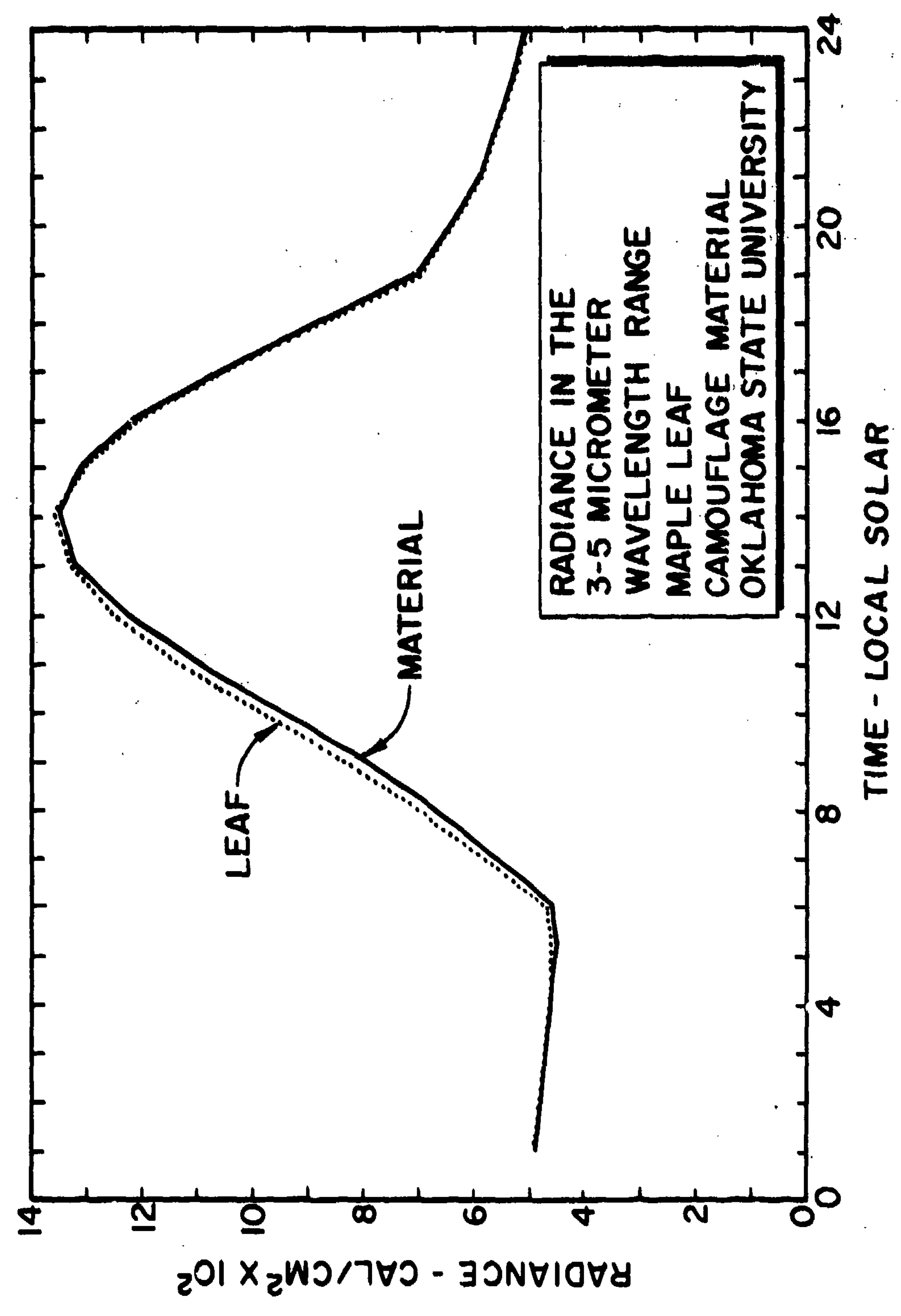

RADIANCE IN THE
3-5 MICROMETER
WAVELENGTH RANGE
MAPLE LEAF
CAMOUFLAGE MATERIAL
OKLAHOMA STATE UNIVERSITY
LEAF
MATERIAL
RADIANCE - CAL/CM^2 X 10^2
0
2
4
6
8
10
12
14
TIME - LOCAL SOLAR
0
4
8
12
16
20
24

Figure 9

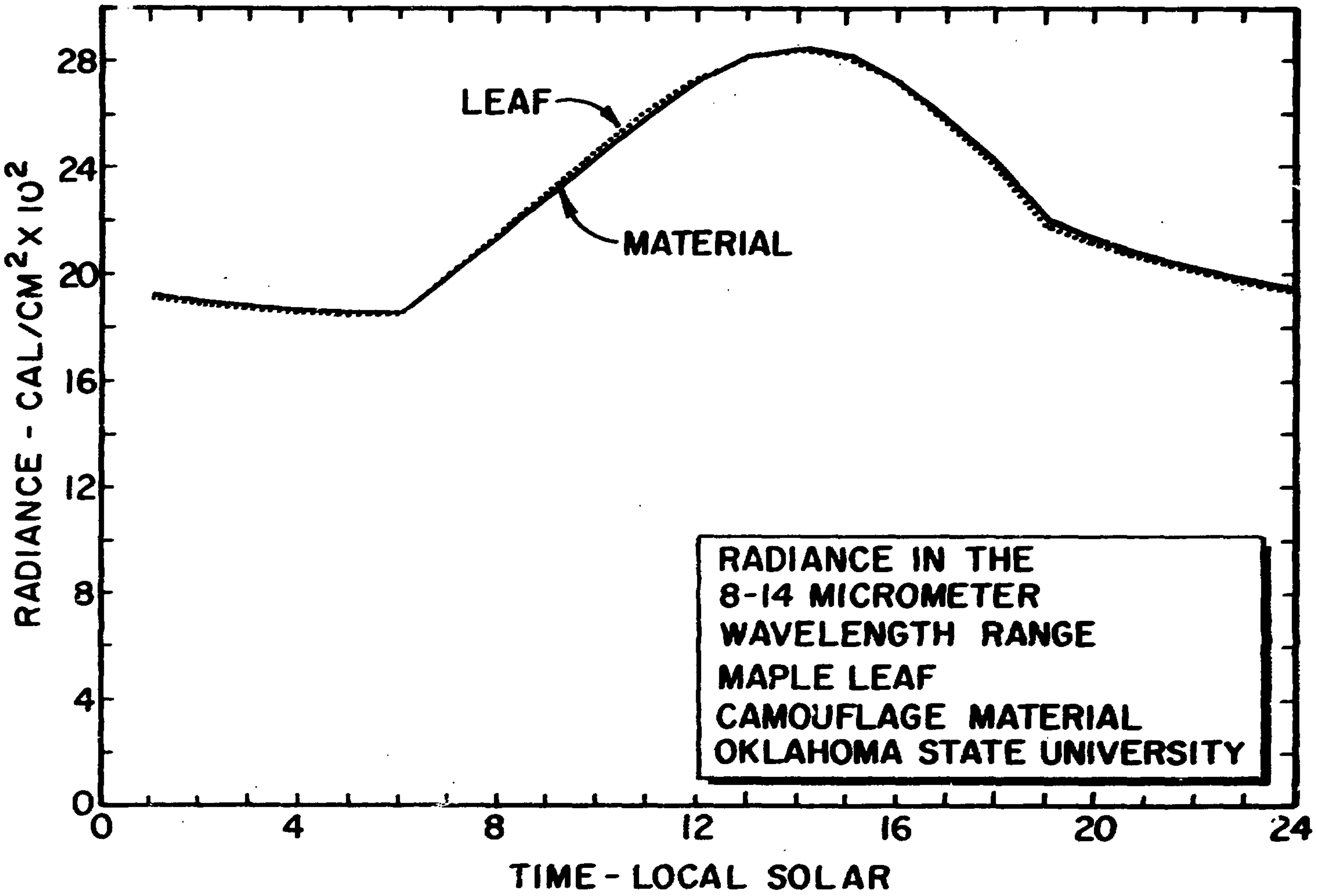

28
24
20
16
12
8
4
0
RADIANCE - CAL/CM^2 X 10^2
0
4
8
12
16
20
24
TIME - LOCAL SOLAR
LEAF
MATERIAL
RADIANCE IN THE
8-14 MICROMETER
WAVELENGTH RANGE
MAPLE LEAF
CAMOUFLAGE MATERIAL
OKLAHOMA STATE UNIVERSITY

Figure 10

This wavelength range is approximately from 0.3 to 2.5 micrometers. Since the visual range is overlapped by the solar range, the visual reflectance is not independent of the solar reflectance. This causes a camouflage material suitable for a leaf emulator to be more reflective than the typical visual camouflage material. [11] The ideal material to be used for both visual and thermal emulation of leaves would be one which had a visual reflectance around 0.3 or lower and a solar reflectance of 0.53. Such materials were reported in reference 11 for the near infrared, i.e., 0.7 to 1.2 micrometers. Values reported are shown in Table II.

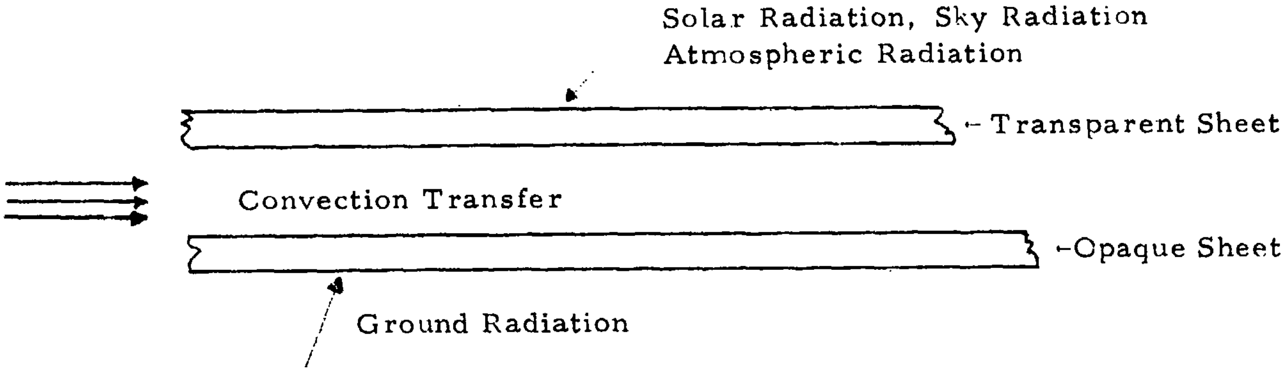
Table II. Infrared Reflectance for Camouflage Cloth (Reference 11)

(From National Military Establishment Specification JAN-C-765)

Fabric Color (No.)	Color	Infrared Reflectance Percentages Relative to Magnesium Oxide (Minimum %)	(Maximum %)
1	Light green	37.0	57.0
2	Dark green	37.0	57.0
3	Sand	24.5	100
4	Field drab	24.5	57.0
5	Earth brown	24.5	57.0
6	Earth yellow	24.5	100
8	Earth red	24.5	57.0
9	Olive drab	24.5	57.0
10	Black	0	24.5
11	White	57.0	100
12	Forest green	24.5	100
13	Desert sand	24.5	100

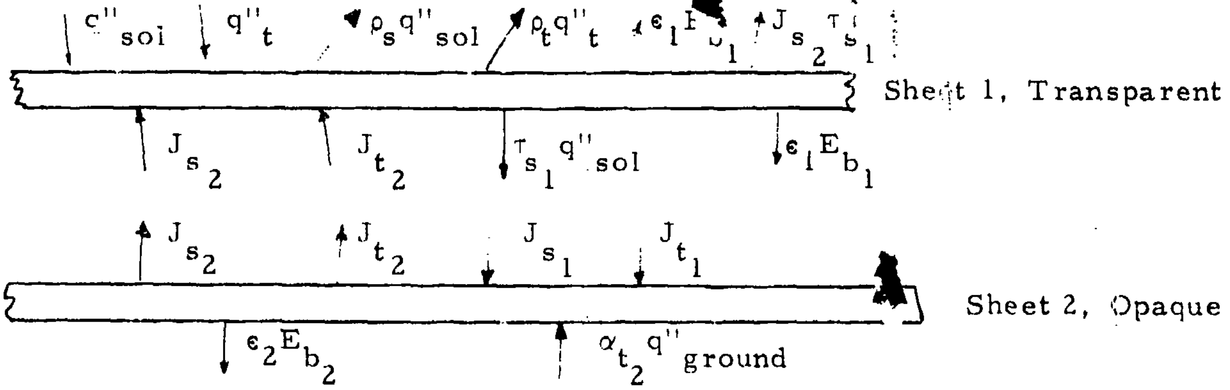
However, it was reported that the production of such materials was quite difficult. Similar work was reported in reference 12.

Transparent Cover Analysis: Since it may be difficult to obtain the desired visual and thermal infrared camouflage with a single material, the possibility of using a visually transparent cover over an opaque material was examined.



Basis for Transparent Cover Analysis
Figure 11

The basic system analyzed is shown in figure 11. A transparent sheet not in contact with an opaque sheet with radiant and convective heat transfer was considered. The energy exchange between the sheets and the atmosphere was analyzed by considering the convective, radiation in solar wavelengths and radiation at long wavelengths energies as uncoupled variables. The basic radiant energy quantities considered as shown diagrammatically in figure 12. In this figure the fluxes indicated



Radiant Fluxes for Transparent Sheet Analysis
Figure 12

are defined as follows:

q''_{sol} is the solar insolation

q''_t is the long wavelength (terrestial) insolation

J_{s_i} is the solar wavelength radiosity of the ith surface

J_{t_i} is the terrestial wavelength radiosity of the ith surface

E_{b_i} is the Plankian radiation of the ith surface, σT_i^4

ϵ_i is the terrestial emittance of the ith surface

ρ_s is the solar wavelength reflectance

ρ_t is the terrestial wavelength reflectance

and

τ_s is the solar wavelength transmittance.

The radiosities were evaluated in terms of the boundary values resulting in the following equations:

$$J_{s_1} = \left[\frac{\tau_{s_1}}{1 - \rho_{s_1}\rho_{s_2}}\right] q''_{sol} \qquad 22$$

$$J_{s_2} = \left[\frac{\rho_{s_2}\tau_{s_1}}{1 - \rho_{s_1}\rho_{s_2}}\right] q''_{sol} \qquad 23$$

$$J_{t_1} = \frac{\rho_{t_1}\epsilon_2 E_{b_2} + \epsilon_1 E_{b_1}}{1 - \rho_{t_1}\rho_{t_2}} \qquad 24$$

$$J_{t_2} = E_{b_2}(1 - \epsilon_{t_1} + \epsilon_{t_1}\epsilon_{t_2}) + \frac{(1 - \epsilon_{t_2})\epsilon_{t_1}E_{b_1}}{\epsilon_{t_2}} \qquad 25$$

Using these values, energy balances on sheet 1 and 2 including convective energy transfer to the surrounds and between the two sheets results in two coupled non-linear equations. These equations are functions of the environmental parameters; q''_{sol}, ambient air temperature, ground temperature, and the radiative properties of the two sheets. In order to assess the possible usefulness of the transparent outer sheet an inner sheet with solar absorptance of 0.6 (dark green) was considered. Using ambient air Temperature of 30°C, relative humidity of 50%, ground temperature 40°C, q''_{sol} of 800 w/m^2, wind speed of 2.5 miles per hour the dark green material temperature calculated was 41°C. With a transparent sheet over the dark green material the calculated temperatures of the transparent sheet (T_1) and the dark green sheet (T_2) with several different transparent sheet properties, is given in Table III. Notice the transparent sheet temperature runs from 37 to 40° Celsius where the uncovered material temperature was 41° Celsius. This indicates the transparent sheet over the camouflage material might be useful if the proper material cannot be obtained. Limited experimental results for this type system are reported in Appendix B.

Table III
Sheet Temperatures Calculated

Sheet Reflectance	Sheet Transmittance	Sheet Absorptance	T_1 °C	T_2 °C
0.10	0.80	0.10	37	46
0.05	0.80	0.15	37	46
0.05	0.75	0.20	39	46
0.10	0.70	0.20	40	45

V. CONCLUSIONS

The thermal model prepared to emulate foliage satisfactorily predicts the diurnal temperature of leaves. This model, like all models, finally depends on the quality of the boundary or driving functions. In this case, the boundary conditions are particularly difficult to predict since the micro-climatalogical values are quite unique for each location. However, the model is quite satisfactory for the evaluation of camouflage materials in that whatever boundary conditions are used the model will indicate the response of the candidate material relative to a particular leaf type.

From the studies made with the thermal model it was determined that thermal infrared camouflage is feasible with simple clothlike material if the radiant properties can be properly tailored to the background. For example, it was found that a material with a solar absorptance of 0.47 and long wavelength emittance of 0.95 would emulate maple leaves. It was also determined that this material would not emulate leaves with larger transpiration rates, e.g. aspen. These leaves are more difficult to emulate but probably could be satisfactorily emulated considering the canopy of trees will have large temperature variations due to shading.

In the process of preparing the thermal model it was noted that the camouflage material must be opaque to thermal infrared if an object is to be camouflaged. Any object above the background temperature will "shine" through a partial camouflage net. This fact makes the physical construction of the camouflage net more difficult. A successful net must have multiple layers of leaf sized camouflage elements. These elements must allow free circulation of ambient air in order to attain temperatures similar to the temperature of the background leaves. Furthermore, the material must have good visual camouflage characteristics. A material with both satisfactory visual and solar reflectance may be difficult to obtain due to the overlap in these spectral regions. Materials with these characteristics have been prepared for the near infrared but have not been reported for the thermal infrared.

Reference

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APPENDIX A

COMPUTER PRINTOUT

```
FORTRAN IV G1  RELEASE 2.0              MAIN

                  DIMENSION B(48),FV(48),WAVE(48),X1(48),X2(48),X3(48),X4(48),X5(48)
                  DIMENSION X9(48)
                  DIMENSION X6(48),X7(48),X8(48),IMAGE(1700),NSCALE(5)
                  COMMON/DATAIN/PI,C2,SIG,TL,EPS,G,K2,CP,Z
                  COMMON DT,M,LAT,DEC,H,LST,L,QA,QR,TA,V,TMAX,TVAR
                  COMMON QB3,QB8,C1,QATM,QG,QE,RU,T,SC,COSTH
                  COMMON QC,HC,ASU,ASL,E,A,RG,EG,ASG,RSG,AG,QST,QSU,QSL,QDF,C4
                  COMMON RH,D,KA,RE,GR,RL,DFS,COND,DELT,TGR
                  COMMON SIND,COSD,SINL,COSL,SINA,COSA,SINS,COSS,SINH,COSH,COSZ
                  REAL LAT,LST,M,KA,K2
              100 FORMAT(//3X,'LST',3X,'QATM',3X,'QG',5X,'QSL',4X,'QSU',5X,'QA',4X,
                 1'QR',5X,'QE',5X,'QC',//)
              101 FORMAT (1X,F5.2,8(1X,F6.3))
              103 FORMAT(3X,F4.1,3X,F4.1,3X,F4.1,3X,F4.1,3X,F4.1,4X,F6.4,3X,F6.4,
                 13X,F6.4,3X,F6.4)
              104 FORMAT (//,3X,'LST',4X,'TAIR',3X,'TLEAF',2X,'TMTRL',2X,
                 1'TGRND',3X,'QB3LEAF',2X,'QB3MTRL',2X,'QB8LEAF',2X,'QB8MTRL'/)
              105 FORMAT('1')
              106 FORMAT(55X,' INPUT DATA',///)
              107 FORMAT(///,60X,'LEAF')
              108 FORMAT (///,57X,'MATERIAL')
                  DATA LB1/'A'/,LB2/'L'/,LB3/'M'/,LB4/'G'/
                  DATA NSCALE/1,0,3,0,0/
            C
            C
            C
            C     THIS PROGRAM CALCULATES THE STEADY STATE TEMPERATURE OF A LEAF OR
            C     MATERIAL FOR CLEAR DAYS.
            C
            C
            C
            C
            C     THE FOLLOWING DATA IS READ IN ON NAMELIST.IF THIS PROGRAM IS RUN
            C     ON A CDC COMPUTER THE NAMLIST DATA CARDS MUST BE MODIFIED FOR
            C     CDC.ADDITIONAL CONSTANTS ARE INITALIZED IN SUBROUTINE BLOCK DATA.
            C     HRS IS THE NUMBER OF HOURS YOU WISH TO RUN THE SIMULATION
            C     DT IS THE TIME INCREMENT(IN MINUTES)YOU WISH TO USE IN THE
            C     CALCULATIONS
            C     DELT IS THE TIME INCREMENT(IN MINUTES) USED IN SUBROUTINE
            C     GTEMP TO CALCULATE THE GROUND TEMPERATURE.
            C     LAT IS THE LATITUDE IN RADIANS.
            C     DEC IS THE DECLINATION ANGLE OF THE SUN IN RADIANS.
            C     SC IS THE VALUE OF THE APPARENT SOLAR RADIATION AT AIR MASS
            C     OF 0.0 AND VARIES WITH THE TIME OF THE YEAR,IN CAL/CM**2-MIN.
            C     C4 IS THE ATMOSPHERIC EXTINCTION COEF. AND VARIES WITH THE TIME OF
            C     YEAR.
            C     C1 IS THE FRACTION OF BEAM RADIATION APPEARING AS DIFFUSE RAD.
            C          VARIES WITH THE TIME OF YEAR.
            C          IS THE LOCAL SOLAR TIME WHEN THE SIMULATION IS STARTED.
            C     D IS THE CHARACTERISTIC DIMENSION OF THE LEAF IN THE DIRECTION OF
            C     THE AIR FLOW.(CM)
            C     RL IS THE INTERNAL RESISTANCE OF THE LEAF,IN SEC/CM.
            C     SLP IS THE SLOPE (IN RADIANS) OF THE SURFACE MEASURED FROM THE
            C     HORZ.
            C     AZM IS THE AZIMUTH ANGLE(IN RADIANS) OF THE LEAF SURFACE MEASURED
            C     FROM THE SOUTH. POSITIVE AZIMUTH IS EAST FACING,NEGATIVE IS WEST.
            C     ASU IS THE SOLAR ABSORPTIVITY OF THE UPPER SURFACE OF THE LEAF.
            C     ASL IS THE SOLAR ABSORPTIVITY OF THE LOWER SURFACE OF THE LEAF.
```

```
      C     A IS THE LONG WAVELENGTH ABSORPTIVITY OF THE LEAF.
      C     E IS THE LONG WAVELENGTH EMISSIVITY OF THE LEAF.
      C     RU IS THE LONG WAVELENGTH REFLECTIVITY OF THE UPPER SURFSCE OF
      C     THE LEAF.
      C     T IS THE LONG WAVELENGTH TRANSMITTANCE OF THE LEAF.
      C     KA IS THE THERMAL CONDUCTIVITY OF AIR,IN CAL/CM-MIN-C
      C     RH IS THE RELATIVE HUMIDITY OF AIR.
      C     TMAX IS THE MAXIMUM AIR TEMPERATURE DURING THE SIMULATION PERIOD
      C     IN DEGREES C
      C     TVAR IS THE MAXIMUM VARIATION IN THE AIR TEMPERATURE DURING THE
      C     SIMULATION TIME,IN DEGREES C.
      C     V IS THE AIR VELOCITY IN CM/MIN.
      C     DFS IS THE THERMAL DIFFUSIVITY OF SOIL,IN SQCM/MIN.
      C     COND IS THE THERMAL CONDUCTIVITY OF SOIL,IN CAL/CM-MIN-C.
      C     RG IS THE LONG WAVELENGTH REFLECTIVITY OF SOIL.
      C     AG IS THE LONG WAVELENGTH ABSORPTIVITY OF SOIL
      C     EG IS THE LONG WAVELENGTH EMISSIVITY OF SOIL.
      C     ASG IS THE SOLAR ABSORPTIVITY OF SOIL.
      C     RSG IS THE SOLAR REFLECTIVITY OF THE SOIL.
      C
      C
      C
      C
      C
      C     OUTPUT DATA
      C     LST IS THE LOCAL SOLAR TIME.
      C     QATM IS THE LONG WAVELENGTH ATMOSPHERIC RADIATION,IN CAL/CM**2-MIN
      C     QG IS THE LONG WAVELENGTH GROUND RADIATION,IN CAL/CM**2-MIN.
      C     QSL IS THE SOLAR RADIATION ABSORBED BY THE LOWER SIDE OF THE LEAF
      C     OR MATERIAL,IN CAL/CM**2-MIN.
      C     QSU IS THE SOLAR RADIATION ABSORBED BY THE UPPER SIDE OF THE
      C     MATERIAL OR LEAF,IN CAL/CM**2-MIN.
      C     QA IS THE TOTAL RADIANT ENERGY ABSORBED BY THE MATERIAL OR LEAF.
      C     QR IS THE TOTAL ENERGY RADIATED FROM THE LEAF,IN CAL/CM**2-MIN.
      C     QE IS THE ENERGY LOST BY THE LEAF DUE TO EVAPORATION.
      C     QC IS THE ENERGY LOST OR GAINED BY THE LEAF OR MATERIAL DUE TO
      C     CONVECTION,IN CAL/CM**2-MIN.
      C     TGRND IS THE GROUND SURFACE TEMPERATURE,IN DEGREES C.
      C     TLEAF IS THE LEAF TEMPERATURE,IN DEGREES C.
      C     TMTRL IS THE MATERIAL TEMPERATURE,IN DEGREES C.
      C     TAIR IS THE AIR TEMPERATURE,IN DEGREES C.
      C     QB3MTRL IS THE DETECTABLE RADIANT ENERGY ABOVE THE MATERIAL
      C     SURFACE IN THE 3-5 MICRON RANGE.
      C     QB8MTRL IS THE DETECTABLE RADIANT ENERGY ABOVE THE MATERIAL
      C     SURFACE IN THE 8-14 MICRON RANGE.
      C     QB3LEAF IS THE DETECTABLE RADIANT ENERGY ABOVE THE LEAF SURFACE
      C     IN THE 3-5 MICRON RANGE.
      C     QB8LEAF IS THE DETECTABLE RADIANT ENERGY ABOVE THE LEAF SURFACE
      C     IN THE 8-14 MICRON RANGE.
      C
      C
      C
            NAMELIST /IN1/HRS,DT,DELT /IN2/LAT,DEC,SC,C1,C4,LST
           1/IN3/D,RL,SLP,AZM /IN4/ASU,ASL,A,E,RU,T /IN5/KA,RH,TMAX,TVAR,V
           2/IN6/DFS,COND,RG,AG,EG,ASG,RSG
            NR=0
         10 READ(5,IN1,END=1000)
            READ(5,IN2)
```

```
 0025                    READ(5,IN3)
 0026                    READ(5,IN4)
 0027                    READ(5,IN5)
 0028                    READ (5,IN6)
 0029                    NR=NR+1
 0030                    GO TO (20,30),NR
 0031                20  WRITE (6,107)
 0032                    GO TO 40
 0033                30  WRITE(6,108)
 0034                    NR=0
 0035                40  WRITE (6,106)
 0036                    WRITE(6,IN1)
 0037                    WRITE(6,IN2)
 0038                    WRITE(6,IN3)
 0039                    WRITE(6,IN4)
 0040                    WRITE(6,IN5)
 0041                    WRITE (6,IN6)
                   C
                   C   INITIALIZE CONSTANTS
                   C
 0042                    H=PI
 0043                    M=0.0
 0044                    ZEN=0.0
 0045                    L=0
 0046                    I=0
 0047                    SIND=SIN(DEC)
 0048                    COSD=COS(DEC)
 0049                    SINL=SIN(LAT)
 0050                    COSL=COS(LAT)
 0051                    SINS=SIN(SLP)
 0052                    COSS=COS(SLP)
 0053                    SINA=SIN(AZM)
 0054                    COSA=COS(AZM)
 0055                    N=60.*HRS/DT
 0056                    WRITE(6,100)
 0057                 50 CONTINUE
 0058                    H=PI-LST*0.262
 0059                    COSH=COS(H)
 0060                    SINH=SIN(H)
 0061                    COSZ=COSL*COSD*COSH+SINL*SIND
 0062                    M=1.0/COSZ
 0063                    IF(M.LT.1.OR.M.GT.6.5)M=0.0
 0064                    IF(COSZ.LT.0.0)COSZ=0.0
 0065                    CALL RAD
 0066                    CALL LEAF
 0067                    RES1=QA-QR-QC-QE
 0068                    TN=TL
 0069                    TL=TL+2.
                   C
                   C
                   C     CALCULATING THE STEADY STATE TEMPERATURE OF THE LEAF OR MATERIAL
                   C
                   C
 0070                    DO 60 K=1,10
 0071                    CALL LEAF
 0072                    RES2=QA-QR-QC-QE
 0073                    IF(ABS(RES2).LE.EPS)GO TO 70
 0074                    DV=(TN-TL)*(RES2/(RES2-RES1))
```

```
      TN=TL
      TL=TL+CV
   60 RES1=RES2
   70 CONTINUE
      CALL DETECT
      WRITE(6,101) LST,QATM,QG,QSL,QSU,QA,QR,QE,QC
      LST=LST+DT/60.
      IF(RL.LT.0.0)GO TO 80
      I=I+1
      X1(I)=LST-(DT/60.)
      X2(I)=TA
      X3(I)=TL
      X4(I)=QB3
      X5(I)=QB8
      GO TO 90
   80 CONTINUE
      I=I+1
      X6(I)=TL
      X7(I)=QB3
      X8(I)=QB8
      X9(I)=TCR
   90 IF(I.LT.N )GO TO 50
      IF(NR.GT.0) GO TO 10
      WRITE (6,104)
      WRITE (6,103) (X1(I),X2(I),X3(I),X6(I),X9(I),X4(I),X7(I),
     1X5(I),X8(I),I=1,N)
      WRITE(6,105)
      GO TO 10
 1000 STOP
      END
```

```
FORTRAN IV G1  RELEASE 2.0              RAD

 0001                   SUBROUTINE RAD
 0002                   COMMON/DATAIN/PI,C2,SIG,TL,EPS,G,K2,CP,Z
 0003                   COMMON DT,M,LAT,DEC,H,LST,L,QA,QR,TA,V,TMAX,TVAR
 0004                   COMMON QB3,QBB,C1,QATM,QG,QE,RO,T,SC,COSTH
 0005                   COMMON QC,HC,ASU,ASL,E,A,RG,EG,ASG,RSG,AG,QST,QSU,QSL,QDF,C4
 0006                   COMMON RH,D,KA,RE,GR,RL,DFS,COND,DELT,TGR
 0007                   COMMON SIND,COSD,SINL,COSL,SINA,COSA,SINS,COSS,SINH,COSH,COSZ
 0008                   REAL LAT,LST,M,KA,K2
                  C
                  C
                  C
                  C
                  C     SUBROUTINE RAD PERFORMS THE FOLLOWING,(1) ESTIMATES THE SOLAR AND
                  C     DIFFUSE RADIATION ON CLEAR DAYS AND THE ATMOSPHERIC AND GROUND
                  C     RADIATION,(2)CALCULATES THE RADIANT ENERGY ABSORBED BY A LEAF
                  C     OF ANY SURFACE ORIENTATION AND,(3) ESTIMATES THE AIR TEMPERATURE
                  C     BASED ON THE MAXIMUM AIR TEMPERATURE AND THE MAXIMUM VARIATION
                  C     IN THE AIR TEMPERATURE DURING THE SIMULATION TIME.
                  C
                  C
                  C
                  C
                  C SOLAR BEAM RADIATION
                  C
 0009                   QST=SC/EXP(C4*M)
 0010                   IF(M.LT.1.OR.M.GT.6.5)QST=0.0
                  C
                  C   DIRECT SOLAR IRRADIATION OF LEAF UPPER SURFACE
                  C
 0011                   COSTH=SIND*SINL*COSS
 0012                   COSTH=COSTH-SIND*COSL*SINS*COSA
 0013                   COSTH=COSD*COSL*COSS*COSH+COSTH
 0014                   COSTH=COSD*SINL*SINS*COSA*COSH+COSTH
 0015                   COSTH=COSD*SINS*SINA*SINH+COSTH
 0016                   IF(COSTH.LT.0.0) COSTH=0.0
 0017                   QSDT=COSTH*QST
                  C
                  C     DIFFUSE SOLAR RADIATION(QDF)INCIDENT ON A SURFACE
                  C
 0018                   QDF=C1*QST
 0019                   FRAC=(1.0+COSS)/2.0
 0020                   QDFT=QDF*FRAC+QDF*(1.0-FRAC)*RSG
                  C
                  C     TOTAL SOLAR RADIATION ABSORBED BY THE TOP SURFACE OF THE LEAF
                  C
 0021                   QSU=ASU*(QSDT+QDFT)
                  C
                  C     AIR TEMPERATURE CALCULATIONS
                  C
 0022                   TME=LST*PI/12.
 0023                   VAR=56.29+29.32*COS(TME)+38.48*SIN(TME)-3.48*COS(2.*TME)-8.35*SIN(
                       12.*TME)
 0024                   TA=TMAX-((TVAR*VAR)/100.)
                  C
                  C     CALCULATING VAPOR PRESSURE OF H2O IN AIR AT TA
                  C
 0025                   P=(4.8*EXP(TA/16.1))*RH
                  C
```

```
                    C       QATM= INCIDENT ATMOSPHERIC RADIATION
                    C
 0026                       TAK=TA+273.
 0027                       QATM=SIG*(TAK**4.)*(.44+.08*SQRT(P))
 0028                       CALL GTEMP
                    C
                    C      SOLAR RADIATION ABSORBED BY THE LOWER SIDE OF THE LEAF
                    C
 0029                       QDFL=QDF*(1.0-FRAC)+QDF*FRAC*RSG
 0030                       QSL=ASL*(QDFL+QST*COSZ*RSG*FRAC)
                    C
                    C       TOTAL RADIANT ENERGY(QA)ABSORBED BY THE LEAF
                    C
 0031                       QA=A*(QATM+QG+RG*QATM)+QSL+QSU
 0032                       RETURN
 0033                       END
```

```
      SUBROUTINE LEAF
      COMMON/DATAIN/PI,C2,SIG,TL,EPS,G,K2,CP,Z
      COMMON DT,M,LAT,DEC,H,LST,L,QA,QR,TA,V,TMAX,TVAR
      COMMON QB3,QB8,C1,QATM,QG,QE,RU,T,SC,COSTH
      COMMON QC,HC,ASU,ASL,E,A,RG,EG,ASG,RSG,AG,QST,QSU,QSL,QDF,C4
      COMMON RH,D,KA,RE,GR,RL,DFS,COND,DELT,TGR
      COMMON SIND,COSD,SINL,COSL,SINA,COSA,SINS,COSS,SINH,COSH,COSZ
      REAL LAT,LST,M,KA,K2
C
C
C
C     SUBROUTINE LEAF CALCULATES THE HEAT TRANSFER TO THE LEAF OR
C     MATERIAL SURFACE BY EVAPORATION AND CONVECTION AND THE HEAT LOST
C     BY THE LEAF DUE TO RADIATION.
C
C
C
      IF(RL.LT.0.0)GO TO 3
C
C     CALCULATION OF RATE OF HEAT TRANSFER BY EVAPORATION(QE)
C     BOUNDARY LAYER EVAP RESISTANCE
C
      RB=(60.*D/V) **0.55
      RB=K2*RB
C
C     TOTAL EVAP RESISTANCE
C
      RT=RL+RB
C
C     DENSITIES FOR Q EVAPORATION
C
      RHOL=1.0/VG(TL)
      RHO=1.0/VG(TA)
      QE=RHOL-RH*RHO
      QE=(2.*60.*580.0*QE)/RT
      IF(QE.LT.0.0)QE=0.0
      GO TO 4
    3 QE=0.0
    4 CONTINUE
C
C     CALCULATION OF THE RATE OF HEAT TRANSFER BY CONVECTION(QC)
C
      TFLM=(TA+TL)/2.0
      ANU=8.032+4.8622E-2*TFLM
      ANU=ANU+6.06E-5*TFLM*TFLM
      RE=V*D/ANU
      GR=G*D**3*ABS(TL-TA)/(ANU*ANU*TFLM)
      IF(GR/RE**2.0.LT.1.)GO TO 1
C
C     CALCULATION OF FREE CONVECTION COEF.(HC).
C
      HC1=(0.497*KA*GR**0.25)/D
      HC2=HC1/2.
      HC=HC1+HC2
      QC=HC*(TL-TA)
      GO TO 2
    1 CONTINUE
C
```

```
FORTRAN IV G1  RELEASE 2.0              LEAF
                      C      CALCULATION OF FORCED CONVECTION COEF.(HC)
                      C
 0033                        HC=0.595*KA*SQRT(RE)/D
 0034                        HC=2.0*HC
 0035                        QC=HC*(TL-TA)
                      C
                      C      ENERGY RADIATED FROM THE LEAF(QR)
                      C
 0036                      2 TLK=TL+273.
 0037                        QR=2.*E*SIG*TLK**4.
 0038                        RETURN
 0039                        END
```

```
FORTRAN IV G1  RELEASE 2.0               DETECT

                          SUBROUTINE DETECT
                          DIMENSION B(50),FV(50),WAVE(50)
                          COMMON/DATAIN/PI,C2,SIG,TL,EPS,G,K2,CP,Z
                          COMMON DT,M,LAT,DEC,H,LST,L,QA,QR,TA,V,TMAX,TVAR
                          COMMON QB3,QB8,C1,QATM,QG,QE,RU,T,SC,COSTH
                          COMMON QC,HC,ASU,ASL,E,A,RG,EG,ASG,RSG,AG,QST,QSU,QSL,QDF,C4
                          COMMON RH,D,KA,RE,GR,RL,DFS,COND,DELT,TGR
                          COMMON SIND,COSD,SINL,COSL,SINA,COSA,SINS,COSS,SINH,COSH,COSZ
                          REAL LAT,LST,M,KA,K2
                    C
                    C
                    C     THIS SUBROUTINE CALCULATES THE RADIANT ENERGY WHICH WILL BE
                    C     DETECTED ABOVE THE RADIATING SURFACE IN THE 3-5 AND THE 8-14
                    C     MICRON RANGE
                    C
                    C
                          WAVE(1)=3.
                          WAVE(2)=5.
                          WAVE(3)=8.
                          WAVE(4)=14.
                          TLK=TL+273.
                          DO 3 I=1,4
                          B(I)=C2/(WAVE(I)*TLK)
                          IF(B(I).LT.2.)GO TO 4
                          FV(I)=0.0
                          DO 5 N=1,5
                          FV(I)=FV(I)+.15*(((EXP(-N*B(I)))/N**4.)*(((N*B(I)+3.)*N*B(I)+6.)
                         1 *N*B(I)+6.))
                        5 CONTINUE
                          GO TO 3
                        4 FV(I)=1.-((.15*B(I)**3.)*(.333-B(I)/8.+(B(I))**2./60.-(B(I))**4./5
                         140.+(B(I))**6./272160.-(B(I))**8./13305600.))
                        3 CONTINUE
                          F1=FV(2)-FV(1)
                          F2=FV(4)-FV(3)
                          F3=.016
                          F4=.002
                          QB3=(E*F1*SIG*(TLK**4.))+(F3*RU*1.94*COSTH)+(F3*T*RSG*
                         11.94*COSZ)
                          QB8=(E*F2*SIG*(TLK**4.))+(F4*RU*1.94*COSTH)+(F4*T*RSG*
                         11.94*COSZ)
                          RETURN
                          END
```

```
                    FUNCTION VG(T)
               C
               C
               C    FUNCTION SUBROUTINE VG(T) CALCULATES THE SPECIFIC VOLUME OF SAT.
               C    WATER AS A FUNCTION OF TEMPERATURE.
               C
               C
                    T=T+273.16
                    X=647.27-T
                    Y=X*(3.24378+(5.8683E-3+1.17024E-8*X*X)*X)
                    Y=Y/(T*(1.0+2.18785E-3*X))
                    PSL=218.167/(10.0**Y)
                    B1=(2641.62*10.0**(80870.0/(T*T)))/T
                    B0=1.89-B1
                    B2=82.546
                    B3=162460.0/T
                    B4=0.21828*T
                    B5=126970.0/T
                    Z=B0*PSL/(T*T)
                    B=B0*(1.0+Z*(B2-B3+Z*(B4-B5)*B0*PSL))
                    VG=4.55504*T/PSL+B
                    T=T-273.16
                    RETURN
                    END
```

```
                  SUBROUTINE GTEMP
                  DIMENSION TG(200)
                  COMMON/DATAIN/PI,C2,SIG,TL,EPS,G,K2,CP,Z
                  COMMON DT,M,LAT,DEC,H,LST,L,QA,QR,TA,V,TMAX,TVAR
                  COMMON QB3,QB8,C1,QATM,QG,QE,RO,T,SC,COSTH
                  COMMON QC,HC,ASU,ASL,E,A,RC,EG,ASG,RSG,AG,QST,QSU,QSL,QDF,C4
                  COMMON RH,D,KA,RE,GR,RL,DFS,COND,DELT,TGR
                  COMMON SIND,COSD,SINL,COSL,SINA,COSA,SINS,COSS,SINH,COSH,COSZ
                  REAL LAT,LST,M,KA,K2
            C
            C
            C     SUBROUTINE GTEMP CALCULATES THE GROUND SURFACE TEMPERATURE
            C     BY AN EXPLICT FINITE DIFFERENCE METHOD.
            C
            C
            C
            C
            C     N IS THE NUMBER OF NODES USED IN CALCULATING THE TEMPERATURE
            C     GRADIENT IN THE SOIL.
            C     DELTX IS THE DISTANCE BETWEEN NODES,IN CM.
            C
            C
                  N=20
                  TIME=0.0
                  DELTX=SQRT(2.*DFS*DELT)
                  QSI=QST*COSZ
                  QSI=QSI+QDF
                  IF(L.GT.0) GO TO 2
                  JJ=N-1
                  DO 3 I=1,N
                3 TG(I)=TMAX-TVAR/2.0
                2 CONTINUE
                  TG1=TG(1)
                  C5=DFS*DELT/(DELTX*DELTX)
                  C6=COND/DELTX
                  TGK=TG(1)+273.0
                  QG=EG*SIG*TGK**4
                  TFLM=(TG1+TA)*0.5
                  ANU=8.082+4.8822E-2*TFLM
                  ANU=ANU+8.06E-5*TFLM*TFLM
                  RHOA=0.353/(TA+273.0)
                  PR=1.0/(CP*RHOA*ANU/KA)**0.66
                  CF=1.0/(2.5*ALOG(160.0/Z)+5.0)**2
                  HG=PR*CF*RHOA*CP*V
                  QUAN=QSI*ASG+QATM*AG-QG
                  TG(1)=(HG*TA+C6*TG(2)+QUAN)/(HG+C6)
                  DO 1 I=2,JJ
                1 TG(I)=TG(I)+C5*(TG(I+1)-2.0*TG(I)+TG(I-1))
                  IF (L.GT.0) GO TO 4
                  IF(ABS(TG1-TG(1)).LT..005) GO TO 5
                  GO TO 2
                4 CONTINUE
                  TIME=TIME+DELT
                  IF(TIME.LT.DT) GO TO 2
                5 L=L+1
                  TGR=TG(1)
                  RETURN
                  END
```

```
FORTRAN IV G1  RELEASE 2.0                BLK DATA

 0001                      BLOCK DATA
 0002                      COMMON/DATAIN/PI,C2,SIG,TL,EPS,G,K2,CP,Z
 0003                      REAL LAT,LST,M,KA,K2
 0004                      DATA PI,C2,SIG,TL,EPS,G/3.1416,14388.,.822E-10,10.,.005,.353E07/
 0005                      DATA K2,CP,Z/.062,.24,5./
                     C
                     C
                     C
                     C     SUBROUTINE BLOCK DATA ALLOWS VARIABLES IN COMMON TO INITIALIZED
                     C     IN A DATA STATEMENT. THE FOWWOWING DATA IS INITIALIZED AS BLOCK
                     C     DATA.
                     C     C2 IS A CONSTANT USED IN PLANCKS SPECTRAL ENERGY DISTRIBUTION
                     C     ,IN MICRONS-DEGREES K
                     C     SIG IS THE STEFAN-BOLTZMAN CONSTANT,IN CAL/CM**2-K**4
                     C     TL IS THE ARBITRARY INITIAL TEMPERATURE OF THE LEAF OR MATERIAL
                     C     SURFACE.
                     C     EPS IS THE PRECISION WITH WHICH THE TEMPERATURE OF THE LEAF OR
                     C     MATERIAL SURFACE IS CALCULATED. NOTE, IF EPS IS SET TOO SMALL
                     C     A DIVIDE CHECK WILL OCCUR IN THE MAIN PROGRAM DUE TO THE SMALL
                     C     CHANGE OF RES1 AND RES2
                     C     G IS THE GRAVITATIONAL CONSTANT,IN CM/MIN**2
                     C     K2 IS A PROPORTIONALITY CONSTANT.
                     C     CP IS THE SPECIFIC HEAT OF AIR,IN CAL/GM-DEGREE C.
                     C     Z IS THE GROUND COVER VEGATION HIEGHT, IN CM.
                     C
                     C
                     C
 0006                      END
```

APPENDIX B

Evaluation of Various Surface Coatings on Camouflage Material Temperatures

Introduction

As shown in Table 1, camouflage material temperatures are several degrees higher than foliage when exposed to solar radiation and slightly lower during the evening hours when no solar insolation is present. This information leads us to the conclusion that the radiative characteristics of the camouflage material must be altered if it is to emulate foliated backgrounds. To accomplish this end, two basic approaches were considered: (1) change the radiative characteristics of the top surface of the material by using a clear spray coating or a transparent acetate cover as previously discussed and; (2) alter the solar and I. R. energy absorbed and emitted from the lower side of the material in order to control its temperature.

Two types of surface configurations were used to evaluate the second approach. The first consisted of bonding a sheet of aluminum foil to the lower surface of the camouflage material. The foil has the effect of lowering material temperatures when large amounts of solar radiation are reflected from the ground and has little or no effect when no reflected solar radiation is present. This is due, in part, to the fact that the foil effectively eliminates the absorbed short wavelength radiation which is reflected from the ground, and eliminates the long wavelength exchange between the lower surface and the ground. In addition, another piece of camouflage material was coated on the lower surface with white lacquer.

The lacquer has the effect of reducing the solar radiation absorbed on the lower side of the material while the long wavelength emittance remains unchanged. Thus the white paint effectively lowers the temperature during periods when solar radiation is present and has little effect at night.

Experimental Procedure, Results and Conclusions

Temperatures of the plain camouflage material and four variations thereof were made and compared to a Botanical Wonder plant (Fatsia Japonica). The measurements were made with Barnes PRT-5 and PRT-10 radiometers and were carried out with varying atmospheric conditions in order to properly evaluate the effect of the coatings. The results of these measurements are presented in Tables B-1 and B-2. In addition the air temperature, plant temperature, plain camouflage material temperature and one variation of the plain material temperature were plotted using data from the PRT-5 and are shown in Figures B-1 through B-4.

No concrete conclusions can be drawn from the preliminary data obtained thus far; however, certain trends are evident. The white lacquer coating lowered the material temperature below that of the plant and plain material during daylight and evening hours (Figure B-3). Both transparent coatings effectively lowered the material temperature during daylight hours, however the spray coating increased the temperature at night, while the acetate cover tended to lower the apparent temperature at night. Unfortunately, the acetate cover reflects large amounts of short wavelength radiation thus producing glare (Figures B-1 and B-4).

Table B-1. Comparison of the effect of various surface coatings on camouflage material temperatures in the 8. -14. micrometer range.

Data Point	Air Temperature in °C	Plant Temperature in °C	MATERIAL TEMPERATURE °C Plain	Transparent Coating	Foil Cover On Back	White Paint On Back	Acetate On Front	Comments
1	4.5	19.0	15.0	12.5		16.0		Mid-morning
2	4.5	15.0	14.0	12.5		13.0		"
3	5.0	17.0	20.0	20.0		21.5		"
4	6.0	17.0	21.0	18.0	17.0	16.0		"
5	6.0	17.0	18.0	16.0	17.0	16.0		"
6	6.0	24.0	24.0	20.0	22.5	19.0		"
7	6.0	22.5	24.0	20.5	22.0	20.0		"
8	6.5	23.5	25.0	24.0	26.0	22.0		"
9	6.5	24.0	26.0	23.0	25.0	23.0		"
10	7.0	19.0	17.0	16.0	18.0	15.0		"
11	11.0	16.0	14.0	13.0	14.0	12.5	9.5	Mid-afternoon
12	10.5	12.0	12.0	12.0	13.0	11.5	11.5	"
13	10.5	12.0	12.5	13.0	13.5	11.5	11.0	"
14	10.5	12.0	11.0	12.0	13.5	11.0	11.0	"
15	10.5	14.5	12.5	12.0	12.5	11.5	11.0	"
16	10.5	13.0	11.0	10.0	12.5	11.0	10.0	"
17	10.0	11.0	11.0	10.0	12.0	11.0	7.5	"
18	10.0	13.0	11.5	11.0	12.0	10.0	9.5	"
19	9.5	13.0	9.0	11.0	12.0	9.5	7.5	"
20	5.0	3.5	3.5	3.5	4.0	2.0	3.5	Evening
21	5.0	2.0	1.5	3.5	2.0	1.5	2.0	"
22	4.5	1.0	2.0	3.5	2.0	2.0	1.0	"
23	4.5	1.0	2.0	2.0	2.0	0.0	- .5	"
24	4.5	1.0	1.0	3.5	2.5	0.0	1.0	"
25	4.0	1.0	1.5	2.0	2.0	0.0	2.5	"

Table B-2. Comparison of the effect of various surface coatings on camouflage material temperatures in the 6.5-20. micrometer range.

Data Point	Air Temperature in °C	Plant Temperature in °C	MATERIAL TEMPERATURE °C					Comments
			Plain	Transparent Coatings	Foil Cover On Back	White Paint On Back	Acetate On Front	
1	4.5	12.0	14.0	13.0		12.0		Mid-Morning
2	4.5	14.0	15.0	13.0		10.0		"
3	4.5	16.0	17.0	17.0		16.0		"
4	5.0	16.0	13.0	13.0	14.0	12.0		"
5	6.0	18.0	20.0	20.0	20.0	17.0		"
6	5.0	19.0	16.0	16.0	19.0	14.0		"
7	6.0	21.0	22.0	22.0	24.0	18.0		"
8	6.5	20.0	21.0	21.0	24.0	19.0		"
9	6.5	24.0	28.0	28.0	28.0	24.0		"
10	6.5	24.0	25.0	26.0	30.0	24.0		"
11	6.5	19.0	16.0	15.0	18.0	14.0		"
12	7.0	19.0	20.0	20.0	21.0	15.0		"
13	11.0	12.0	9.0	9.0	10.0	8.0	8.0	Mid-Afternoon
14	10.5	10.0	9.0	9.0	10.0	9.0	8.0	"
15	10.5	10.0	8.0	8.0	10.0	7.0	7.0	"
16	10.5	10.5	8.0	8.0	10.5	7.0	7.0	"
17	10.5	11.0	9.0	9.0	10.0	8.0	7.0	"
18	10.5	10.0	7.0	7.0	9.0	7.0	6.0	"
19	10.0	10.0	7.0	7.0	9.0	6.0	4.0	"
20	10.0	10.0	7.0	7.0	8.0	7.0	6.0	"
21	9.5	9.0	4.0	6.0	8.0	5.0	5.0	"
22	5.0	-2.0	-2.0	-2.0	0.0	-2.0	-2.0	Evening
23	5.0	-3.0	-3.0	-3.0	-1.0	-4.0	-3.0	"
24	5.0	-3.0	-3.0	-3.0	-2.0	-4.0	-4.0	"
25	4.5	-3.0	-4.0	-3.0	-1.0	-4.0	-2.0	"
26	4.5	-3.0	-4.0	-4.0	-2.0	-5.0	-4.0	"
27	4.5	-3.0	-3.0	-2.0	-2.0	-4.0	-3.0	"
28	4.0	-3.0	-2.0	-2.0	-3.0	-3.0	-2.0	"

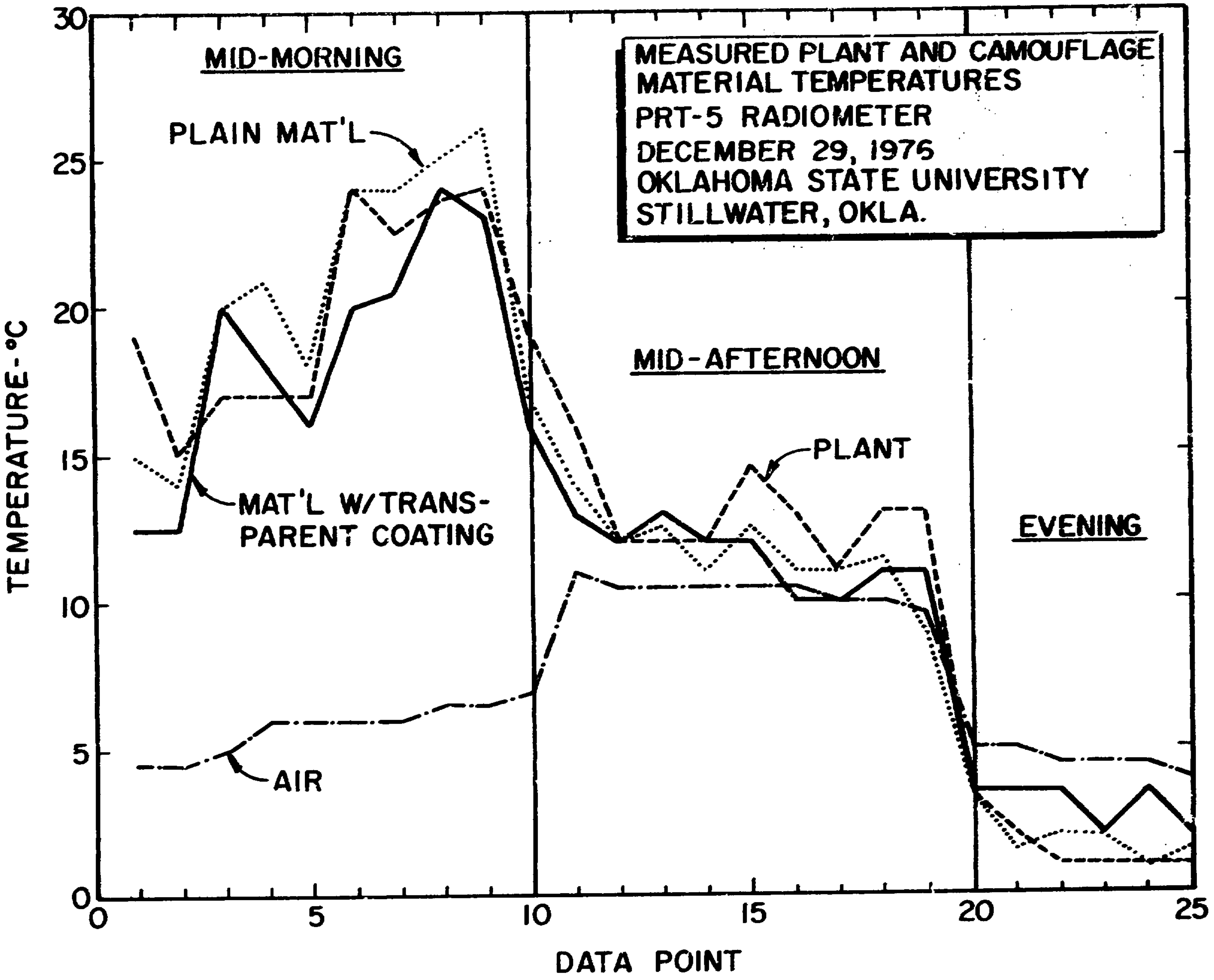
MEASURED PLANT AND CAMOUFLAGE
MATERIAL TEMPERATURES
PRT-5 RADIOMETER
DECEMBER 29, 1976
OKLAHOMA STATE UNIVERSITY
STILLWATER, OKLA.
MID-MORNING
MID-AFTERNOON
EVENING
PLAIN MAT'L
MAT'L W/TRANS-PARENT COATING
PLANT
AIR
TEMPERATURE - °C
30
25
20
15
10
5
0
DATA POINT
0
5
10
15
20
25

Figure B-1

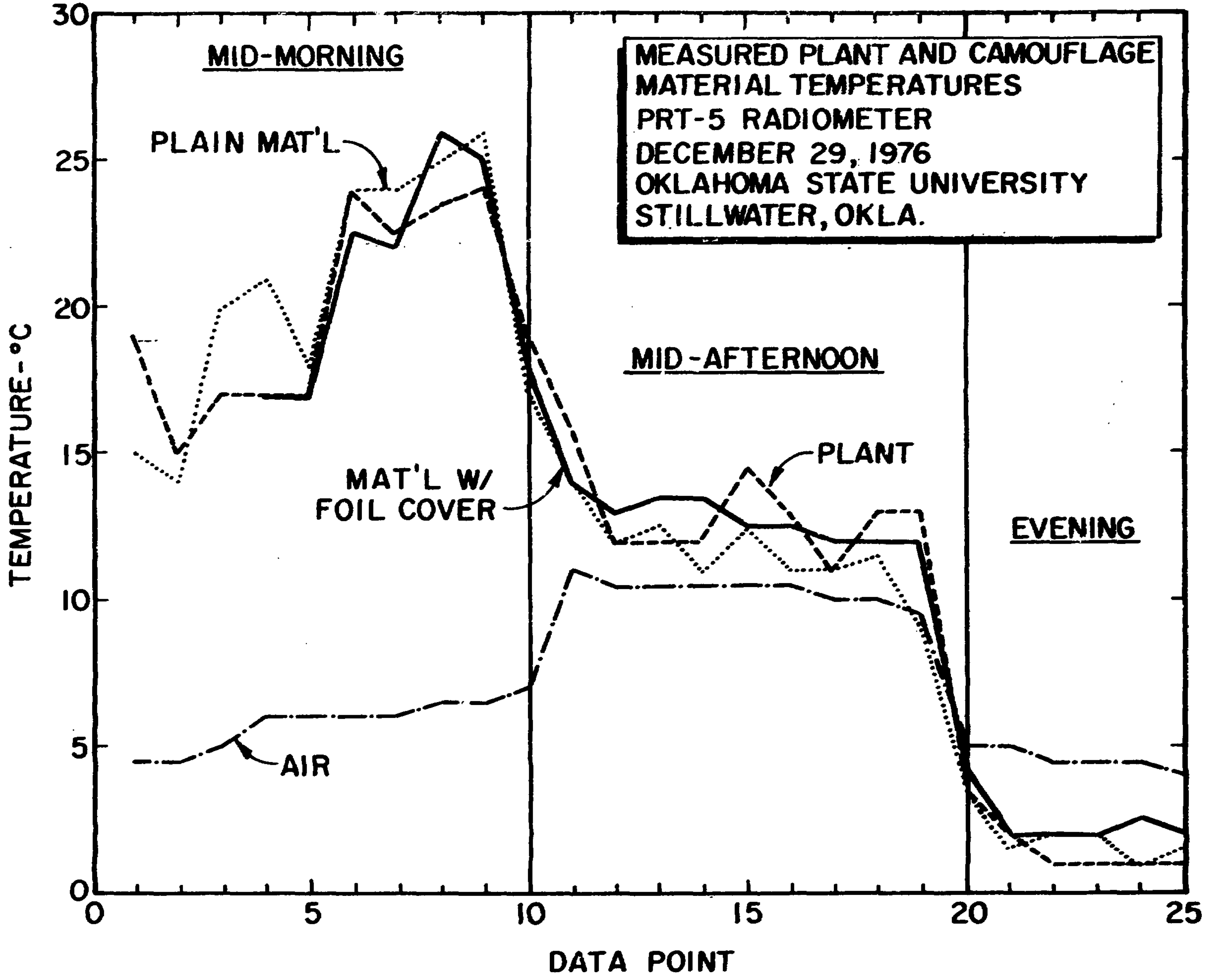
MEASURED PLANT AND CAMOUFLAGE
MATERIAL TEMPERATURES
PRT-5 RADIOMETER
DECEMBER 29, 1976
OKLAHOMA STATE UNIVERSITY
STILLWATER, OKLA.
MID-MORNING
MID-AFTERNOON
EVENING
PLAIN MAT'L
MAT'L W/ FOIL COVER
PLANT
AIR
TEMPERATURE - °C
DATA POINT
0
5
10
15
20
25
30

Figure B-2

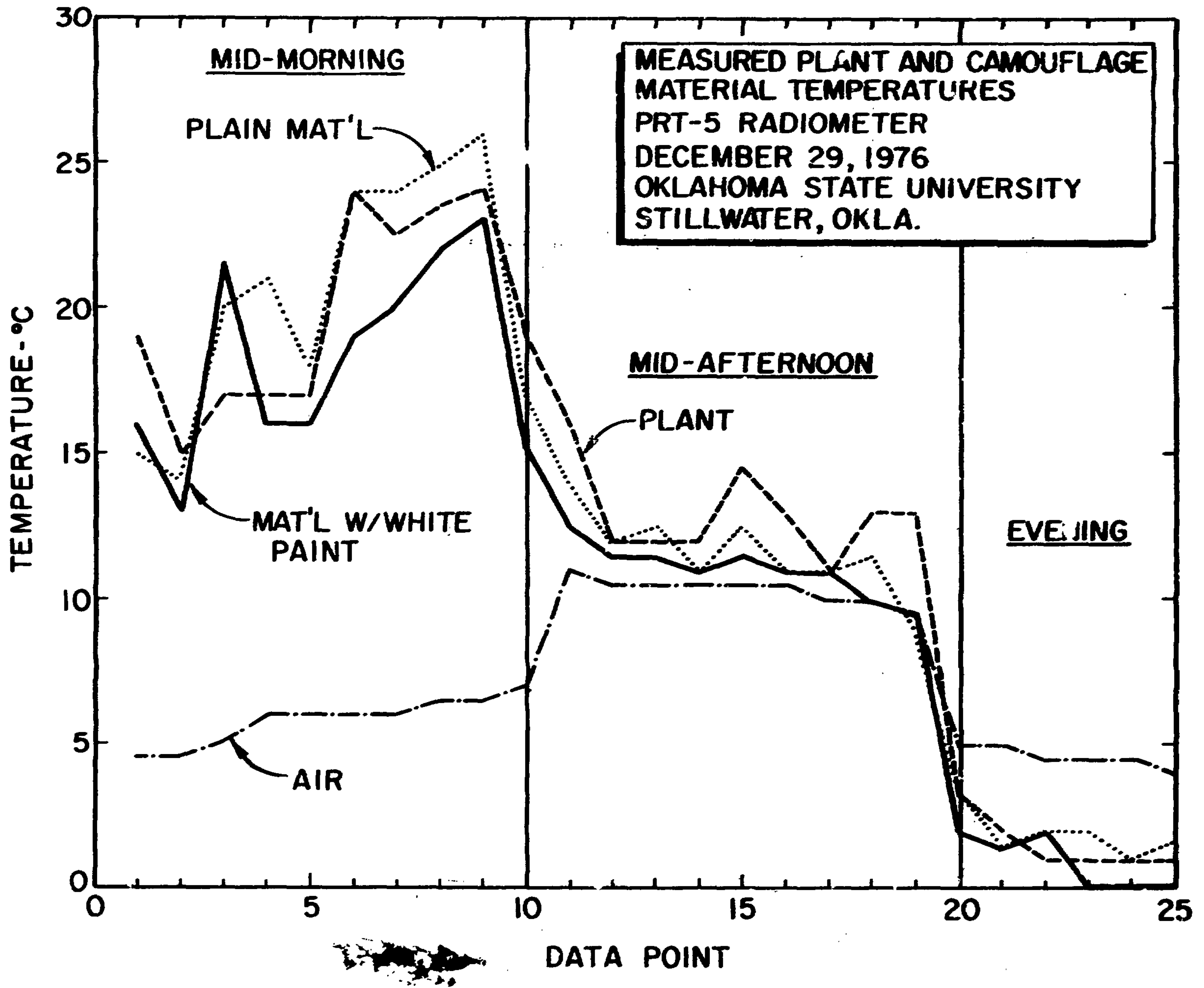
MEASURED PLANT AND CAMOUFLAGE
MATERIAL TEMPERATURES
PRT-5 RADIOMETER
DECEMBER 29, 1976
OKLAHOMA STATE UNIVERSITY
STILLWATER, OKLA.
MID-MORNING
MID-AFTERNOON
EVENING
PLAIN MAT'L
MAT'L W/WHITE PAINT
PLANT
AIR
TEMPERATURE - °C
0
5
10
15
20
25
30
DATA POINT
0
5
10
15
20
25

Figure 3-3

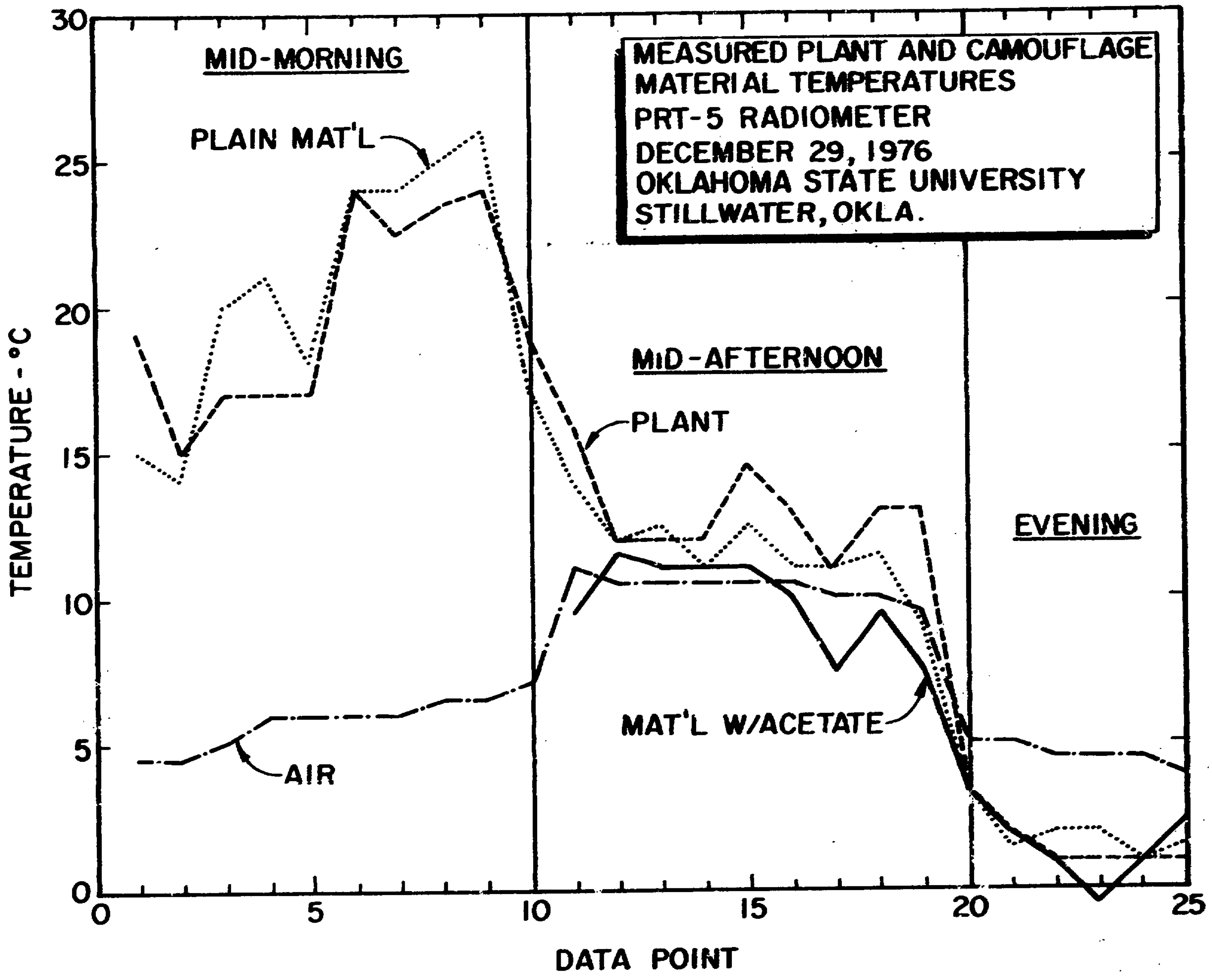MEASURED PLANT AND CAMOUFLAGE
MATERIAL TEMPERATURES
PRT-5 RADIOMETER
DECEMBER 29, 1976
OKLAHOMA STATE UNIVERSITY
STILLWATER, OKLA.
MID-MORNING
MID-AFTERNOON
EVENING
PLAIN MAT'L
PLANT
AIR
MAT'L W/ACETATE
TEMPERATURE - °C
30
25
20
15
10
5
0
DATA POINT
0
5
10
15
20
25

Figure B-4

The foil cover produced the most promising trends. It effectively lowered temperatures during the mid-morning, and mid-afternoon hours and slightly raised temperatures during the evening hours. In addition, it followed the plant temperature more closely than the other variations (Figure B-2). This configuration holds the added advantage that most of the radiation emitted from a hot object placed under the material would be reflected off the lower side.

The measurements made thus far are only preliminary and were designed to establish various trends by altering certain radiative properties. It is not known if the materials tested could be used under field conditions, however it is evident that progress can be made towards emulating foliated backgrounds with continued research in this area.