DESCRIPTION AND TESTING OF THREE MOISTURE SENSORS

FOR MEASURING SURFACE WETNESS ON CARBONATE BUILDING STONES

By Randolph B. See, Michael M. Reddy, and Richard G. Martin

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CONVERSION FACTORS

The International System of Units (SI) in this report may be converted to
inch-pound units by using the following conversion factors:

Multiply	By	To obtain
centimeter	0.3937	inch
millimeter (mm)	0.03937	inch

Temperature can be converted to degree Fahrenheit (°F) or degree Celsius
(°C) by the following equations:

$$°F = 9/5 \ °C + 32 \qquad °C = 5/9 \ °F - 32$$

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ABSTRACT

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 onsite conditions of variable relative humidity and temperature for 8 weeks at Newcomb, New York. Laboratory tests indicated that relative humidity alone did not cause sensors to become saturated with water. However, relative humidity did control the rate at which sensors dried after being saturated with distilled water. Onsite 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 only responded 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 rapid rates (Ashton and Sereda, 1982). The action of sulfur dioxide, dissolved in water, causes rapid deterioration of carbonate building stones. Sulfur dioxide (in the presence of surface moisture) reacts with calcium carbonate, and, through several reactions, forms gypsum, which is more soluble in water than calcium carbonate (Schaffer, 1932). As part of a study to determine the effects of acid precipitation on calcium carbonate building stones (Reddy and others, 1986), 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 (Reddy and others, 1986) have had to estimate sulfur-dioxide loading rates because duration of wetness was not available.

Purpose and Scope

The purpose and scope of this report 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 (Haise and Kelley, 1946; Postlethwaite and Trickett, 1956), leaf-surface moisture (Gillespie and Kidd, 1978), condensation in building walls (Padfield and others, 1985) and corrosion of metals (Sereda, 1974; Sereda and others, 1982).

DESCRIPTION OF SENSORS AND TESTS
Description of Sensors

To measure relative humidity, a Campbell Scientific Model 201 thermistor[1] and relative-humidity probe was used (fig. 1A). The Model 201 relative-humidity probe contains a Phys-Chemical Research Model PCRC-11 electro-humidity 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 liquid-water formation directly on the humidity sensor. Changes in relative humidity cause the surface resistivity of the relative-humidity sensor to vary.

3 INCHES
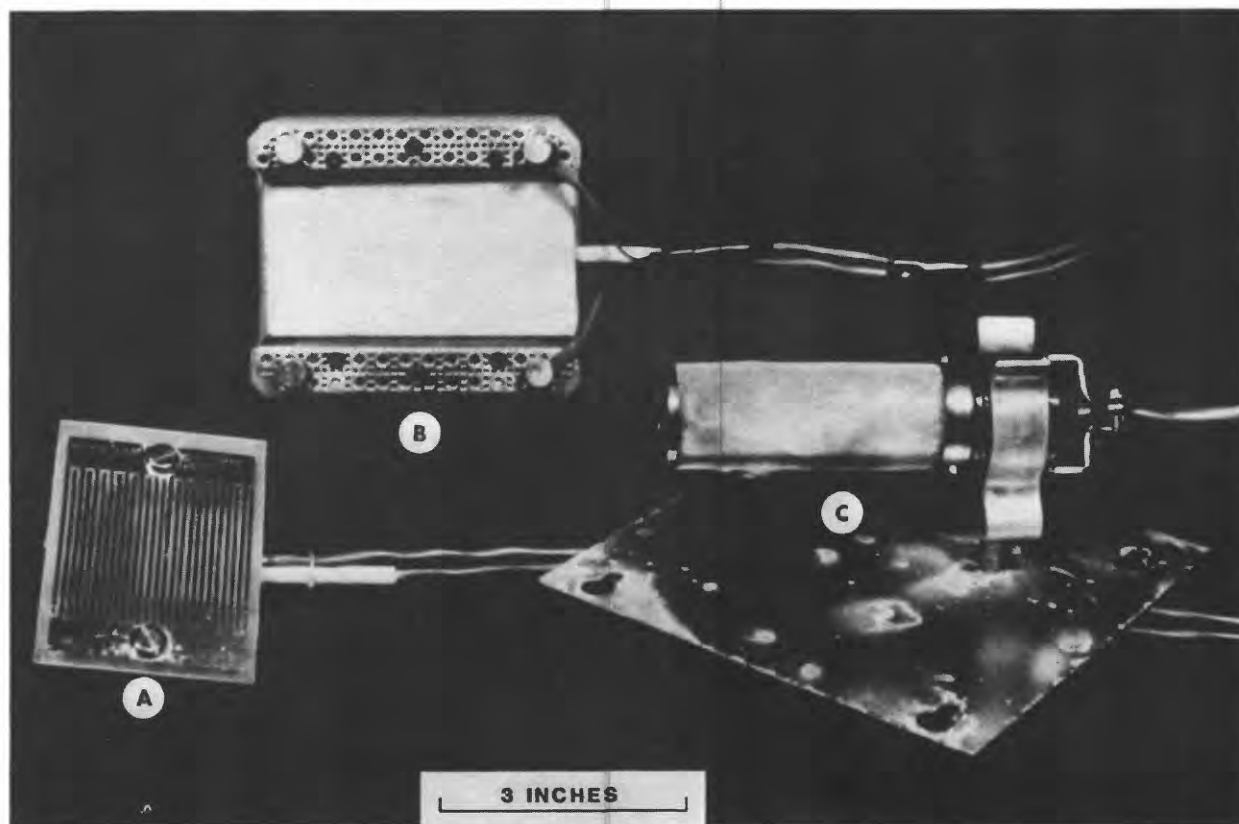
Figure 1.--Three moisture sensors: A. Relative-humidity probe; B. uncoated circuit grid; and C. limestone-block resistor.

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[1]Use of trade names is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

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A second sensor, the gypsum-coated circuit grid (fig. 1B), 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 to simulate a plant-leaf surface for examinations of leaf-moisture retention (Gillespie and Kidd, 1978). This sensor consists of a circuit board with interlacing fingers of gold-plated copper. The sensor was coated with 5 mm 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 figure 2. Gypsum was prepared by baking 'Baker analyzed' reagent calcium-sulfate-dihydrate-powder at 140 °C for 24 hours. A matrix to coat the sensor was prepared using 80 parts water to 100 parts calcium sulfate, by weight (Morrison, 1983).
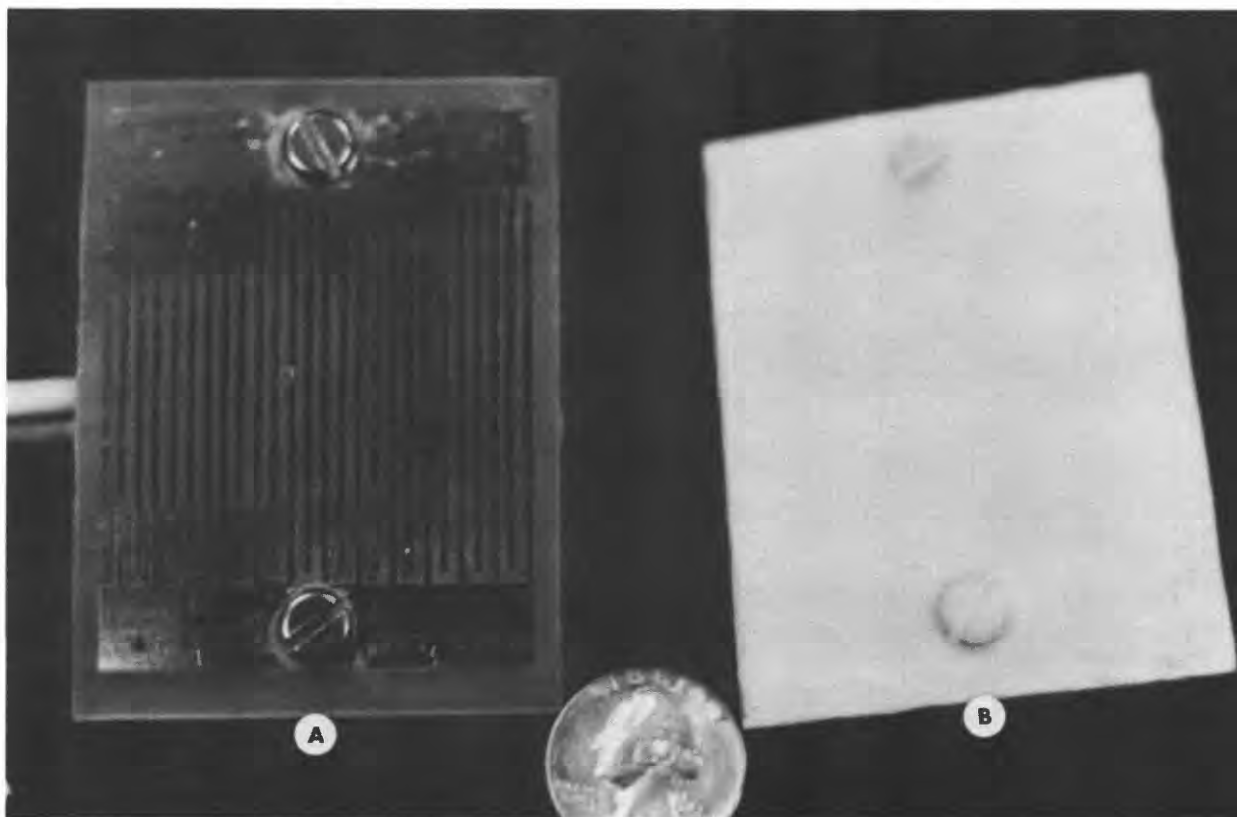
Figure 2.--Two circuit grids: A. Uncoated; and B. gypsum coated.

The third sensor was developed to monitor moisture within an actual limestone sample (fig. 1C). A 10-cm × 5-cm × 1-cm block of limestone was mounted between two electrodes; resistivity of the limestone block was measured as the water content of the block changed. Schematic wiring diagrams of the gypsum-coated circuit grid and of the limestone-block resistor are presented in figure 3.

In order to make resistivity measurements, all three sensors were excited with a 4-volt, 700-hertz, square-wave current. By using an alternating current, the polarity of the electrodes was changed rapidly, avoiding polarization of the sensors by direct current. Sensors were excited and

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Notes: R_c = Resistance of gypsum-coated sensor

R_s = Resistance of limestone-block sensor

(T) = Temperature probe associated with sensor

AC,H; AC,L; H; GND are terminal labels on the Campbell CR21 datalogger.
Cables used are from Campbell Scientific, Inc.. Alternating current inputs are
used for these sensors.
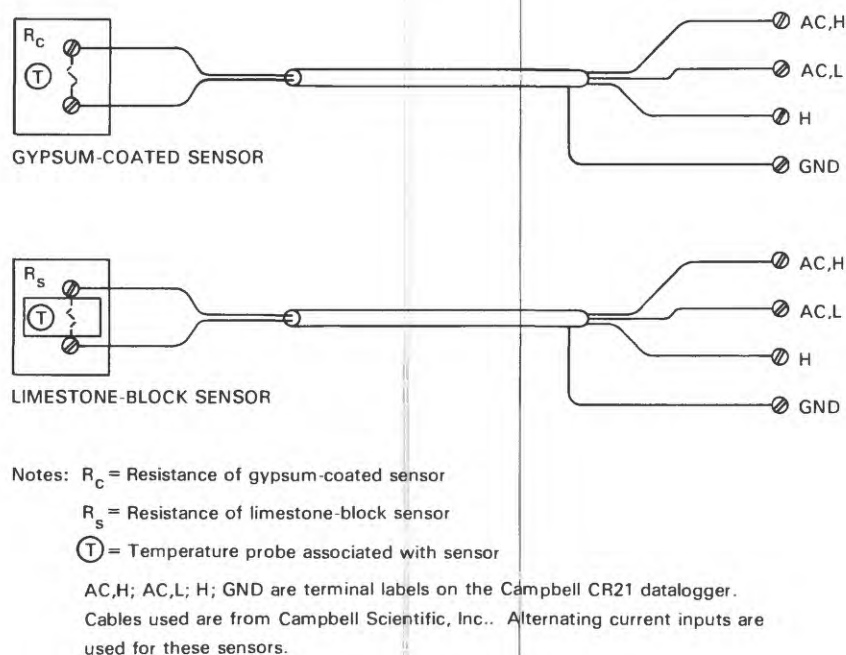
Figure 3.--Schematic wiring diagrams for the gypsum-coated circuit grid
and the limestone-block resistor.

resistivity was monitored at hourly intervals with a Campbell CR21 micro-
logger. The sensor voltage readings were processed to record a "wetness
factor" that ranged from 0 to 100 percent. For the relative-humidity probe,
the wetness factor is equivalent to relative humidity.

Each sensor has an associated 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.

Sensor Calibration

The relative-humidity probe was manufactured to + or - 1 percent
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. Geo-
logical Survey's water-quality laboratory in Denver, Colorado, by noting the
voltage when the sensors were dry, and then, again, when the sensors were
saturated with distilled water. The slope multipliers and zero offsets for
each sensor were calculated with the following equations:

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wetness factor = $M(V_{sw})-B$,   (1)

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

$B = -M(V_{sd})$ (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.

Laboratory Tests

After calibration, the three sensors were suspended in a closed glass chamber (fig. 4) over saturated salt solutions to provide conditions of known

Figure 4.--Closed glass chamber for testing sensors.

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relative humidity. The salt solutions used and the reported equilibrium
relative humidity of the solutions are shown in table 1 (Weast, 1979). 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
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.

Table 1.--*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*[1]

Solid phase	Given temperature (degrees Celsius)	Relative humidity above saturated solution (percent)
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

[1]Weast, 1982, p. E-44.

Onsite Tests

After the laboratory testing, the sensors were tested onsite at the
Newcomb, New York, National Acid Precipitation Assessment Program research
site (figs. 5 and 6). The sensors were operated continuously onsite from
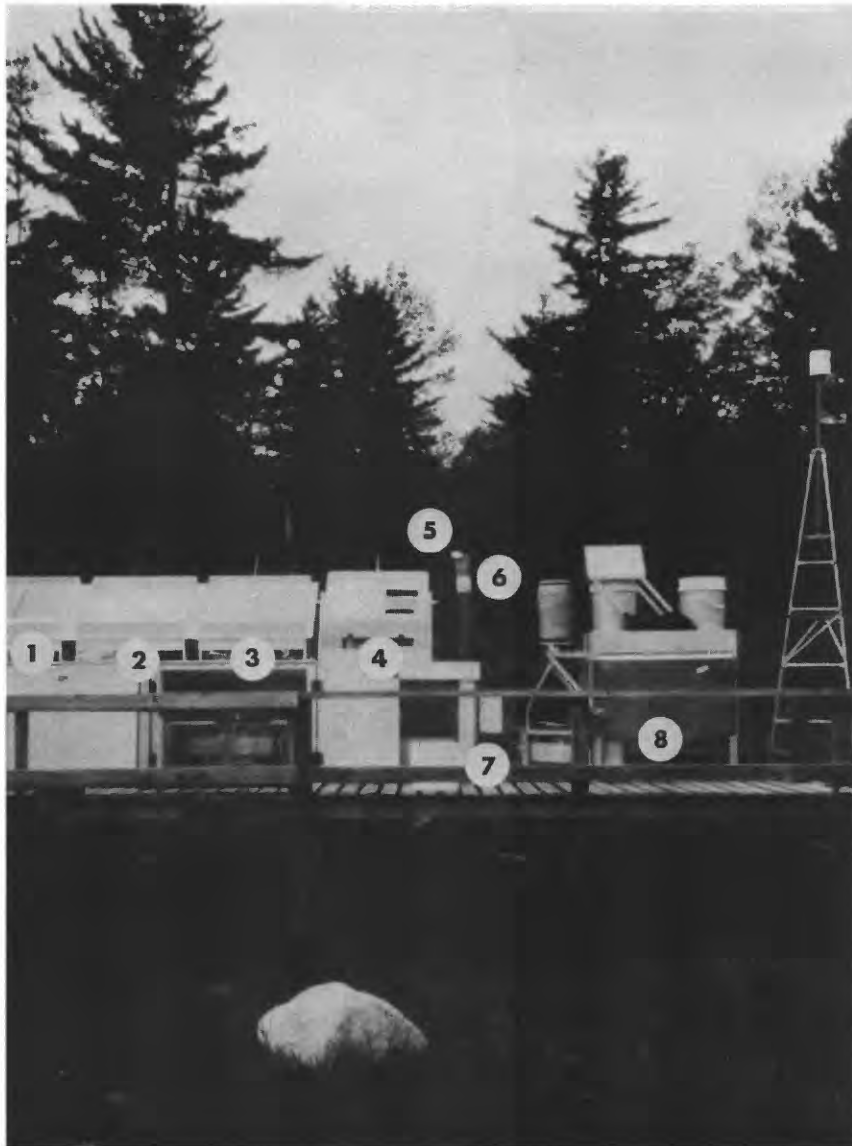August 1 through October 8, 1986.

Figure 5.--Equipment at Newcomb, New York: (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; (8) recording precipitation monitor.

TESTING RESULTS
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-percent relative-humidity atmosphere
produced by a saturated lithium chloride solution, the dry sensors indicated
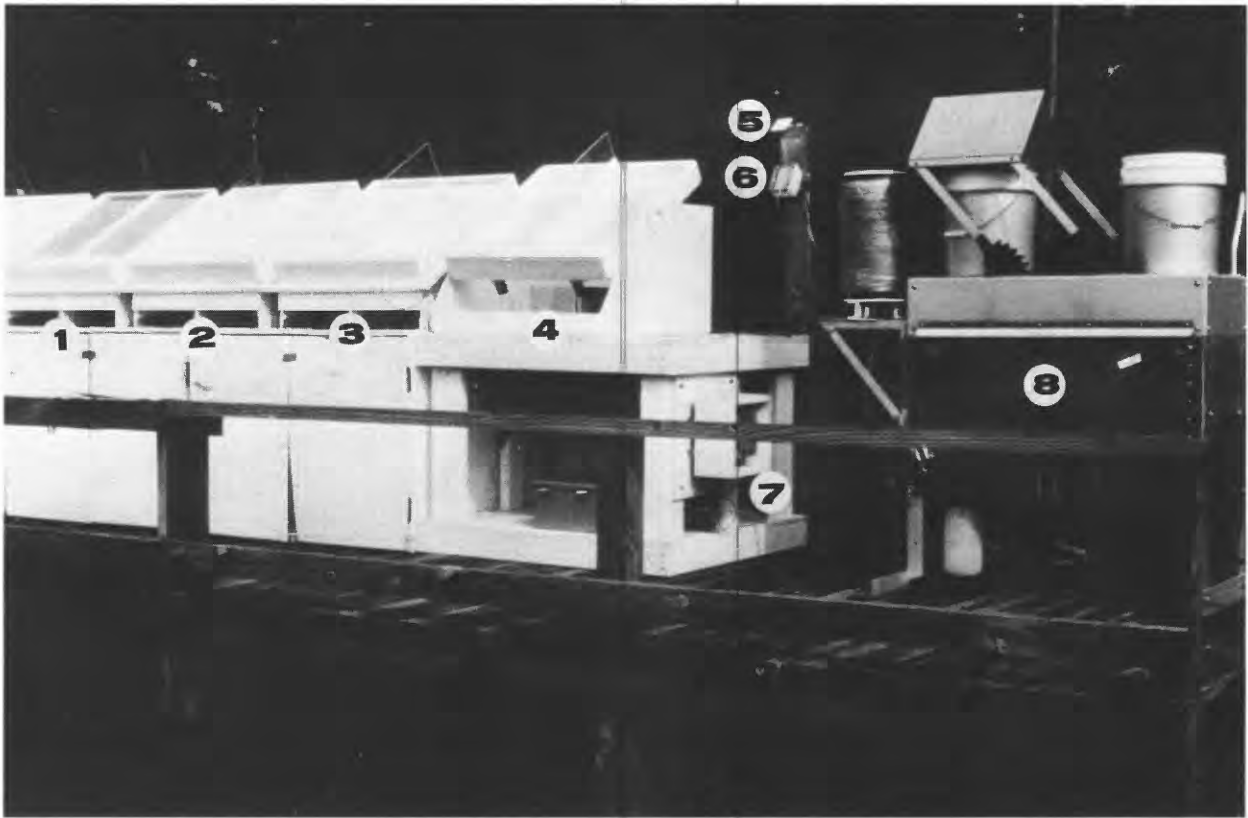
Figure 6.--Detailed photograph of equipment at Newcomb, New York:
(1) Limestone, (2) glass, and (3) marble experiments; (4) adjustable-
angle runoff experiment; (5) gypsum-coated circuit grid; (6) limestone-
block resistor; (7) relative-humidity probe; and (8) recording precipi-
tation monitor.

no increase in readings after 24 hours of exposure. After saturation with
distilled water, the sensors took 55 hours to return to their original
readings (figs. 7 and 8). Relative humidity remained high during the first 48
hours, apparently because the moisture evaporating from the other two 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 percent for 48 hours; then readings quickly decreased to about 0 percent.
During the 55 hours, the readings of the limestone-block resistor decreased
continuously as moisture evaporated from the block.

A third test exposed the sensors to a relative humidity of 31 percent
produced by a saturated calcium chloride hexahydrate solution (fig. 9).
During this test, relative humidity increased to 85 percent and then
decreased to a plateau at 65 percent before decreasing to the prewetting value
of 25 percent. As in the experiment conducted at 15-percent 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 relative humidity was 40 percent). The sensors indicated an un-
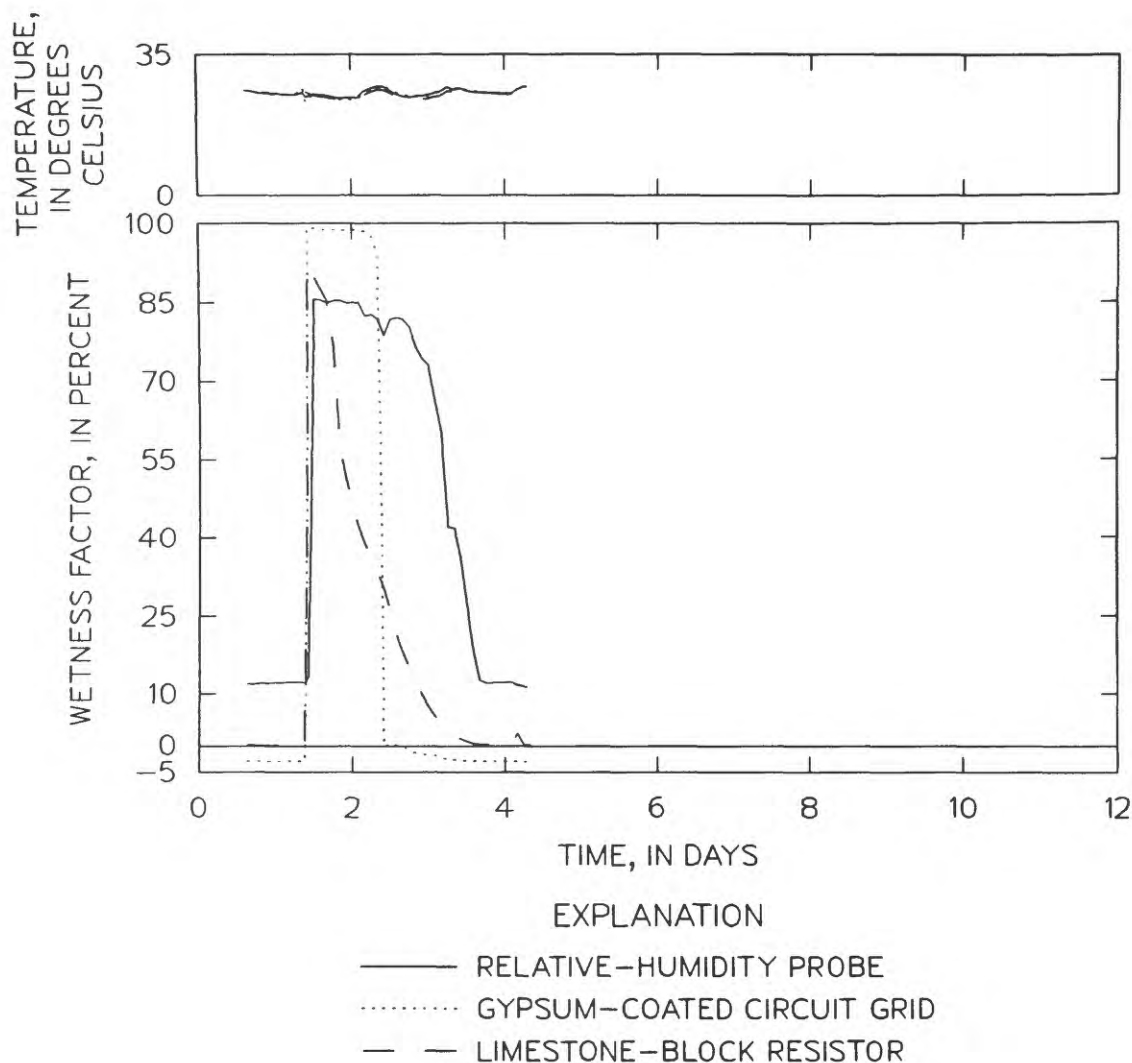expected decrease in drying time under these cooler conditions (fig. 10).

Figure 7.--Temperatures and drying curves for the relative-humidity probe, gypsum-coated circuit grid, and limestone-block resistor over anhydrous calcium sulfate.

When the sensors were tested in 81-percent relative humidity over a saturated ammonium chloride solution, drying times for the gypsum-coated circuit grid and limestone-block resistor were extended to 144 hours (fig. 11). Similar to the test at 15-percent relative humidity, the gypsum-coated circuit grid maintained wetness-factor readings near 100 percent until the 7th day. Between the 7th and 8th days, readings decreased markedly to about 20 percent and then generally continued to decrease to less than 15 percent. The limestone-block resistor also almost dried completely by the end of the 8th day; however the decrease in wetness-factor readings was gradual after the 2d day. Relative humidity in the chamber decreased slowly from a maximum of 89 percent to 83 percent when the test was ended.
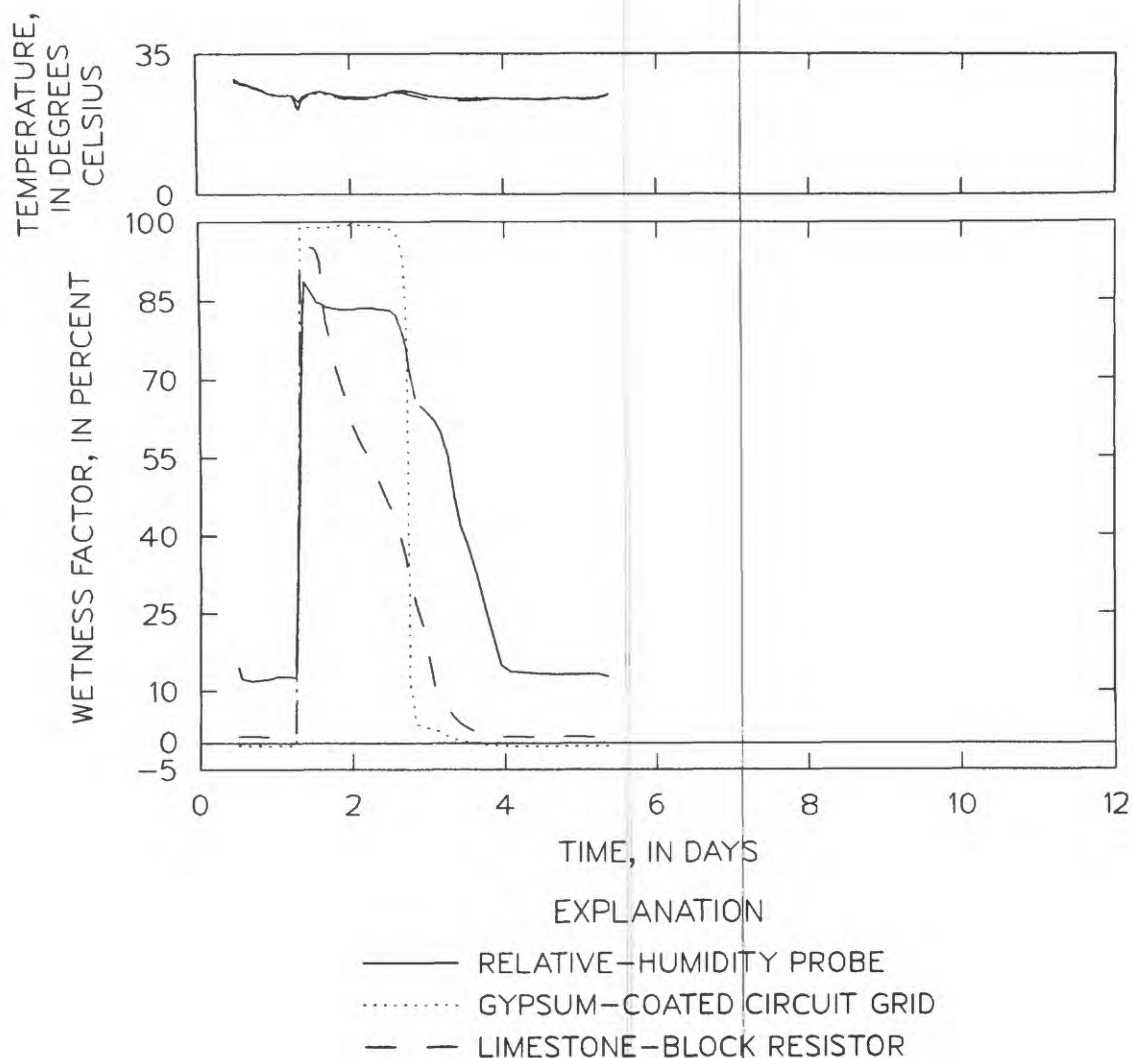
Figure 8.--Temperatures and drying curves for the relative-humidity probe, gypsum-coated circuit grid, and limestone-block resistor over a saturated lithium chloride solution with a nominal relative humidity of 15 percent.

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 percent in 12 hours. 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 resistor readings remained near 0 percent for 3.5 days until the limestone-block resistor was soaked with distilled water. After adding distilled water during the 3d day, both the gypsum-coated circuit grid and the limestone-block resistor maintained a wetness factor near 100 percent for the duration of the test. The relative-humidity probe indicated 93 percent when the distilled water was added (fig. 12).
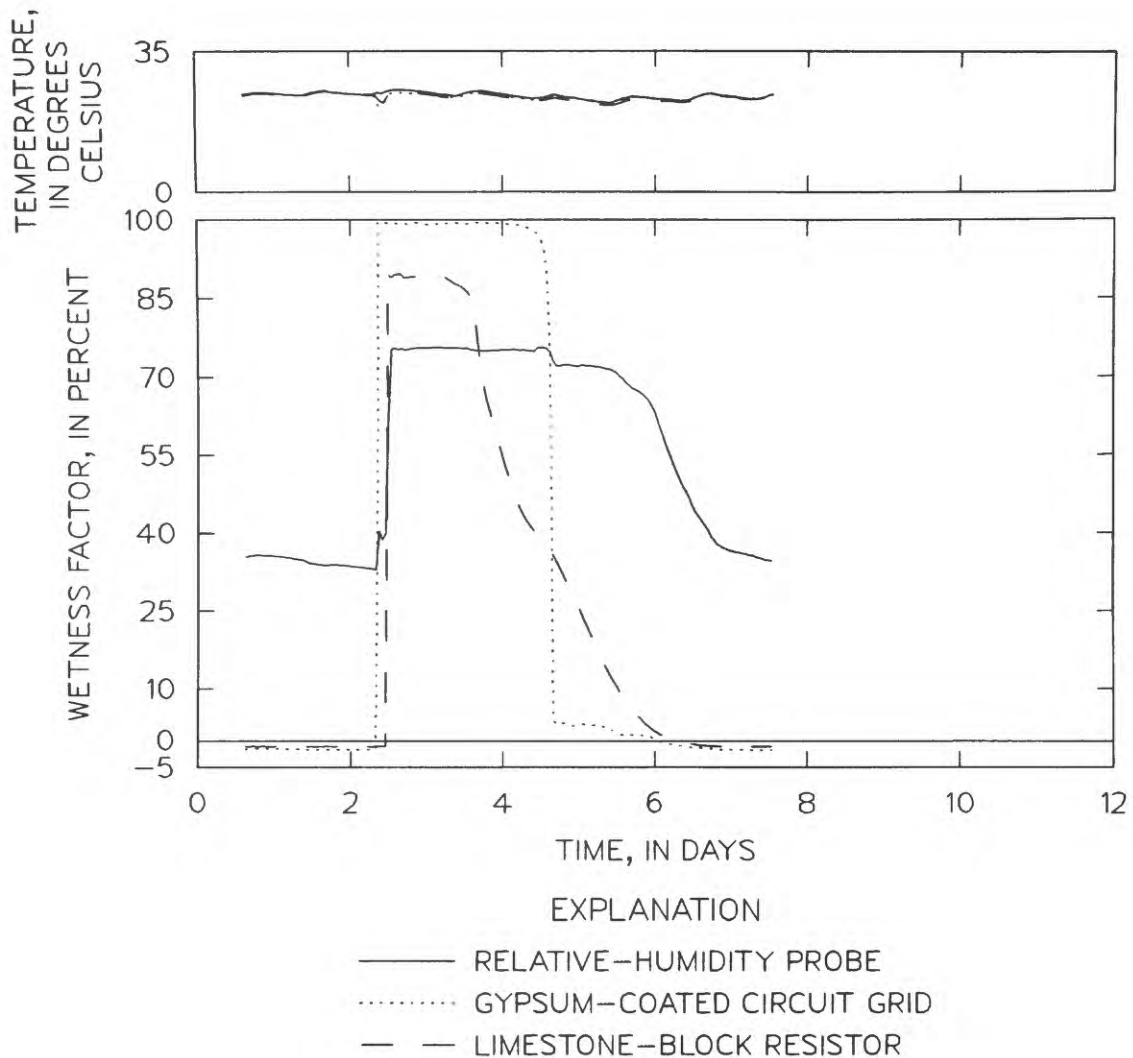
Figure 9.--Temperatures and drying curves for the relative-humidity probe, gypsum-coated circuit grid, and limestone-block resistor over a saturated calcium chloride hexahydrate solution with a nominal relative humidity of 31 percent.

The laboratory tests indicate that the three sensors operated as expected, responding to changes in humidity with altered rates of drying. However, further studies are being performed to explain the decreased drying time of the sensors in the refrigerator study. The wetness factor increases to near 100 percent when the sensors are wet with liquid water; however, increased humidity alone is not enough moisture to wet the limestone-block resistor within 3 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 (Newman, 1931):
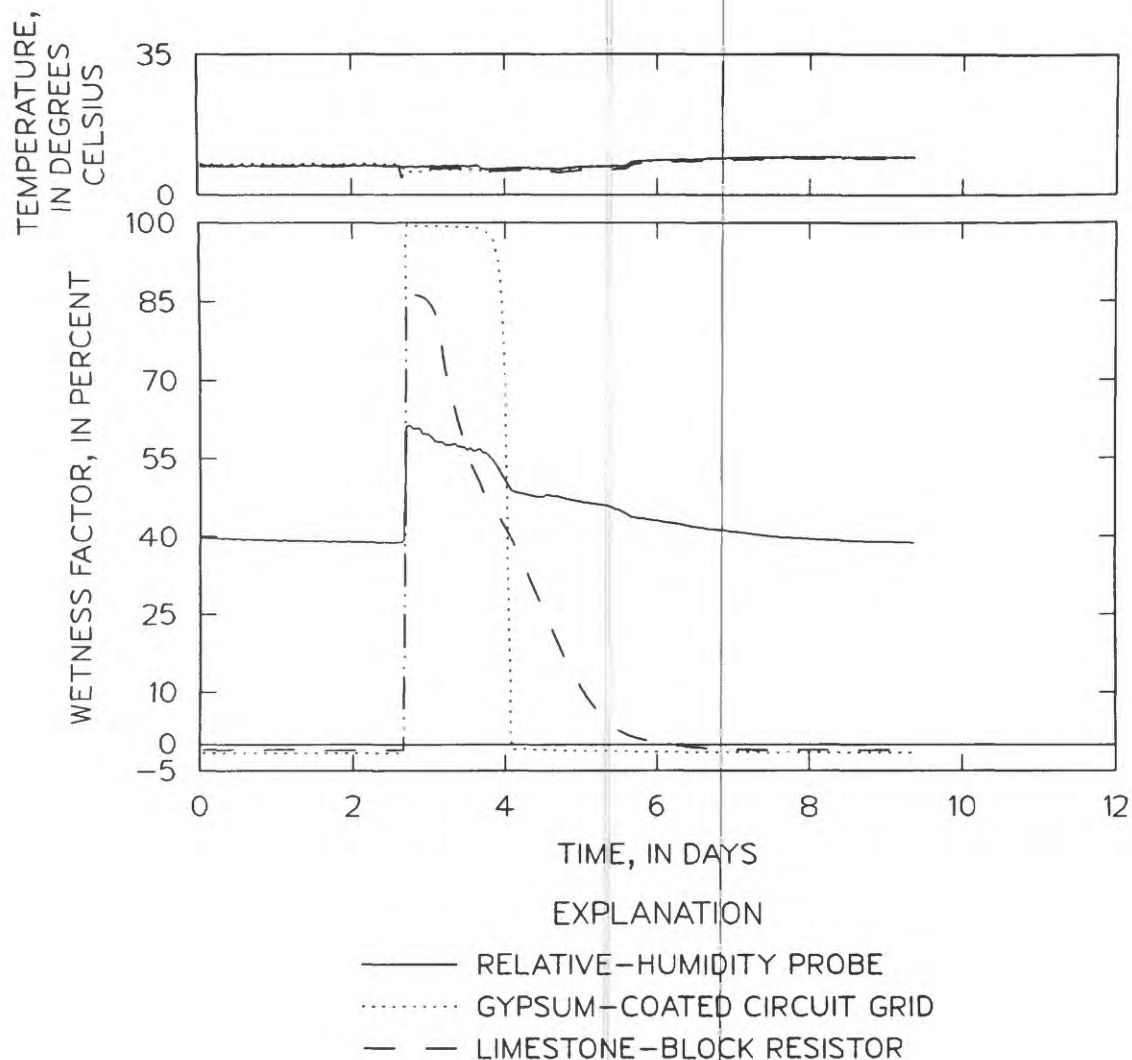
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Figure 10.--Temperatures and drying curves for the relative-humidity probe, gypsum-coated circuit grid, and limestone-block resistor over a saturated calcium chloride hexahydrate solution with a nominal relative humidity of 40 percent.

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.

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 indicate that the sensors are performing as expected at simulating the actual response of a porous solid, in this case carbonate-stone building materials.
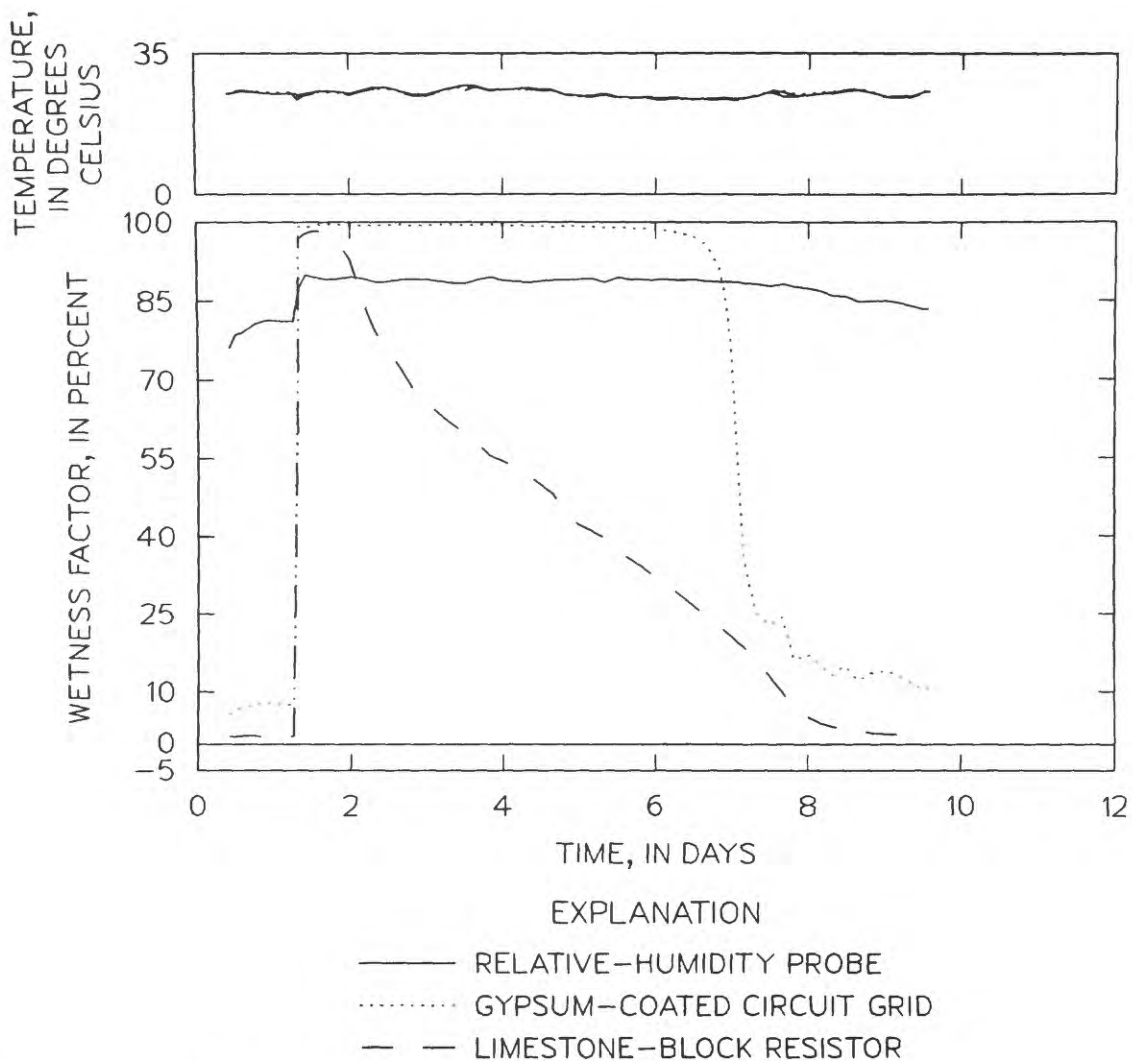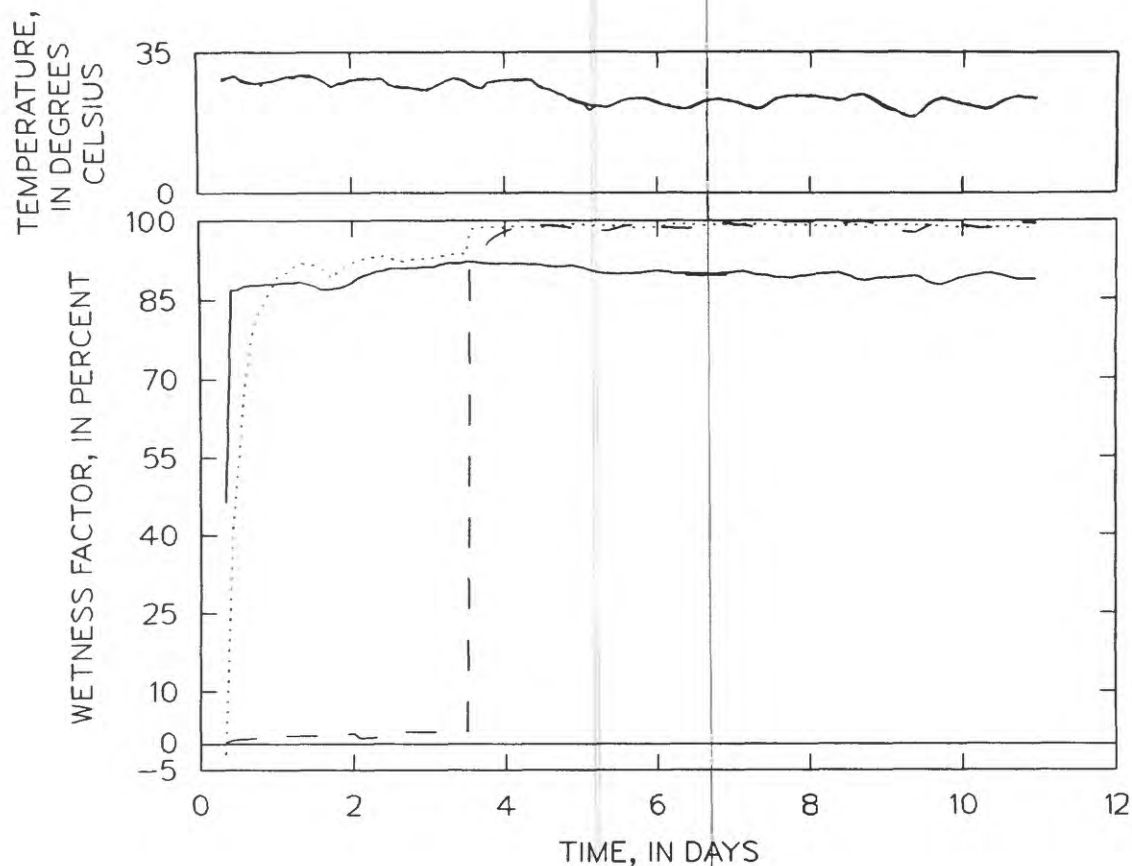
Figure 11.--Temperatures and drying curves for the relative-humidity probe, gypsum-coated circuit grid, and limestone-block resistor over a saturated ammonium chloride solution with a nominal relative humidity of 81 percent.

Onsite Tests

Onsite tests of the three sensors at Newcomb, New York, indicated that a diurnal wetting cycle was recorded by the relative-humidity probe and the gypsum-coated circuit grid (fig. 13). Both of these sensors recorded small wetness-factor values during midday and both recorded a wetness-factor value of about 100 percent 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 percent. Rainstorms produced rapid wetting followed by rapid drying. The limestone-block resistor appeared to dry more rapidly onsite, because of wind, solar insolation, and temperature effects that were not present in the laboratory tests.

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Figure 12.--Temperatures and drying curves for the relative-humidity probe, gypsum-coated circuit grid, and limestone-block resistor over distilled water.

OPERATIONAL PROBLEMS

The three sensors performed according to expectations in the laboratory and onsite; 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 3 weeks of onsite 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.
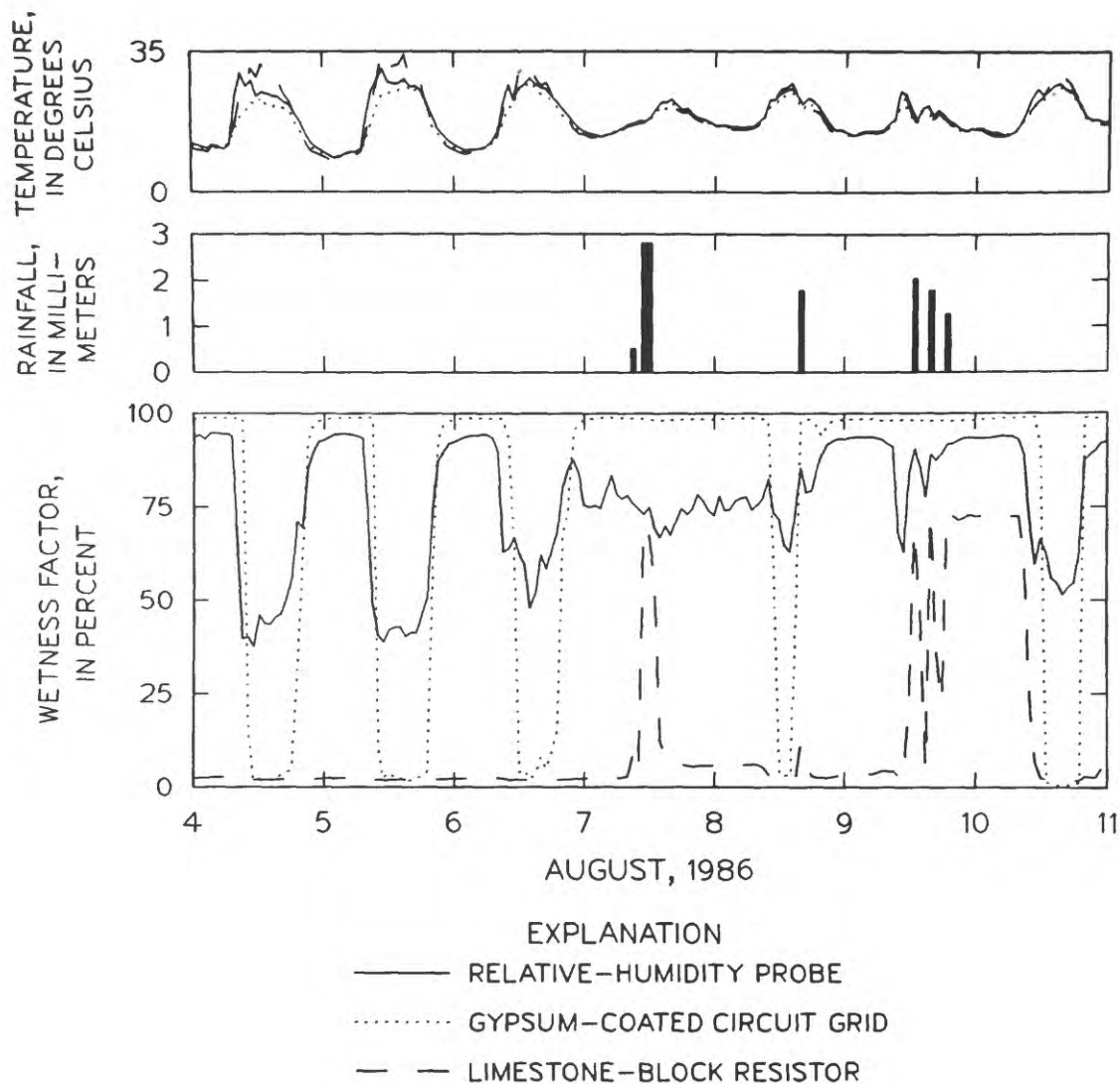
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Figure 13.--Temperatures, rainfall, and drying curves for the relative-humidity probe, gypsum-coated circuit grid, and limestone-block resistor at Newcomb, New York, August 4 to August 11, 1986.

SUMMARY AND CONCLUSIONS

Three moisture sensors were developed to determine surface moisture on carbonate stone 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 a rapid rate of 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.

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