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Field experience has shown that, when a sling psychrometer is used in the presence of high thermal radiation flux, the indicated dry-bulb and wet-bulb temperatures may be considerably in error. Tests were made under controlled laboratory conditions to determine the magnitude of the errors which might be expected under various environmental conditions. The results are shown graphically. The effect of these temperature errors on the calculated heat exchange between a workman and the environment has also been investigated and the results are tabulated. The results of a study of the effect of wick length on wet-bulb error due to stem conduction are also included in the paper.

Introduction

A REVIEW OF THE LITERATURE revealed many papers on the subject of psychrometry. The relationship between the true thermodynamic wet-bulb temperature and the wet-bulb temperature as indicated by a psychrometer has been the subject of many careful studies, and the effect of radiation on this relationship has been discussed in detail. In all these studies the surrounding surfaces were always at air temperature.

The sling psychrometer is frequently used to determine the dry- and wet-bulb temperatures in hot industrial plants. Field experience has shown that, when this instrument is used in the presence of high thermal radiation flux, the temperatures obtained may be seriously in error.[1] To get more accurate information on the magnitude of these errors, and to determine their effect on calculated heat stress indices, a laboratory study was made under controlled environmental conditions. A companion study to investigate the effect of wick length on wet-bulb readings was also conducted. This paper presents the results of these studies.

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Thermal Radiation Effects on Readings

Test Instruments and Facilities

Tests were conducted in an environmental test chamber 15 feet long, 12 feet wide, and 9.3 feet high.[2] Air temperature in the chamber can be maintained at any desired level from 40° to 150° F, and over most of this range the relative humidity can be varied from 15% to 90%.

Radiant energy for the tests was provided by two electrically heated panels, each 3 feet wide and 5½ feet high, located side by side near the end of the room. At still air conditions, the panel temperatures can be controlled at any desired level up to approximately 325° F above the ambient air temperature.

The *sling psychrometer* used in the study was a commercially available instrument with a die-cast frame having a dull, dark-gray finish. Attached to the frame were two mercury-in-glass thermometers having a range of 20° to 120° F with ½-degree graduations.

The thermometers used were purchased from the psychrometer manufacturer. Thermometers vary slightly in length, and since the position of the top of the thermometers was fixed by holes in the psychrometer frame, the extension of the thermometers beyond the end of the frame depended on the thermometer length. The wet-bulb thermometer used throughout these tests permitted a wick length of approximately 5/8 inch from the top of the bulb to the end of the metal frame.

An *aspirated psychrometer* which was designed and built at the Laboratory of Engineering, Bureau of Occupational Safety and Health, Cincinnati, Ohio, was used to obtain the dry- and wet-bulb temperatures with which the sling psychrometer readings were compared. The thermometer bulbs in this instrument were well shielded and insulated from radiant effects. Air was drawn over the thermometer bulbs by a small centrifugal fan driven by a 115-volt motor. The instrument was checked for radiation pickup by locating it in the beam of a 650-watt bathroom-type heater which was operated intermittently. No changes in dry- and wet-bulb temperatures due to variations in radiation intensity were observed.

Thermometers used in the aspirated psychrometer was duplicates of those on the sling psychrometer. The thermometers for both instruments were calibrated against a National Bureau of Standards Certified Thermometer, and indicated corrections were made in all data.

A globe thermometer, consisting of a 6-inch-diameter, blackened copper sphere, fitted with a mercury-in-glass thermometer, was used to obtain measurements of the radiant environment.

The air velocity at each point of reading was measured with an Alnor Type 8500 thermoanemometer.

Test Procedure

Readings were taken at various combinations of dry-bulb, wet-bulb, and globe temperatures. The range of each of these variables included in the tests was as follows:

Dry-bulb temperature	70°–90° F
Wet-bulb temperature	60°–65° F
Globe temperature	80°–160° F

Each set of readings consisted of a globe temperature, dry- and wet-bulb temperatures taken with the aspirated psychrometer, dry- and wet-bulb temperatures taken with the sling psychrometer, and air velocity, all taken in the above-named order. No tests were made until the air and globe temperatures in the room had reached equilibrium.

All readings were taken along a center line normal to the face of the radiant panels and at a height of 3½ feet above the floor. Since temperatures, particularly the globe temperature, varied with distance from the heated panel surface, it was important that all readings in a given set be taken at the same location. Reading locations were therefore marked on the floor, and the different instruments were centered on these marks. The center point for the sling psychrometer reading was marked by the end of a pipe cleaner extending horizontally from a ring stand.

All sling psychrometer measurements were taken with the thermometers facing the heated panels. For tests at the larger wet-bulb depressions, the distilled water applied to the wet-bulb wick was precooled to within a few degrees of the wet-bulb temperature.

The first series of tests, consisting of 33 sets of readings, was conducted under still air conditions (air velocities 15 to 35 fpm). In a second series consisting of 9 sets of readings, the room-air velocity at the point of measurement was held at approximately 225 fpm.

A third series of tests was conducted at still air conditions to determine if the errors caused by radiation pickup could be reduced by using a highly reflective psychrometer frame. For these tests the psychrometer frame was wrapped with aluminum foil and the thermometers were replaced on top of the foil.

In every set of readings the temperatures obtained with the sling psychrometer were higher than those indicated by the aspirated psychrometer. The differences between the readings of the two instruments, after corrections obtained from thermometer calibrations, were judged to be the errors in the sling psychrometer readings resulting from radiation pickup.

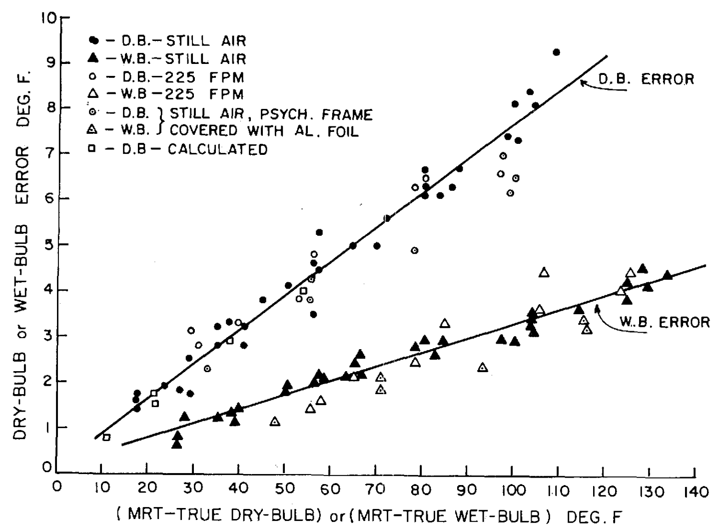

FIGURE 1. Errors in sling psychrometer readings due to radiation pickup (DB error versus MRT—DB, WB error versus MRT–WB).

Results of Radiation Pickup on Sling Psychrometer Readings

The results of this portion of the study are shown in Figures 1 and 2. In Figure 1 the errors in sling psychrometer readings due to radiation pickup are plotted against the differences between the mean radiant temperature (MRT) and the true dry-bulb or wet-bulb temperatures. Mean radiant temperatures were calculated by the equation

$$\mathrm{MRT} = [T_g^4 + 1.03 \times 10^8 \sqrt{V}\,(t_g - t_a)]^{0.25} - 460 \qquad (1)$$

where T_g = globe temperature (°F absolute).
V = air velocity (fpm).
t_g = globe temperature (°F).
t_a = air temperature (°F).

The dry-bulb and wet-bulb data collected in the first series of tests, made at nominally still air conditions, are shown by solid circles and solid triangles, respectively. The straight lines in Figure 1 were fitted to these points by the method of least squares. Both of these lines, if extended, will pass very near the origin. The open circles and open triangles show data obtained in tests made with air velocities of approximately 225 fpm. With the coordinates used in Figure 1, these data show fair agreement with the data obtained at still air conditions.

The dry- and wet-bulb data obtained with the psychrometer frame wrapped with aluminum foil are shown by dots within circles and dots within triangles, respectively, in Figure 1. It will be noted that these points fall below the dry-bulb and wet-bulb error curves, indicating that radiation pickup was reduced somewhat by making the sling psychrometer frame highly reflective. However, the amount of improvement resulting from this change is relatively small.

According to Threlkeld,[3] the error caused by radiation on an unshielded dry-bulb thermometer can be calculated by the equation

$$t_{db} - t_a = C\,(\mathrm{MRT} - t_{db}) \qquad (2)$$

where t_{db} = actual reading of the irradiated thermometer (°F).
t_a = true dry-bulb temperature (°F).
C = a constant which depends on air velocity, dry-bulb temperature, and MRT.

With this equation, errors were calculated for the five conditions listed in Table I, all of which are within or near the dry-bulb temperature range covered in the tests. The calculated errors for these five points are shown by squares in Figure 1. The agreement between theory and field measurements appears to be excellent.

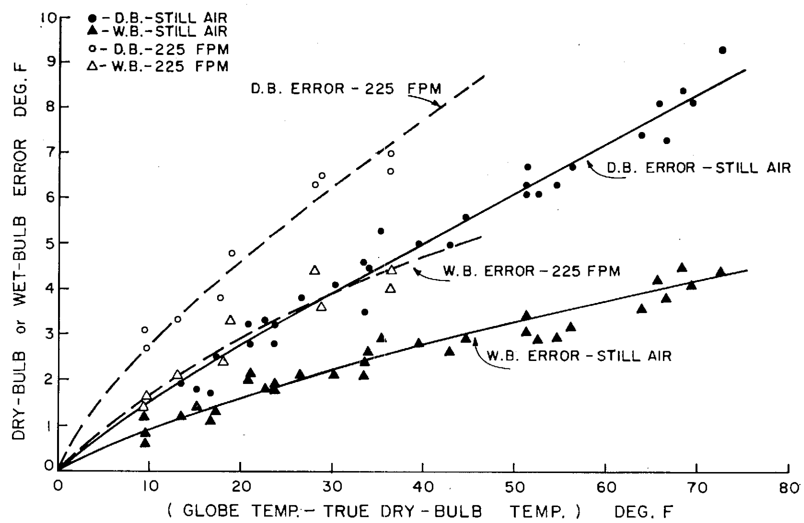

FIGURE 2. Errors in sling psychrometer readings due to radiation pickup (DB and WB errors versus globe–DB).

TABLE I

Calculated Dry-Bulb Thermometer Error Due to Radiation (°F)

MRT	t_{db}	MRT-t_{db}	C^a	Error t_{db}-t_a	t_a	MRT-t_a
120	100	20	0.085	1.7	98.3	21.7
120	85	35	0.082	2.9	82.1	37,9
120	70	50	0.079	4.0	66.0	54.0
90	80	10	0.075	0.75	79.25	10.75
90	70	20	0.073	1.5	68.5	21.5

[a]Values of C were determined for an air velocity over the thermometer bulb of 900 fpm.

TABLE II

Variation in Differences (°F)

MRT	DB	WB	MRT–WB	MRT–DB
85	85	55	30	0
100	85	70	30	15
115	85	85	30	30

Although Figure 1 has been useful in demonstrating the effect of the reflectivity of the psychrometer frame, and in showing the agreement between theory and experimental results, the wet-bulb error curve is likely to be applied incorrectly. Dry- and wet-bulb temperature readings might logically be expected to be in error due to radiation, only when the MRT differs from the dry-bulb temperature. However, no such limitation is indicated in the wet-bulb error curve of Figure 1. This curve seems to suggest that the wet-bulb error is dependent only on the difference between MRT and wet-bulb temperature, regardless of whether that difference is due entirely to MRT elevation, to wet-bulb depression, or to a combination of the two. These various conditions are illustrated in Table II where the same value of MRT – wet-bulb is shown for MRT elevations of 0°, 15°, and 30°F.

To avoid the above difficulty, both dry- and wet-bulb errors have been plotted against the difference between globe and dry-bulb temperatures in Figure 2. As in Figure 1, the shape of the curves for still air conditions is reasonably well defined by the plotted points. However, as might be expected with the coordinates of Figure 2, the points for 225-fpm air velocity fall considerably above the still air curves. Although these points are few in number and rather scattered, dashed curves have been drawn through them.

All the curves of Figure 2 have been drawn by eye, and all have been extended to pass through the origin. It is self-evident that the dry-bulb curves should pass through the origin, for when globe and dry-bulb tem-

TABLE III
Examples of Effect of Sling Psychrometer Errors on Calculated Heat Transfer Rates and Heat Stress Indices

	A		B		C		D		E		F	
	True	Sling	True	Sling	True	Sling	True	Sling	True	Sling	True	Sling
1. Dry-bulb temperature (°F)	100	105	100	107.7	100	107.7	85	93.5	85	93.5	95	103.5
2. Wet-bulb temperature (°F)	70	72.7	70	74.7	85	89.7	70	75.1	65	70.1	70	75.1
3. Globe temperature (°F)	140	140	140	140	140	140	130	130	130	130	140	140
4. Air velocity (fpm)	25	25	225	225	225	225	225	225	225	225	225	225
5. MRT (°F)	163	160	201	191	201	191	201	189	201	189	208	197
6. Vapor pressure (mm Hg)	10.6	11.7	10.6	13.0	26.7	30.9	14.7	17.3	10.3	12.4	11.9	14.6
7. Relative humidity (%)	22	21	22	21	55	50	48	43	34	31	28	27
8. Convection (Btuh)	30	50	100	250	100	250	−190	−30	−190	−30	—	170
9. Radiation (Btuh)	1190	1140	1860	1680	1860	1680	1860	1650	1860	1650	1980	1790
10. Metabolism (Btuh)	750	750	750	750	750	750	750	750	750	750	750	750
11. E_{req} (Btuh)	1970	1940	2710	2680	2710	2680	2420	2370	2420	2370	2730	2710
12. E_{max} (Btuh)	610	580	2270	2100	1100	800	1970	1780	2290	2140	2170	1980
13. AET (min)	11	11	34	26	9	8	33	25	115	65	27	21
14. HSI	323	334	119	128	246	335	123	133	106	111	126	137
15. Effective temperature (°F)	93	94	93	94	98	100	92	93	90	91	93	94

peratures are the same there can be no radiation error.

The literature provides ample evidence that the wet-bulb error curves should also pass through or very near the origin. For conditions of zero MRT elevation and adequate air velocity, Kiefer and Stuart[4] state that radiation to an unshielded wetted bulb of a mercury thermometer "may be accounted with adequate accuracy by reducing the observed wet-bulb temperature by about 1.6% of the difference between the dry-bulb and wet-bulb thermometer readings." For the same conditions Madison[5] gives this error as "within about ½ of 1% of the true thermodynamic wet-bulb depression," and Carrier and Mackey[6] report that "except for exact research work, the error . . . is negligible." The optimum air velocity over the wet-bulb is given as about 500 fpm by Arnold,[7] about 1000 fpm by Dropkin,[8] and between 800 and 900 fpm by Carrier and Mackey.[6] The *ASHRAE Handbook of Fundamentals*[9] recommends a velocity of 900 fpm or more. It is estimated that the air velocity over the sling psychrometer dry- and wet-bulbs during tests averaged about 900 and 1050 fpm, respectively.

Effect of Temperature Error on Heat Stress Indices

As previously indicated, one of the objectives of the study was the investigation of the effect of radiation-produced errors in sling psychrometer readings on calculated heat stress indices. Three of the more widely used heat stress indices have therefore been calculated for six combinations of environmental conditions which have been designated by letters A through F in Table III. The conditions that would be measured in the field (dry-bulb, wet-bulb, globe temperatures, and air velocity) are listed in lines 1 through 4 of the table. The true values of these parameters are given in the first column under each condition. Dry- and wet-bulb temperatures listed in the adjoining columns are those that would be indicated for the environment by a sling psychrometer. These values were obtained by adding the corrections taken from the error curves of Figure 2 to the true temperatures.

Lines 5, 6, and 7 of the table give the MRT, vapor pressure, and relative humidity derived from the data listed above them. It will be noted that in all cases the MRT is lower and the vapor pressure is higher when calculated from sling psychrometer readings than when based on true conditions.

The heat transfer rates between man and his environment, listed in lines 8 through 12 of Table III, were calculated by Hatch's revised equations[10] as modified by Hertig and Belding[11] for the effect of light work clothes. These equations are

$$E_{req} = M + R + C \qquad (3)$$

$$R = 17.5\ (MRT - 95) \qquad (4)$$

$$C = 0.756V^{0.6}\ (t_a - 95) \qquad (5)$$

$$E_{max} = 2.8V^{0.6}\ (42 - VP) \qquad (6)$$

where E_{req} = required evaporative heat loss (Btuh).
M = metabolic heat production (Btuh)
R = radiative heat exchange (Btuh).
C = convective heat exchange (Btuh).
E_{max} = maximum evaporative heat loss (Btuh).
MRT = mean radiant temperature (°F) (see equation 1).
V = air velocity (fpm).
t_a = air temperature (°F).
VP = water vapor pressure of the air (mm Hg).

A metabolic rate of 750 Btuh was assumed for all conditions.

The allowable exposure time (AET) and the heat stress index (HSI) given in lines 13 and 14 were calculated by the following equations given by Belding and Hatch.[12]

$$AET = \frac{250 \times 60}{E_{req} - E_{max}} \qquad (7)$$

$$HSI = \frac{E_{req}}{E_{max}} \times 100 \qquad (8)$$

The heat transfer rates and the allowable exposure time may also be obtained from nomographs prepared by McKarns and Brief.[13]

The effective temperature, corrected for radiation, which is given in line 15 of Table III was determined by the following three-step procedure.[14]

1. Determine the vapor pressure (or absolute humidity) at the intersection of the dry-and wet-bulb temperature lines on the psychrometric chart.
2. Determine the pseudo wet-bulb temperature indicated by this vapor pressure (or absolute humidity) and a dry-bulb temperature equal to the globe temperature.
3. On the effective temperature chart draw a line from globe temperature on the dry-bulb scale to the pseudo wet-bulb temperature on the wet-bulb scale, and read the corrected ET at the intersection of this line and the observed air velocity line.

Effect of Wick Length

When a sling psychrometer is used to determine environmental conditions, the bulb of the wet-bulb thermometer is cooled by evaporation of water from the wick, but the stem of the thermometer remains at the temperature of the ambient air. The wetted wick should extend far enough above the thermometer bulb to cool the stem immediately above the bulb, and thus prevent the conduction of heat from the stem to the bulb. If the wick is too short, the true wet-bulb temperature will not be reached.

The length of wick required depends on several factors, one of which is the wet-bulb depression, or the difference between stem and bulb temperatures. Previous work has shown that wet-bulb depressions of 40°F or more may be encountered in hot industries, and tests have been made to determine the length of wick required under such conditions to eliminate errors due to stem conduction.

To study the effect of wick length on wet-bulb readings, additional holes were drilled in the frames of two identical psychrometers so that the wet-bulb thermometers could be extended an additional 1½ inches beyond the ends of the frames. The instruments were then fastened to a plywood disk 180 degrees apart with the thermometer bulbs extending beyond the edge of the disk. This assembly was mounted on the end of a shaft and rotated at such a speed that the wet bulbs were moving through the air at a velocity of 1000 fpm.

During each run one of the wet-bulb thermometers was fitted with a wick extending 2 inches above the top of the bulb, while shorter wicks of various lengths were applied to the other thermometer. Long and short wicks were alternated on the two thermometers to cancel out any differences in the thermometer calibrations.

All tests to determine the effect of wick length were made at approximately 105°F dry-bulb and 65°F wet-bulb temperatures. Throughout the tests the globe temperature was within one degree Fahrenheit of the dry-bulb temperature.

The results of the study of the effect of wick length on wet-bulb error are shown in Figure 3. At the specified test conditions, it was found that, when the wick terminated just at the top of the bulb, the resulting wet-bulb reading was too high by approximately 1.3°F. No errors were evident when the wick extended 0.8 inch or more above the bulb.

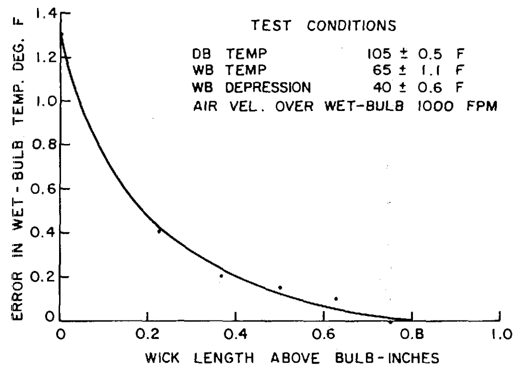

FIGURE 3. Effect of wick length on error in wet-bulb temperature due to stem conduction.

Discussion

All tests reported in this paper were made with typical field instruments, and the accuracy of the results is therefore limited to that which may be attainable with such instrumentation.

The results should be considered strictly applicable only to the range of test conditions covered, and to the sling psychrometer used in the tests. It has been shown that the magnitude of the radiation errors was changed by altering the emissivity of the psychrometer frame.

In spite of the above limitations, the authors believe that Figure 2 may be helpful. It can be used in predicting the approximate size of errors likely to occur when a sling psychrometer is used in the presence of high thermal radiation flux and, thus, where the error would be significant will discourage the use of this type of psychrometer under such conditions.

An inspection of the environmental data listed in Table III shows that, in the six examples selected, the sling psychrometer indicated dry- and wet-bulb temperatures which were higher than the true temperatures by as much as 8.5°F and 5.1°F, respectively. If one were interested in these temperatures per se, such errors would be unacceptable. However, data in the lower part of the table indicate that such temperature errors do not produce serious errors in the sum of the calculated heat exchange rates, and may or may not appreciably affect the calculated heat stress indices.

Because of the difference in dry-bulb temperature, the convective heat gain is lower and the radiative gain is greater when calculated for true conditions than for sling psychrometer indications. However, the total evaporative cooling requirements (E_{req}) based on the two sets of data are almost identical.

The ratio of dry- and wet-bulb errors is such that the vapor pressures determined from true and sling psychrometer readings do not differ greatly. At conditions of low vapor pressure the values of E_{max} for the two sets of data are also in good agreement, but at higher vapor pressures, as in condition C of Table III, differences become appreciable. Since the HSI is determined by the ratio of E_{req} to E_{max}, the values of this index also show good agreement at low vapor pressures, but differ appreciably for condition C.

The AET is inversely proportional to the difference E_{req}–E_{max}. For severe conditions such as A or C of Table III where this difference is large, the values of AET for the true and sling psychrometer data are almost identical. However, as this difference decreases and the allowable exposure time increases, this index becomes very sensitive, and the values calculated for the two sets of data can differ considerably as shown for condition E.

In determining the radiation-corrected effective temperature by the described method, the observed dry- and wet-bulb temperatures are used only to obtain the vapor pressure, which in turn is used to find the pseudo wet-bulb. As already indicated, the differences in vapor pressures for the two sets of data are small, and the corrected effective temperatures based on true and sling psychrometer temperatures are in good agreement.

Figure 3 shows that, if the wick on the wet-bulb thermometer covers only the bulb, the error due to stem conduction will be about 1.3°F. It also shows that, to reduce this error to zero, the wick should extend at least 0.8 inch above the top of the bulb. These values were obtained in an environment in which the MRT was the same as the dry-bulb temperature. When the psychrometer is exposed to high thermal radiation flux, both of these values would increase slightly. Threlkeld[15] recommends that the wick extend "one or two inches beyond the sensing bulb to help reduce heat conduction along the stem."

Earlier in the paper it was stated that the wick on the wet-bulb thermometer used in the radiation studies extended only ⅝ inch above the top of the bulb. A longer wick would undoubtedly have been used if the stem conduction tests had preceded the study of radiation effects. However, from Figure 3 it is evident that the maximum error attributable to the short wick was not more than 0.1°F, and this is well within the limits of accuracy of the study.

Conclusions

1. Sizable errors in dry- and wet-bulb temperatures will result when a sling psychrometer is used in the presence of high thermal radiation flux.

2. The rather large radiation-produced temperature errors obtained with a sling psychrometer will result in relatively small errors in the sum of the calculated heat transfer rates between man and his environment.

3. The rather large radiation-produced temperature errors obtained with a sling psychrometer may produce either large or small errors in the calculated heat stress index, depending on *(a)* the heat stress index being used and *(b)* the environmental conditions.

4. The wet-bulb wick should extend at least 0.8 inch (approximately one bulb length for the average thermometer) above the top of the bulb to eliminate errors due to stem conduction.

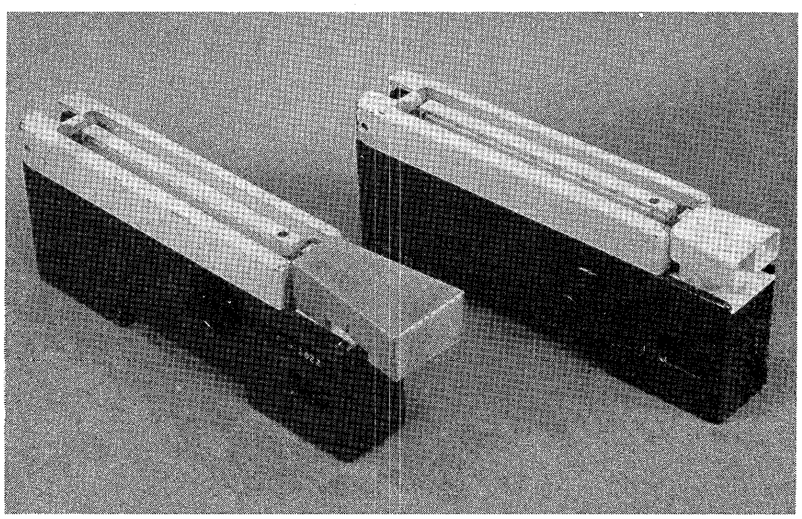

FIGURE 4. Aspirated psychrometer with and without radiation shield.

Instrument for Field Measurements

Author's Note:

When the sling psychrometer was shown to be unsuited for use in the presence of thermal radiation, a search was immediately made for another instrument that could be used in the field to measure dry- and wet-bulb temperatures. A Psychron, a battery-powered aspirated psychrometer manufactured by the Friez Instrument Division of The Bendix Corporation, was tested in the environmental test chamber and was found to be only slightly affected by thermal radiation. An aluminum shield was made to clip onto the removable air intake cowl which covers the thermometer bulbs, and with this shield in place, no error due to radiation pickup could be detected. This instrument also permits the use of a wick long enough to eliminate errors due to stem conduction. Two other advantages of the battery-powered psychrometer over the sling psychrometer become apparent in heat stress studies: (1) it appreciably reduces the drudgery of taking a large number of readings in a hot environment, and (2) it practically eliminates thermometer breakage which can be quite high with the sling. Pictures of this psychrometer with and without the shield are shown in Figure 4.

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