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Three moisture sensors were tested as a means for determining the surface wetness on carbonate building stones exposed to conditions that produce deposition of moisture. A relative-humidity probe, a gypsum-coated circuit grid, and a limestone-block resistor were tested as sensors for determining surface wetness. Sensors were tested under laboratory conditions of constant relative humidity and temperature and also under on-site conditions of variable relative humidity and temperature for eight weeks at Newcomb, NY. Laboratory tests indicated that relative humidity alone did not cause sensors to become saturated with water. However, the rates of drying indicated by the sensors after an initial saturation were inversely related to the relative humidity. On-site testing of the relative-humidity probe and the gypsum-coated circuit grid indicated that they respond to a diurnal wetting and drying cycle; the limestone-block resistor responded only to rainfall.

INTRODUCTION

Most processes of rock weathering involve moisture as a direct agent of the process; the presence of moisture films enables deterioration processes to proceed at more rapid rates.[1] The action of sulfur dioxide, dissolved in water, causes increased deterioration of carbonate building stones. Sulfur dioxide (in the presence of surface moisture) reacts with calcium carbonate, and, through several reactions, forms gypsum (calcium sulfate dihydrate), which is more soluble in water than calcium carbonate.[2] As part of a study to determine the effects of acid precipitation on calcium carbonate building stones,[3] a practical method was investigated to determine a time of wetness or a wetness factor for surfaces exposed to cyclic atmospheric conditions that produce surface depositions of moisture. Prior studies[3] have had to estimate sulfur dioxide loading rates because duration of wetness was not available.

A. Purpose and scope

The purpose and scope of this article are to describe three moisture sensors that were tested to develop a wetness factor for use in calculations of carbonate-stone deterioration. One sensor measures relative humidity directly for a reference. The second and third sensors were designed to simulate a carbonate-stone surface; they were modeled after similar devices used in a variety of applications including soil moisture,[4,5] leaf-surface moisture,[6] condensation in building walls,[7] and corrosion of metals.[8,9]

I. DESCRIPTION OF SENSORS AND TESTS

A. Description of sensors

To measure relative humidity, a Campbell Scientific model 201 relative-humidity probe[1] was used [Fig. 1(A)]. The model 201 relative-humidity probe contains a Phys-Chemical Research model PCRC-11 electrohumidity sensor and a Fenwal UUT-51J1 thermistor. Both the relative-humidity sensor and its associated thermistor are shielded in a stainless-steel, 40-mesh screen to impede contact of liquid water directly on the humidity sensor. The model 201 relative-humidity probe is protected from insolation and direct rainfall by a wooden cover. Changes in relative humidity cause the surface resistance of the relative-humidity sensor to vary.

A second sensor, the gypsum-coated circuit grid [Fig. 1(B)], was developed by modifying a Campbell model 231 leaf-wetness sensor. The gypsum-coated circuit grid is modeled after similar sensors coated with latex paints (without a gypsum coating) to simulate a plant-leaf surface for examinations of leaf-moisture retention.[6] This sensor consists of a circuit board with interlacing fingers of gold-plated copper. The sensor was arbitrarily coated with 5-mm-thick gypsum to spread the water droplets in contact with the sensor over the entire surface of the sensor. The coated and the uncoated sensor are shown in Fig. 2. Gypsum was produced by baking "Baker analyzed" reagent calcium sulfate dihydrate powder
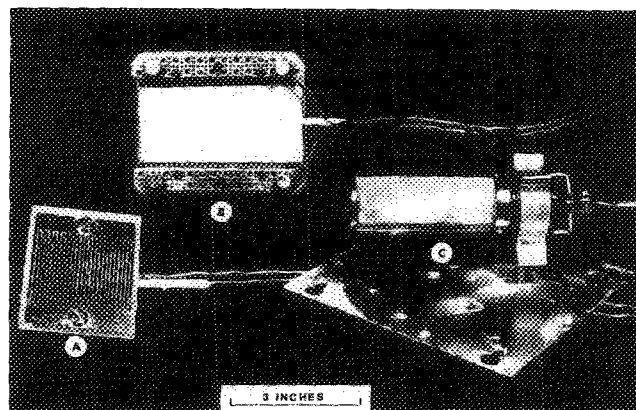

FIG. 1. Three moisture sensors: (A) relative-humidity probe, (B) uncoated circuit grid, and (C) limestone-block resistor.
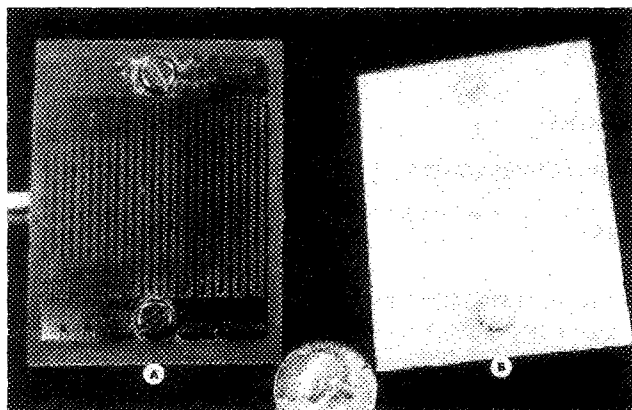
FIG. 2. Two circuit grids: (A) uncoated, (B) gypsum-coated.

at 140 °C for 24 h, and slurry to coat the sensor was prepared using 80 parts water to 100 parts dried calcium sulfate, by weight.[10]

A third sensor was developed which monitored moisture within an actual limestone sample (Fig. 1). A $10 \times 5 \times 1$-cm block of limestone was selected to provide a sensor of appropriate strength and a size similar to the gypsum-coated leaf sensor. The limestone block was mounted between two brass electrode plates. Contact between the electrode and the stone was assured by placing a foam-backed tape between the electrode plate and the plastic mount, thus firmly pressing the electrode plates against the limestone block. Electrical resistance of the limestone block varied as the water content of the stone changed.

In order to make moisture measurements, all three sensors were excited with a 4-V, 700-H square-wave current from the Campbell CR21 micrologger. Schematic wiring diagrams for the limestone-block sensor and the gypsum-coated leaf-wetness sensor are presented in Fig. 3. The alternating current avoids polarization of the sensors. The signal presented to the monitoring channel of any given sensor was proportional to the current flow through the sensor. Each sensor has a thermistor attached to it to determine the temperature in the microclimate surrounding the sensor. Thermistors were used to record any changes in temperature that may have significantly affected the wetness-factor reading for a given sensor. Temperature thermistors associated with each of the sensors did not show a noticeable increase in temperature with the application of the 4-V excitation cur-

rent. Sensors were excited and measurements were made at hourly intervals with the micrologger. The sensor readings were processed to record a "wetness factor" that ranged from 0% to 100%. For the relative-humidity sensor, the wetness factor is equivalent to relative humidity.

B. Sensor calibration

The relative-humidity probe was manufactured to $\pm 1\%$ tolerance with respect to standard calibration curves established by the manufacturer and calibrated in an environmental chamber. The gypsum-coated circuit grid and the limestone-block resistor were calibrated in the U.S. Geological Survey's water-quality laboratory in Denver, CO, by noting the voltages presented to the monitoring channels when the sensors were dry, and again when the sensors were saturated with distilled water. The slope multipliers and zero offsets for each sensor were calculated with the following equations:

$$\text{wetness factor} = M(V_{sw}) + B, \tag{1}$$

$$M = 100/(V_{sw} - V_{sd}), \tag{2}$$

and

$$B = -M(V_{sd}), \tag{3}$$

where M is the slope multiplier, V_{sw} is the voltage when the sensor is wet, V_{sd} is the voltage when the sensor is dry, and B is the zero intercept.

C. Laboratory tests

After calibration, the three sensors were suspended in a closed glass chamber over saturated salt solutions to provide conditions of known relative humidity. The salt solutions used and the reported equilibrium relative humidity of the solutions are shown in Table I.[11] The chamber was constructed from a 200-mm (inside diameter) glass desiccator. A hole was cut in the center of the cover as a port for the sensor cables. The cable port was sealed with silicon caulking to prevent the exchange of gases. The thickness of the glass jar provided a thermal mass that buffered minor changes in laboratory temperatures. During each of these laboratory tests, the air-dried sensors were inserted in the chamber and then operated for several hours to measure the dry-state readings. Then the sensors were removed from the chamber, saturated with distilled water, and reinstalled into
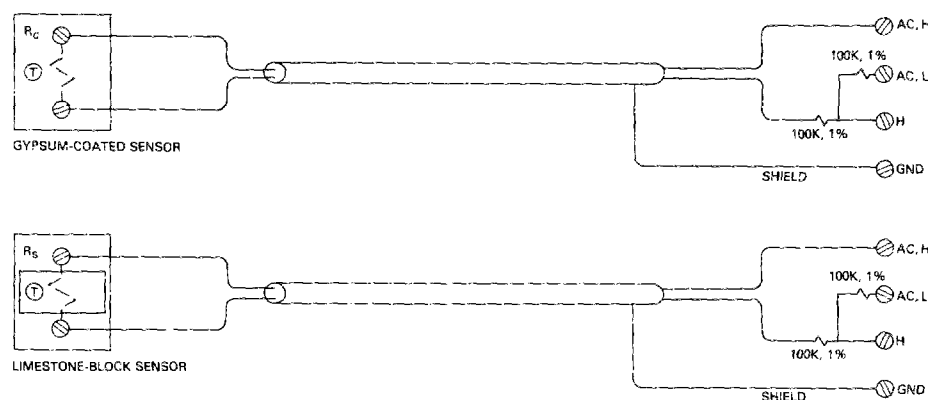

FIG. 3. Schematic wiring diagram for the gypsum-coated circuit grid and the limestone-block resistor.[2] R_c is the resistance of the gypsum-coated sensor; R_s is the resistance of the limestone-block sensor; T is the temperature probe associated with the sensor. AC,H; AC,L; H; and GND are terminal labels on the Campbell CR21 data logger. ac excitation and analog measurement circuits are both connected internally to terminal L. Cables used are from Campbell Scientific, Inc.

TABLE I. Relative humidity at a given temperature within a closed space, when an excess of the indicated substance is in contact with a saturated aqueous solution of the given solid phase.[a]

Solid phase	Given temperature (°C)	Relative humidity above saturated solution (%)
Lithium chloride	20	15
Calcium chloride hexahydrate	24.5	31
	20	32.3
	18.5	35
	10	38
	5	39.8
Ammonium chloride	30	77.5
	25	79.3
	20	79.5

[a] Weast (1982), p. E-44.

the chamber. After being saturated with distilled water, the sensors were monitored until an equilibrium with the salt solution appeared to have been reached; then each test was terminated. During the testing periods, the chamber was sealed to prevent the transfer of gases into or out of the chamber. The chamber was left undisturbed until equilibrium conditions were reached; then each test was terminated.

D. On-site tests

After the laboratory testing, the sensors were tested on site at the Newcomb, NY, National Acid Precipitation Assessment Program research site (Fig. 4). The sensors were

operated continuously on site from 1 August through 8 October 1986.

II. TESTING RESULTS

A. Laboratory tests

Laboratory tests of the sensors suspended in a closed glass chamber over a saturated salt solution indicated that drying times for the sensors were related to the equilibrium relative humidity of the salt solutions. Increased relative humidity in the chamber slowed the evaporation process, causing the sensors to remain wet for longer periods.

When the dry sensors were enclosed in the glass chamber with a desiccant (anhydrous calcium sulfate) or in a 15% relative-humidity atmosphere produced by a saturated lithium chloride solution, the dry sensors indicated no increase in readings after 24 h of exposure. After saturation with distilled water, the sensors took 55 h to return to their original readings (Figs. 5 and 6). Relative humidity remained high during the first 48 h, apparently because the moisture evaporating from the two other sensors buffered the relative humidity in the chamber, by providing a steady supply of moisture at a rate similar to the rate at which the salt solution could absorb additional moisture. The gypsum-coated circuit grid maintained a reading near 100% for 48 h; then readings quickly decreased to about 0%. During the 55 h, the readings for the limestone-block sensor decreased continuously as moisture evaporated from the block.

A third test exposed the sensors to a relative humidity of 31% produced by a saturated calcium chloride hexahydrate solution (Fig. 7). During this test, relative humidity increased to 85% and then decreased to a plateau at 65% before decreasing to the prewetting value of 25%. As in the experiment conducted at 15% relative humidity, the relative humidity in the chamber appeared to be buffered by the moisture loss from the gypsum-coated circuit grid and the limestone-block resistor. This experiment was repeated while the chamber was kept cool in a refrigerator (nominal
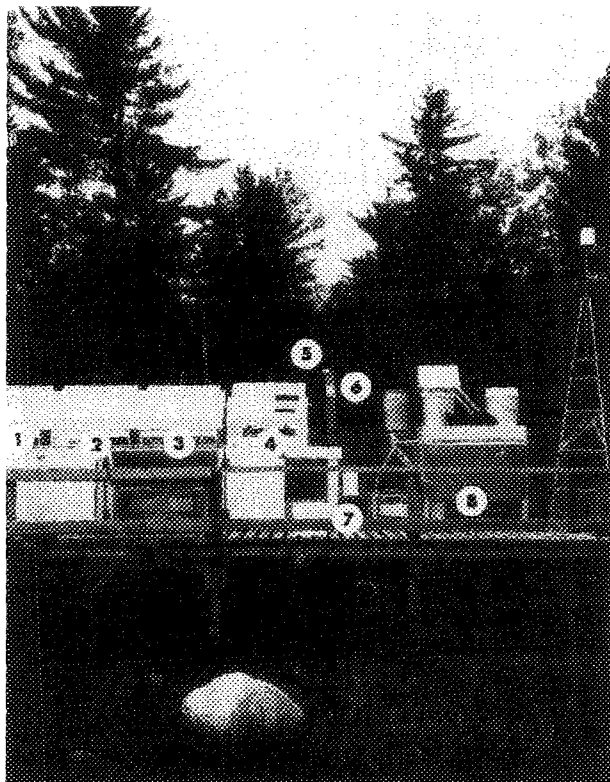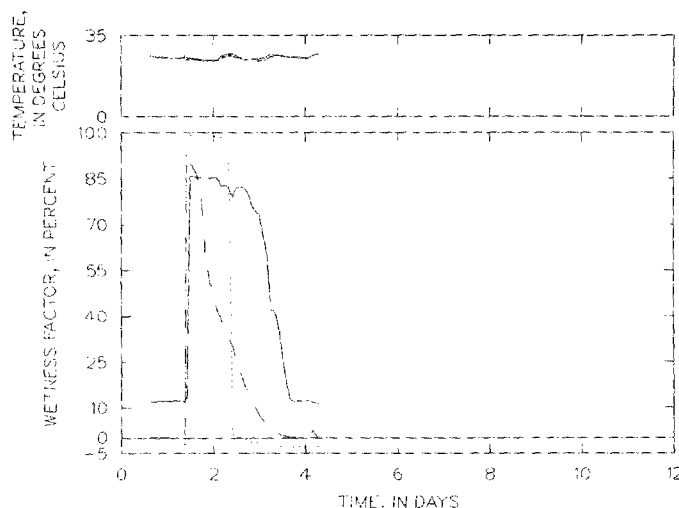

FIG. 4. Equipment at Newcomb, NY: (1) limestone, (2) glass, and (3) marble experiments; (4) adjustable-angle runoff experiment; (5) gypsum-coated circuit grid; (6) limestone-block resistor; (7) relative-humidity probe; and (8) recording precipitation monitor.

FIG. 5. Temperatures and drying curves for the relative-humidity probe (—), gypsum-coated circuit grid (...), and limestone-block resistor (– –) over anhydrous calcium sulfate.
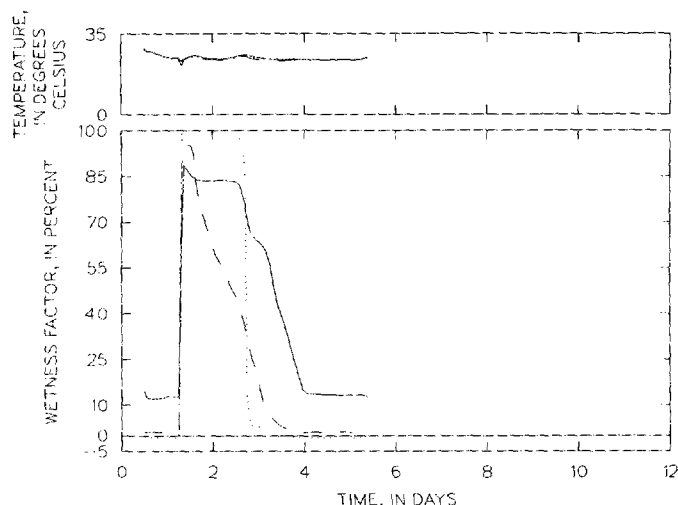
FIG. 6. Temperatures and drying curves for the relative-humidity probe (—), gypsum-coated circuit grid (···), and limestone-block resistor (– –) over a saturated lithium chloride solution with a nominal relative humidity of 15%.

FIG. 8. Temperatures and drying curves for the relative-humidity probe (—), gypsum-coated circuit grid (···), and limestone-block resistor (– –) over a saturated calcium chloride hexahydrate solution with a nominal relative humidity of 40%.

relative humidity was 40%). The sensors indicated an unexpected decrease in drying time under these cooler conditions (Fig. 8).

When the sensors were tested in 81% relative humidity over a saturated ammonium chloride solution, drying times for the gypsum-coated circuit grid and limestone-block resistor were extended to 144 h (Fig. 9). Similar to the test at 15% relative humidity, the gypsum-coated circuit grid maintained wetness-factor readings near 100% until the seventh day. Between the seventh and eighth days, readings decreased markedly to about 20% and then generally continued to decrease to less than 15%. The limestone-block resistor also almost dried completely by the end of the eighth day; however, the decrease in wetness-factor readings was gradual after the second day. Relative humidity in the chamber decreased slowly from a maximum of 89% to 83% when the test was ended.
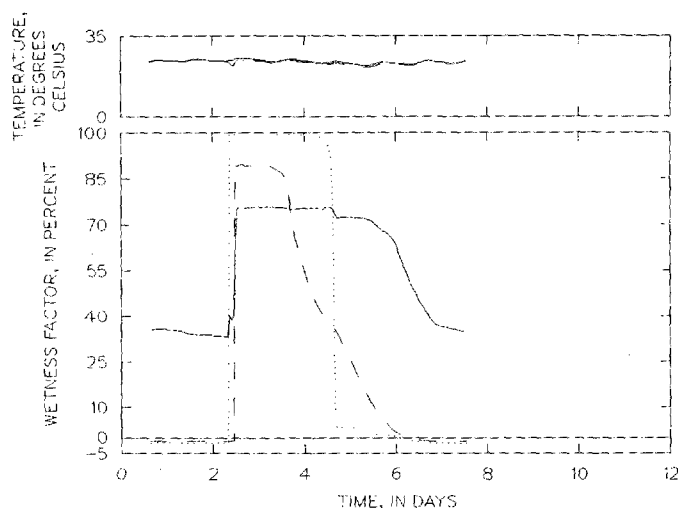
A final laboratory test was conducted with the dry sensors suspended over distilled water in the closed glass chamber. The high humidity caused the gypsum-coated circuit grid to reach a wetness factor of 90% in 12 h. No visible evidence of condensation occurred on any of the sensors; however, the gypsum-coated circuit grid darkened slightly as wetness-factor readings increased. Limestone-block sensor readings remained near 0% for 3.5 days until the limestone-block resistor was soaked with distilled water. After adding distilled water during the third day, both the gypsum-coated circuit grid and the limestone-block resistor maintained a wetness factor near 100% for the duration of the test. The relative-humidity probe indicated 93% when the distilled water was added (Fig. 10).

The laboratory tests indicate that the three sensors operated as expected, responding to changes in humidity with

FIG. 7. Temperatures and drying curves for the relative-humidity probe (—), gypsum-coated circuit grid (···), and limestone-block resistor (– –) over a saturated calcium chloride hexahydrate with a nominal relative humidity of 31%.
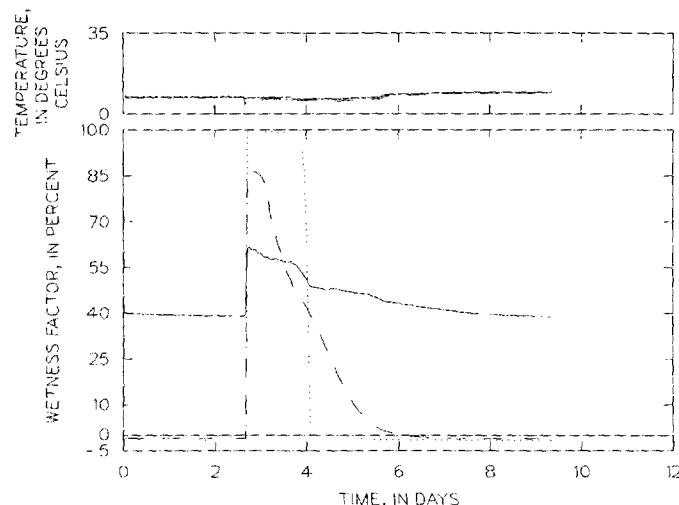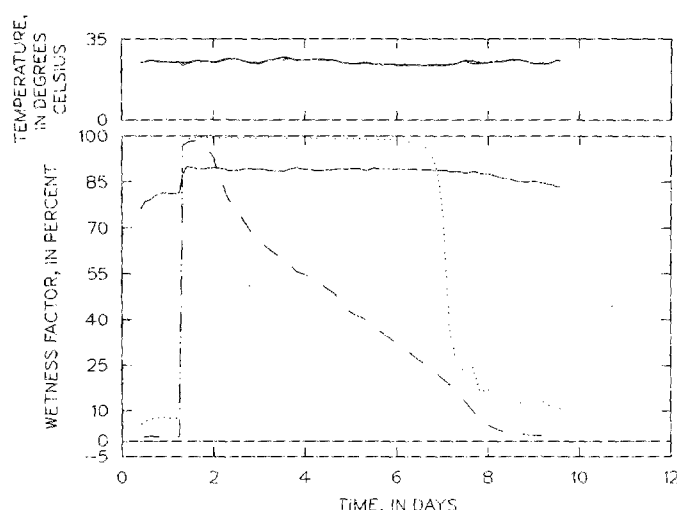

FIG. 9. Temperatures and drying curves for the relative-humidity probe (—), gypsum-coated circuit grid (···), and limestone-block resistor (– –) over a saturated ammonium chloride solution with a nominal relative humidity of 81%.
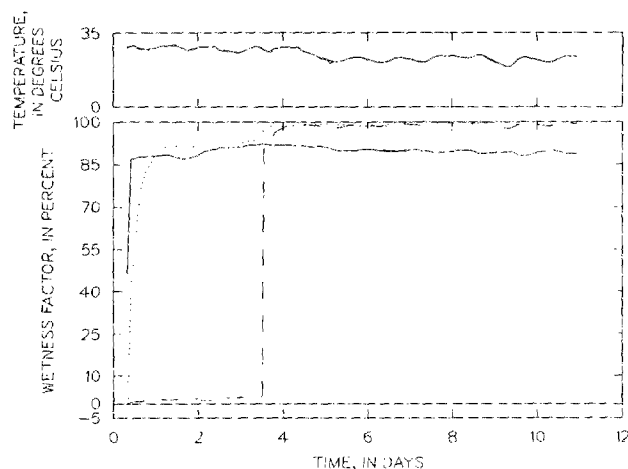
FIG. 10. Temperatures and drying curves for the relative-humidity probe (—), gypsum-coated circuit grid (···), and limestone-block resistor (– –) over distilled water.

FIG. 11. Temperature, rainfall, and drying curves for the relative-humidity probe (—), gypsum-coated circuit grid (···), and limestone-block sensor (– –) at Newcomb, NY, 4–11 August 1986.

altered rates of drying. However, further studies are being performed to explain the decreased drying time of the sensors in the refrigerator test. The wetness factor increases to near 100% when the sensors are wet with liquid water; however, increased humidity alone did not transport sufficient moisture to wet the limestone-block resistor within three days.

Under controlled laboratory conditions, all three sensors indicated three distinct drying periods that have been observed in early studies of the drying of porous solids[12]: (1) a constant drying-rate period while the surface remains wet; (2) a decreasing drying-rate period as the fraction of the wetted surface decreases; and (3) a second decreasing drying-rate period controlled by the rate at which moisture diffuses to the surface from the interior of the material.

Observation of these three periods of drying rate indicates that the sensors are performing as expected at simulating the actual response of a porous solid, in this case carbonate-stone building materials.

B. On-site tests

On-site tests of the three sensors at Newcomb, NY, indicated that a diurnal wetting cycle was recorded by the relative-humidity probe and the gypsum-coated circuit grid (Fig. 11). Both of these sensors recorded small wetness-factor values during midday and both recorded a wetness-factor value of about 100% toward evening and through the night. During dry periods, higher midday temperatures and increased solar insolation decreased the relative humidity and dried out the gypsum-coated circuit grid daily.

The limestone-block resistor did not record a diurnal cycle; evidently, evening dew formation was not enough to wet this sensor. Only when precipitation occurred did the wetness factor recorded by this sensor increase to more than 6%. Rainstorms produced rapid wetting followed by rapid drying. The limestone-block resistor appeared to dry more rapidly on site, because of wind, solar insolation, and temperature effects that were not present in the laboratory tests.
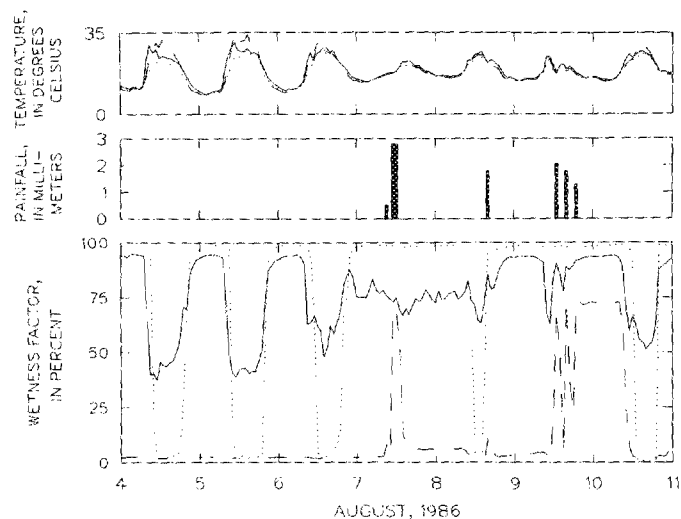
III. OPERATIONAL PROBLEMS

The three sensors performed according to expectations in the laboratory and on site; however, some problems were evident. The relative-humidity probe appears to perform satisfactorily; however, it will require semiannual replacement of the resistor chip to maintain accurate relative-humidity measurements. Some of the gypsum coating on the circuit grid was washed off with each rainstorm. After about three weeks of on-site testing, a pronounced thinning of the gypsum surface was observed; a more permanent coating material will have to be identified if this type of sensor is to be used on a long-term basis. Some corrosion problems at the electrical-contact points were noted on the limestone-block resistor; improvements in this design might incorporate stainless-steel instead of aluminum and brass fittings.

IV. DISCUSSION

Three moisture sensors were developed to determine surface moisture on carbonate building stones. A relative-humidity probe measured relative humidity directly. The second sensor consisted of a gypsum-coated circuit grid designed to simulate the surface of a carbonate stone. The third sensor was constructed from a small limestone block, providing a carbonate-stone surface on which moisture was measured.

Preliminary testing of these three sensors as a means of estimating the time of wetness of stone building materials has been evaluated. Determination of when an adequate film of water is present on carbonate-stone surfaces to facilitate reaction between acid-forming gases (such as sulfur dioxide) and the stone is the desired result of these tests. Each of the three sensors that have been tested provides a means for making different estimates of the deposition of surface moisture on stones. Further studies need to be made to determine which sensor is most appropriate in detecting surface-moisture depths that facilitate the uptake and corrosive action of acid-forming gases.

ACKNOWLEDGMENTS

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