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Final Report

SOME HEAT TRANSFER CHARACTERISTICS OF TWO THERMOCOUPLE PROBES

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ABSTRACT

A thermocouple probe with flat-plate radiation shields was tested in a wind tunnel to determine steady-state radiation errors for small solar elevation angles. The probe had been used in the U. S. Army Quartermaster Research and Engineering Command micrometeorological investigation in the Antarctic. Test data are given for various radiation intensities and angles of incidence and for various wind speeds and directions. Data are interpolated from these results to provide corrections for temperature profiles measured at the Scott-Amundson South Pole Station. A second probe, without a shield, was compared with shield probes when mounted over a snow surface in northern Michigan during a winter night. The experimental results are discussed and test equipment and procedures are described.

1. INTRODUCTION

Accurate measurement of air temperature with thermocouple probes in the atmospheric surface layer is dependent upon both wind and thermal radiation conditions. In the presence of solar radiation, when the wind is light, the probes are likely to be in thermal equilibrium at a temperature higher than that of air. In the absence of solar radiation, with light winds, and particularly with a cold, cloudless atmosphere, the probes tend to be in thermal equilibrium at a temperature lower than that of the air. Only in windy, cloudy conditions are probes likely to indicate true air temperatures. In other words, ideal measurement conditions exist when the radiative heat transfer between a probe and its environment is negligible in comparison to the transfer by convection.

The problem of radiation error is particularly significant in measuring air-temperature profiles near the ground because of the increase of wind speed with height. A probe within a meter from the ground might have a radiation error of 1°C, while an identical probe at 6 or 8 meters above the ground would have no discernible radiation error. At any one time the two probes might have the same radiative heat transfer rates but would experience entirely different wind speeds and, therefore, different convective heat transfer rates. This difficulty has impeded research on relationships between wind and temperature profiles near the ground and on heat transfer in the atmospheric surface layer.

Radiation error in temperature measurement presents a difficult problem also in specifying climatic extremes. Both the highest and lowest temperatures in a region are likely to be recorded under clear conditions with light winds. These are exactly the conditions that yield the greatest radiation errors, errors that, in either case, tend to indicate greater extremes than actually existed.

Two types of thermocouple probes were used in the U. S. Army Quartermaster Research and Engineering Command Antarctic micrometeorological investigation. In the presence of solar radiation, thermocouple junctions were mounted in rectangular radiation shields made of thin, flat, reflective aluminum plates. The junctions were formed by twisting pairs of No. 36 B and S gauge copper and constantan wires. It is known that radiation shields of this type reduce radiation errors but since the shield plates are normally mounted horizontally, the thermocouple junctions were exposed directly to solar radiation for low sun angles.

In the absence of solar radiation, i.e., in the winter months, thermocouple probes without shields were used. These were long, thin probes with the thermocouple junctions and their leads imbedded in ceramic insulation. Air temperature measurements made with these probes in clear weather with light winds may be expected to have significant errors due to unrestricted radiative heat loss.

This report gives the results of a series of wind tunnel tests to determine steady state radiation errors for the shielded thermocouple junctions for small solar elevation angles. Test data are given for different azimuth and elevation angles of direct radiation and for various wind speeds and relative directions. Data are interpolated from these results to provide, for various wind speeds, specific corrections for temperature profiles measured at the Scott-Amundson South Pole Station.

Evaluation of performance characteristics of the unshielded probe used in the absence of solar radiation was restricted to a few nighttime field tests over snow. Because of limitations in time and funds it was not possible to continue the evaluation.

2. CONCLUSIONS

The steady-state radiation error for the probe with a flat-plate radiation shield varies in a consistent way with wind speed and relative direction and with radiation intensity and azimuth and elevation angles. The error varies directly with intensity of radiation and is greatest for radiation striking the probe horizontally from the side on which the junction is mounted. It is greatest, also, for least wind speed and for wind aligned in direction with the long dimension of the probe. With appropriate interpolation the test data may be used to correct temperature observationsif the following information is known:

(a) Wind speed;
(b) Wind direction relative to probe;
(c) Radiation intensity;
(d) Radiation elevation angle; and
(e) Radiation azimuth angle.

The probe without a shield may indicate an air temperature at least 0.10 to 0.15 degrees colder than real when near a snow surface under a clear, cold atmosphere when the wind is from 0.5 to 3 mph.

Experimental and theoretical findings of others may be used to extend these results to other wind speeds.

3. RESULTS

The results of the wind tunnel tests for the shield probe are given in Tables I through III in terms of temperature errors in degrees Fahrenheit, for different wind speeds and directions and different radiation intensities, elevation angles and azimuth angles. Since the errors represent increases in probe temperature caused by incident radiation, the values should be subtracted from measurements made in the field under similar conditions.

The probe that was tested had been used for measurement of temperature profiles at the South Pole Station. It was a standard item as obtained from Thornthwaite Associates* except that for the tests the two inner plates of the shield were removed as they were for the South Pole measurements in order to prevent the accumulation of snow near the thermocouple junction. The probe is shown in Figure 1. It may be seen, also, in Figures 2, 3 and 4. Details of the probe and of the test equipment and procedures are given in Section 5.

The data in Table I-A are displayed in Figures 6 through 10. Each figure shows relationships between steady state radiation errors and radiation intensity for different wind speeds at a given radiation elevation angle. The plotted points were obtained by interpolation from graphs prepared to show radiation error as a function of wind speed for various test conditions. The interpolation was made to obtain lines for wind speeds in even units to facilitate further interpolation. As seen

*A thermocouple probe of nearly identical construction (except for its supporting elements) was described by Portman (1957).

in Tables I, II and III most of the original data were obtained for fractional units of wind speed.

The figures show that radiation error for these data is a linear function of radiation intensity. Thus, linear interpolation may be used to obtain radiation errors for different radiation intensities. The results are discussed in Section 4.

Temperature corrections for six different observation periods, one to three days each, at the South Pole Station in 1958 are listed in Table IV. The six periods were those during which measurements of solar radiation at normal incidence were made by Mr. Kirby J. Hanson.* Temperature corrections for these days were obtained by interpolation from test results selected on the basis of South Pole Station wind observations and solar elevation angles. The test data used for the corrections are identified in Table V and the probe orientation at the South Pole Station is shown in Figure 11. In the cases of two entries for a given parameter in Table V, approximately linear interpolation was used to obtain appropriate corrections.

Results of nighttime field tests of the unshielded rod probe over snow are given in Table VI. Included, also, are similar data for the shield probe for comparison. The temperature differences were obtained by arranging a thermocouple circuit so that the outputs of both the rod probe and the shield probe were recorded directly with reference to a second shield probe. The latter was quite similar to the one tested in the wind tunnel but had a smaller, soldered thermocouple junction and

*Dr. Harry Wexler, Director of Meteorological Research, U. S. Weather Bureau kindly supplied the radiation data in advance of its publication.

thinner shield plates. Figure 4 shows the two test arrangements and the relative wind directions during the tests. In Figure 5 are two photographs of test arrangement "B".

As revealed by the averages for the separate test periods given in Table VI, the temperature of the rod probe for the first three tests was lower than that of the University of Michigan reference probe but the situation was reversed for the fourth test. During the last test, as noted in the table, all probes were covered with frost. The results are discussed in Section 4.

4. DISCUSSION

The experimental results presented in the previous section may be interpreted in terms of steady-state heat transfer rates between an isolated cylinder and its environment. If only heat transfer by radiation, q_r, and forced convection, q_c, are considered, the heat balance per unit length of the cylinder may be expressed as

$$q_c = q_r \qquad (1)$$

or

$$h(T-T_a) = R + r - e\sigma T^4 \qquad (2)$$

in which
- h = convective heat transfer coefficient
- T = cylinder temperature, °A
- T_a = air temperature, °A
- R = "short-wave" radiation received
- r = "long-wave" radiation received
- e = emissivity of cylinder
- σ = Stefan-Boltzmann constant.

It is assumed that the end effects are negligible and that the cylinder is isothermal. The quantity $(T-T_a) = \Delta t$ is the steady-state radiation error if the cylinder is used as an air temperature probe.

The heat transfer coefficient, h, may be expressed in terms of the Nusselt number, Nu, which is related to the Reynolds number, Re, and the Prandtl number, Pr, (See McAdams, 1942 or Jacob, 1949). Thus

$$\begin{aligned} Nu &= \frac{hD}{k} = f(Re, Pr) \\ Re &= \frac{uD}{\nu} \\ Pr &= \frac{\nu \rho C_p}{k} \end{aligned} \qquad (3)$$

in which D = diameter of cylinder
ν = kinematic viscosity
u = air speed
f = empirically determined function
k = thermal conductivity
ρ = density
C_p = specific heat at constant pressure

According to Jacob (1949, p. 560), Hilpert found that for wires 0.002 to 0.1 cm in diameter, the Nusselt number could be expressed as

$$Nu = B\ Re^n \tag{4}$$

in which B and n depend on Re. Thus,

$$h = k\ B\ \nu^{-n}\ D^{n-1}\ u^n \tag{5}$$

and from (2)

$$\Delta t = (R + r - e\sigma T^4)\ h^{-1} \tag{6}$$

$$= (R + r - e\sigma T^4)\ k^{-1}\ B^{-1}\ \nu^n\ D^{1-n}\ u^{-n} \tag{7}$$

From Hilpert's data an appropriate value for n is about 0.4 for the wind tunnel test data. Equation (7) shows, therefore, that for conditions otherwise constant, the radiation error

(1) increases linearly with radiation intensity,
(2) decreases with increasing wind speed, and
(3) increases with increase in diameter of probe.

As revealed by Figures 6 through 10 the wind tunnel data show the expected linear dependence on radiation intensity. The fact suggests that changes in the term $e\sigma T^4$ were insignificant during the test interval and that linear interpolation and extrapolation may be used to determine radiation errors for intensities other than those measured.

The dependency of one set of test data on wind speed is shown in

Figure 13 in which temperature errors and wind speeds are plotted in logarithmic co-ordinates. Shown also is a dashed line whose slope is -0.4. It appears that the wind tunnel results may be extrapolated to low wind velocities with the aid of such a relationship. The possible influence of free convection at very low velocities, however must be considered so that extrapolation below 0.5 mph with these data is probably not reliable.

The applicability of wind tunnel test data to measurements in the Antarctic may be examined by considering Equation 6 for both test and measurement conditions. The ratio of radiation errors for the wind tunnel to those for the Antarctic is

$$\frac{\Delta t_{wt}}{\Delta t_{aa}} = \left[\frac{R + (r - e\sigma T^4)_{wt}}{R + (r - e\sigma T^4)_{aa}}\right] \left(\frac{h_{aa}}{h_{wt}}\right) \tag{8}$$

The term $(r - e\sigma T^4)_{wt}$ is negligible in comparison to R and $(r - e\sigma T^4)_{aa}$ is negative, but not large, so that the first term on the right is probably somewhat larger than unity. An estimate of the heat transfer coefficient ratio may be made if it is assumed that an equation of the type

$$h = K R_e^{\alpha} P_r^{\beta} \tag{9}$$

is valid for both conditions with K, α and β invariant. Then

$$\frac{h_{aa}}{h_{wt}} = \left(\frac{\nu_{aa}}{\nu_{wt}}\right)^{\beta-\alpha} \left(\frac{k_{aa}}{k_{wt}}\right)^{1-\beta} \left(\frac{\rho_{aa}}{\rho_{wt}}\right)^{\beta} \left(\frac{c_{p_{aa}}}{c_{p_{wt}}}\right)^{\beta}$$

from the defining relationships after eliminating u and D. For relationships like Equation (9), Jacob (1949, p. 563) gives the following values obtained by Ulsamer:

$$\alpha = 0.385$$

$$\beta = 0.31$$

For the temperature and pressure conditions:

wind tunnel	78°F and 985mb
South Pole Station	-100°F and 680mb

the ratios are

$$\left(\frac{\nu_{aa}}{\nu_{wt}}\right)^{\beta-\alpha} \approx 0.71^{-0.075}$$ (Handbook of Chemistry and Physics, 37th ed.)

$$\left(\frac{k_{aa}}{k_{wt}}\right)^{1-\beta} \approx 0.67^{0.69}$$ (Zemansky, 1943)

$$\left(\frac{\rho_{aa}}{\rho_{wt}}\right)^{\beta} \approx \left(\frac{c_{p_{aa}}}{c_{p_{wt}}}\right)^{\beta} \approx 1$$ (Handbook of Meteorology, 1945)

and

$$\frac{h_{aa}}{h_{wt}} \approx 0.8$$

It appears, therefore, that the product of the two ratios on the right side of Equation (8) is near unity so that the wind tunnel results may be applied directly to the South Pole measurements.

The results of the field tests I, II and III for the rod probe may be considered minimum radiation errors for the conditions of the experiment since the reference shield probe itself was probably colder than the air. In test IV the presence of frost on all probes undoubtedly accounted for the reversal of temperature differences. Either the heat required for change of state--more on the larger rod probe than on the fine wire shielded junction--or the modification of surface by the frost cover could account for the rod probe indicating higher temperatures than the shield probe.

Extension of these findings to other situations with the aid of a heat-balance equation such as Equation (6) is difficult for several reasons. Perhaps the most important difficulty is the lack of information on long wave radiation exchange between the probe and its environment. Another difficulty is the fact that conduction within the rod may be an important term in this case. Finally, it should be noted that there appears to be no information on Nusselt numbers in the literature for blunt-ended rods with sub-sonic flow at various angles.

The results are significant, nonetheless, for revealing the order of magnitude of radiation error for unshielded probes in an Antarctic environment without solar radiation.

5. EQUIPMENT AND PROCEDURES

Thermocouple Probes--The shield probe is shown in Figure 1 and can be seen in test arrangements shown in Figures 2, 3 and 5. (In Figure 5 the QMRE shield probe is the one on the left.) The shield plates were made of "Alzak Aluminum" and were highly reflective on the outward facing surfaces, but painted black on the inward ones. The upper plate was 2-5/8 x 9-11/16 x 0.032 inches and the lower 8-9/16 x 1-5/16 x 0.32 inches. They were about one-half inch apart. The twisted thermocouple junction can be seen in Figure 1, about two-thirds of the distance between the connector and the spacer near the end of the probe. The remainder of the thermocouple lead wire between the plates was covered with a thin fiber insulation.

The unshielded (rod) probe is shown in Figure 5 in the field test arrangement. It is a standard element manufactured by Thermo-electric Co. The outer diameter of the rod housing the thermocouple junction was 0.040 inches and it was 12 inches long.

Wind Tunnel Test Equipment and Procedures--The shield probe was tested in a 14' x 8' x 5.5' working section of a low speed wind tunnel. The tunnel is a closed loop, double return type with a contraction ratio of approximately 4 to 1 at the Venturi section. The air is circulated by an adjustable-pitch, axial-flow fan powered by a variable speed d.c. motor. Air speed in the tunnel is measured by a pitot tube and a micro-manometer.

The test arrangement in the wind tunnel is shown in Figures 2 and

3, looking upwind in the former and downwind in the latter. Attached to the stand supporting the shield probe is a Dwyer wind speed probe which was calibrated with the tunnel pitot tube. The radiation source was a 250 watt Ken-Rad infrared lamp positioned on a ring stand as shown in the figures. Radiation intensity of the lamp for different positions was determined with a standard Eppley pyrheliometer. The reference thermocouple junction for the probe was placed about 5 feet upwind at the same distances from the tunnel floor and walls as the probe. The lamp and probe positions were altered to obtain the orientations required.

The temperature difference between the test probe and the reference junction was recorded directly with a Leeds and Northrup Speedomax Model S, AZAR recorder. A Leeds and Northrup DC amplifier was used to provide the desired sensitivity. For each test measurement, the radiation intensity and the tunnel wind speed were held constant for a period sufficiently long to assure that steady-state conditions prevailed.

Field Test Equipment and Procedures--The test arrangements over snow are shown in Figures 4 and 5. The three probes were mounted side by side approximately 2 1/2 inches apart and 14 inches above a smooth snow surface. Wind speed at the same height was measured with a Beckman and Whitley Model 170-34 anemometer, and net radiation with a Beckman and Whitley Model N188-1 net exchange radiometer.

The reference probe was a shielded thermocouple junction made of No. 36 B and S gauge copper and constantan wires. The junction was made by soldering the ends together with a minimum overlap. The probe was quite similar to that tested in the wind tunnel except that there were two inner, parallel plates, equally spaced between the external ones.

The thermocouple outputs were recorded with the same system as that used in the wind tunnel. A switching arrangement permitted alternate recording of the difference between the two shield probes and the rod and the shield probe.

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Table I-A

Radiation Errors: Wind Perpendicular to Probe from Junction Side; Radiation Perpendicular from Side Opposite Junction

Radiation Elev. angle Degrees	Radiation Intensity ly/min	Wind Speed, mph 4.3	5.8	8.0	10.1	13.7	18.4	23.3	33.9	Temp. deg. F.
0.0	0.48	0.53	0.30	0.27	0.25	0.21	----	----	----	78.2
0.0	0.72	0.66	0.53	0.39	0.31	0.31	----	----	----	78.2
0.0	0.87	0.75	0.62	0.48	0.40	0.35	----	----	----	78.2
0.0	0.87	----	----	----	----	0.40	0.38	0.35	0.33	75.3
0.0	1.10	0.93	0.80	0.62	0.53	0.48	----	----	----	78.2
0.0	1.44	1.15	1.02	0.80	0.74	0.62	----	----	----	78.2
0.0	1.44	----	----	----	----	0.62	0.58	0.53	0.49	75.3
5.0	0.72	0.75	0.62	0.47	0.39	0.31	----	----	----	77.8
5.0	0.87	0.86	0.71	0.51	0.44	0.38	----	----	----	77.8
5.0	0.87	----	----	----	----	0.35	0.33	0.31	0.29	75.3
5.0	1.10	1.00	0.77	0.57	0.52	0.41	----	----	----	77.8
10.0	0.87	0.62	0.42	0.33	0.27	0.22	----	----	----	78.0
10.0	0.87	----	----	----	----	0.22	0.20	0.20	0.18	75.3
10.0	1.10	0.66	0.60	0.33	0.29	0.27	----	----	----	78.0
10.0	1.27	0.66	0.49	0.35	0.29	0.24	----	----	----	78.0
10.0	1.44	0.67	0.55	0.38	0.33	0.29	----	----	----	78.0
10.0	1.44	----	----	----	----	0.33	0.31	0.27	0.22	75.3
15.0	1.44	0.33	0.27	0.15	0.11	0.09	----	----	----	78.0
15.0	1.44	----	----	----	----	0.15	----	0.13	0.11	75.3
20.0	1.10	0.22	0.11	0.04	0.00	0.00	----	----	----	78.0
20.0	1.44	0.29	0.11	0.04	0.02	0.02	----	----	----	78.0
20.0	1.44	----	----	----	----	0.11	----	0.09	0.07	----
20.0	1.94	0.31	0.27	0.13	0.11	0.07	----	----	----	78.0
30.0	1.44	0.15	0.07	0.00	0.00	0.00	----	----	----	78.0
30.0	1.44	----	----	----	----	0.11	----	0.09	0.07	----

Table I-B

Radiation Errors: Wind Perpendicular to Probe from Junction Side; Radiation Parallel to Probe from End Opposite Connector

Radiation Elev. angle Degrees	Radiation Intensity ly/min	Wind Speed, mph 4.3	5.8	8.0	10.1	13.7	18.4	23.3	33.9	Temp. deg. F.
0.0	0.72	0.29	0.20	0.13	0.09	0.04	----	----	----	78.2
0.0	1.10	0.29	0.20	0.13	0.11	0.07	----	----	----	78.2
0.0	1.44	0.31	0.22	0.16	0.10	0.08	----	----	----	78.2
10.0	1.10	0.22	0.11	0.04	0.02	0.00	----	----	----	79.5
10.0	1.44	0.27	0.20	0.07	0.04	0.02	----	----	----	79.5
20.0	1.10	0.18	0.11	0.02	0.00	0.00	----	----	----	79.5
20.0	1.94	0.20	0.11	0.04	0.02	0.00	----	----	----	79.5

Table I-C

Radiation Errors: Wind Perpendicular to Probe from Junction Side; Radiation Parallel to Probe from Connector End

Radiation Elev. angle Degrees	Radiation Intensity ly/min	Wind Speed, mph 4.3	5 8	8.0	10.1	13.7	18.4	23.3	33.9	Temp. deg. F.
20.0	1.10	0.42	0.33	0.18	0.13	0.09	----	----	----	79.5
20.0	1.94	0.58	0.49	0.31	0.24	0.20	----	----	----	79.5

Table II-A

Radiation Errors: Wind Sixty Degrees from Perpendicular, from Junction Side; Radiation Perpendicular from Side Opposite Junction

Radiation Elev. angle Degrees	Radiation Intensity ly/min	Wind Speed, mph 4.3	5.8	8.0	10.1	13.7	18.4	23.3	33.9	Temp. deg. F.
0.0	0.87	1.00	0.80	0.62	0.53	0.44	----	----	----	79.5
0.0	1.44	1.46	1.24	0.95	0.84	0.71	----	----	----	79.5
5.0	0.87	0.84	0.71	0.55	0.47	0.40	----	----	----	79.5
10.0	0.87	0.62	0.49	0.31	0.27	0.22	----	----	----	79.5
10.0	1.44	0.80	0.60	0.44	0.40	0.33	----	----	----	79.5
15.0	1.44	0.53	0.44	0.27	0.22	0.18	----	----	----	78.5
20.0	1.10	0.31	0.18	0.13	0.09	0.04	----	----	----	78.5
20.0	1.44	0.29	0.18	0.13	0.10	0.07	----	----	----	78.5
20.0	1.94	0.29	0.18	0.12	0.08	0.07	----	----	----	78.5
30.0	1.44	0.13	0.08	0.02	0.00	0.00	----	----	----	78.5

Table II-B

Radiation Errors: Wind Sixty Degrees from Perpendicular, from Junction Side; Radiation Perpendicular from Junction Side

Radiation		Wind speed, mph									Temp.
Elev. angle Degrees	Intensity ly/min	4.3	5.8	8.0	10.1	13.7	18.4	23.3	28.2	33.9	deg. F.
0.0	0.87	1.02	0.88	0.71	0.63	0.55	----	----	----	----	78.0
0.0	0.87	----	----	----	----	0.55	0.49	0.44	0.42	0.40	77.0
0.0	1.10	----	----	----	----	0.70	0.58	0.53	0.49	0.46	77.0
0.0	1.44	1.60	1.39	1.12	1.02	0.86	----	----	----	----	78.0
0.0	1.44	----	----	----	----	0.84	0.75	0.66	0.60	0.58	77.0
5.0	0.87	1.00	0.84	0.66	0.57	0.52	----	----	----	----	78.0
5.0	0.87	----	----	----	----	0.58	0.49	0.47	0.42	0.38	77.0
10.0	0.87	0.95	0.75	0.57	0.46	0.40	----	----	----	----	78.0
10.0	0.87	----	----	----	----	0.49	0.42	0.38	0.33	0.31	77.0
10.0	1.44	1.24	1.06	0.86	0.75	0.66	----	----	----	----	78.0
10.0	1.44	----	----	----	----	0.71	0.62	0.53	0.49	0.46	77.0
15.0	1.10	0.75	0.60	0.49	0.42	0.35	----	----	----	----	77.0
15.0	1.10	----	----	----	----	0.39	0.33	0.30	0.26	0.22	77.0
15.0	1.44	1.22	0.97	0.80	0.69	0.62	----	----	----	----	77.0
15.0	1.44	----	----	----	----	0.42	0.35	0.31	0.27	0.24	77.0
20.0	1.44	0.42	0.27	0.15	0.12	0.12	----	----	----	----	77.0
20.0	1.44	----	----	----	----	0.08	0.05	0.04	----	0.04	77.0
20.0	1.94	0.57	0.49	0.35	0.27	0.24	----	----	----	----	77.0
20.0	1.94	----	----	----	----	0.20	0.17	0.14	----	0.11	77.0
30.0	1.44	0.09	0.02	0.02	0.00	0.00	----	----	----	----	77.0
30.0	1.44	----	----	----	----	0.02	0.00	0.00	----	0.00	77.0

Table II-C

Radiation Errors: Wind Sixty Degrees from Perpendicular, from Junction Side; Radiation Parallel to Probe from End Opposite Connector

Radiation Elev. angle Degrees	Radiation Intensity ly/min	4.3	5.8	8.0	Wind speed, mph 10.1	13.7	18.4	23.3	28.2	33.9	Temp. deg. F.
0.0	1.10	0.24	0.15	0.09	0.07	0.04	----	----	----	----	77.5
10.0	1.10	0.11	0.07	0.02	0.00	0.00	----	----	----	----	77.5
20.0	1.44	0.11	0.07	0.02	0.00	0.00	----	----	----	----	77.5

Table III-A

Radiation Errors: Wind Parallel to Probe from End Opposite Connector; Radiation Perpendicular to Probe from Side Opposite Junction

Radiation Elev. angle Degrees	Radiation Intensity ly/min	4.3	5.8	8.0	Wind speed, mph 10.1	13.7	18.4	23.3	28.2	33.9	Temp. deg. F.
0.0	1.44	4.24	2.70	1.52	1.32	1.08	----	----	----	----	80.0
0.0	1.44	----	2.79	1.72	----	----	----	----	----	----	80.0

Table IV

Temperature Corrections in Degrees F., for Selected Periods at the Amundsen-Scott South Pole Station (Values to be subtracted from observed data)

Date		Wind speed, mph 4.3	5.8	8.0	10.0	13.7	18.4	23.3	28.2	33.5
2 March	(a)	1.00*	0.90*	0.70*	0.62	0.55	0.45	0.42	0.38	0.33
	(b)	0.88	0.72	0.51	0.44	0.37	0.33	0.30	0.30	0.28
4, 5, 6 March	(a)	0.79	0.67	0.52	0.45	0.38	0.36	0.30	0.30	0.30
	(b)	0.93	0.74	0.54	0.48	0.38	0.35	0.33	0.30	0.28
5, 8, 9 November	(a)	1.20	0.95	0.80	0.70	0.50	0.35	0.30	0.25	0.25
	(b)	0.50	0.35	0.25	0.20	0.13	0.09	0.08	0.08	0.08
6 November	(a)	0.91	0.71	0.58	0.50	0.38	0.25	0.22	0.21	0.20
	(b)	0.32	0.24	0.13	0.10	0.09	0.09	0.09	0.09	0.09
10, 13 November	(a)	0.78	0.59	0.46	0.38	0.30	0.19	0.17	----	0.14
	(b)	0.38	0.28	0.19	0.15	0.10	0.08	0.07	0.07	0.07
	(c)	0.49	0.40	0.24	0.18	0.14	----	----	----	----
	(d)	0.20	0.11	0.02	0.01	----	----	----	----	----
16, 17 November	(a)	0.31	0.22	0.14	0.12	0.09	0.07	0.05	0.05	0.05
	(b)	0.28	0.17	0.10	0.06	0.05	0.05	0.04	0.04	0.03
	(c)	0.49	0.40	0.24	0.18	0.14	----	----	----	----
	(d)	0.20	0.11	0.04	0.02	0.01	----	----	----	----

*Extrapolated value.

(a) Radiation from junction side of probe.
(b) Radiation from side opposite junction.
(c) Radiation from connector end of probe.
(d) Radiation from end opposite connector.

Table V

Test Data Used for Compiling Temperature Corrections given in Table IV

Date		Radiation Intensity, ly/min	Radiation Elevation Angle, deg.	Wind Direction Relative Thermo-couple wire in probe, deg.
2 March	(a)	1.10	0 and 15	30
	(b)	1.10	5 and 10	30
4, 5, 6 Mar		1.10 and 0.87	5	90
4, 8, 9 Nov		1.44	15	30
6 Nov		1.44	15	90
10, 13 Nov		1.44	15 and 20	30 and 90
16, 17 Nov		1.44	15 and 20	90

Table VI

Temperature Differences for Nighttime Tests over Snow

(ΔT = U. of M. probe temperature minus QMRD probe temperature)

Test Number	I	II	III	IV*
Date	20 Feb. 1960	20 Feb. 1960	20 Feb. 1960	23 Feb. 1960
Time, EST	1920-1929	1937-1946	1948-1958	2026-2050
Sky Condition	Clear	Clear	Clear	Clear
Net Radiation, ly/min	0.013	0.017	0.020	-----
Probe Arrangement	As in Fig. 4(A)	As in Fig. 4(A)	As in Fig. 4(A)	As in Fig. 4(B)
Wind Direction, deg.	340	340	340	330
Temperature, deg. F.	-4.0	-4.0	-4.0	1.4
Temp. Gradient, deg. F. ($T_{4m} - T_{1/2m}$)	7.0	7.0	7.0	16.0

	I Shield Probe °F	I Rod Probe °F	I Wind mph	II Shield Probe °F	II Rod Probe °F	II Wind mph	III Shield Probe °F	III Rod Probe °F	III Wind mph	IV Shield Probe °F	IV Rod Probe °F	IV Wind mph
	.54			.09			.41		3.5		-.23	0.3
		.50	0.4		.45	1.9		.41		.45		1.8
	.54			.13			.31				-.27	
		.63			.36			.18		.05		1.9
	.49		0.8	.18		2.6	.31		3.5		-.41	1.8
		.05			.23			.23		0		
	.36			.09		3.3	.27				-.45	1.9
		.41			.41			.31	2.5	.18		
	.27		0.9								-.49	0.8
		.49								.05		1.2
											-.67	
										.09		1.4
											-.27	1.8
										0		
											-.18	1.9
Averages	.44	.42	0.7	.12	.36	2.6	.33	.28	3.2	.12	-.37	1.5

*All probes were covered with frost during test No. IV.

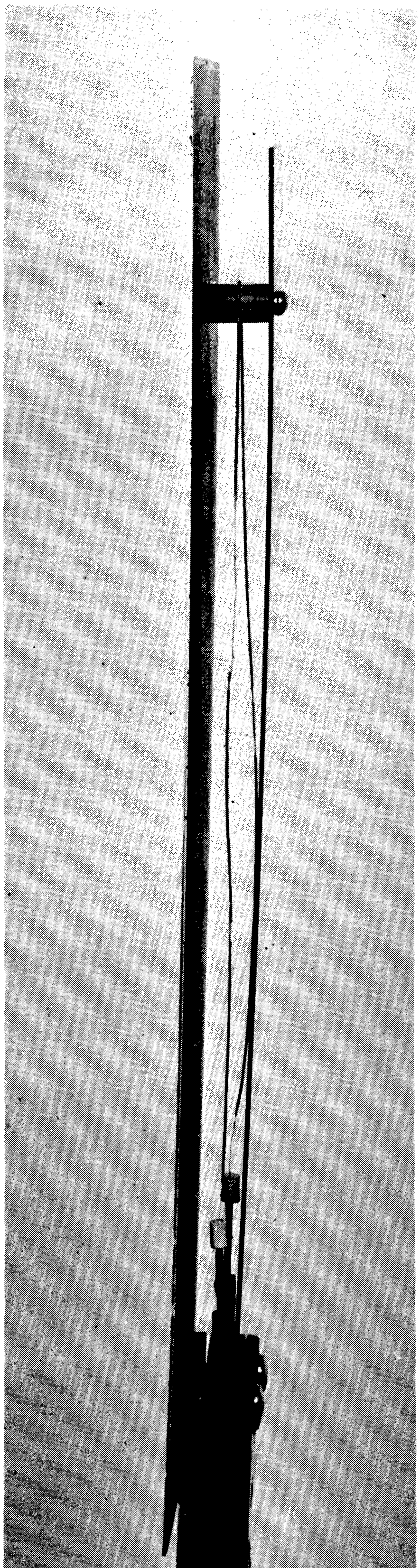

Figure 1. Side view of shield probe.

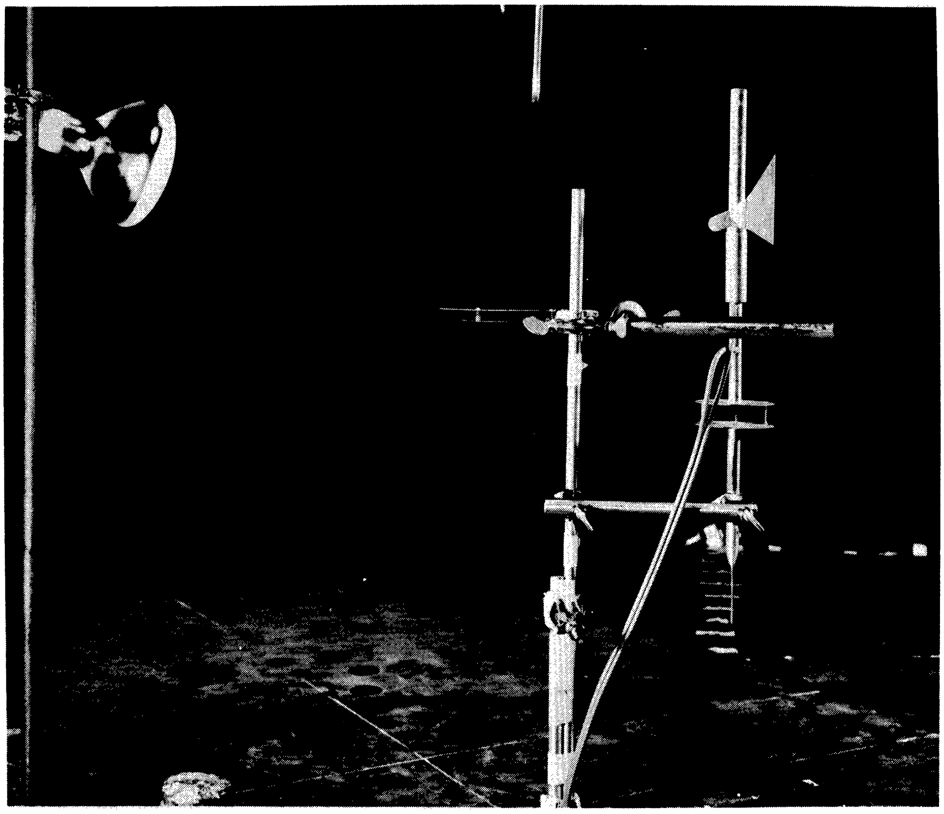

Figure 2. Wind tunnel test arrangement, looking upwind.

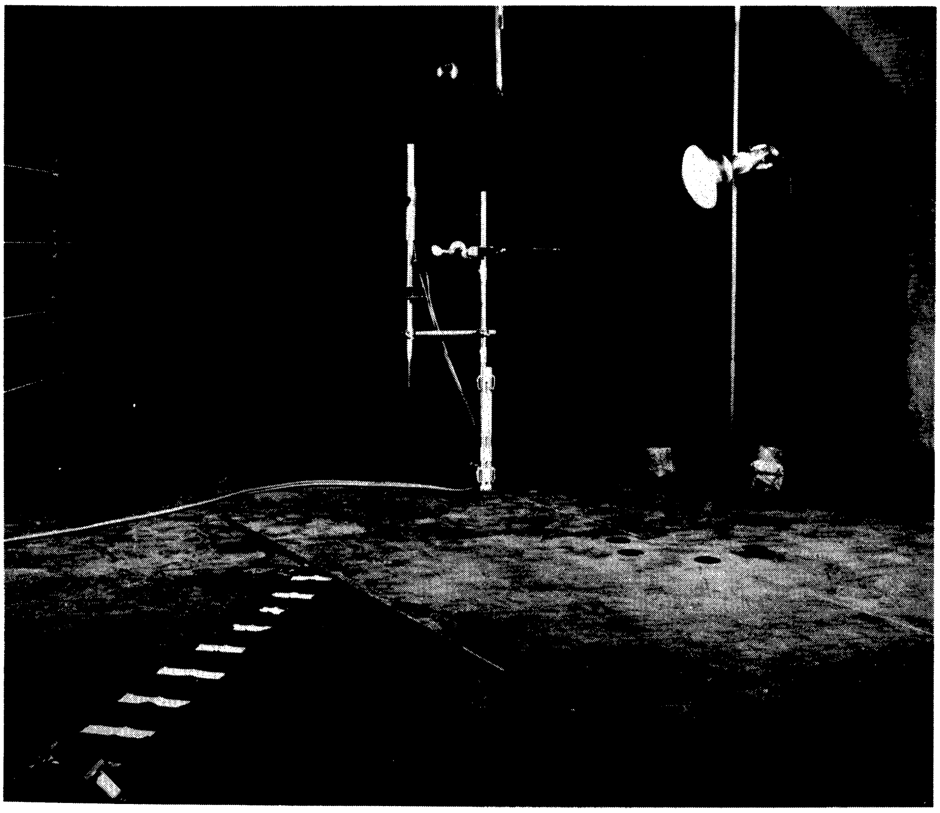

Figure 3. Wind tunnel test arrangement, looking downwind.

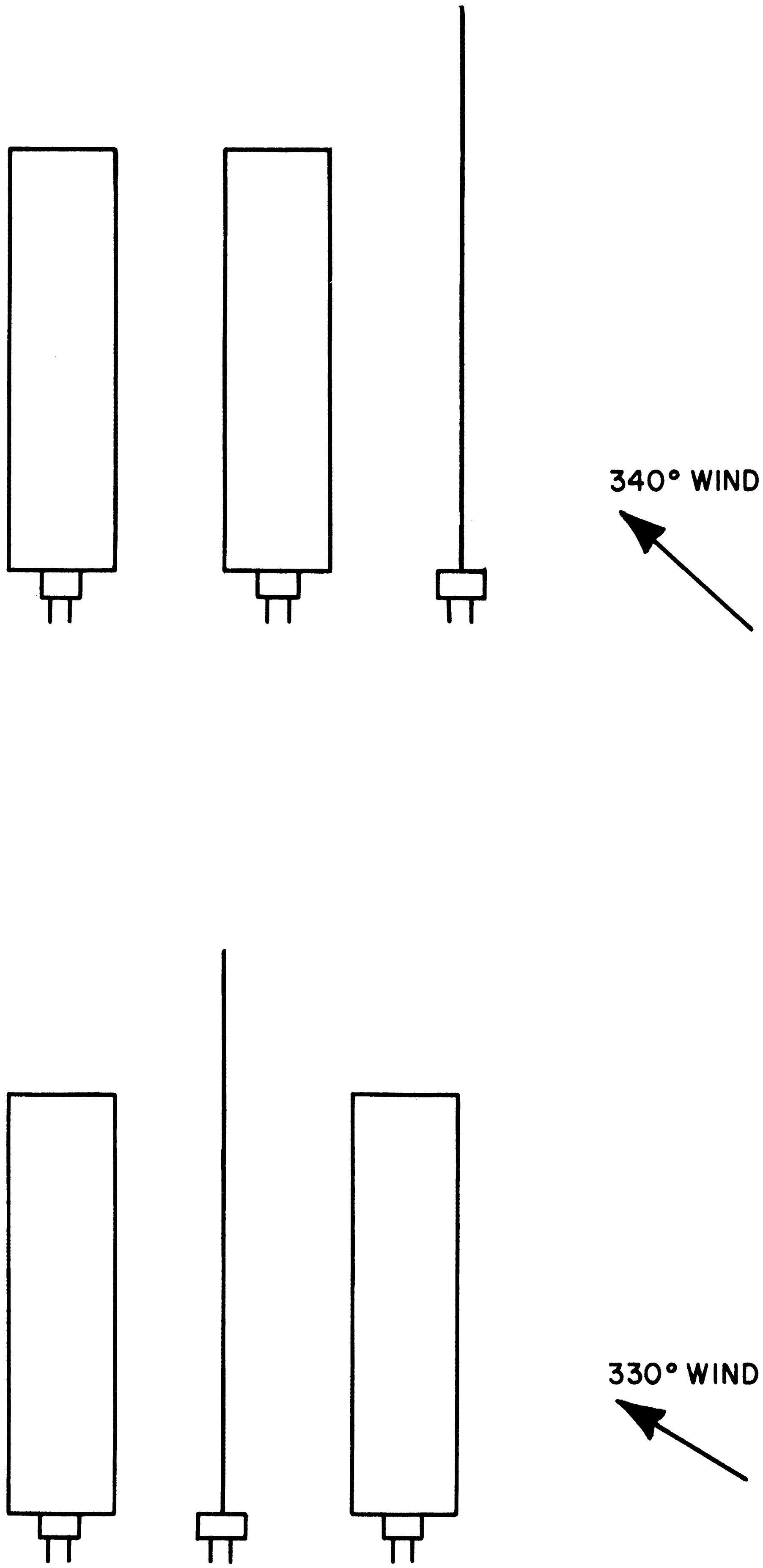

Figure 4. Test arrangements over snow.

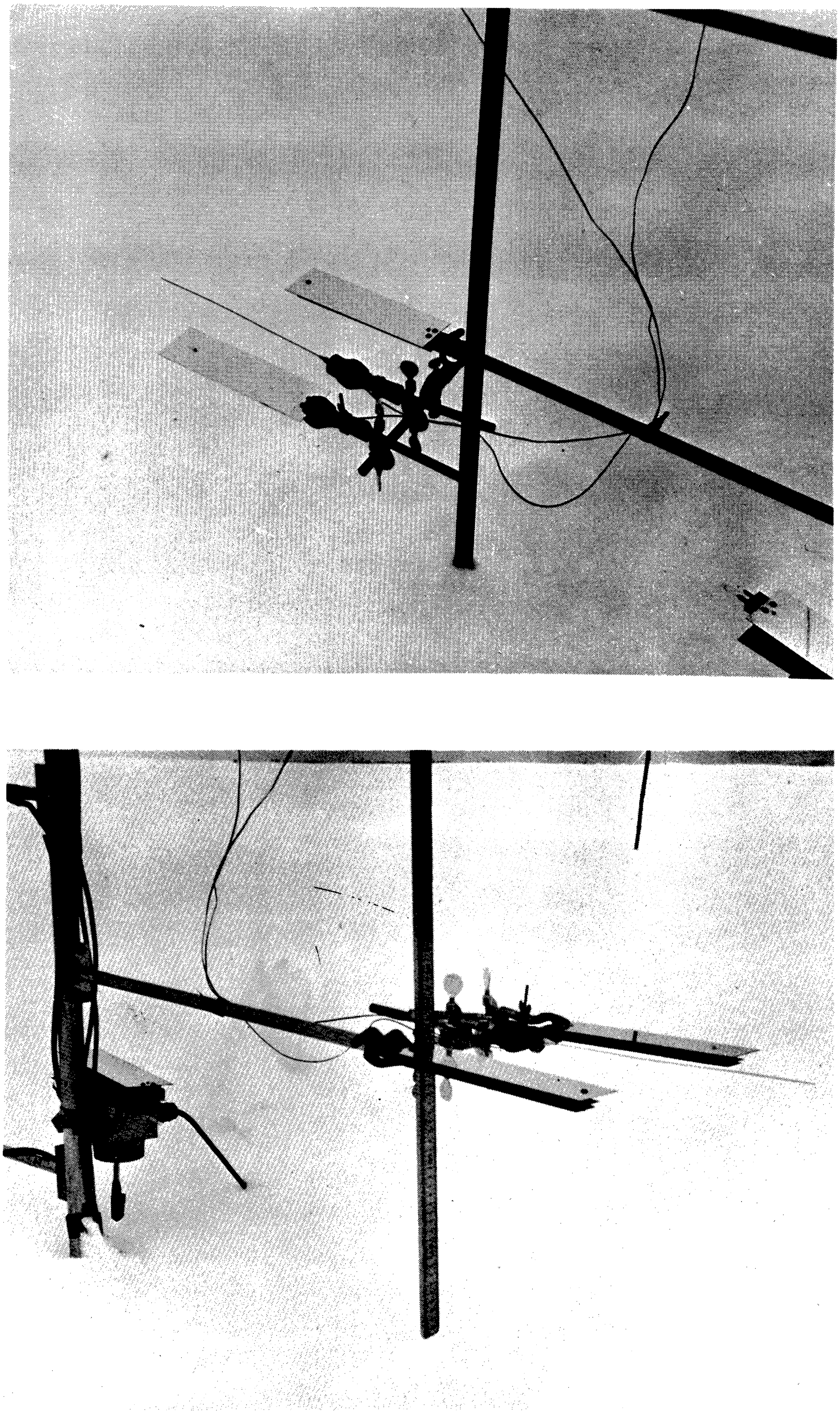

Figure 5. Two views of test arrangement "B" over snow.

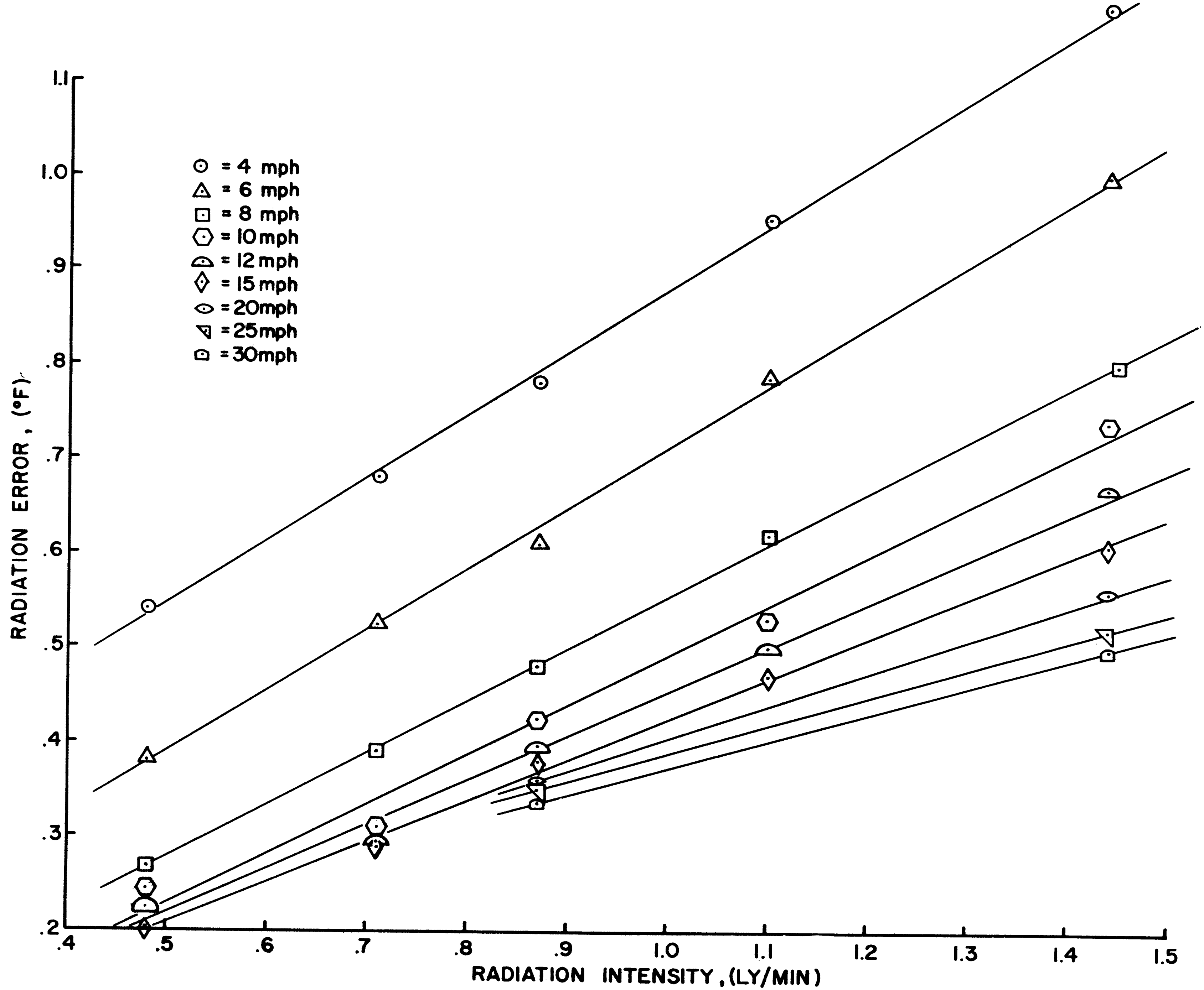

Figure 6. Radiation errors versus radiation intensity for different wind speeds; radiation elevation angle of 0.0 degrees.

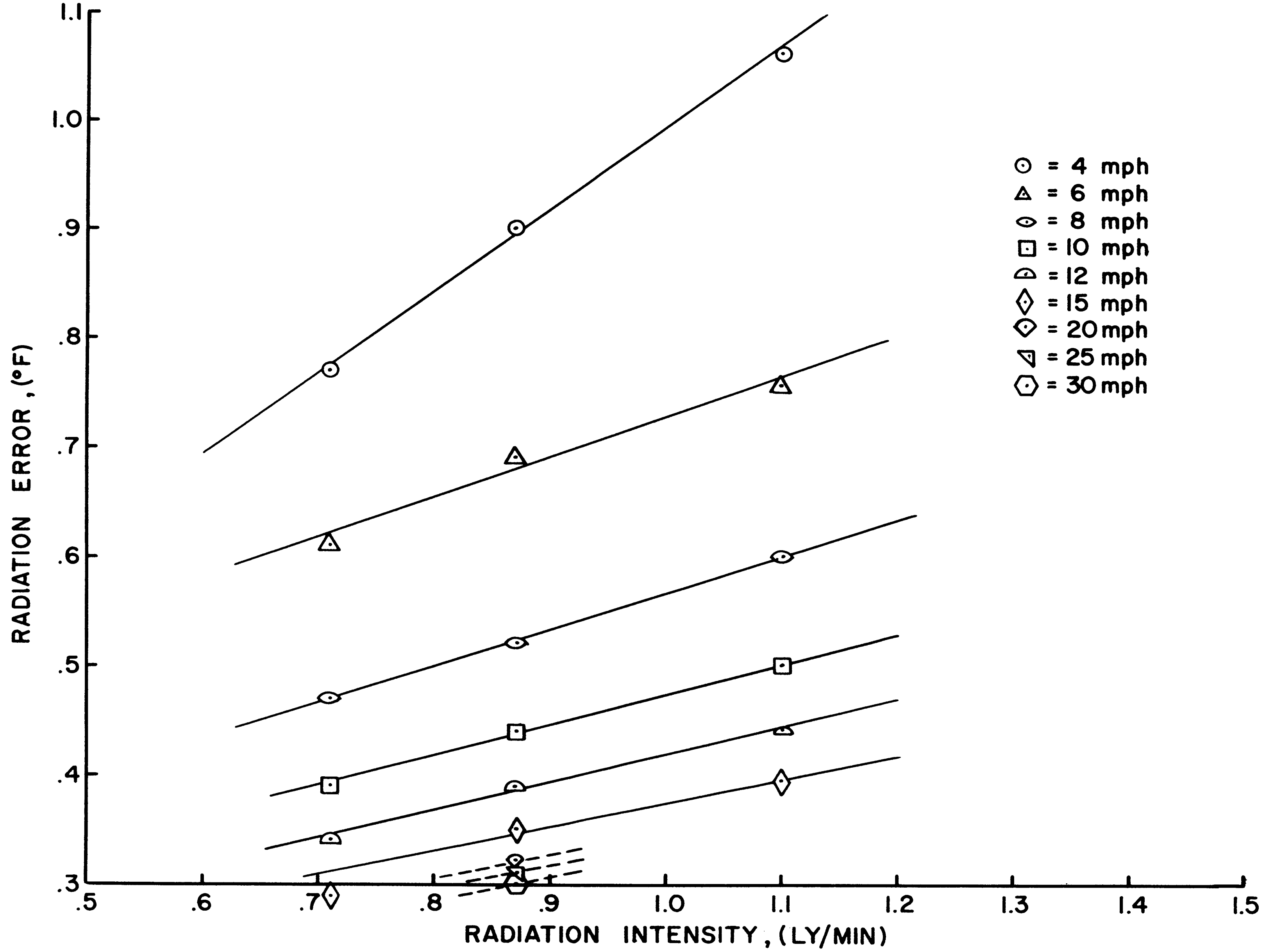

Figure 7. Radiation errors versus radiation intensity for different wind speeds; radiation elevation angle of 5.0 degrees.

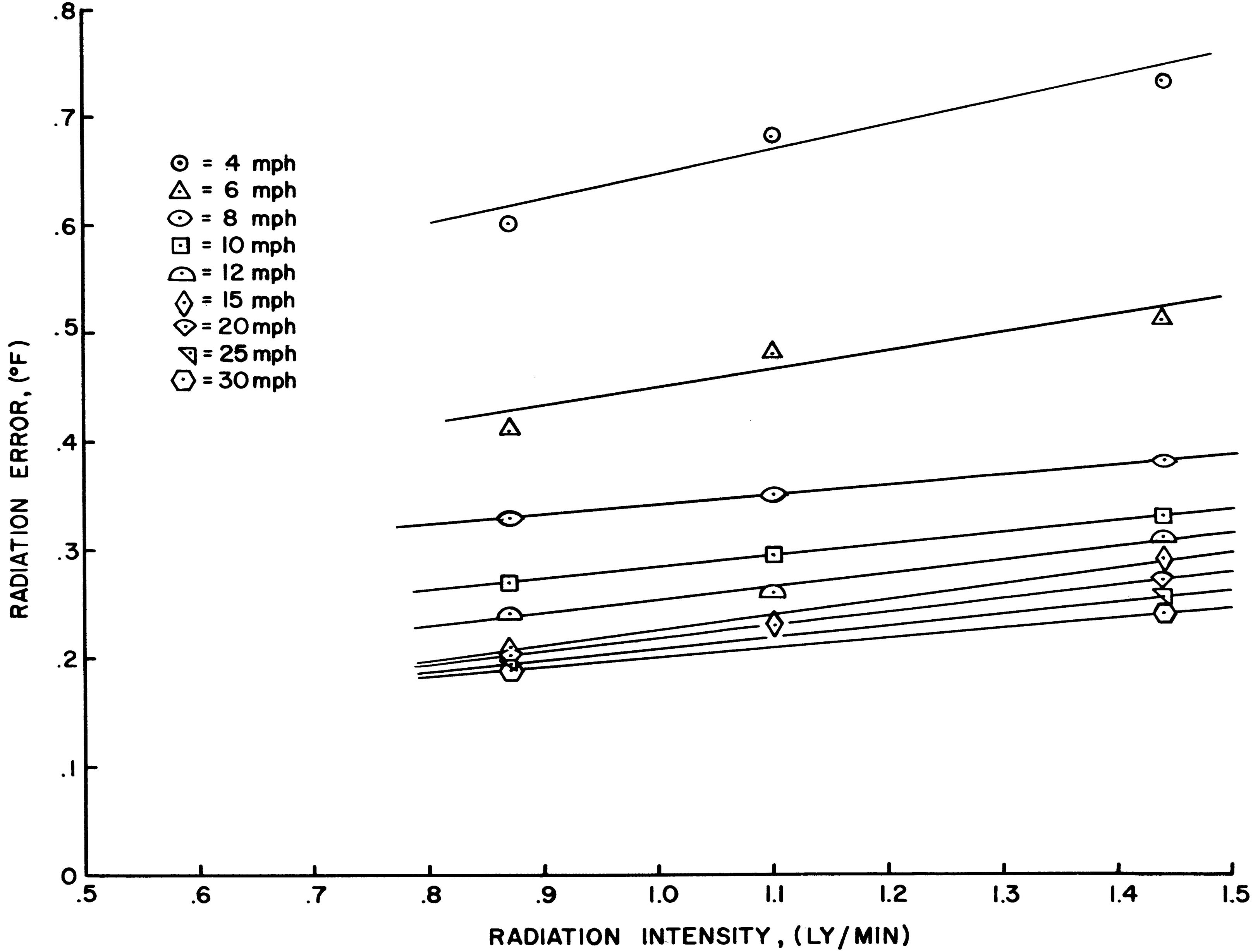

Figure 8. Radiation errors versus radiation intensity for different wind speeds; radiation elevation angle of 10.0 degrees.

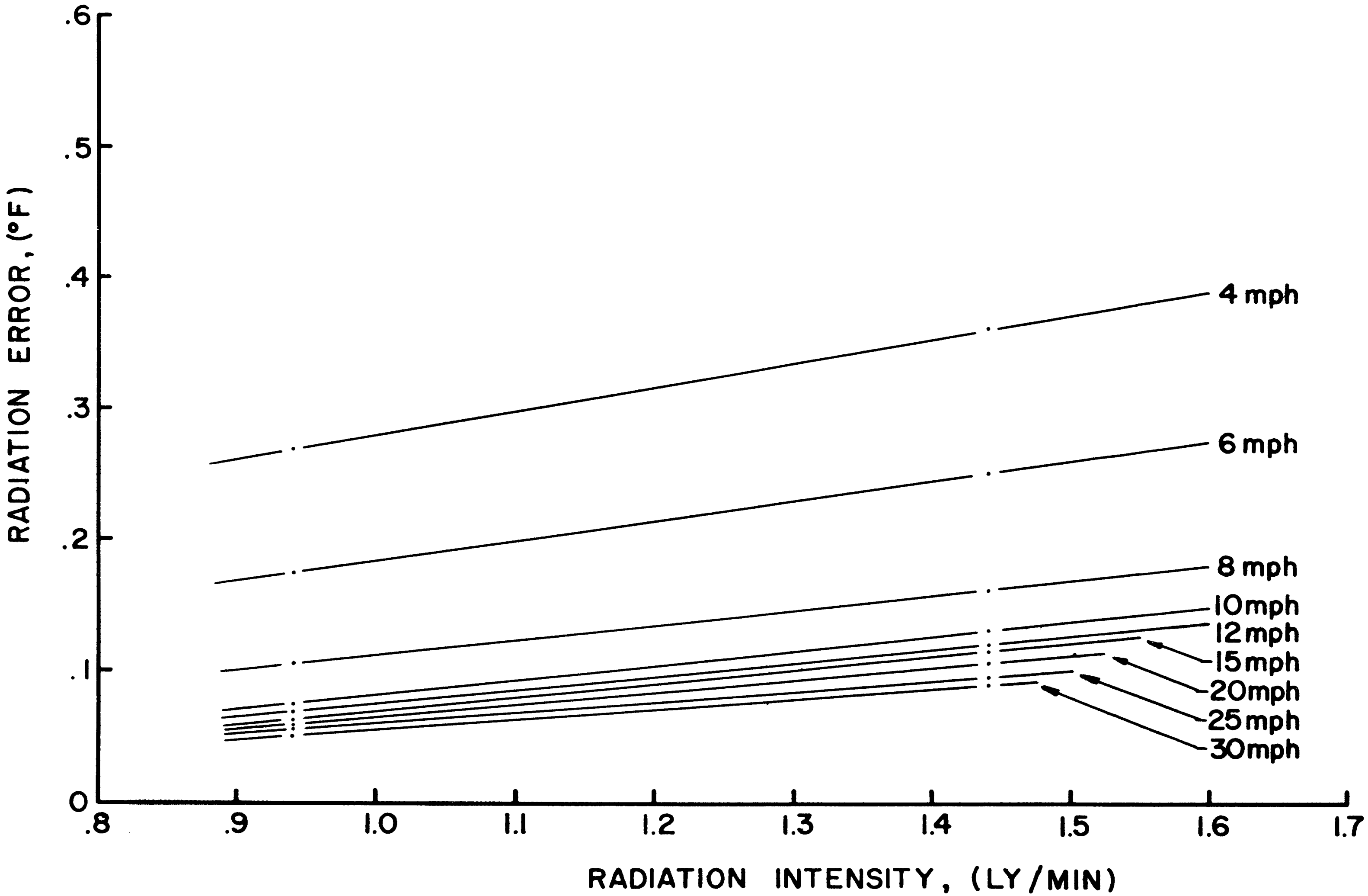

Figure 9. Radiation errors versus radiation intensity for different wind speeds; radiation elevation angle of 15.0 degrees.

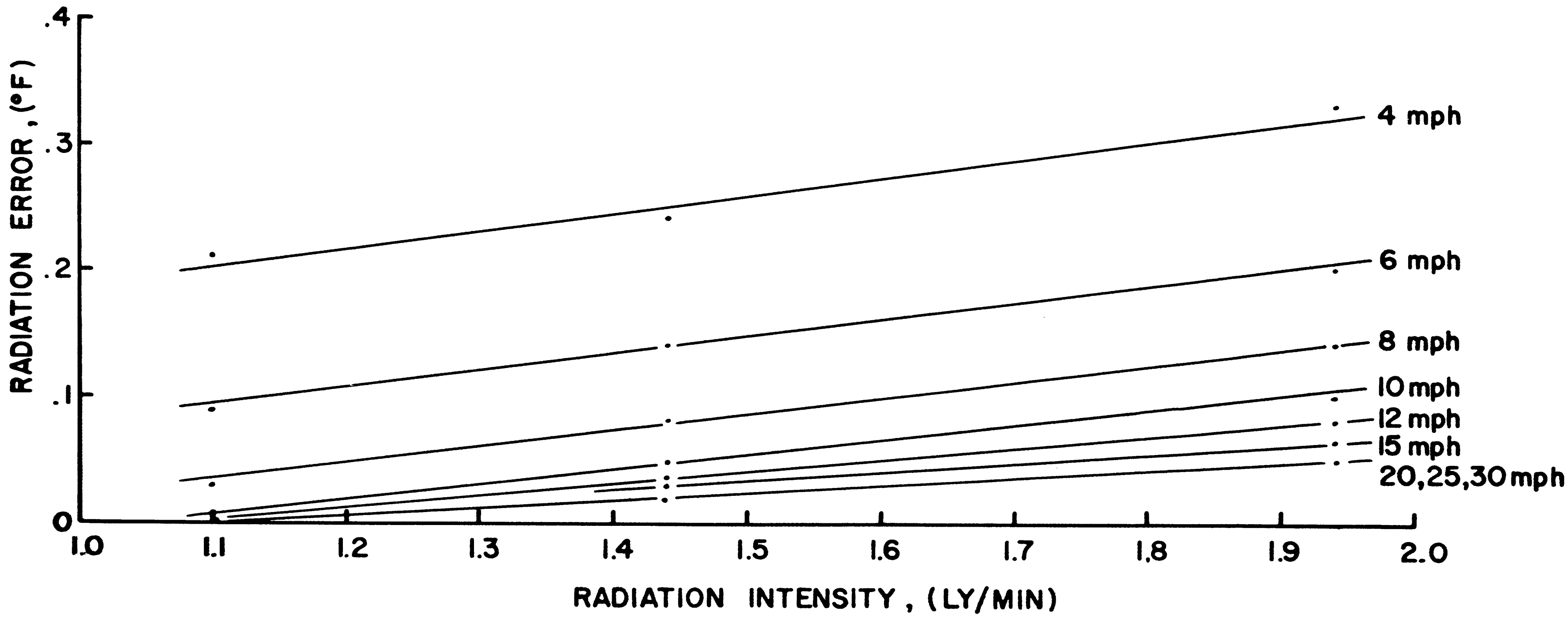

Figure 10. Radiation errors versus radiation intensity for different wind speeds; radiation elevation angle of 20.0 degrees.

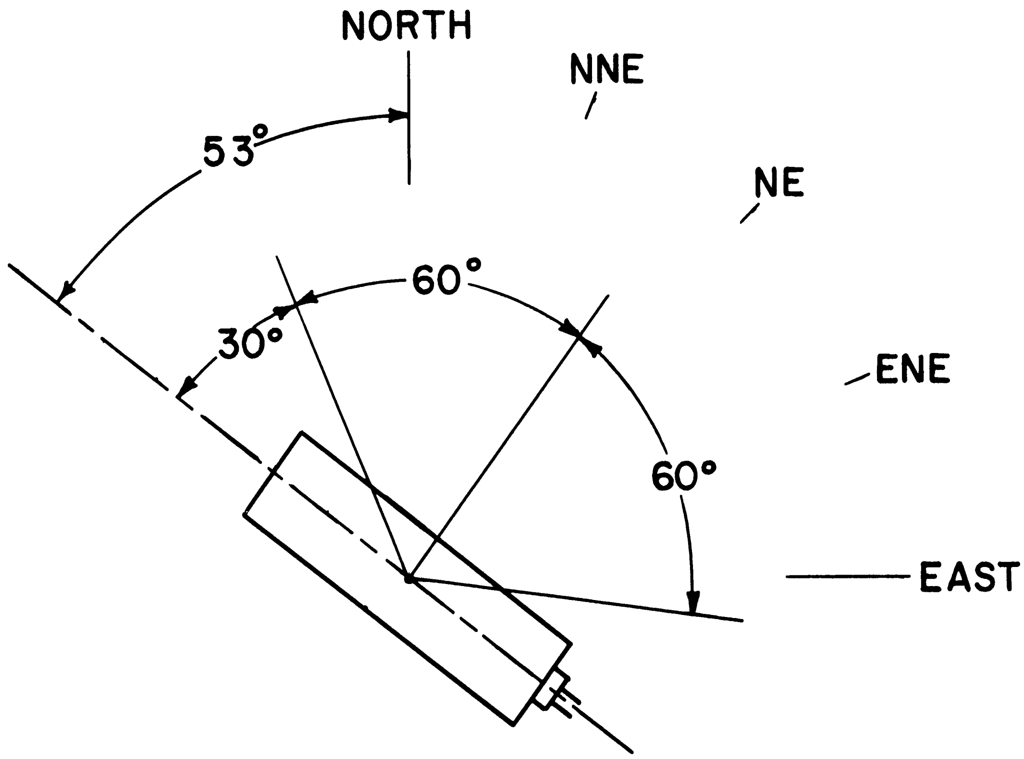

Figure 11. Probe orientation at South Pole Station.

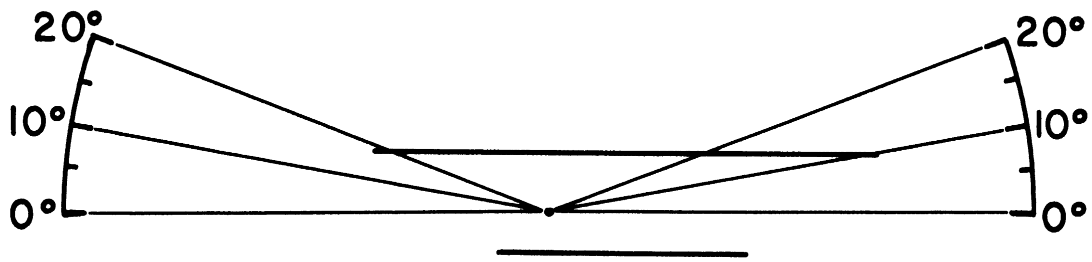

Figure 12. Thermocouple junction position in shield with respect to elevation angles.

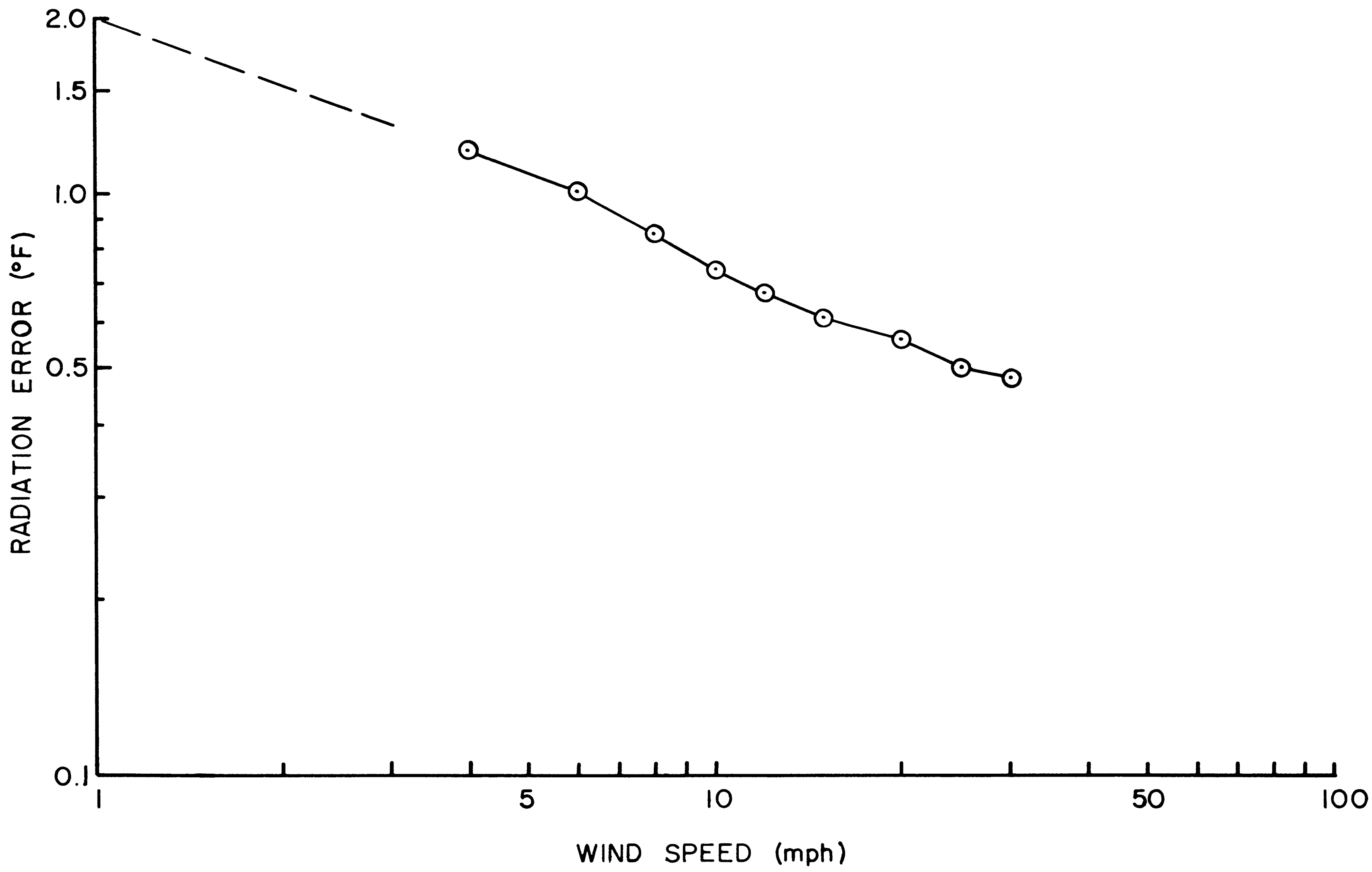

Figure 13. Radiation Errors versus Wind Speed. (Data from Figure 5 for radiation intensity = 1.44 ly/min.)