LBL-12049
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ENERGY & ENVIRONMENT DIVISION

RADIATIVE COOLING TEST FACILITY AND PERFORMANCE EVALUATION OF 4 MIL ALUMINIZED POLYVINYL FLUORIDE AND WHITE PAINT SURFACES

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November 1980

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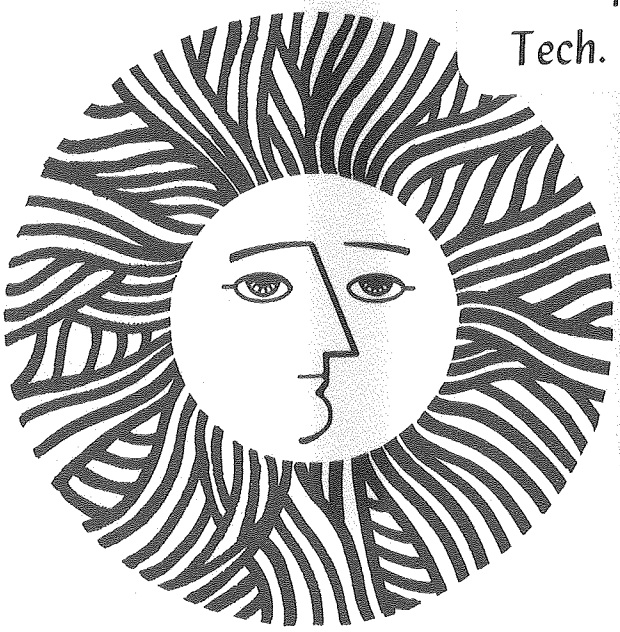

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RADIATIVE COOLING TEST FACILITY

AND

PERFORMANCE EVALUATION OF 4 MIL

ALUMINIZED POLYVINYL FLUORIDE AND WHITE PAINT SURFACES*

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ABSTRACT

Surfaces exposed to the night sky cool to temperatures below that of the air. This cooling is due to the nature of the atmospheric thermal radiation. Materials with dissimilar spectral characteristics behave differently.

The purpose of the Radiative Cooling Test Facility is to provide a means for quantitative measurement of the cooling rates of exposed surfaces and assemblies. Emphasis is placed upon assemblies which are specifically designed to produce radiative cooling and which therefore offer promise for the reduction of temperatures and/or humidities in occupied spaces. This report documents the hardware and software used to operate the facility, and presents the results of the first comprehensive experiments.

A microcomputer-based control/data acquisition system was employed to study the performance of two prototype radiator surfaces: 4 mil aluminized polyvinyl fluoride (PVF) and white painted surfaces set

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* This work was supported by the Research and Development Branch, Passive and Hybrid Division of the Office of Solar Applications for Buildings, U.S. Department of Energy, under Contract No. W-7405-ENG-48.

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below polyethylene windscreens. The cooling rates R for materials tested were determined and can be approximated by the following equation

$$R = a(\sigma T_{air}^4 - S) - 4b\sigma T_{air}^3 (T_{air} - T_{surface}),$$

where

S = Total thermal radiance of the sky (Wm^{-2})

σ = Stefan-Boltzmann constant (5.67×10^{-8} Wm^{-2} K^{-4})

T_{air} = Absolute air temperature (^{o}K)

$T_{surface}$ = Absolute radiator surface temperature ($^{\circ}K$)

and the constants a and b are given by

$a = 0.74$, $b = 1.00$ (4 mil aluminized polyvinal fluoride)

$a = 0.78$, $b = 1.09$ (white paint)

Computer simulations of radiative cooling assemblies were used to confirm that, with proper measurement techniques, the measured values of the constants a and b are nearly independent of the magnitudes of wind speed, air temperature, and sky radiance. Thus the cooling performance equation given in this abstract is applicable to a wide range of conditions, requiring only the sky radiance and the absolute air and surface temperatures as input values.

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INTRODUCTION

With the present desire to decrease the amount of energy consumed in all sectors of our society, the concern for finding alternative methods to cool buildings has developed. One method is radiative or sky cooling, where heat is transferred by radiation from a building's surface to the sky. The most important properties that govern this process are the radiative properties of the sky and of the surface.

The "resource" for radiative cooling is determined by the amount and spectral distribution of downward directed atmospheric radiation, and the effectiveness of a radiator assembly is influence by the spectral characteristics of the radiator plate and glazing material. Both topics are under investigation by our group at LBL. Spectral infrared sky radiance measurements have been taken by radiometers at various locations across the United States. Some of this data was recently processed and analyzed by Berdahl and Fromberg[1]. The research involving radiator surfaces is the topic of this paper. This work consists of testing different materials (with emphasis on surfaces which have selective radiative properties) and studying their cooling performance. The remainder of the paper discusses the principles of radiative cooling, describes the test facility and computer model developed to simulate the cooling process, and presents results from the initial experiments.

PRINCIPLES OF RADIATIVE COOLING

As shown in Fig. 1a[2], the sky emits roughly like a blackbody, except between 8 and 13 microns (the atmospheric window) where the radiance is significantly lower. Outside the atmospheric window the emission from clear skies is due primarily to water vapor and carbon dioxide. The area under the curve represents the amount of energy radiated over the whole spectrum. If a blackbody at the same temperature is exposed to the sky, a net energy transfer will result. The surface will cool down until the area under it's curve is equal to the area under the sky radiation curve (see Fig. 1b).

From this figure, it is evident that the blackbody gains energy from the sky outside the 8 to 13 micron range and loses energy within this range. If, however, the surface could reflect the radiant energy outside the atmospheric window and remain highly emissive within the window (a selective property), it would cool down further or be capable of emitting more energy[3,4,5]. This selective property is only advantageous for operating the surface at temperatures below that of the air. Otherwise, a blackbody would be more effective.

The emittance of the surface as a function of direction is also important[6]. Since the infrared sky radiation is more intense at angles further from the zenith, it is desirable to have a higher reflectance from the surface at these angles. This would decrease the energy absorbed by the surface, and permit the dissipation of more heat at low

temperatures.

So far only radiative heat transfer has been mentioned. An exposed surface is also subjected to heat gains by convection and conduction. If the temperature of a surface is at or very close to ambient, then the energy transfer due to these modes is very small. But if there is a temperature difference between the plate and ambient, a substantial heat gain will result. The minimum temperature to which the surface can cool by radiation will be greatly affected by heat gains from convection. Therefore, the surface must be isolated from the environment. This is accomplished by insulating the bottom and sides of the radiator surface and covering the top with an infrared transparent film (windscreen)[7,8]. The entire assembly will be referred to as a radiator panel. It is necessary that the windscreen be transparent in the infrared so the energy radiated from the surface is not absorbed. The film must also resist deterioration from the weather and sunlight for practical applications.

TEST FACILITY

The purpose of the test facility is to measure the amount of radiative cooling a specific material or assembly of materials will produce when exposed to the sky. This is accomplished by controlling the radiator surface temperature with an electrical resistance strip heater and recording the power applied to it, and by monitoring meteorological conditions and other relevant information. The "sky temperature" is monitored with a pyrgeometer which measures the total thermal radiance of the sky at wavelengths from 3 to 40 microns. A preliminary description of the facility was given last year[2].

The test facility was designed, constructed, and operated at Lawrence Berkeley Laboratory (the roof and fourth floor of Building 90). It consists of a microcomputer control and data acquisition system, radiator panels, and electronic interfacing modules (see figure 2). The test facility has the capability of testing as many as eight different radiator assemblies at one time. The following sections will discuss each element in detail.

Radiator Panels

The radiator panels are Kydex (Acrylic and PVC) boxes injected with styrofoam insulation. Each surface to be tested is mounted on a 53 x 94 cm aluminum plate. A resistance heating element is attached to the back side of each plate (see figures 3 and 4)[2]. This assembly is located in a recessed area on top of the box that is covered by a windscreen.

Six thermistors are attached to various points on the radiator panel. Three are in contact with the plate at the center, side, and corner, one is cemented to the windscreen, and the rest are tied to the side to be used as spares.

Microcomputer System*

The radiative cooling test facility uses a microcomputer based on the Zilog Z80A microprocessor. It is a general purpose microcomputer, useful for computing of any kind, in addition to data acquisition. Thus it is possible to develop the control and data acquisition programs on the computer as well as to run the experiment itself. The block labelled microcomputer in Fig.2 is composed of a Monolithic Systems Corp. 8004 CPU board with the Z80A processor, 32K RAM (read/write memory) and 8K of EPROM (programmable read only memory). It contains parallel and serial input/output circuits and an Advanced Micro Devices AM9511 arithmetic unit to facilitate mathematical operations.

In addition to the memory on the CPU board, an additional 16K of RAM is included on a separate board from Godbout Electronics for a total memory capacity of 56K. 1K of memory address space is also reserved for the analog-digital converters. The details of the memory map are given in Figure 6.

Besides the main computer memory, there is a dual floppy disk system on which data and programs can be stored. The disk system utilizes an Intel SBC-204 disk controller and two Morrow Designs floppy disk drives.

Input and output signals can be digital or analog. For signals such as temperature, heater power, wind direction, etc., that use analog sensors, the system includes two RTI-1200 Real Time Interface boards which allow for 32 channels each of analog input. Digital signals such as switch closures are connected to the parallel input port on the computer board.

Finally, a Real Time clock board fabricated by LBL monitors the AC power line and interrupts the computer on every half cycle in order to implement time and data keeping functions and to allow periodic servicing of programmed routines such as recording data, changing radiator temperatures, ending experiments, etc.

Operator interface to the system is through a Lear Siegler ADM-3A video display terminal connection to the serial I/O port of the computer.

Interfacing Hardware

The outputs from the sensing devices are modified before reaching the analog inputs of the computer. This is performed by circuits housed in the signal conditioner chassis (see Fig.2). This chassis houses circuits which modify the outputs of the thermistors and watt transducers. The thermistors are connected in a voltage divider circuit as shown in Figure 5 (see Appendix A for further details). The watt transducer signals pass through an averaging circuit with a time constant of 10

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*The reader not interested in hardware and software details should skip to the section, COMPUTER SIMULATION.

seconds. The Real Time Clock board is also in this chassis.

The Climet weather chassis contains the circuits for signal conditioning the ambient and dewpoint temperature probe and pyrgeometer outputs (see Appendix B). The temperature signals are conditioned to be directly proportional to temperature and the pyrgeometer output is amplified with a gain of approximately 1000.

The temperature control chassis contains solid-state relays and watt transducers. The relays are controlled by the output port of the computer and are turned on and off to modulate the power to the heaters. A voltage proportional to the heater power is produced by the watt transducers, and passes into the signal conditioner chassis.

Software

Disk Operating System

The floppy disks are organized into 128 byte blocks of data divided into 77 tracks of 26 blocks each, totalling 256K. The CP/M disk operating system keeps track of data by keeping file names and information about the location of files. To the user, a file is simply a set of characters sequentially accessed for a serial file, or an array of records of any size for a random access file. The programmer does not need to know where to look on the disk for a file or where to get more disk space to enlarge a file; CP/M manages the requirements. CP/M also provides the environment for the editor, assembler, compiler and interpreter used in the development of the user programs.

User Programs

Each user program is coded in assembly language or an implementation of the BASIC language called CBASIC. In applications where high speed is a requirement assembly language is used. BASIC programs are easier to write and debug and are therefore used when speed is of no concern.

Functions coded in assembly language are routines to keep track of time and date, to read the A/D channels, to convert data to engineering units, to control the radiator temperatures and to manipulate power to the heaters. Some of these routines are accessed by CBASIC programs and others are serviced automatically whenever the clock interrupts the computer. When an interrupt occurs, the computer stops execution of the ongoing program and services the clock, controller, and power routines. After the clock is updated, a flag is checked to determine whether a temperature controlling experiment is being run. If not, the computer services the power routine. Otherwise a manipulated eight bit variable representing heater duty cycle is calculated from a control algorithm. This computation is performed once a second for each channel. When this computation is completed, the state of the heaters (on-off) is determined in the power routine by examining the manipulated variable for each cell. An eight bit word is formed and sent to an output port of the computer which controls the relay switches of the heaters. Since this occurs on every interrupt or every 8.3 milliseconds and the

manipulated variable represents a number between 0 and 255, the period of the duty cycle is 2.12 seconds.

Finally, after these three routines are completed, the computer returns to the operating program in CBASIC. This cycle of events runs continuously and is invisible to the operator.

A proportional integral control algorithm is implemented in calculating the manipulated variables. The discrete time step version employed is written as:

$$\text{DELTA M} = KP(C(n-1) - C(n)) + KI(R(n) - C(n))$$

where DELTA M is the change in the manipulated variable, KP and KI are the proportional and integral gains; R and C are the setpoint and actual temperatures, and $n = 0,1,2,\ldots.$ represents the discrete time. The gains are determined using the Ziegler-Nichols Rules for discrete time (see Appendix C).

As mentioned previously, the CBASIC programs store constants used by the assembly language functions. These include the offset and gain for each of the 64 A/D channels, which are calculated by a separate program. These constants are stored automatically when the microcomputer system is started up.

There are two programs written in CBASIC which are employed when performing an experiment. The initial one sets the constants to be used during a test. These include the control gains, the thermistor channels to be used in the temperature control algorithm, the time intervals for servicing the CBASIC functions, file names, and other required data. When this is completed, a second program is run which starts the experiment and continuously watches the clock to determine when a routine needs to be serviced. These routines consist of taking data, closing files, stopping the test, and performing other activities. When an experiment is completed, the computer stops the test and returns to the initial program.

For each experiment, three files are created; a parameter, data, and comment file. The parameter file contains all the constants used in the experiment and the comment file gives a brief description of the test. Finally, the data file consists of all the information recorded from the tested radiator panels.

COMPUTER SIMULATION

A computer model was written by to simulate the heat transfer of a radiator panel exposed to the sky[9]. The details of the program will not be presented in this report, but the equations and several aspects of the results will be presented.

Radiation occurs between the plate and sky, plate and windscreen, and windscreen and sky. Equations were written to calculate the net heat gain due to radiation of the plate and of the windscreen[10,11,12]. Convective heat transfer is present in the air space between the windscreen and plate, and between the windscreen and the outside air. Conduction occurs through the insulated back and sides of the radiator panel. The equations employed in the program are given in Appendix D.

The results of this program are used more qualitatively than quantitatively. The sensitivity of the relationship between efficiency η and dimensionless temperature difference τ is to be determined for different operating parameters. Let R be the heat dissipated by the radiator plate. The quantities η and τ are defined as:

$$\eta \equiv \frac{R}{(1 - \varepsilon_{sky})\ \sigma T_{air}^4}$$

and

$$\tau \equiv \frac{4(T_{air} - T_{surface})}{(1 - \varepsilon_{sky})\ T_{air}} \quad .$$

The sky emissivity ε_{sky} is defined as the total thermal radiance of the sky S divided by the radiance emitted by a blackbody at air temperature. The purpose for introducing η and τ is to normalize the experimental data. Therefore, it is important to have the function η (τ) remain constant when changes occur in the operating parameters.

The program was used to determine the sensitivity of the efficiency η to sky emissivity, air temperature, and wind speed. Two different surfaces operated under the same conditions have been compared.

From the results shown in figures 7 and 8, it is apparent that the sensitivity due to changes in sky emissivity and air temperature are rather small. Therefore, η and τ calculated in this manner can be adequately used to characterize the results obtained from experimental measurements. It is also shown that increasing the wind speed decreases the efficiency. The reason for this effect is that the convective heat transfer coefficient between the windscreen and air is increased by the wind. A further example of the use of η and τ is presented in Appendix E.

Two different surfaces (1/2 mil aluminized polyvinyl fluoride and white paint) are compared in figure 9. From the graph it is obvious that the Tedlar surface is more efficient (has a larger cooling power) than the white surface at higher values of τ, which is attributable to its selective property.

EXPERIMENT

The microcomputer control and data acquisition system allows many different types of experiments to be performed. The radiators can be controlled to maintain a specific set point temperature, track the ambient temperature (with or without an offset), or radiate a constant heat flux. The operating modes can remain fixed or change at set time intervals. For example, the set point might decrease by three degrees every hour until a lower limit is reached, then increase back to its initial value.

The types of radiator panels that are presently available are listed in Appendix F. The three radiator panels tested for this report had surfaces consisting of white paint and 4 mil aluminized polyvinyl fluoride.* One was exposed with glazing (white paint) and the other two (white paint and polyvinyl fluoride) were covered with 2 mil polyethylene windscreens. These were mounted horizontally in the test rack with their testing surfaces facing upward.

Several operating procedures are common to all of the tests. First, the experiments began in the evening and ended about seven o'clock the next morning. Data is recorded every five minutes and consisted of the date, time, dewpoint and ambient temperatures, pyrgeometer reading (sky radiance measurement), electric heater power, and the six thermistor temperatures for each panel. The watt transducer values are sampled every 10 seconds and averaged over the five minute recording interval to obtain the power to the heater. When the experiment requires maintaining a setpoint, the thermistor in the center of the plate is used by the control algorithm. The same control gains are used in all the tests. Finally, the data files are closed and reopened every hour to minimize the possibility of lost data. Closing the data file every hour prevents the information recorded from being lost if the system fails.

After a test is completed, the data from the three files (parameter, comment, data) is combined into a fourth file in the format to be printed out. During this procedure, the difference between the ambient and plate temperatures is calculated (the plate temperature is obtained from the center thermistor), the power is converted from watts to watts per square meter using the effective area (see Appendix G), and the sky emissivity is computed from the pyrgeometer reading and air temperature. This file is then transferred to the main LBL computer system and printed.

After the data was printed, it was subjected to a selection process. This involves manually examining and selecting data points. During most of the experiments, a variable was changed once an hour. Therefore, conditions were usually dynamic soon after this occurred and damped out approximately 40 minutes later. When the readings were steady, the data was averaged and recorded.

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* The polyvinyl fluoride (PVF) used was Tedlar, Type B, manufactured by Dupont Corporation.

RESULTS

Although a number of tests were performed, the data from only eight will be presented here. The information from the remaining tests was thought to be in error due to the pyrgeometer being out of calibration, water seeping inside the radiator boxes, etc. The details for each test and the selected steady state data points are given in Appendix H.

For each data point, the efficiency n and the dimensionless temperature difference τ was calculated and plotted. Points with negative τ were omitted from the graphs. In figures 10 and 11 the data from five of the experiments are shown for radiators with polyvinyl fluoride and white paint surfaces. Points where the windscreen temperature was at or below the dewpoint temperature were omitted from these plots, because it was expected that condensation would be present on the windscreen. Also shown in each of these figures is a least squares fit of the data points. In both cases the correlation factor was greater than 0.988. The standard error of estimate for the polyvinyl fluoride radiator was 0.021 and 0.033 for the white paint radiator. Comparing these two curves in figure 12, it is obvious that the polyvinyl fluoride surface has higher efficiency at values of τ greater than 0.22. This behavior is consistent with the results obtained from the computer model.

The effects of wind and windscreen condensation are shown in figures 13 and 14. The solid lines are the least squares fits from figures 10 and 11. The circles represent points where the windscreen temperature is at or below the dewpoint temperature. It is obvious that condensation on the windscreen reduces the efficiency. This is due to infrared absorption by the water. To prevent condensation from forming, a fan was set up to blow air over the radiator panels. The purpose of this was to keep the windscreen temperature above the dewpoint. The triangles represent the results obtained under these test conditions. The windscreen temperature on the polyvinyl fluoride dropped below the dewpoint temperature at high values of τ. It is not known whether condensation occurred in this case. The windscreen temperature on the white paint radiator remained above the dewpoint temperature the entire time. In both cases the efficiency was below the solid line. This was caused by the fan's raising the windscreen temperature. Again, the results are consistent with the computer model.

The temperatures of the ambient air, radiator surface, and windscreen are shown for one test in figure 15 as a function of cooling power. Since the power was decreased every hour, the plot also shows how the temperatures varied during the test. It is evident that the radiator surface temperature is greater than the windscreen temperature at high power values and becomes less than the windscreen temperature as the power is decreased. This transition affects the heat transfer coefficient between the radiator surface and the windscreen. In the first instance, convective losses are enhanced because the plate is warmer than the windscreen. As the surface becomes cooler than the screen, convection is suppressed and conduction becomes the dominant nonradiative mode of heat transfer. Also, from the left side of the graph it can be seen how the windscreen temperature is affected by a decrease in the air temperature.

Finally, it is of interest to determine the emissivity of the white paint. This was accomplished by removing the windscreen from a white paint radiator and performing an experiment in which the radiator tracked the ambient temperature. This procedure eliminates the effects of the windscreen and non-radiative heat losses. Therefore, the net heat transferred from the radiator surface could be expressed as:

$$R = \varepsilon_{rad} (1 - \varepsilon_{sky}) \sigma T_{air}^4 \quad .$$

This assumes that the white paint is a gray surface. Solving for ε_{rad} gives:

$$\varepsilon_{rad} = \frac{R}{(1 - \varepsilon_{sky}) \sigma T_{air}^4} \quad .$$

The data from this test was examined for points where the temperature difference between the radiator surface and air was closest to zero. Also, it was required that the sky conditions be steady. Several twenty minute time intervals were found to satisfy these criteria and points within each of these data set were averaged (see Appendix I). The emissivities calculated were 0.91 and 0.89. It is important to note that these figures are very sensitive to sky emissivity. A 0.01 change in ε_{sky} results in a 0.04 change in surface emissivity. Since the pyrgeometer in our experiments is accurate to about ± 0.02, the values of the white paint emissivity have an uncertainty of about $\pm .08$.

CONCLUSIONS

There is a great deal of information that can be extracted from the results of these experiments. Implementing the efficiency curves for the radiator panels, one can estimate the amount of cooling that can be achieved given the sky emissivity, air temperature, and radiator surface temperature. The equation for the cooling power R is:

$$R = \eta(1 - \varepsilon_{sky})\ \sigma T_{air}^4$$

where

$$\eta = -1.09\tau + 0.78 \qquad \text{(white paint)}$$

$$\eta = -1.00\tau + 0.74 \qquad \text{(aluminized Tedlar)}$$

and

$$\tau = \frac{4\ (T_{air} - T_{surface})}{(1 - \varepsilon_{sky})\ T_{air}} \quad .$$

From figures 13 and 14 it is evident that wind and condensation produce undesirable effects. Therefore, techniques should be devised to isolate the radiator panel from these elements.

The comparison between the polyvinyl fluoride and white paint surfaces shows that their performances are similar. This indicates that the polyvinyl fluoride surface is only moderately selective. The reason for this can be seen in the reflectance measurement shown in Appendix J. This graph indicates that the 4 mil polyvinyl fluoride is rather absorptive outside the 8-13 micron atmospheric window. Also shown in Appendix J is the reflectance measurement for 1/2 mil polyvinyl fluoride. This thickness is not as absorptive outside the atmospheric window as the 4 mil. Therefore, its performance compared with that of the white paint should be much different. Experiments implementing the 1/2 mil polyvinyl fluoride were not performed because the material was not available.

A technique for measuring the sky emissivity is suggested by our experiment with the unglazed white paint radiator maintained at air temperature. Knowing the surface emissivity, air temperature, and power to the heater, one could calculate the sky emissivity. If these parameters were known precisely, this method could be more accurate than using the pyrgeometer.

Finally, our testing experience suggests that the weather conditions should fall under certain criteria to obtain accurate results. The sky emissivity should be equal to or less than 0.85. It is also desirable that the wind speed be less than 4 mph (1.8 m/s). This limit was determined by comparing the wind speed and data points taken during test

RCA1027 (see Appendices H and K). Around 3:30 am, the wind speed increased from 2 mph to 4 mph. This is approximately the same time a noticeable decrease in the efficiency occurred. Therefore, 4 mph was chosen as the limit. Also, data points where the windscreen temperature is at or less than the dewpoint temperature should be omitted. The reason is that windscreen condensation is likely, which will result in lower efficiency values.

A point should be made concerning the wind speed limit. It was observed during windy conditions that the windscreen would vibrate. This movement increases the heat transfer coefficient between the windscreen and the radiator, which decreases the efficiency. The wind speed limit is hardware dependent. For example, if a radiator panel is designed so that the windscreen is supported at numerous points, then the wind would need to reach a higher speed before the panel's performance would be affected.

Plotting η and τ with data that meets the criteria mentioned above, one obtains the performance of a radiator panel. Since the parameters η and τ are nearly independent of the details of the test, the results determine the essential thermal properties of the panel.

There are a few improvements that should be made to the test facility. A more accurate method of measuring the sky emissivity is needed. This is important since many of the calculations are sensitive to this measurement. The wind speed should be measured near the test rack. Presently, the closest measurement is approximately a quarter mile away. Also, the control gains need to be adjusted to improve the performance of the temperature control system.

There are many experiments that remain to be performed. Some of these include testing different radiator and windscreen materials, changing the angle of the radiator panel, shading the panel from the sun to produce cooling during the day, and testing the radiators with collimators or other reflecting devices. Finally, the spectral characteristics of the radiator panels used in the experiments should be entered into the computer model. Then the computed results could be compared directly with those from the experiments.

With further research optimizing selective surfaces, radiator panel configurations, and operating procedures, radiative cooling could be a viable means of cooling buildings in the future.

ACKNOWLEDGEMENTS

We are grateful to Stephen Kanzler and David Evans for their computer hardware and software skills that were indispensable throughout the design and start-up of the control/data acquisition system. Richard Fromberg originally suggested constructing the computer model of a radiator panel. Finally, we thank Charlotte Standish, whose secretarial skills contributed to the final form of this paper.

This work was supported by the Research and Development Branch, Passive and Hybrid Division of the Office of Solar Applications for Buildings, U.S. Department of Energy, under Contract No. W-7405-ENG-48.

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APPENDICES

APPENDIX A: SPECIFICATIONS AND CALIBRATION OF THERMISTORS

The resistance and corresponding temperature for the thermistors is given in the table below. Since the natural log of the resistance versus temperature relationship is not quite linear, a least squares fit to a quadratic function was implemented. Points between -20 and 50 °C were used in the fit resulting in the following equation.

$$\ln R_t = A\,T^2 + B\,T + C$$

where,

$A = 0.00014282$
$B = -0.051169$
$C = 9.1923$

solving for T,

$$T = \frac{-B - (B^2 - 4A(C - \ln R_t))^{1/2}}{2A}$$

The resistance was determined by measuring the voltage across the thermistor (see figure 5 for circuit).

$$R_t = \frac{V\,R_o}{(V_r - V)}$$

$V_r = +15$ V
$R_o = 31600$ ohms
V = voltage measured by the microcomputer

RESISTANCE VERSUS TEMPERATURE —40° to +100°C

TEMP°C	RES	TEMP°C	RES	TEMP°C	RES	TEMP°C	RES	TEMP°C	RES
−40	100.9K	−10	16.59K	+20	3748	+50	1080	+80	376.6
39	94.46K	9	15.72K	21	3583	51	1040	81	364.7
38	86.44K	8	14.89K	22	3426	52	1002	82	353.1
37	82.85K	7	14.12K	23	3277	53	964.6	83	342.0
36	77.64K	6	13.38K	24	3135	54	929.3	84	331.3
35	72.79K	5	12.70K	25	3000	55	895.4	85	321.0
34	68.28K	4	12.05K	26	2872	56	863.0	86	311.0
33	64.07K	3	11.43K	27	2750	57	831.9	87	301.4
32	60.15K	2	10.85K	28	2633	58	802.1	88	292.2
31	56.49K	−1	10.31K	29	2523	59	773.5	89	283.3
−30	53.08K	0	9795	+30	2417	+60	746.0	+90	274.7
29	49.89K	+1	9309	31	2317	61	719.7	91	266.4
28	46.92K	2	8850	32	2221	62	694.4	92	258.4
27	44.14K	3	8416	33	2130	63	670.2	93	250.6
26	41.54K	4	8006	34	2042	64	646.9	94	243.2
25	39.11K	5	7618	35	1959	65	624.6	95	236.0
24	36.84K	6	7252	36	1880	66	603.1	96	229.0
23	34.71K	7	6905	37	1805	67	582.4	97	222.3
22	32.72K	8	6576	38	1733	68	562.7	98	215.8
21	30.86K	9	6265	39	1664	69	543.6	99	209.5
−20	29.11K	+10	5971	+40	1598	+70	525.3	+100	203.5
19	27.47K	11	5692	41	1535	71	507.7		
18	25.94K	12	5428	42	1475	72	490.8		
17	24.50K	13	5177	43	1418	73	474.5		
16	23.15K	14	4939	44	1363	74	458.9		
15	21.88K	15	4714	45	1310	75	443.8		
14	20.69K	16	4500	46	1260	76	429.3		
13	19.57K	17	4297	47	1212	77	415.4		
12	18.51K	18	4105	48	1167	78	402.0		
11	17.52K	19	3922	49	1123	79	389.1		

YSI PRECISION THERMISTOR

LN 7595

YSI 44030

RESISTANCE 3000 OHMS @25°C

Interchangeability: ±0.1°C (See Tolerance Curves).

Max. Operating Temp: 100°C (212°F). Extended operation or continued cycling above 75° will cause thermistor to eventually exceed tolerances.

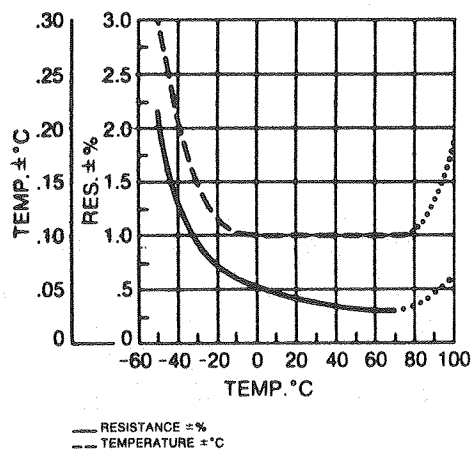
Time Constant, Max: 1 sec. in well stirred oil, 10 sec. in still air. Time constant is the time required for a thermistor to indicate 63% of a newly impressed temperature.

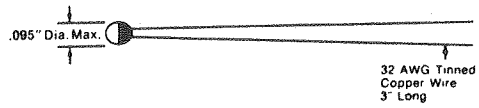
Dissipation Constant, Min: 8mW/°C in well stirred oil, 1mW/°C in still air. Dissipation constant is the power in milliwatts to raise a thermistor 1°C above surrounding temperature.

Color Code: Orange epoxy body, black end.

Storage Temperature: -80° to +75°C (-112° to +167°F).

Tolerance Curves: The following curves indicate conformance to standard resistance temperature values as a % of resistance, and as a maximum interchangeability error expressed as temperature.





APPENDIX B: CONVERSION FACTORS FOR READING THE POWER AND WEATHER INSTRUMENTS

Power = 20.41 V_m (watts)

Ambient Temperature = 83.3 V_m - 34.4 (°C)

Dew Point Temperature = 83.3 V_m - 34.4 (°C)

Pyrgeometer = 210. V_m (watts/m^2)

V_m = voltage measured by microcomputer (volts)

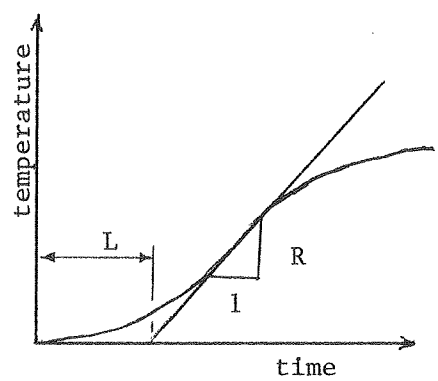
APPENDIX C: CALCULATION OF CONTROL GAINS

The gains implemented in the control algorithm were intially estimated by using the Ziegler-Nichols Rules for proportional-integral action(discrete time). Their final values were derived by experiment. To attain the intial values, a heater on one of the radiator panels was set to 100% power and the temperature of the plate was recorded every second. Once the temperature reached steady state, the maximum slope and corresponding x-intercept were determined (see below). With these values the gains were calculated from the following equations.

$$K_p = \frac{0.9}{R(L + T)} - .5\,K_i$$

$$K_i = \frac{0.27\,T}{R(L + .5T)^2}$$

Where "T" is the time step.



unit step response

APPENDIX D: EQUATIONS USED IN THE COMPUTER SIMULATION OF RADIATOR PANEL PERFORMANCE

Listed below are the equations that calculate the net heat gain due to radiation of the plate and of the windscreen. All surfaces were assumed to produce only specular reflection.

For the plate,

$$q = \int d\omega \cos\theta \int d\lambda \; \epsilon_r \left[\frac{t_s \epsilon_a W(T_a) + \epsilon_s W(T_s) + r_s \epsilon_r W(T_r)}{1 - r_r r_s} - W(T_r) \right]$$

For the windscreen,

$$q = \int d\omega \cos\theta \int d\lambda \; \epsilon_s \left[\epsilon_a W(T_a) + \frac{r_r t_s \epsilon_a W(T_a) + r_r \epsilon_s W(T_s) + \epsilon_r W(T_r)}{1 - r_r r_s} - 2W(T_s) \right]$$

where,

λ = wavelength

ϵ_a = spectral emittance of the atmosphere

t_s, r_s, ϵ_s = spectral transmittance, reflectance, and emittance of the windscreen

ϵ_r, r_r = spectral emittance and reflectance of the radiator plate

$W(T)$ = blackbody function (also a function of wavelength)

T_a, T_s, T_r = temperatures of air, windscreen, and radiator plate

ω = solid angle

θ = zenith angle (radiator is horizontal)

The spectral properties of the materials and the emissivity of the atmosphere depend upon θ as well as λ. The materials properties also depend on the polarization of the radiation.

Listed below are the equations implemented to determine the convective and conductive heat transfer between the windscreen and air and the windscreen and radiator surface. The back insulation was assumed to have a thermal conductivity of 0.3 W/m^2k.

$$q = h A \Delta T$$

$$Nu_L = \frac{h L}{k}$$

$$Re_L = \frac{V L}{\nu}$$

$$Gr_L = \frac{g \beta}{\nu^2} L^3 (\Delta T)$$

Pr of air = 0.720

where,

h = heat transfer coefficient

V = wind velocity

L = characteristic length of panel (1 meter)

ν = kinematic viscosity

ρ = mass density of air

g = acceleration of gravity

β = temperature coefficient of volume expansion of air

ΔT = temperature difference

k = thermal conductivity of air

q = heat transfer

A = area

s = spacing between windscreen and radiator surface

Windscreen/Air (with wind) [14]

Laminar $Re_L < 5 \times 10^5$ use $\overline{Nu}_L = .664\ Re_L^{1/2}\ Pr^{1/3}$

Turbulent $Re_L > 5 \times 10^5$ use $\overline{Nu}_L = .036\ Pr^{1/3}\ (Re_L^{.8} - 23200.)$

Windscreen/Air (without wind) [15]

$T_s > T_a$ $10^5 < Gr_L < 7 \times 10^7$ use $\overline{Nu}_L = .54\ (Gr_L\ Pr)^{1/4}$

$7 \times 10^7 < Gr_L$ use $\overline{Nu}_L = .12\ (Gr_L\ Pr)^{1/3}$

$T_s < T_a$ $3 \times 10^5 < Gr_L < 3 \times 10^{10}$ use $\overline{Nu}_L = .27\ (Gr_L\ Pr)^{1/4}$

Windscreen/Radiator Surface [16]

$T_s > T_r$ $Nu = 1.0$

$T_s < T_r$ $10^4 < Gr_s < 4 \times 10^5$ use $Nu_s = .195\ Gr_s^{1/4}$

$4 \times 10^5 < Gr_s$ use $Nu_s = .068\ Gr_s^{1/3}$

APPENDIX E:

AN ILLUSTRATION OF THE USE OF EFFICIENCY η AND THE DIMENSIONLESS TEMPERATURE DIFFERENCE τ.

The plots of η versus τ shown in the text are useful because, for a given radiator panel, the line of η vs τ is nearly independent of the detailed conditions of the test method. Figures 7 and 8 show the relative insensitivity of the η vs τ curves to air temperature, sky emissivity, and wind speed. A complete theoretical analysis of the utility of η vs τ plots is beyond the scope of this work. However, as an illustration, a simple special case will be further analyzed.

Consider a grey-body radiator plate with emissivity ε_{rad}. Assume that only radiative heat transfers are significant and that the windscreen, if present, is perfectly transparent. Then the net radiative heat transfer from the radiating plate is

$$\begin{aligned} R &= \varepsilon_{rad} \left[\sigma T_{rad}^4 - \varepsilon_{sky}\, \sigma T_{air}^4 \right] \\ &= \varepsilon_{rad}\, \sigma T_{air}^4 \left[\left(\frac{T_{rad}}{T_{air}} \right)^4 - \varepsilon_{sky} \right] . \end{aligned} \tag{E.1}$$

To obtain a form for R which is a linear function of the temperature difference $\Delta T = T_{air} - T_{rad}$ one can expand $(T_{rad}/T_{air})^4$ in a power series in ΔT and substitute it into equation (E.1). Discarding terms quadratic and higher order in ΔT, one has

$$R \cong \varepsilon_{rad}\, \sigma T_{air}^4 \, (1-\varepsilon_{sky}) - 4\varepsilon_{rad}\, \sigma T_{air}^4 \left(\frac{\Delta T}{T_{air}} \right) \tag{E.2}$$

The defining equations for efficiency η and dimensionless temperature difference τ are

$$\eta \equiv \frac{q_{net}}{(1-\varepsilon_{sky})\, \sigma T_{air}^4} \tag{E.3}$$

and

$$\tau \equiv \frac{4\Delta T}{(1-\varepsilon_{sky})\, T_{air}} \tag{E.4}$$

The use of these relations in equation (E.2) yields

$$\eta = \varepsilon_{rad} - \varepsilon_{rad}\, \tau \tag{E.5}$$

This equation has the expected form

$$\eta = a - b\tau \quad ,$$

with a and b constants characteristic of the radiator panel. In the present case $a = b = \varepsilon_{rad}$. In general, of course, a and b are affected by the optical properties of the windscreen, by the selective character of the radiator, and by the non-radiative heat transfer coefficients.

APPENDIX F:

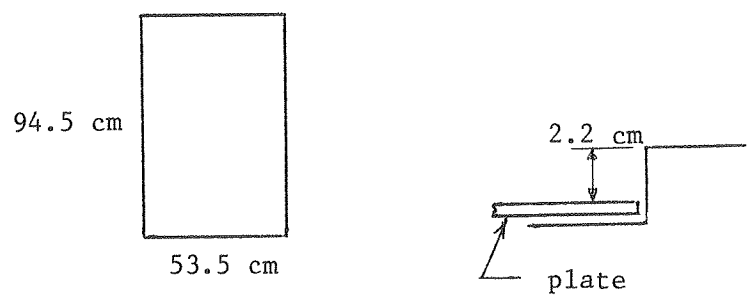
TYPES OF RADIATOR PANELS AVAILABLE FOR TESTING

	Plate Finish	Collimator	Windscreen
No. 1	Type B Tedlar (4 mil)	none	2 mil Polyethylene
No. 2	Type B Tedlar (4 mil)	none	2 mil Polyethylene
No. 3	White Paint	none	2 mil Polyethylene
No. 4	Type B Tedlar (4 mil)	1" Aluminum	2 mil Polyethylene
No. 5	Type B Tedlar (4 mil)	2" Aluminum	2 mil Polyethylene
No. 6	Type S Tedlar (4 mil)	3" Aluminum	2 mil Polyethylene
No. 7	White Paint	3" Aluminized Plastic	2 mil Polyethylene
No. 8	White Paint	3" Aluminized NEMA G	2 mil Polyethylene

APPENDIX G: EFFECTIVE AREA CALCULATION

The plate's exposure to the sky is partially blocked by the side walls of the radiator box. Therefore, an effective area was determined and implemented in the calculations involving the area of the plate. The method employed for determining the effective area is given below.

The shape factor for the view from the plate to the side walls was calculated implementing an equation found in Appendix C (example 12) of Thermal Radiation Heat Transfer [13]. The following dimensions were used.



$F_{p-sw} = .062$

therefore,

$F_{p-sky} = .938$

effective area = $A_{actual} * F_{p-sky}$

$A_{eff} = .474 \ m^2$

APPENDIX H:

TESTING NOTES AND DATA

RADIATIVE COOLING TEST LOG SHEET

	DATE	TIME
START	10/17/80	19.08
STOP	10/18	

TEST CODE NAME RCA1017

POSITIONS USED 1 2 3 4 (5) (6) 7 8

TEST DESCRIPTION:

Cell No. 5 = 4 mil Tedlar type B
Cell No. 6 = white paint
polyethylene wind screens (2 mil)

Test started at a constant power of 150 watts/m² and decreased to 0 W/m² by 15, changing every hour.
New polyethylene windscreens were installed.

TEST PURPOSE: To collect a variety of data points from which the performance of the radiator panels could be measured as a function of temperature difference (between the air and radiator surface).

COMMENTS:

RADIATIVE COOLING TEST LOG SHEET

	DATE	TIME
START	10/18/80	20:30
STOP	10/19	7:30

TEST CODE NAME RCA1018

POSITIONS USED 1 2 3 4 (5) (6) 7 8

TEST DESCRIPTION:

Cell No. 5 = 4mil Tedlar type B
Cell No 6 = white paint
polyethylene windscreens (2 mil)
Test started with a constant power of approximately 125 W/m² and decreased by 15 W/m², changing every hour down to 0 W/m².

TEST PURPOSE: To collect a variety of data points, from which the performance can be measured as a function of temperature difference (between the air and radiator surface).

COMMENTS: Some condensation formed on the windscreen during the test.

RADIATIVE COOLING TEST LOG SHEET

	DATE	TIME
START	10/19/80	20:20
STOP	10/20/80	7:15

TEST CODE NAME RCA1019

POSITIONS USED 1 2 3 4 (5) (6) 7 8

TEST DESCRIPTION:

Cell No. 5 = 4 mil Tedlar type B
Cell No. 6 = white paint
polyethylene windscreens (2 mil)

Test started with a set point temperature of 3 °C and increased to 21 °C by 3 degree increments, changing every hour.

TEST PURPOSE: To collect a variety of data points, from which performance of the radiator panels could be measured as a function of temperature difference (between the air and radiator surface)

COMMENTS: Some condensation formed on the windscreen during the test.

RADIATIVE COOLING TEST LOG SHEET

	DATE	TIME
START	10/26/80	19:20
STOP	10/27	9:30

TEST CODE NAME RCA1026

POSITIONS USED 1 2 3 4 (5) (6) 7 8

TEST DESCRIPTION:

Cell No. 5 = 4 mil Tedlar type B
Cell No. 6 = white paint
polyethylene windscreens (2 mil)

Test started with a constant power of 60 watts/m² and decreased to 0 w/m² by 10 w/m², changing every hour.
A fan is blowing over the radiator panels.

TEST PURPOSE: To see if blowing air over the windscreens of the panels prevents condensation from forming, by elevating the temperature of the windscreen.

COMMENTS: The windscreen of cell 5 did drop below the dew point temperature, but the windscreen temperature of cell 6 did not.

RADIATIVE COOLING TEST LOG SHEET

	DATE	TIME
START	10/27/80	17:50
STOP	10/28	7:45

TEST CODE NAME RCA1027

POSITIONS USED 1 2 3 4 (5) (6) 7 8

TEST DESCRIPTION:

Cell No. 5 = 4 mil Tedlar type B
Cell No. 6 = white paint
polyethylene wind screens (2 mil)

Test started with a constant power of approximately 100 W/m² and decreased to 0 W/m² by 10 W/m² decrements changing every hour.

TEST PURPOSE: To collect a variety of data points, from which the performance of the radiator panels could be measured as a function of temperature difference (between the air and radiator surface).

COMMENTS: This test gave a broad range of data points where the plate was cooler than the air. The procedure implemented in this test is recommended for other tests.

RADIATIVE COOLING TEST LOG SHEET

	DATE	TIME
START	10/28/80	18:40
STOP	10/29/	8:35

TEST CODE NAME RCA1028

POSITIONS USED 1 2 3 4 (5) (6) 7 8

TEST DESCRIPTION:

Cell No. 5 = 4 mil Tedlar type B
Cell No. 6 = white paint.
polyethylene wind screens (2 mil)

Test started at 0 W/m² and increased to approximately 60 W/m² by 10 W/m² increments changing every hour.

TEST PURPOSE: To collect a variety of data points from which the performance of the radiator panels could be measured as a function of temperature difference (between the air and radiator surface).

COMMENTS: Results showed a hysteresis effect when going from 0 to 60 W/m² and then from 60 to 0 W/m²

RADIATIVE COOLING TEST LOG SHEET

	DATE	TIME
START	10/29/80	18:20
STOP	10/30	8:10

TEST CODE NAME RCA1029

POSITIONS USED 1 2 3 4 (5) (6) 7 8

TEST DESCRIPTION:

Cell No. 5 = 4 mil Tedlar type B
Cell No. 6 = white paint
polyethylene windscreens (2 mil)
Test started at a constant power of 0 W/m² and increased to 60 W/m² by 10 W/m² increments changing every hour.

TEST PURPOSE: To collect a variety of data points from which the performance of the radiator panel could be measured as a function of temperature difference (between the air and radiator surface).

COMMENTS:

RADIATIVE COOLING TEST LOG SHEET

	DATE	TIME
START	11/02/80	
STOP	11/03	

TEST CODE NAME RCA1102

POSITIONS USED 1 (2) 3 4 (5) (6) 7 8

TEST DESCRIPTION:

Cell No. 2 = white paint without windscreen
Cell No. 5 = 4 mil Tedlar type B
Cell No. 6 = white paint
polyethylene windscreen

Test tracked the ambient temperature with a zero offset.

TEST PURPOSE: To obtain data to calculate the emissivity of the white paint.

COMMENTS: Only the data for cell 2 was printed out and studied.

RADIATIVE COOLING TEST DATA TABLE

date	time hr mn	ambient temp. °C	dewpoint temp. °C	windscreen temp. °C	ambient-plate temp. °C ΔT	power w/m^2	emissivity ϵ_{sky}	efficiency η	ambient-plate τ
10/17/80	20:00	14.1	4.7		-10.0	158.1	.72	1.46	-.50
"	20:55	14.3	4.3		-8.9	140.0	.72	1.29	-.44
"	22:00	13.6	3.2		-7.3	124.2	.72	1.17	-.36
"	22:55	13.6	2.9		-5.3	110.3	.73	1.07	-.27
10/17	00:10	10.9	8.0	9.1	-4.7	96.6	.73	.97	-.245
"	1:13	10.3	8.2	8.2	-2.8	81.6	.74	.86	-.15
"	2:10	10.2	7.5	5.8	-1	66.0	.73	.69	-.005
"	3:05	9.4	7.2	6.5	1.5	51.5	.74	.55	.082
"	4:10	12.3	4.4		6.6	34.0	.73	.33	.34
"	5:00	10.6	4.6	4.2	9.0	18.4	.725	.18	.46
"	6:10	10.2	5.0	3.5	12.6	.6	.73	.006	.65
"	7:00	9.3	6.0	2.1	6.7	18.4	.74	.196	.36

Test Code RCA 1017
Radiator Type Tedlar 4 mil type B
Channel No. 5

RADIATIVE COOLING TEST DATA TABLE

date	time hr mn	ambient temp. °C	dewpoint temp. °C	windscreen temp. °C	ambient-plate temp. °C ΔT	power w/m^2	emissivity ϵ_{sky}	efficiency η	ambient-plate τ
10/18/80	21:20	11.6	7.9	—	-10.3	126.0	.74	1.30	-.57
"	22:20	13.1	5.3	—	-6.5	109.2	.73	1.06	-.34
"	23:20	12.3	6.8	—	-3.9	95.8	.73	.94	-.202
10/19/80	00:20	10.7	6.9	8.6	-2.5	80.5	.74	.84	-.14
"	1:25	12.1	4.1	7.7	1.3	64.0	.74	.66	.070
"	2:20	10.3	7.4	6.5	2.3	49.6	.74	.52	.12
"	3:20	11.8	4.2	6.3	5.3	33.2	.74	.34	.29
"	4:15	13.2	3.8	5.0	11.0	17.6	.74	.18	.59
"	5:25	13.1	2.9	3.3	14.5	.4	.74	.004	.78
"	6:20	12.0	4.2	4.7	11.0	17.7	.74	.18	.59
"	7:00	12.2	3.3	—	8.8	33.8	.74	.35	.47

Test Code RCA 1018
Radiator Type 4 mil Tedlar type B
Channel No. 5

RADIATIVE COOLING TEST DATA TABLE

date	time hr mn	ambient temp. °C	dewpoint temp. °C	windscreen temp. °C	ambient-plate temp. °C ΔT	power w/m^2	emissivity ϵ_{SKY}	efficiency η	ambient-plate τ
10/19/80	21:10	15.9	5.6	5.7	12.3	9.6	.74	.093	.65
"	22:10	12.0	7.6	6.9	5.8	32.0	.74	.33	.31
"	23:10	14.8	2.6	7.1	5.8	47.4	.74	.47	.31
10/20/80	00:05	12.3	6.0	7.6	.4	70.7	.74	.72	.022
"	1:05	12.7	4.4		-2.2	86.4	.75	.91	-.123
"	2:10	12.9	5.3		-5.1	105.7	.735	1.05	-.27
"	3:15	13.7	5.1		-7.3	121.6	.74	1.22	-.39
"	4:10	13.9	4.4		-4.2	99.5	.745	1.01	-.23
"	5:10	13.6	4.7		-1.4	82.4	.75	.86	-.078
"	6:15	11.8	5.3		-.2	67.4	.75	.72	-.011
"	7:15	12.4	4.8		3.4	51.9	.75	.55	.19

Test Code RCA1019
Radiator Type 4 mil Tedlar type B
Channel No. 5

RADIATIVE COOLING TEST DATA TABLE

date	time hr mn	ambient temp. °C	dewpoint temp. °C	windscreen temp. °C	ambient-plate temp. °C ΔT	power w/m^2	emissivity ϵ_{SKY}	efficiency η	ambient-plate τ
10/26/80	20:30	12.6	5.3	10.5	-4.3	106.3	.73	1.04	-.22
"	21:20	12.2	5.7		-3.9	97.1	.73	.96	-.20
"	22:20	11.8	6.7		-3.2	85.7	.75	.92	-.18
"	23:15	11.9	7.0	9.9	-1.8	74.7	.745	.78	-.1
10/27	00:25	11.8	7.0	9.4	-.1	64.6	.75	.59	-.005
"	1:25	11.3	6.8	8.3	1.75	54.5	.74	.56	.095
"	2:25	11.2	6.9	7.7	3.6	43.9	.74	.46	.19
"	3:25	10.8	7.1	7.1	5.5	32.7	.75	.35	.31
"	4:20	10.6	7.3	6.8	7.6	21.7	.75	.24	.43
"	5:20	10.8	7.3	6.5	9.9	11.8	.75	.13	.56
"	6:20	10.5	6.3	5.5	12.1	.2	.74	.002	.66
"	7:20	10.8	5.8	5.9	10.9	12.0	.74	.13	.56

Test Code RCA1026
Radiator Type 4 mil Tedlar type B
Channel No. 5

RADIATIVE COOLING TEST DATA TABLE

date	time hr mn	ambient temp. °C	dewpoint temp. °C	windscreen temp. °C	ambient-plate temp. °C ΔT	power w/m^2	emissivity ϵ_{sky}	efficiency η	ambient-plate τ
10/27/80	18:40	16.6	6.0		-1.95	101.1	.72	.90	-.096
"	19:40	16.5	4.6		-1.67	94.8	.72	.85	-.082
"	20:35	16.8	2.4		0.4	84.6	.70	.70	.018
"	21:35	17.3	.8		2.9	74.1	.70	.61	.13
"	22:40	17.1	.3		5.3	63.3	.70	.52	.24
"	23:40	16.8	0.0		6.55	54.3	.695	.45	.30
10/28	00:40	16.7	-.7		9.45	43.6	.685	.35	.41
"	1:40	16.8	-1.6		11.8	33.1	.69	.27	.53
"	2:35	16.6	-2.4		14.0	21.5	.69	.17	.62
"	3:35	13.9	1.8		14.2	11.8	.695	.10	.65
"	4:35	13.8	1.75	3.8	17.0	.2	.69	.0017	.76
"	5:40	14.3	-2.2		15.4	11.8	.685	.097	.68
"	6:40	14.4	-2.3		13.65	21.5	.685	.18	.60
"	7:40	14.3	-2.0		11.2	32.4	.68	.26	.49

Test Code RCA 1027
Radiator Type 4 mil Tedlar type B
Channel No. 5

RADIATIVE COOLING TEST DATA TABLE

date	time hr mn	ambient temp. °C	dewpoint temp. °C	windscreen temp. °C	ambient-plate temp. °C ΔT	power w/m^2	emissivity ϵ_{sky}	efficiency η	ambient-plate τ
10/28/80	19:35	17.3	2.7	7.8	16.5	.4	.71	.0034	.78
"	20:25	16.8	1.9	7.9	14.8	12.0	.71	.103	.70
"	21:25	16.7	1.3	7.6	13.6	21.7	.71	.18	.64
"	22:25	16.6	1.4	6.6	11.85	33.1	.70	.28	.55
"	23:30	16.0	1.4	7.7	8.8	43.5	.705	.37	.41
10/29	00:30	15.7	2.0	8.4	6.55	55.2	.71	.48	.31
"	1:15	15.9	1.1	10.1	4.8	64.2	.71	.56	.23
"	2:30	16.7	.9	8.7	6.8	54.6	.70	.45	.31
"	3:20	16.3	.8	7.4	8.55	43.5	.70	.36	.39
"	4:20	13.3	2.3	6.6	8.6	32.6	.71	.29	.41
"	5:30	14.4	1.1	5.0	12.1	21.4	.71	.19	.58
"	6:30	13.8	1.3	4.5	13.8	11.6	.715	.106	.67

Test Code RCA 1028
Radiator Type 4 mil Tedlar type B
Channel No. 5

RADIATIVE COOLING TEST DATA TABLE

date	time hr mn	ambient temp. °C	dewpoint temp. °C	windscreen temp. °C	ambient-plate temp. °C ΔT	power w/m^2	emissivity ϵ_{sky}	efficiency η	ambient-plate τ
10/29/80	19:05	19.3	3.6	12.0	16.25	.4	.715	.0033	.78
"	20:00	19.2	3.5	11.7	14.85	12	.71	.10	.70
"	21:00	18.9	3.8	12.3	13.0	22.1	.72	.19	.64
"	22:00	18.4	3.0	10.3	10.75	33.1	.71	.28	.51
"	23:00	18.1	3.6	9.7	9.05	44.3	.715	.38	.44
10/30	00:00	17.9	3.1	10.5	6.4	54.5	.72	.48	.31
"	0:40	17.7	2.8	10.4	5.3	63.9	.71	.54	.25
"	2:05	16.6	3.2	9.1	5.0	54.1	.73	.51	.26
"	3:10	16.4	2.5	7.9	8.1	44.0	.71	.38	.39
"	4:05	16.4	2.5	6.8	11.1	33.1	.695	.27	.50
"	5:10	15.8	2.3	5.2	13.15	22.2	.70	.19	.61
"	6:05	15.5	2.7	4.2	15.4	12.1	.70	.10	.71
"	7:10	14.2	2.6	5.2	16.3	.2	.71	.0018	.78

Test Code: RCA1029
Radiator Type: 4 mil Tedlar type B
Channel No.: 5

RADIATIVE COOLING TEST DATA TABLE

date	time hr mn	ambient temp. °C	dewpoint temp. °C	windscreen temp. °C	ambient-plate temp. °C ΔT	power w/m^2	emissivity ϵ_{sky}	efficiency η	ambient-plate τ
10/17/80	20:05	14.3	4.3		-8.7	158.9	.72	1.47	-.43
"	21:05	14.2	4.2		-7.7	139.9	.72	1.29	-38
"	22:05	13.4	3.1		-6.3	125.5	.72	1.17	-.314
"	22:55	13.7	3.0		-4.2	110.9	.73	1.02	-.22
10/18	00:05	11.0	7.9		-3.9	97.5	.73	.976	-.203
"	1:10	10.3	8.2	8.2	-2.2	82.4	.75	.90	-.124
"	2:10	10.1	7.5	7.7	.1	66.5	.73	.67	.005
"	3:05	9.4	7.2	6.0	1.4	51.8	.74	.55	.076
"	4:10	12.3	4.4	6.0	6.0	34.0	.72	.32	.30
"	5:05	10.6	4.6	4.2	8.1	18.1	.73	.18	.42
"	6:10	10.1	5.0	3.0	11.2	.2	.73	.002	.59
"	7:10	9.4	5.7	2.6	6.8	18.1	.74	.19	.37

Test Code: RCA1017
Radiator Type: white paint
Channel No.: 6

RADIATIVE COOLING TEST DATA TABLE

date	time hr mn	ambient temp. °C	dewpoint temp. °C	windscreen temp. °C	ambient-plate temp. °C ΔT	power w/m^2	emissivity ϵ_{sky}	efficiency η	ambient-plate τ
10/19/80	21:30	11.6	7.9		-9.2	127.0	.74	1.31	-.50
"	22:30	11.4	6.5		-6.7	109.8	.74	1.14	-.362
"	23:25	12.2	6.9		-3.3	97.2	.73	.96	-.17
10/20	0:22	10.7	6.9		-1.9	81.0	.73	.81	-.099
"	1:20	12.0	4.1		1.6	64.7	.735	.65	.085
"	2:20	10.2	7.4	6.9	2.2	49.8	.73	.50	.12
"	3:20	11.8	4.2	5.7	4.9	33.3	.73	.33	.25
"	4:25	13.5	3.3	4.9	10.6	17.5	.73	.17	.55
"	5:20	13.2	3.0	3.3	13.2	.2	.74	.002	.71
"	6:30	13.0	4.15	5.3	9.9	17.6	.75	.19	.55
"	7:30	13.0	4.0	6.3	8.1	33.4	.74	.34	.44

Test Code RCA 1018
Radiator Type white paint
Channel No. 6

RADIATIVE COOLING TEST DATA TABLE

date	time hr mn	ambient temp. °C	dewpoint temp. °C	windscreen temp. °C	ambient-plate temp. °C ΔT	power w/m^2	emissivity ϵ_{sky}	efficiency η	ambient-plate τ
10/19/80	21:10	16.0	5.6	5.5	11.0	1.3	.735	.012	.57
"	22:10	11.95	7.6	6.5	5.9	24.2	.745	.25	.32
"	23:00	14.5	3.1		5.7	42.0	.75	.43	.32
10/20	00:00	12.2	6.1		.3	69.6	.745	.73	.016
"	1:10	12.7	4.3		-2.3	89.6	.74	.91	-.12
"	2:11	12.9	5.3		-5.0	112.3	.743	1.15	-.27
"	3:11	13.7	5.2		-7.3	129.9	.74	1.3	-.39
"	4:10	14.0	4.4		-4.1	106.3	.74	1.06	-.22
"	5:10	13.6	4.7		-1.4	86.9	.745	.89	-.077
"	6:10	11.8	5.3		-2	70.2	.76	.78	-.012
"	7:10	12.8	4.7		3.9	49.9	.75	.52	.22

Test Code RCA 1019
Radiator Type white paint
Channel No. 6

RADIATIVE COOLING TEST DATA TABLE

date	time hr mn	ambient temp. °C	dewpoint temp. °C	windscreen temp. °C	ambient-plate temp. °C ΔT	power w/m²	emissivity ϵ_{sky}	efficiency η	ambient-plate τ
10/26/80	20:25	12.6	5.3		-3.0	107.5	.73	1.05	-.16
"	21:15	12.3	5.6		-3.1	97.9	.73	.96	-.16
"	22:30	11.8	6.8		-2.7	86.4	.75	.92	-.15
"	23:25	11.8	7.2		-1.3	75.5	.74	.78	-.07
10/27	00:20	11.9	7.0		.23	64.8	.757	.71	.013
"	1:20	11.5	6.8		1.85	54.5	.74	.56	.10
"	2:25	11.2	7.0	9.0	3.4	44.1	.74	.46	.18
"	3:20	11.0	7.0	8.7	5.0	32.7	.75	.35	.28
"	4:20	10.6	7.3	8.2	6.7	21.6	.74	.23	.36
"	5:20	10.8	7.3	8.0	8.7	11.7	.745	.124	.48
"	6:20	10.6	6.3	7.3	10.7	0.0	.74	0	.58
"	7:30	10.5	5.8	7.3	9.0	11.8	.74	.124	.49

Test Code RCA1026
Radiator Type white paint
Channel No. 6

RADIATIVE COOLING TEST DATA TABLE

date	time hr mn	ambient temp. °C	dewpoint temp. °C	windscreen temp. °C	ambient-plate temp. °C ΔT	power w/m²	emissivity ϵ_{sky}	efficiency η	ambient-plate τ
10/27/80	18:40	16.7	5.0		-1.4	104.6	.725	.95	-.07
"	19:40	16.5	4.6		-1.0	96.9	.72	.87	-.049
"	20:40	16.9	2.2		1.1	86.3	.70	.72	.051
"	21:40	17.2	0.8		3.2	75.2	.70	.62	.15
"	22:40	17.1	.2		5.15	64.4	.70	.53	.24
"	23:40	16.4	.05		6.0	55.2	.70	.46	.28
10/28/80	00:40	16.7	-.7		8.6	44.1	.69	.36	.38
"	1:40	16.9	-1.6		10.55	33.4	.69	.27	.47
"	2:35	16.55	-2.4		12.45	21.7	.69	.18	.55
"	3:35	13.95	1.8		12.6	11.8	.695	.10	.58
"	4:30	13.8	1.0		14.7	0.0	.69	0.0	.66
"	5:40	14.3	-2.2		13.6	11.7	.68	.094	.56
"	6:35	14.5	-2.4		12.1	21.7	.68	.17	.53

Test Code RCA1027
Radiator Type white paint
Channel No. 6

RADIATIVE COOLING TEST DATA TABLE

date	time hr mn	ambient temp. °C	dewpoint temp. °C	windscreen temp. °C	ambient-plate temp. °C ΔT	power w/m²	emissivity ε sky	efficiency η	ambient-plate τ
10/28/80	19:30	17.3	2.8	9.3	14.8	.1	.71	.00085	.70
"	20:25	16.9	1.9	9.4	13.1	11.8	.71	.10	.62
"	21:30	16.75	1.4	8.4	12.3	21.7	.705	.19	.58
"	22:20	16.7	1.3	7.6	11.0	32.6	.70	.27	.51
"	23:30	16.0	1.4	8.8	8.0	43.8	.71	.38	.38
10/29	00:30	15.7	2.0	9.6	6.2	55.3	.72	.50	.31
"	1:20	16.2	1.1	11.8	4.7	64.3	.715	.57	.23
"	2:20	16.6	1.1	9.7	6.0	54.4	.71	.47	.29
"	3:30	15.1	.7	7.7	7.2	43.7	.70	.37	.33
"	4:20	13.3	2.3	6.9	7.9	32.7	.71	.30	.38
"	5:30	14.4	1.1	6.0	10.95	21.4	.715	.19	.53
"	6:30	13.75	1.3	5.7	12.3	11.4	.715	.104	.60
"	7:30	14.0	1.8	6.0	14.2	0.0	.72	0.0	.71

Test Code RCA 1028
Radiator Type white paint
Channel No. 6

RADIATIVE COOLING TEST DATA TABLE

date	time hr mn	ambient temp. °C	dewpoint temp. °C	windscreen temp. °C	ambient-plate temp. °C ΔT	power w/m²	emissivity ε sky	efficiency η	ambient-plate τ
10/29/80	19:05	19.3	3.5	13.8	14.5	.2	.72	.0017	.71
"	20:00	19.2	3.4	13.4	13.0	11.9	.72	.13	.68
"	21:05	18.8	3.8	14.0	11.45	21.9	.72	.19	.56
"	21:50	18.8	3.1	13.2	9.9	33.1	.71	.28	.47
"	23:00	17.8	3.6	10.7	8.0	43.9	.71	.37	.38
"	23:50	17.9	3.3	11.0	6.1	55.2	.72	.484	.30
10/30	1:00	17.8	2.8	11.5	5.2	64.3	.71	.55	.25
"	2:05	16.6	3.2	10.1	4.55	54.3	.725	.50	.23
"	3:05	16.4	2.5	8.7	7.55	44.1	.71	.38	.36
"	4:05	16.4	2.5	8.1	10.1	33.0	.70	.28	.47
"	5:10	15.8	2.3	6.1	11.95	21.9	.70	.18	.55
"	6:05	15.6	2.5	5.8	13.7	11.9	.70	.10	.63
"	7:05	14.15	2.5	6.2	14.2	0.0	.71	0.0	.68

Test Code RCA 1029
Radiator Type white paint
Channel No. 6

APPENDIX I: CALCULATION OF WHITE PAINT EMISSIVITY

The emissivity of the white paint was determined by performing an experiment which held the radiator surface equal to the air temperature. Due to deficencies in the temperature control system and changing environmental conditions, there were only two times during the test when the air temperature, plate temperature, and power were steady. The data points are shown on the following page. The values in each time interval were averaged and the white paint emissivity was calculated implementing the equation below.

$$\epsilon_{w.p.} = \frac{R}{(1-\epsilon_{sky})\,\sigma\, T_{air}^{4}}$$

$\epsilon_{WP} = .91$ (time 1)

$\epsilon_{WP} = .89$ (time 2)

Test Code RCA 1102

Radiator Type white paint (w.o. windscreen)

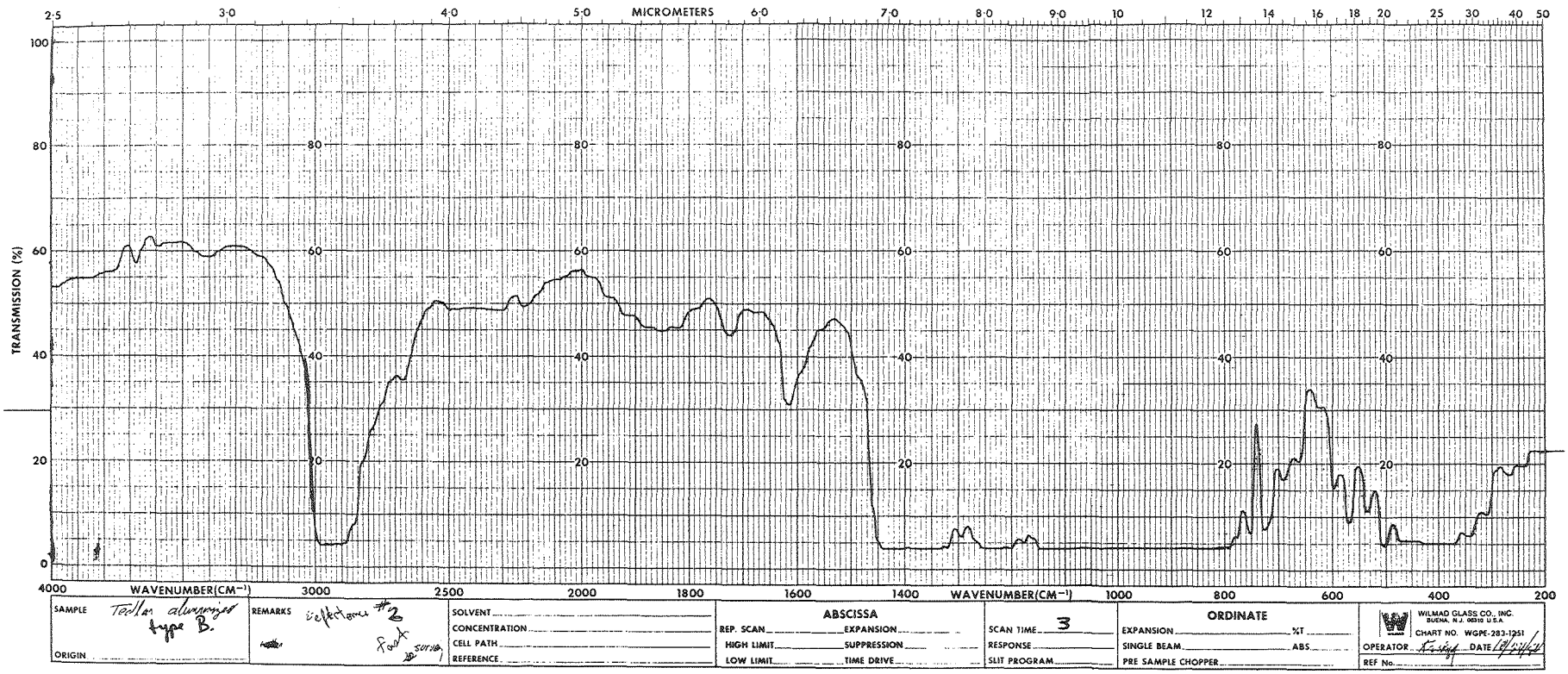
Channel No. 2

RADIATIVE COOLING TEST DATA SHEET

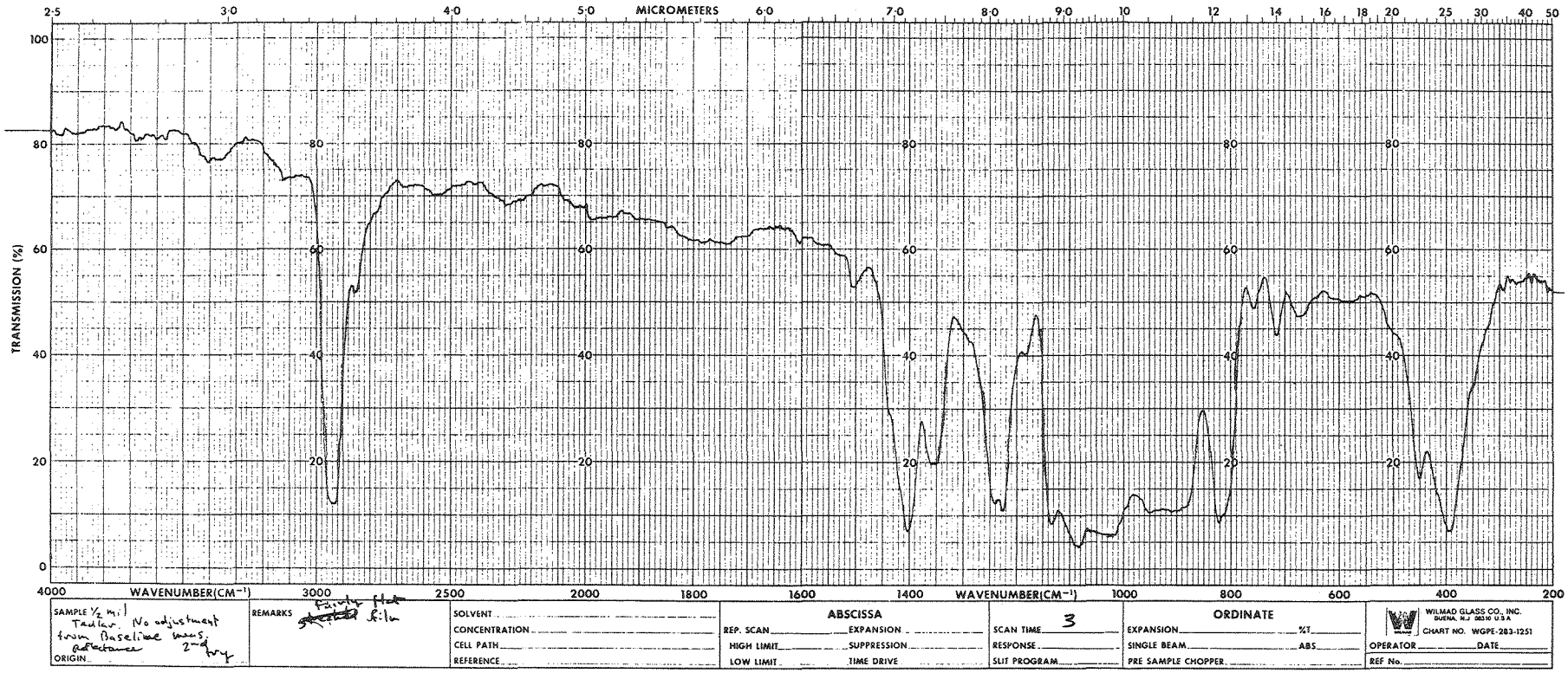
date	time hr mn	ambient temp. C	dewpoint temp. C	windscreen temp. C	ambient-plate temp. C ΔT	power w/m*m	emissivity ϵ_{sky}	efficiency	ambient-plate dimensionless	
11/3/86										
"	2:10	16.3	11.3		0.1	79.7	.78			time 1
"	2:15	16.3	11.3		0.0	81.4	.78			
"	2:20	16.2	11.3		0.0	78.5	.78			
"	2:25	16.3	11.3		0.1	78.5	.78			
11/3/86										
"	3:30	14.0	11.3		-0.1	74.9	.78			time 2
"	3:35	14.3	11.3		-0.1	74.9	.78			
"	3:40	14.3	11.1		0.1	78.5	.78			
"	3:46	14.2	11.0		0.1	75.7	.78			

APPENDIX J:

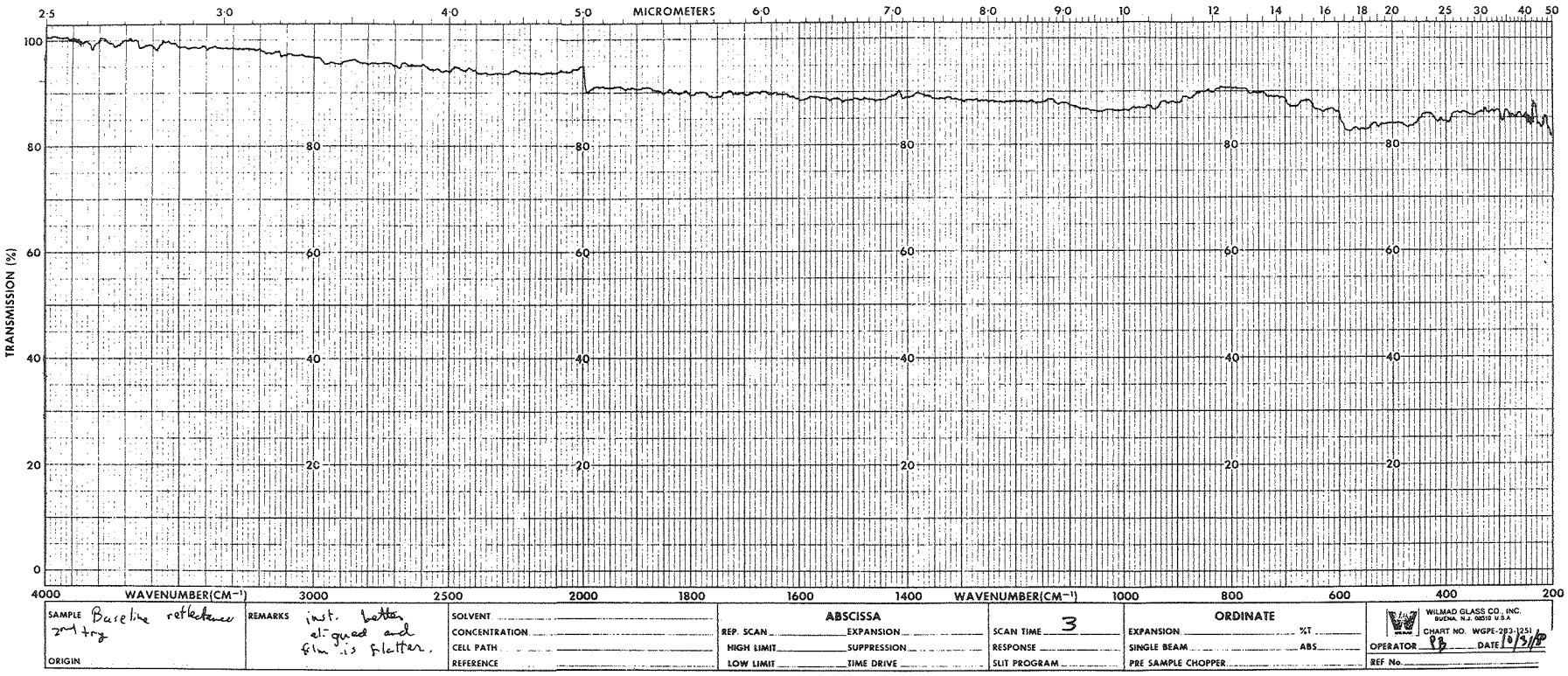
SELECTED SPECTRAL MEASUREMENTS



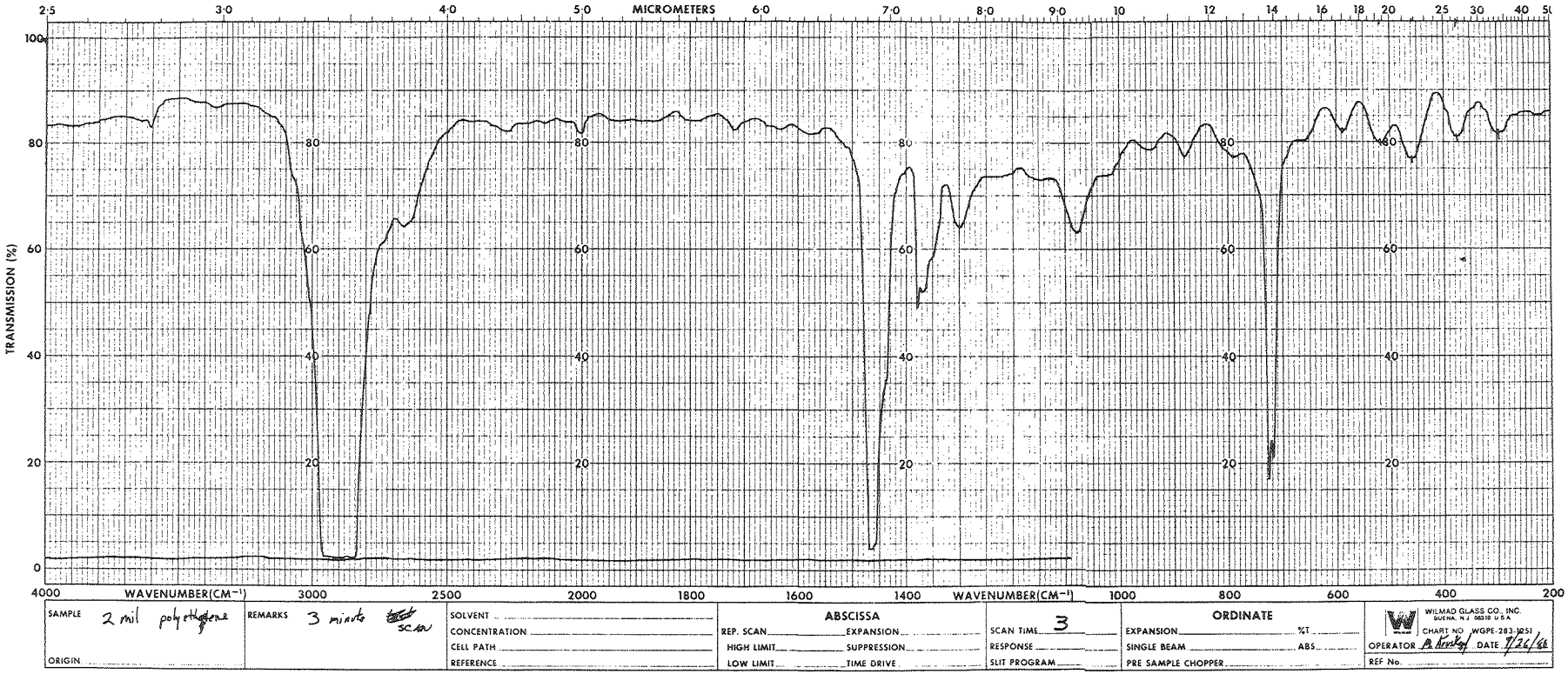
Reflectance measurement of 4 mil polyvinyl fluoride, aluminized on backside.



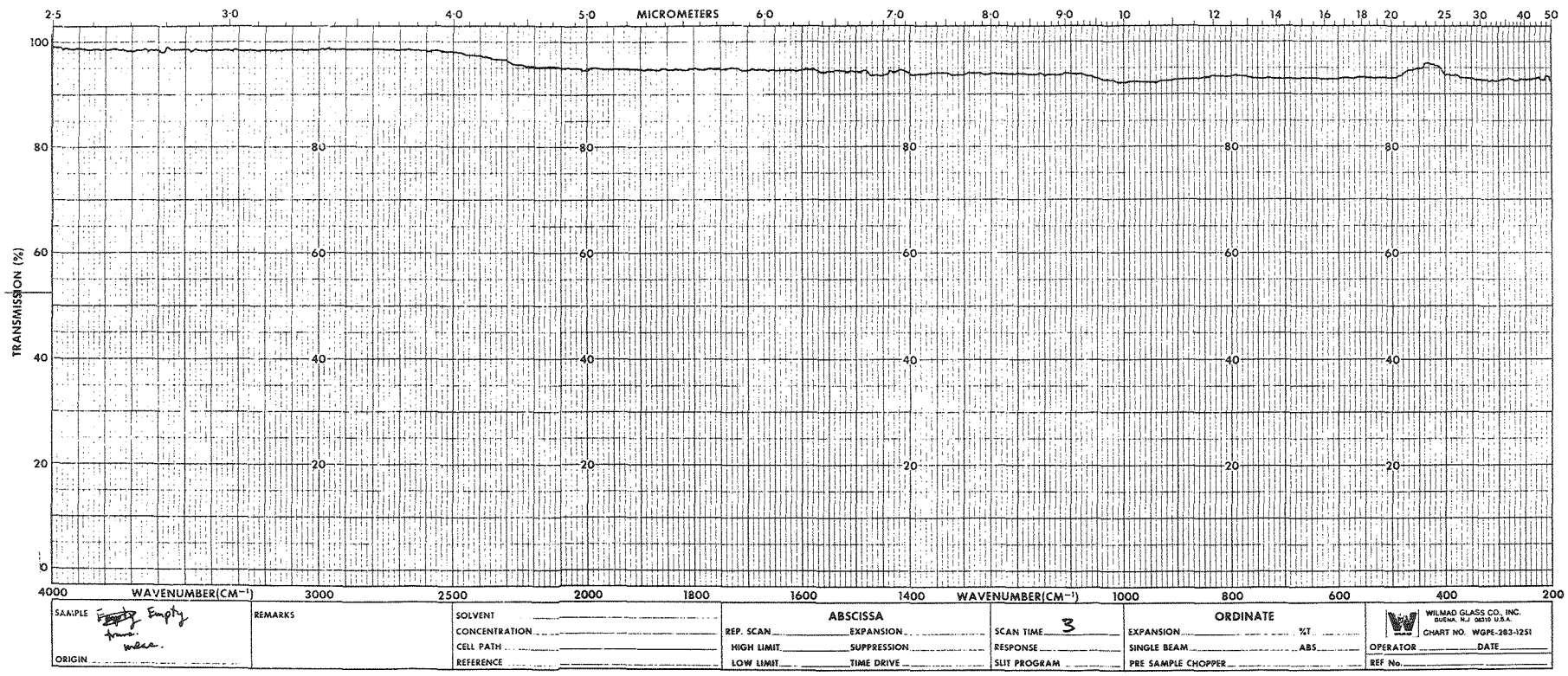
Reflectance measurement of 1/2 mil polyvinyl fluoride, aluminized on backside.



Baseline reflectance for measurement of 1/2 mil polyvinyl fluoride. (Reflectance of a freshly evaporated aluminum film ≅ 100%).



Transmission measurement of 2 mil polyethylene.



Transmission measurement with test chamber empty.

WIND SPEED DATA *

testcode	PM						AM							
	6	7	8	9	10	11	12	1	2	3	4	5	6	7
RCA1026	2	4	4	4	4	3	0	2	0	2	3	5	4	4
RCA1027	2	3	5	2	2	2	1	2	3	1	4	10	24	30
RCA1028	1	2	1	1	0	2	1	3	0	0	1	0	1	1
RCA1029	6	6	6	6	2	1	0	0	1	1	0	0	0	1
RCA1025	3	2	2	2	2	2	1	2	1	2	1	2	1	2

* Measurements were taken from the roof of Building 70. Speed in miles per hour.

FIGURES

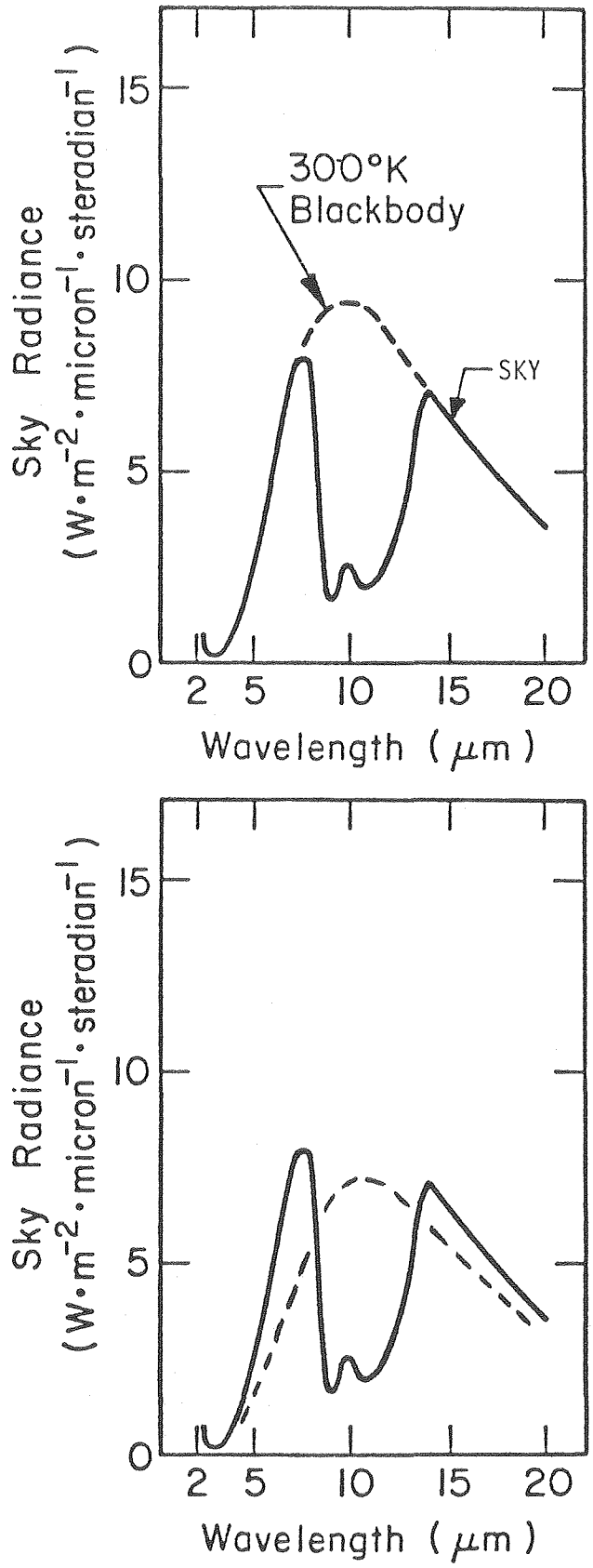


Fig.1. Spectral radiance of the clear zenith sky compared with (a) the radiance of a 300°K blackbody, and (b) a cooler black body.

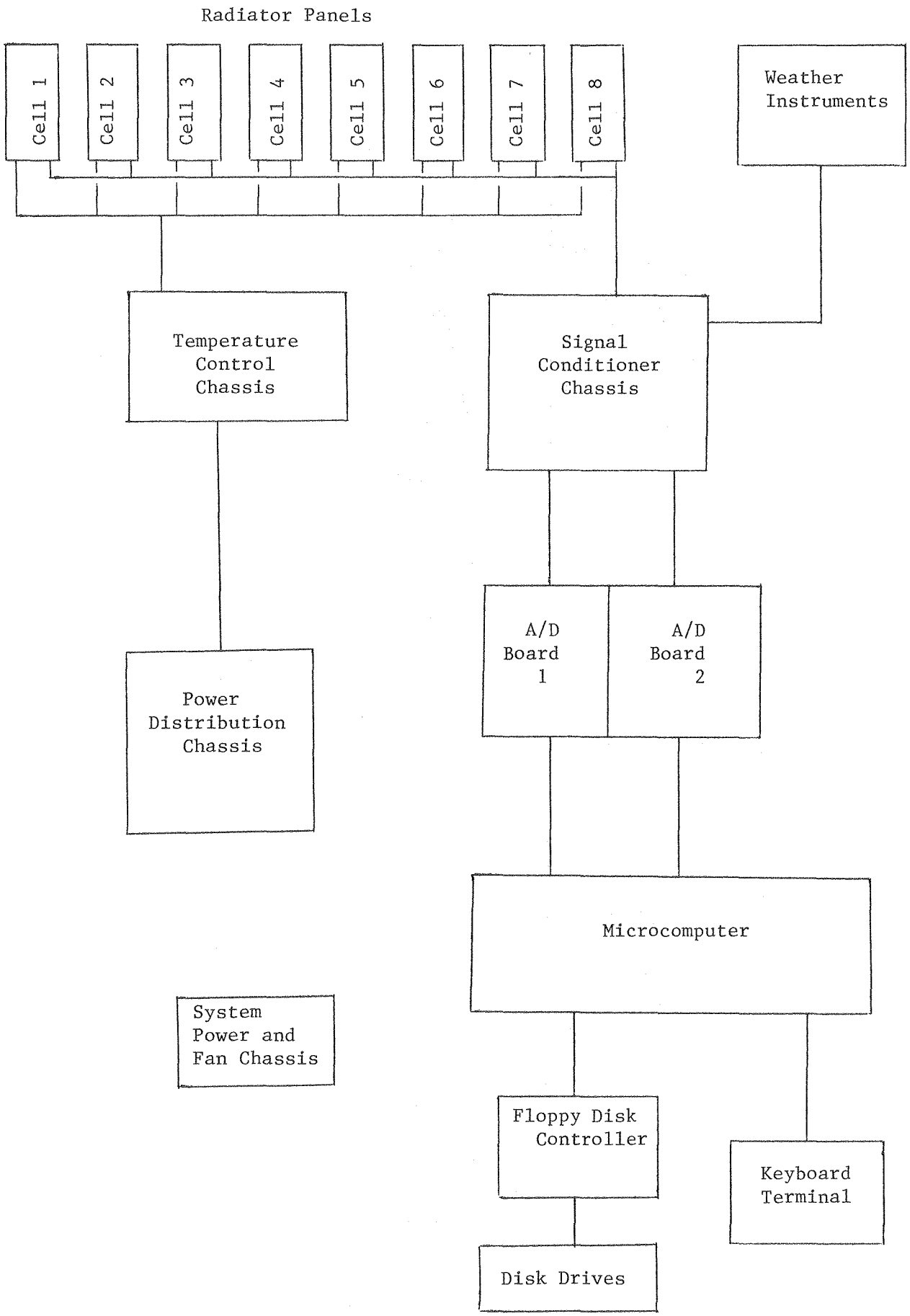


figure 2. Radiator Test Facility Block Diagram

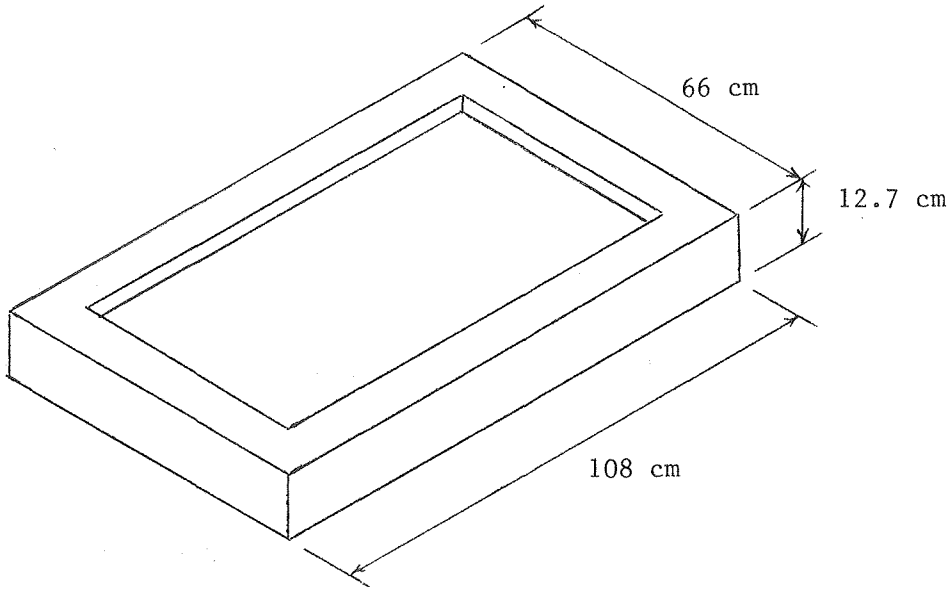


figure 3. Radiator Panel

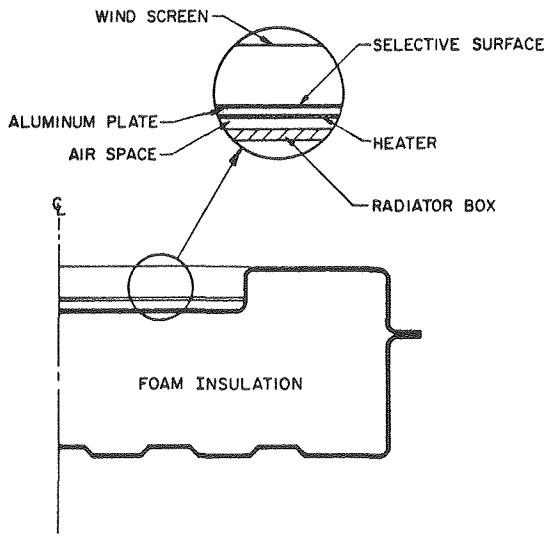
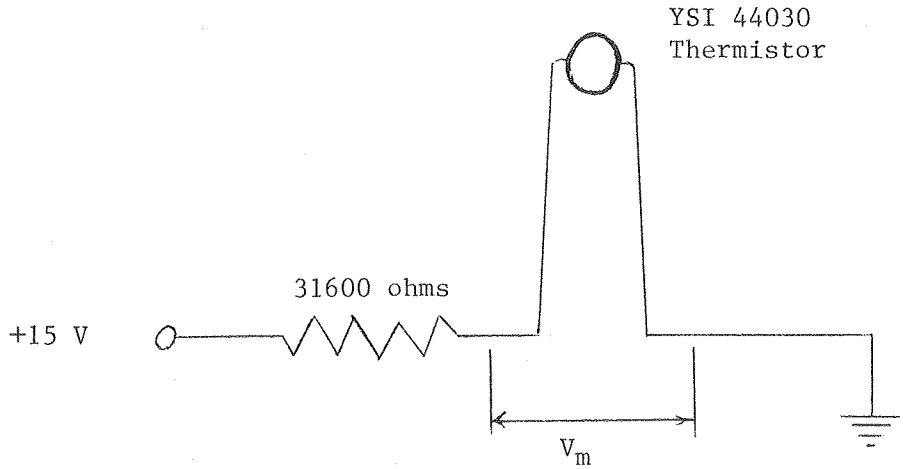
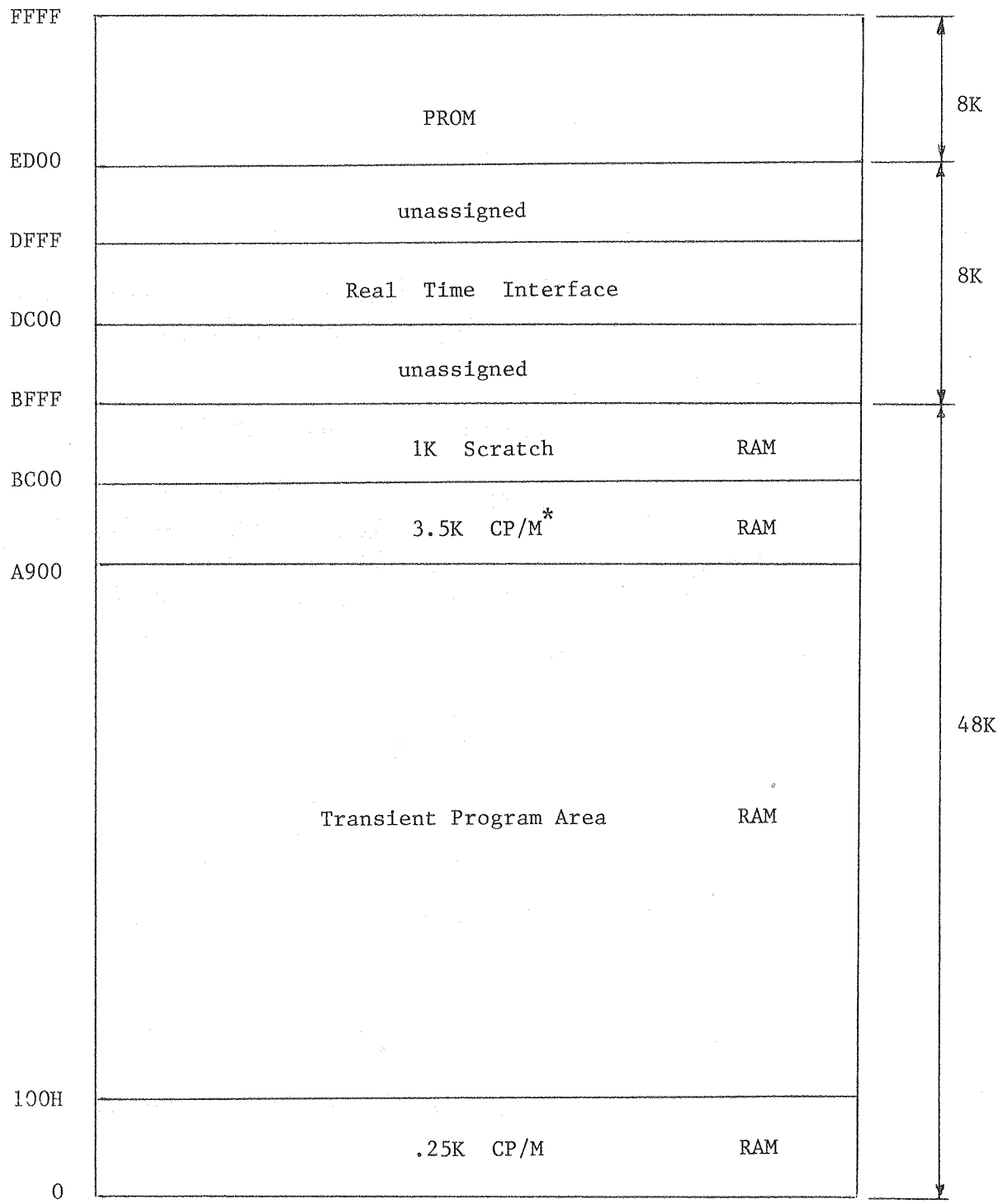


figure 4. Radiator assembly showing insulating box, radiator, and windscreen.



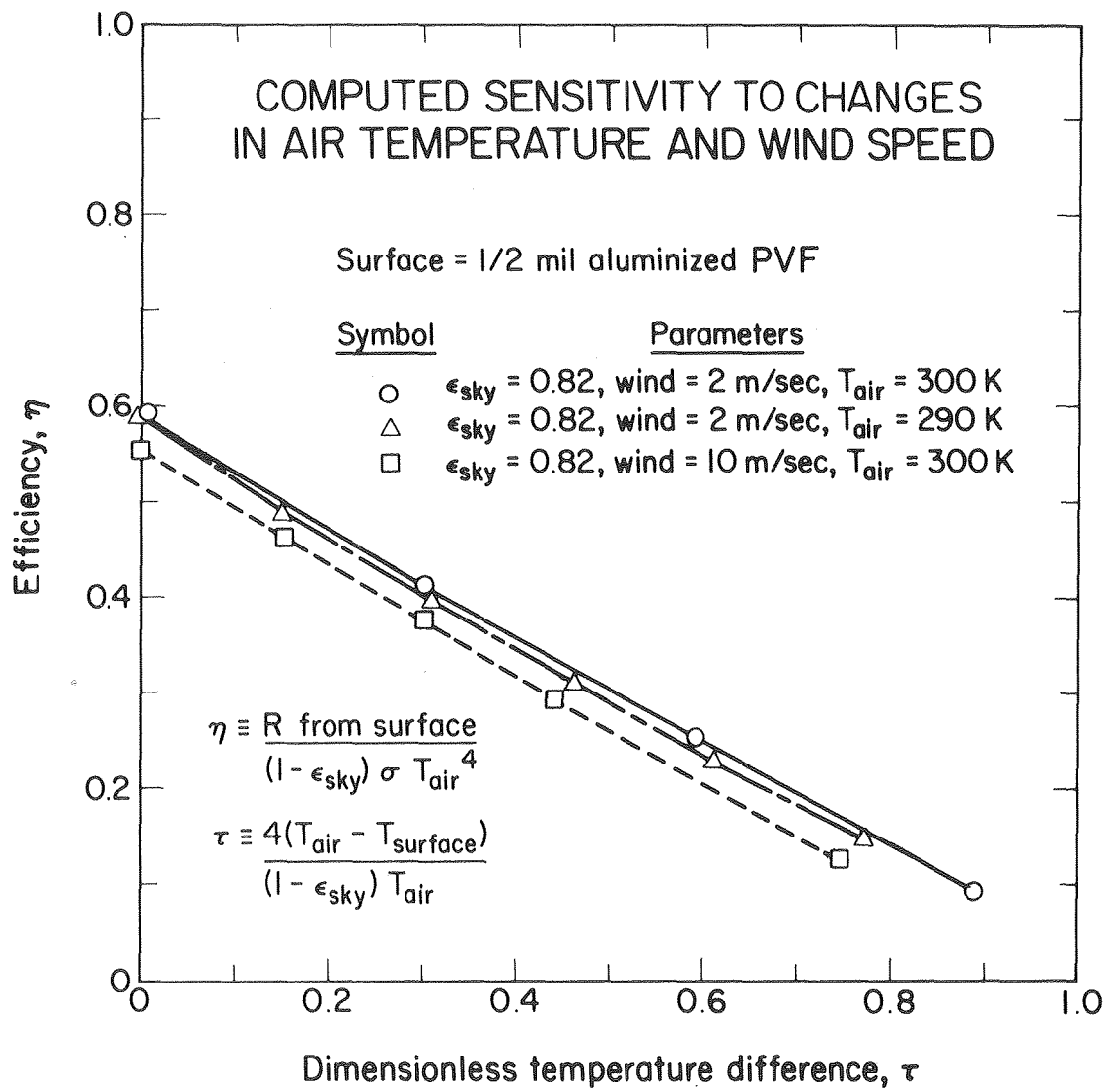
V_m= voltage read by microcomputer

figure 5. Thermistor Circuit



* Control Program For Microcomputers

figure 6. Computer Memory Map



XBL 8012-2538

Fig.7. Computed efficiency curves showing the sensitivity to changes in the wind speed and ambient air temperature.

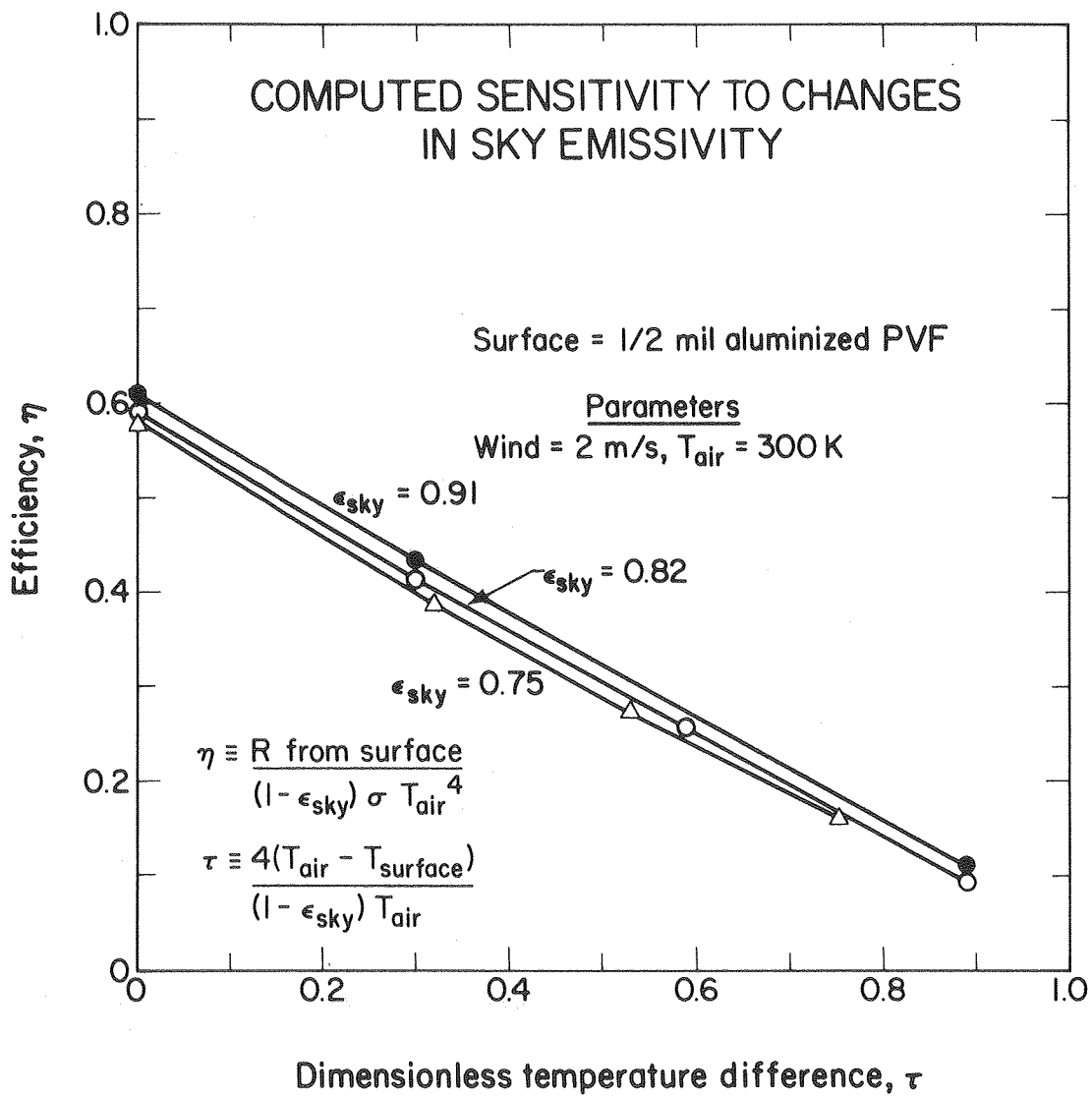
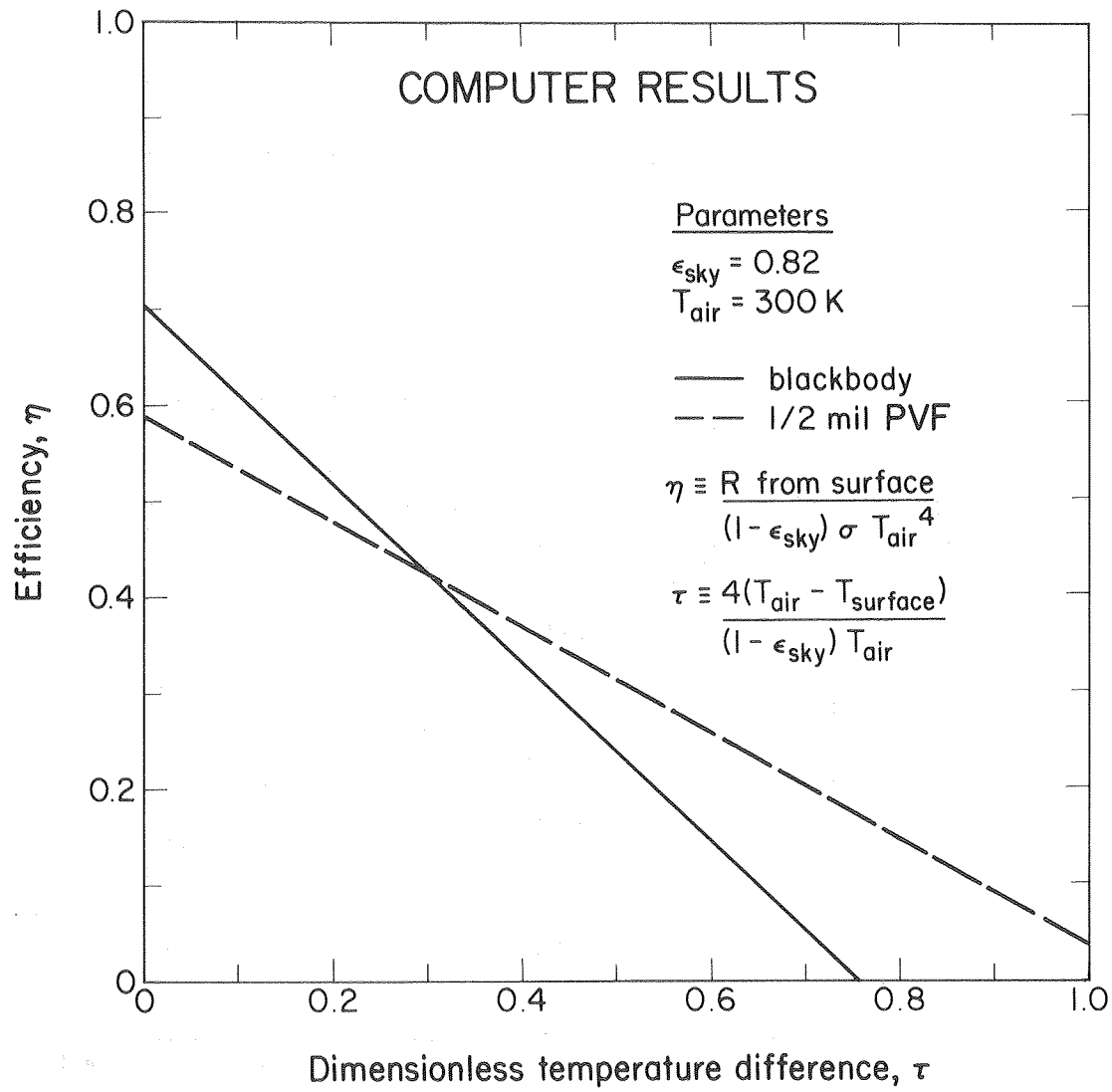
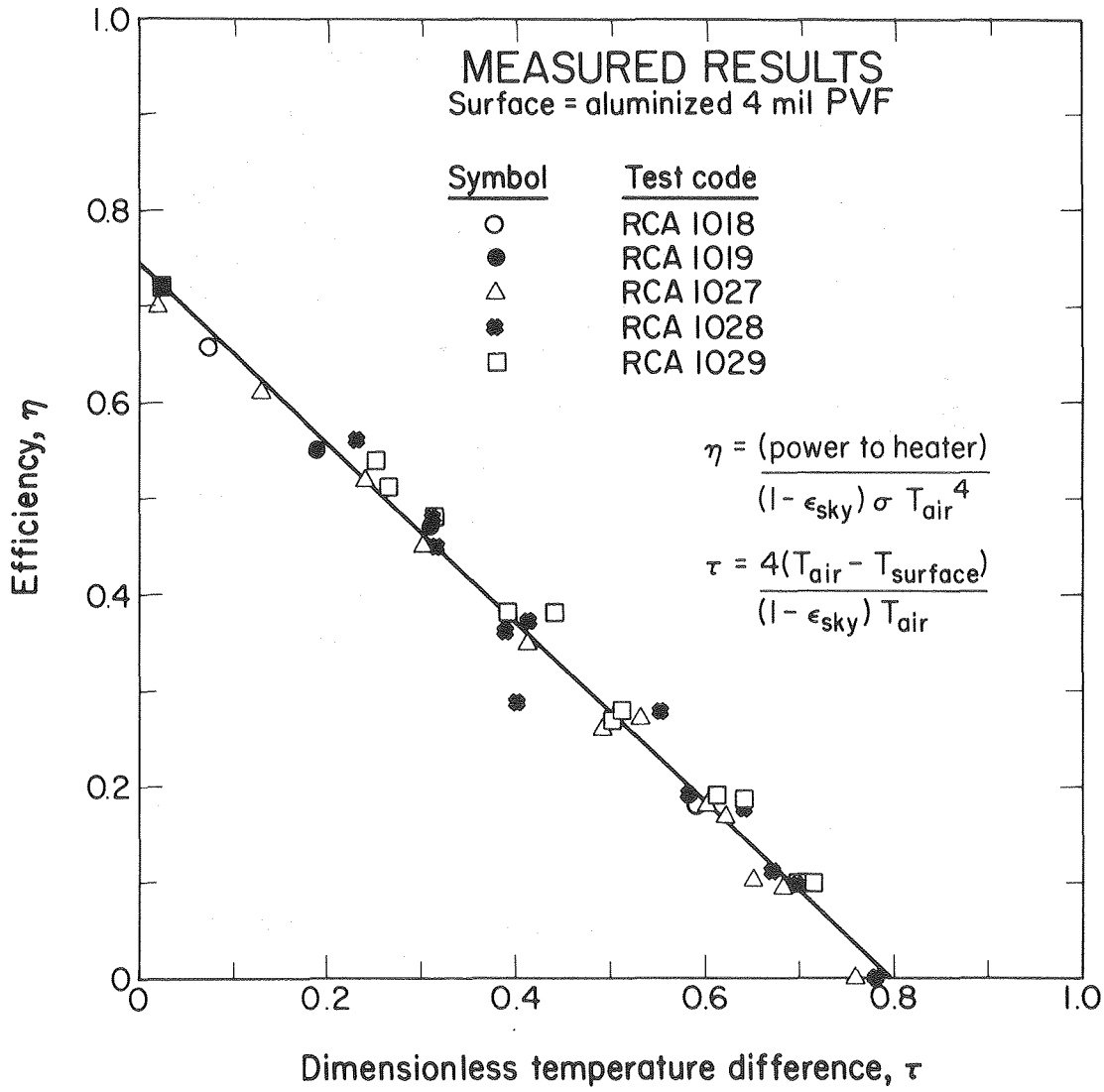


Fig.8. Computed efficiency curves showing the sensitivity to changes in sky emissivity.



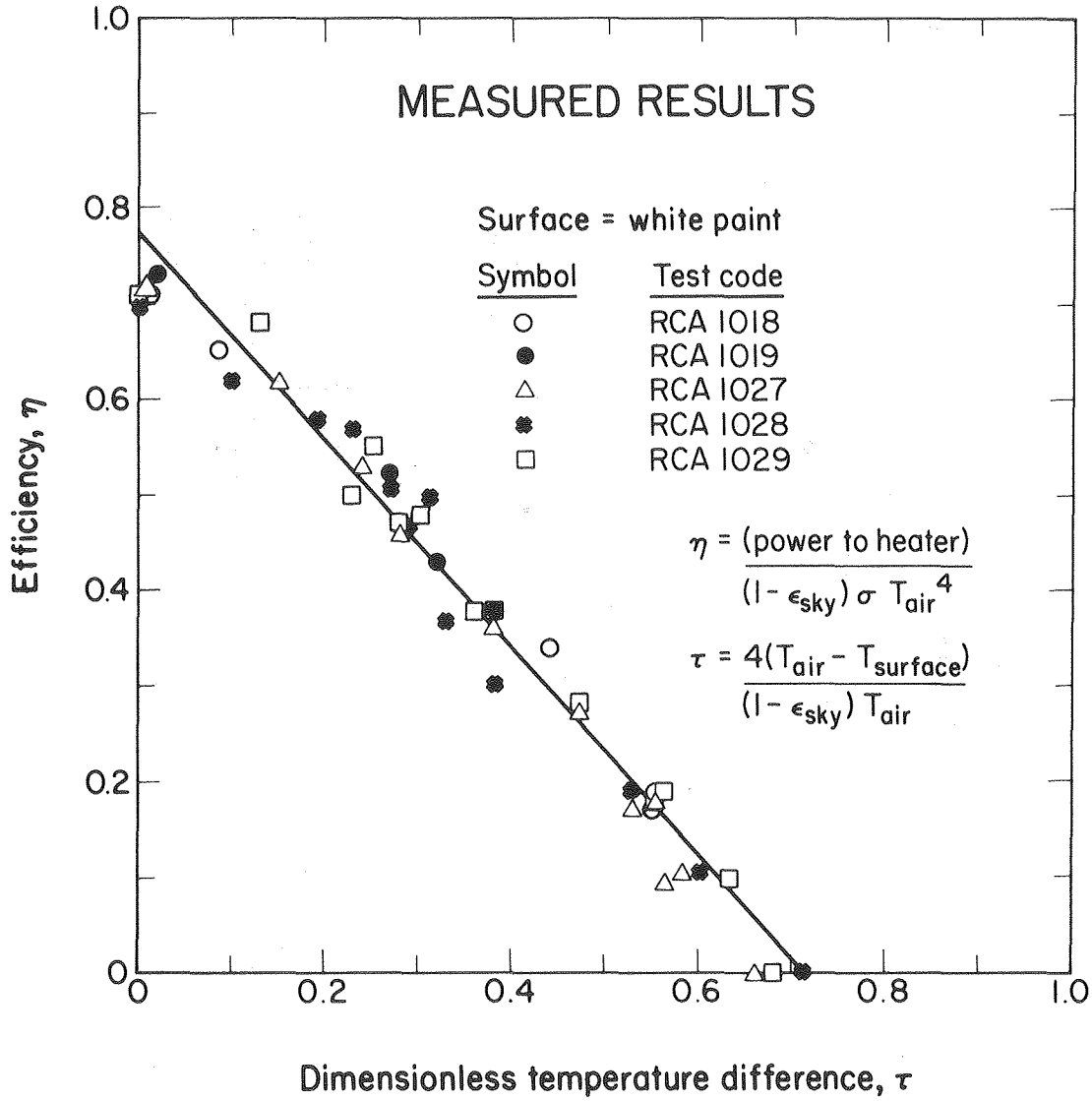
XBL 8012-2546

Fig.9. Computed results for selective and non-selective (blackbody) radiators.



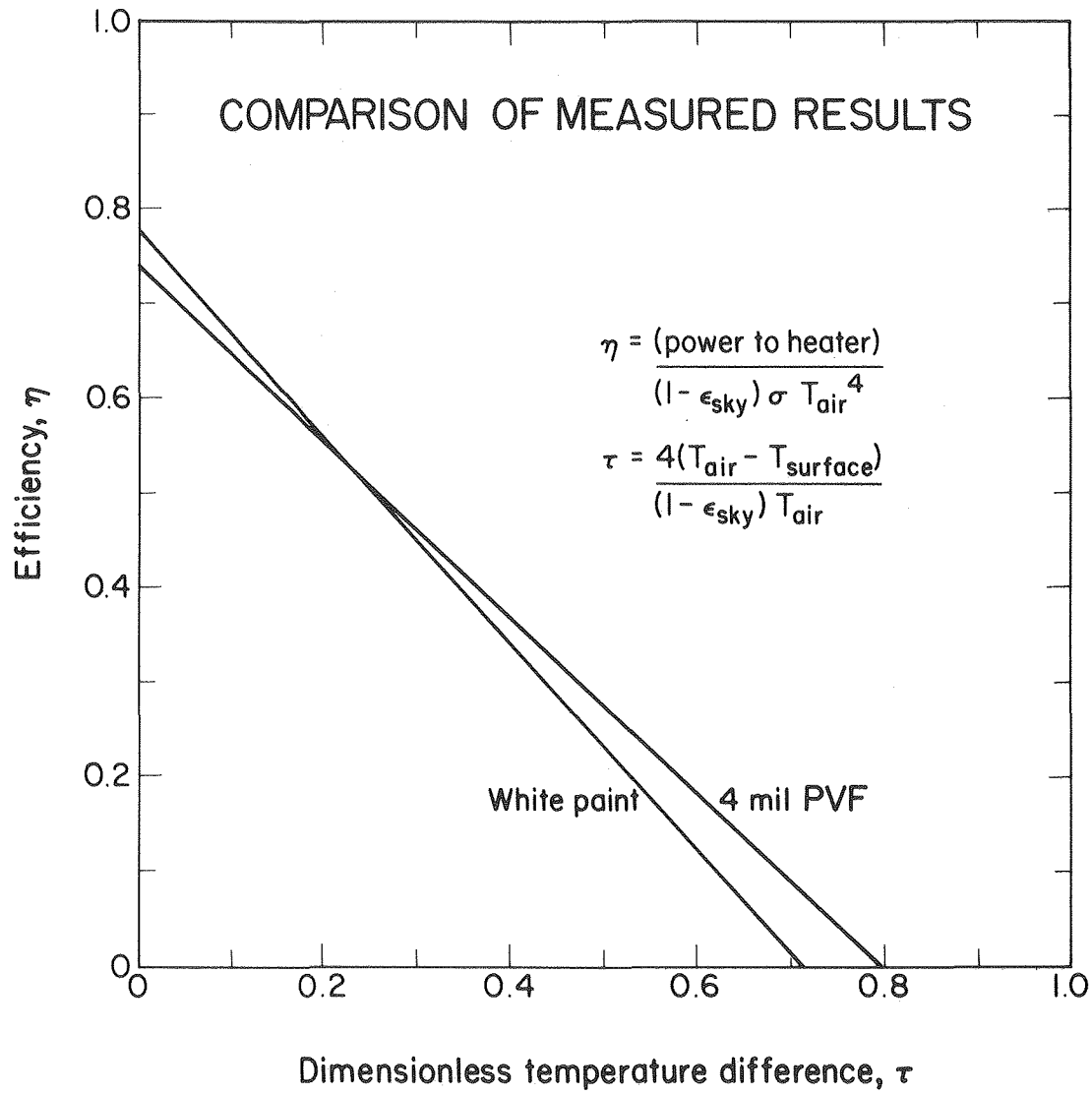
XBL 8012-2542

Fig.10. Measured performance results for a 4 mil aluminized PVF radiator with a polyethylene windscreen. The solid line is a least squares fit.



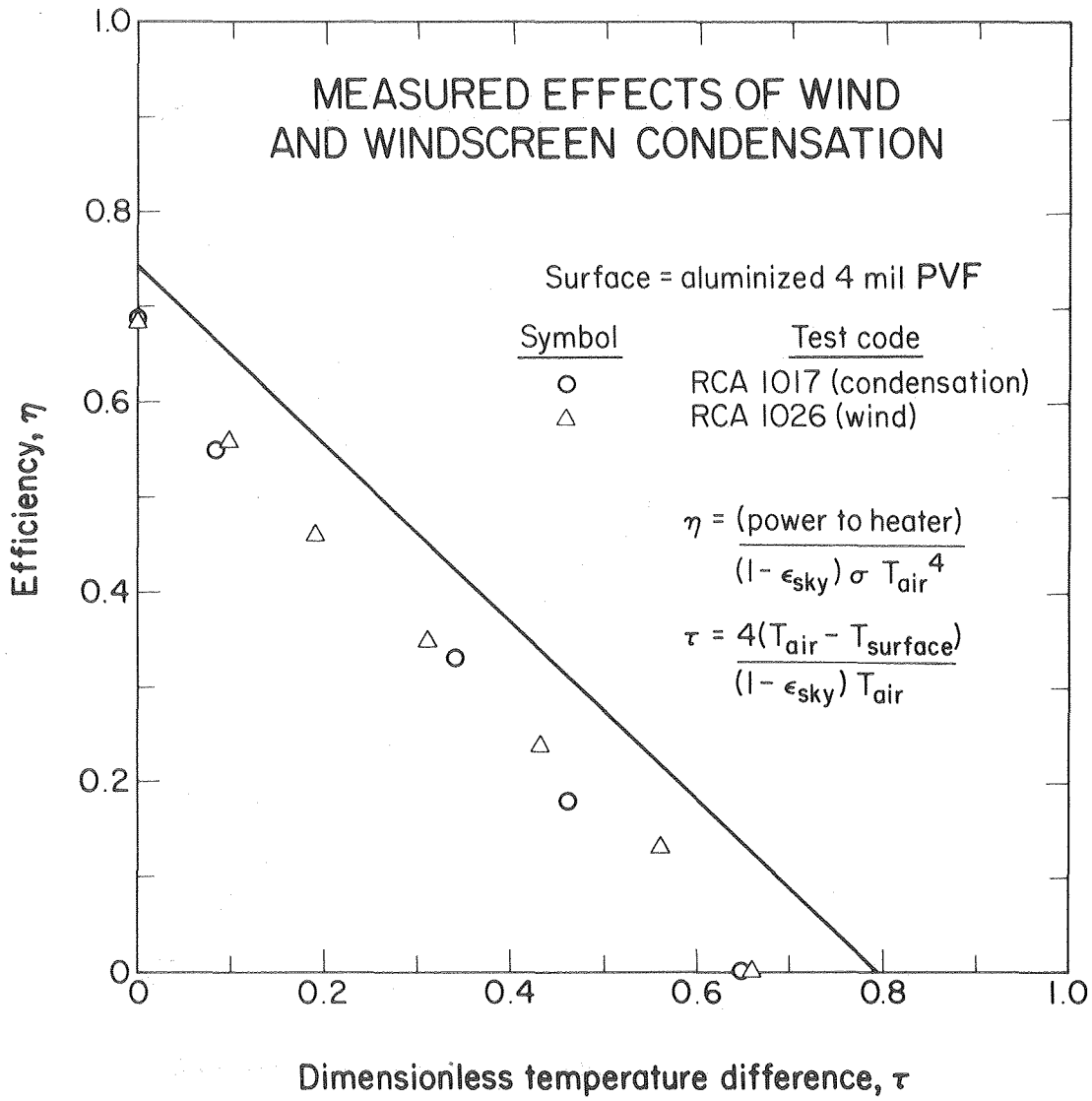
XBL 8012-2543

Fig. 11. Measured performance results for a white painted radiator with a polyethylene windscreen. The solid line is a least squares fit.



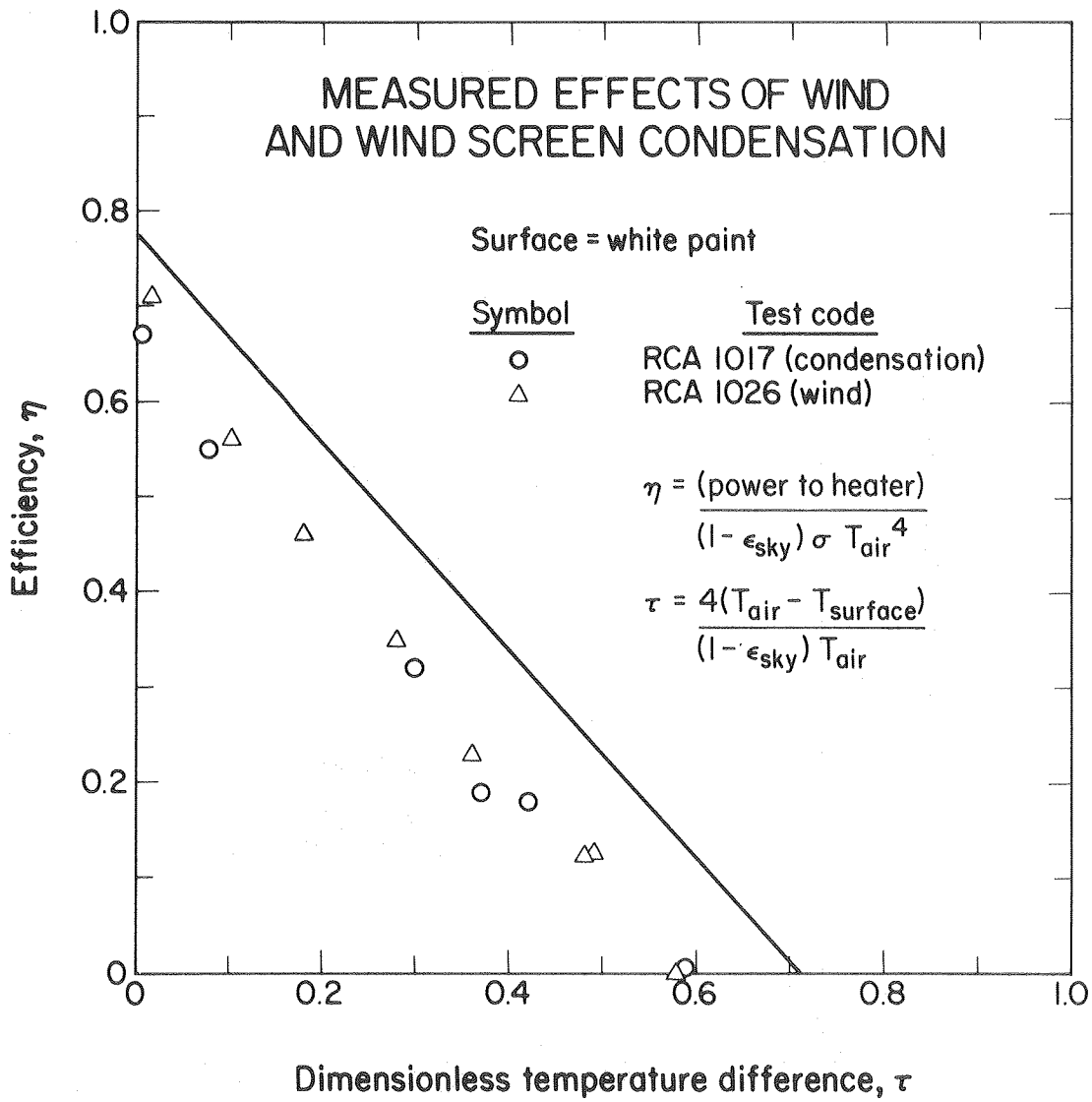
XBL 8012-2541

Fig.12. Comparison of the measured performance of the white paint and PVF radiators.



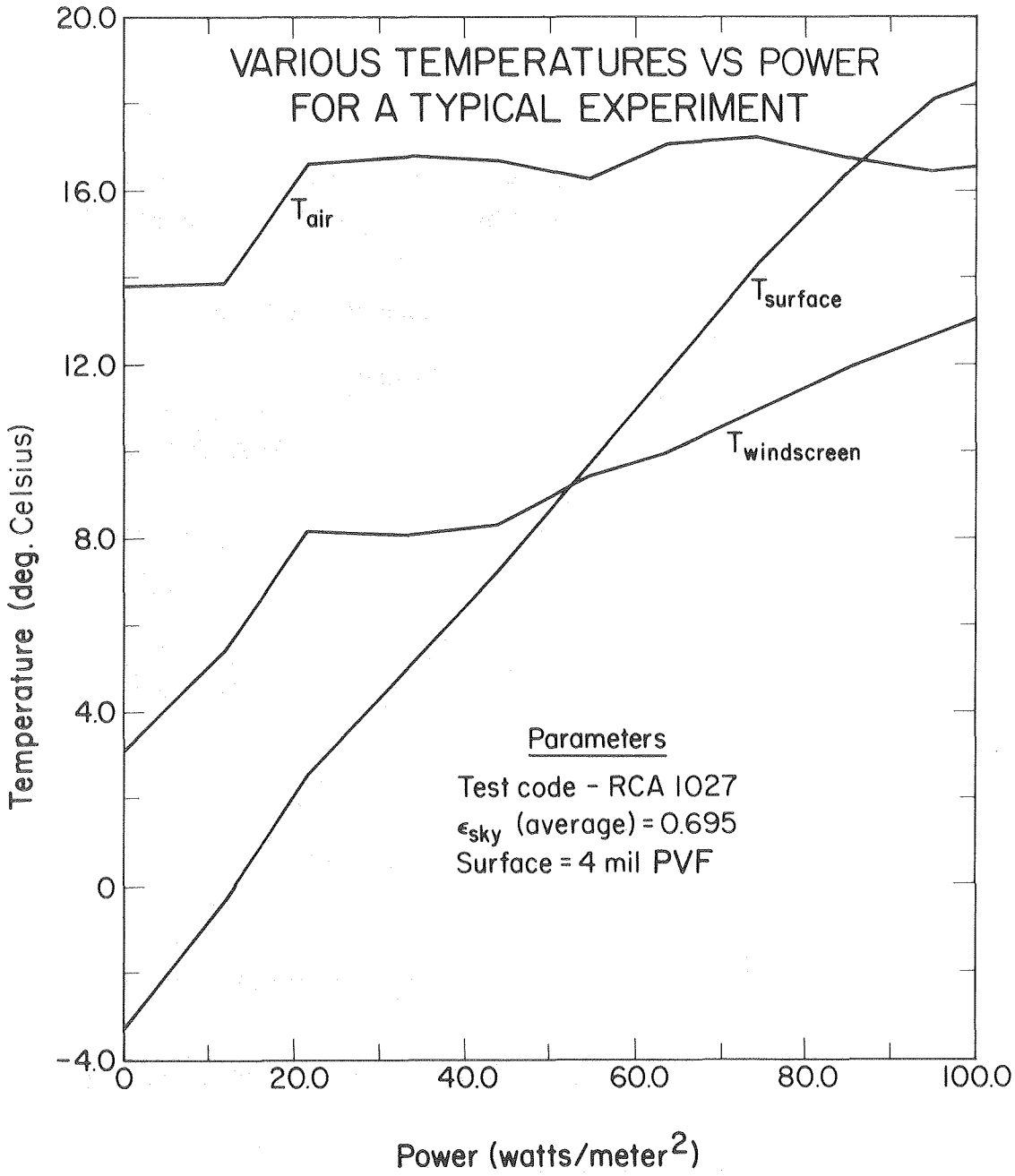
XBL 8012-2544

Fig.13. The detrimental effects of wind and windscreen condensation (PVF radiator).



XBL 8012-2545

Fig.14. The detrimental effects of wind and windscreen condensation (white paint radiator).



XBL 8012-2539

Fig.15. Various temperatures versus radiated cooling power. For small values of cooling power the radiator surface is the coldest portion of the system. For larger values of cooling power the radiator surface is warmer than the windscreen temperature.