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AN EVALUATION OF SELECTED INSTRUMENTS USED TO MEASURE THE MOISTURE CONTENT OF HARDENED CONCRETE

by

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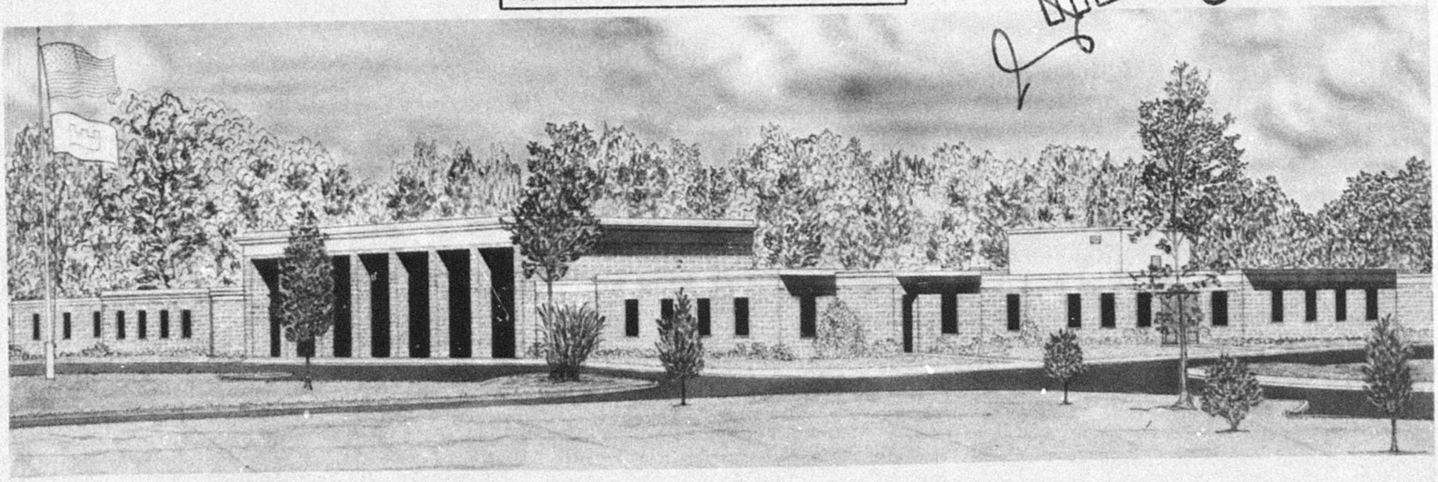

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Six types of gages for measuring moisture content of hardened concrete were studied to determine their behavior in long-term service. They were evaluated with respect to stability of measurement and response to moisture change. The gages were mounted in a 12- by 12- by 18-in. copper box and the box was filled with concrete and a copper lid soldered to it. The gages were monitored for a period of 800 days. For the first 194 days the gages were read in a hermetically sealed environment, then for 326 days (194 to 520 days) the copper lid was removed and the box was exposed to a 50 percent relative humidity (Continued)

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atmosphere. From 520 to 722 days, the concrete specimen was exposed to 50 percent relative humidity after being entirely removed from the copper box, and for the last 78 days of the test, from 722 to 800 days, the bare concrete block was monitored in a 100 percent relative humidity atmosphere (fog room). The results of the test indicated that two gages (the ionic barrier moisture gage and the Bouyoucos moisture gage) reacted the most favorably during the entire 800-day test period. Both types of gages gave results that were responsive to environmental changes and stable with respect to time.

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PREFACE

The study reported herein was conducted by personnel of the Concrete Laboratory (CL) of the U. S. Army Engineer Waterways Experiment Station (WES) under the sponsorship of the Office, Chief of Engineers (OCE), U. S. Army, as a part of Civil Works Investigation Engineering Studies Item ES 625 (now WU 31138). The study was authorized in October 1967 by OCE first indorsement of a WES letter entitled "Proposal for Evaluation of Five Embedded Moisture Meters for Moisture Measurement in Concrete (ES Item 625.5)," dated July 1967. Mr. James Rhodes of the Concrete Branch, Engineering Division, OCE, served as the technical monitor.

The study was conducted under the general supervision of Mr. Bryant Mather, Chief, CL, and Mr. J. M. Polatty, Chief, Engineering Mechanics Division, CL, and under the direct supervision of Mr. J. E. McDonald, Chief, Structures Branch, CL.

This report was prepared by Mr. E. F. O'Neil, Structures Branch, CL, and Mr. McDonald.

Directors of WES during this study and the preparation and publication of this report were COL L. A. Brown, CE, BG E. D. Peixotto, CE, and COL G. H. Hilt, CE. Technical Directors were Messrs. J. B. Tiffany and F. R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To obtain
inches	25.4	millimetres
feet	0.3048	metres
cubic feet	0.02831685	cubic metres
ounces (mass)	28.34952	grams
pounds (mass)	0.4535924	kilograms
pounds (force) per square inch	0.006894757	megapascals
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: C = (5/9)(F - 32). To obtain Kelvin (K) readings, use: K = (5/9)(F - 32) + 273.15.

AN EVALUATION OF SELECTED INSTRUMENTS USED TO MEASURE THE MOISTURE CONTENT OF HARDENED CONCRETE

PART I: INTRODUCTION

Background

1. Second only to the problem of cracking due to temperature stresses in mass concrete structures is the problem of cracking due to the development of shrinkage stresses which result from uneven distribution of moisture in the concrete. In order to prevent the causes of this shrinkage cracking, a basic understanding of the movement of moisture throughout the pore structure of the mass concrete is necessary. This can be accomplished through the use of moisture monitoring instrumentation.

2. The free moisture (that part of the mixing water that does not combine with the portland cement during the hydration process) remaining in the pores and capillaries formed during the hydration process migrates through the concrete subject to changing conditions that include: heat of hydration, pore pressure, dimensional changes of the structure, temperature changes, and humidity. For example, evaporation of surface water causes a loss of molecules in the surface pores of the concrete, thus creating negative pore pressures. This, in turn, draws water molecules from interior pores. Conversely, if the atmosphere surrounding a structure is at 100 percent relative humidity, moisture will be absorbed into the pores of the concrete.

3. The problem of tracking moisture movement in mass concrete is not one of lack of knowledge, but one of lack of instrumentation that can effectively record moisture movement with respect to ambient conditions and time. The instruments presently available for measuring moisture content do not provide a measurement that is reliable over long periods of time. This study presents results of tests of six types of moisture gages and discussions of their behavior with respect to extended periods of time.

Objective

4. The objective of this investigation was to test six types of moisture measuring instruments to identify a suitable and economical instrument for measurement of moisture in concrete. The investigation was aimed at finding a meter sensitive to moisture change and capable of long-term accuracy.

Scope

5. The testing was performed on six types of instruments: four were embedded in the concrete, one was inserted into a well cast into the specimen, and one was placed on the specimen. After preliminary individual tests of the various instruments, all were evaluated using a common specimen by monitoring the instruments periodically for 800 days. The readings were taken (a) during the hydration period when the specimen was sealed in a copper box, (b) during a period when the top of the copper box was removed to allow moisture to excape through only one surface and to prevent lateral and longitudinal moisture movement, (c) throughout a period when the entire box was stripped from the specimen, allowing moisture movement through all surfaces, and (d) during a period when the specimen was placed in a 100 percent relative humidity atmosphere.

PART II: MATERIALS, MIXTURE, TEST EQUIPMENT, AND PROCEDURES

Materials

6. The materials used in the concrete mixture were crushed limestone aggregate, type II portland cement, and limestone sand. An unreinforced specimen was cast from this mixture in a box 12 by 12 by 18 in.* long. The box was made of 16-gage (0.0625-in.) copper, with holes cut in the 18-in.-long sides to accept four open-wire-line gages, two soil moisture gages, two ionic barrier moisture gages, two Bouyoucos gages, and four wells to accept Monfore relative humidity gages. These gages were either soldered or epoxied into the copper box and concrete was placed around them.

Mixture

7. The concrete mixture used for the specimen contained 3/4-in. maximum size crushed limestone aggregate with 1.9 percent entrapped air. The mixture had a slump of 2 in. and was proportioned as follows to give a 28-day compressive strength of 6000 psi.

Material	Solid Volume, ft^3	Saturated Surface Dry Batch Weight, lb
Type II cement	3.473	681.5
Fine aggregate	8.305	1381.5
Coarse aggregate	10.569	1784.4
Water	4.653	289.86
	27.000	4137.26

Test Equipment

8. Moisture change within the concrete was measured by gages embedded in the concrete or placed on the surface of the specimen. Six

* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 4.

types of gages were evaluated for long-term stability, reliability, and accuracy. These gages are described in paragraphs 9-23.

Open-wire-line (OWL) gage

9. The OWL gage (Figure 1), which was developed at the U. S. Army Engineer Waterways Experiment Station (WES) for use in soil studies, utilizes the suitability of L-band, electromagnetic wave frequencies to

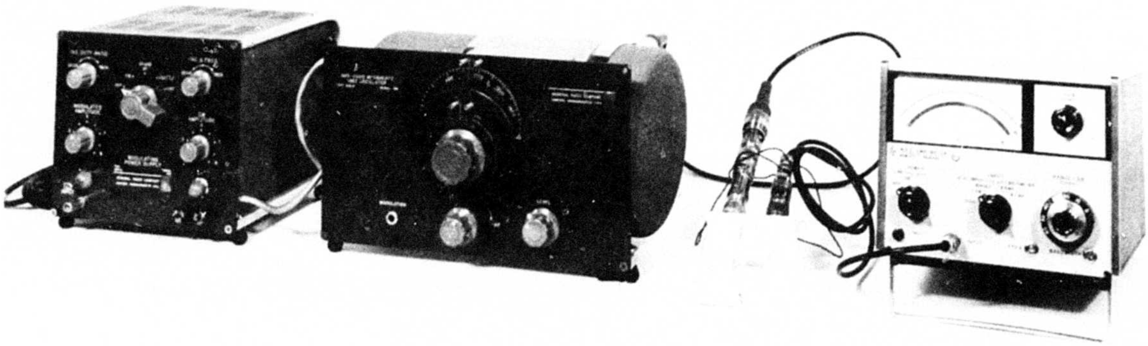

Figure 1. OWL probe and associated instrumentation

moisture content measurements. Since at these L-band frequencies, the moisture content, relative dielectric constant, is relatively insensitive to small frequency variations, only simple relationships exist for calculating the relative dielectric constant.

10. The probe was constructed as a shortened five-wire transmission line in which the outer four wires were common with ground. The inner wire was connected to an excitation source so that a standing wave could be set up on the line. The front and back plates of the gage were made of copper sheet and the 0.8-cm-diameter brass wires were arranged in an 8-cm square to form the four outer wires. The center brass rod was connected on one end plate to a type N connector for the input and shorted on the other end to the ground back plate. A tap was made to the middle of the center wire; the other end of the tap went to a type N connector and, ultimately, to the null measuring meter.

11. The operation of the OWL probe is based on standing wave techniques. The frequency of the oscillator connected to the center-tapped probe was varied through its 1- to 2-GHz range to find the minimum

readings or voltage nulls on the standing wave ratio meter. The standing wave ratio meter is connected to the center-tapped probe through a crystal detector. The nulls occur whenever there is a minimum in the standing wave on the transmission line. As the frequency of the oscillator is varied, the minimum point moves along the transmission line until it coincides with the position of the center-tapped probe. Since the standing wave length varies with the moisture content, the position of the null (the oscillator frequency of the null) also varies with moisture content.

Monfore relative humidity gage

12. The Monfore gage (Figure 2) operates on the principle of electrical resistivity. The sensitive portion of the gage consists of a 1-in. length of Dacron thread that is length-sensitive to changes in relative humidity. The thread is attached to a 2-in. length of fine advance wire connected to a galvanometer. As the thread is subjected to changes in relative humidity, it elongates or contracts, shortening or

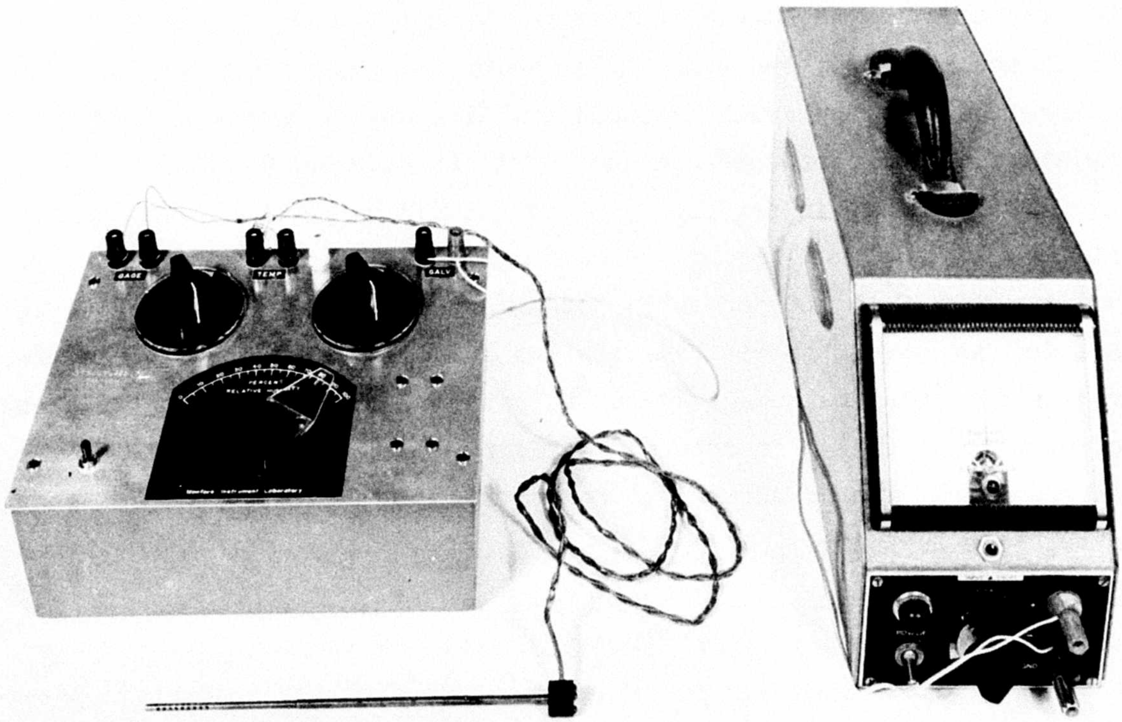

Figure 2. Monfore gage and associated instrumentation

lengthening the piece of advance wire, respectively. When length changes occur, the advance wire changes its resistivity and requires adjustment of the relative humidity bridge to neutralize the bridge.

13. The thread-wire mechanism of the Monfore gage is housed in a 3-in.-long, 1/8-in.-outside-diameter brass tube. The bottom third of the tube is perforated to allow the moisture to reach the Dacron thread inside the tube. The 8-in. overall length of the gage allows the humidity-sensitive portion to be placed deep enough into the concrete to give a reading of the specimen's internal moisture. The remainder of the 8-in. length consists of a 5/32-in.-outside-diameter brass tube that makes up the body of the gage. The entire gage is connected to the relative humidity bridge and galvanometer by electrical cables extending from the end of the gage body. A 5/32-in.-inside-diameter humidity well was used to receive the gage. The well was 6-3/4 in. long and was cast into the concrete when the mixture was being placed in the copper box. This was accomplished by inserting a 5/32-in.-outside-diameter rod, the same length as the Monfore gage, into the well to make a cavity at the bottom of the well inside which the gage would be placed to measure the concrete relative humidity. The well remained closed to the atmosphere except when a measurement was being made.

14. The gage is read by a relative humidity variable resistance bridge. One scale of the bridge covers the complete range of relative humidity from 0 to 100 percent; another extended range linear scale is included for use in special calibration studies. Two decade resistors provide the relative humidity span adjustment. The change in resistance accompanying a change in relative humidity creates an imbalance in the galvanometer. The adjustment to rezero the galvanometer measures change in relative humidity.

Bouyoucos soil block

15. The Bouyoucos gage (Figure 3) measures the electrical resistance of a block of gypsum permanently embedded in the concrete. The resistance of the gypsum varies with the moisture content in the gypsum block, which is a function of the moisture content of the concrete. As the concrete dries, the block loses moisture and the electrical resistance

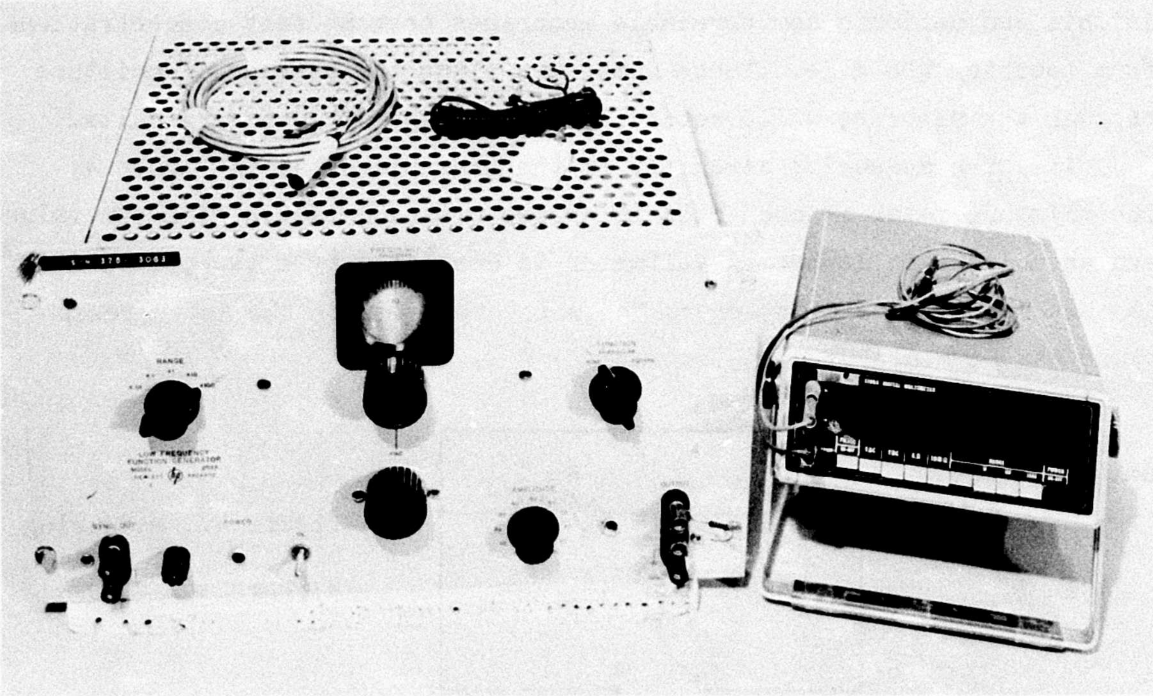

Figure 3. Ionic barrier moisture meter (left), Bouyoucos soil block, and associated instrumentation

is increased. The blocks consist of a pair of stainless steel screen electrodes firmly positioned 1/4 in. apart and cast in a 1-1/16- by 1-1/4- by 5/8-in. block of plaster of paris (calcined gypsum). The standard gage has 10-ft rubber-coated leads.

Ionic barrier moisture meter

16. This meter (Figure 3) works on the same principle as the Bouyoucos gage, that of electrical resistivity. It differs basically from the Bouyoucos gage or any other electrical resistivity gage in that salt ions in the moisture are blocked from contact with the gage. Concentrations of dissolved salts, corrosion of the electrodes due to reaction with dissolved salts, and leaching out of salts can account for as much as 40 percent change in the calibration resistance of a conventional electrical resistance moisture meter at a given moisture content.*

* A. Klein and L. J. Trescony, "Ionic Barrier Moisture Meter for Measurement of Moisture Content and Moisture Distribution in Concrete," University of California, Division of Structural Engineering and Structural Mechanics, Structural Engineering Laboratory, Berkeley, Calif.

Anionic and cationic semipermeable membranes prevent salt concentrations from touching the gage. These membranes allow the passage of moisture through the membrane while retarding the passage of corrosive salts.

17. The measuring circuitry of the meter is shown in Figure 4. The moisture meter is connected in series with a resistor of known value and an audio oscillator. A voltmeter is connected by a two-pole switch so that the voltage drop across the moisture meter or the known resistance can be measured.

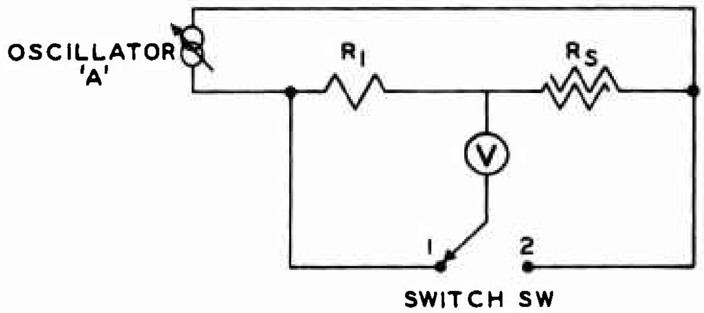

Figure 4. Measuring circuitry of ionic barrier moisture meter

18. To determine the resistance of the meter, R_s, the oscillator is set to 1000 Hz. The output voltage of the oscillator is adjusted until the voltage across the 1000 Ω (ohm) resistor, R_1, is 0.01 volt. This gives a current of 0.00001 A (ampere). When this setting has been obtained, the switch is changed to position 2, and the voltage across the ionic barrier meter is read. The impedance of the moisture gage is then calculated from the measured voltage and the known current.

Soil moisture gage

19. The soil moisture gage (Figure 5) is basically an electrical resistivity meter and works on the principle of varying resistance between two electrodes with varying moisture content. The cell consists of two 0.625-in.-square, 60-mesh electrode screens separated by a processed fiberglass binding which provides a coupling that varies with the surrounding moisture content. The cell also has a small thermistor for temperature measurements. The gage leads complete the two circuits and are approximately 6 ft long. The entire assembly is welded into a 1- by 1.5- by 0.05-in. perforated case which allows moisture to seep into the gage.

20. The gage's metering is basically a self-powered a-c ohmmeter. The alternating current is generated in a vacuum tube circuit and passed through the soil cell or the thermistor, depending upon whether soil moisture or temperature is being measured. The current is then rectified for indication of the output d-c microammeter.

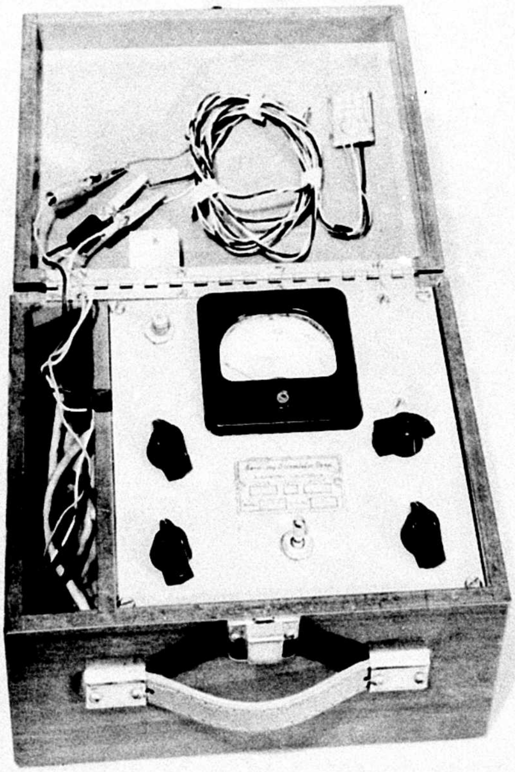

Figure 5. Soil moisture gage and a-c ohmmeter

Nuclear surface backscatter method

21. Of the six moisture measuring methods reviewed, the only one that does not require an internal instrument to determine moisture content is the nuclear surface backscatter method (Figure 6). Therefore, it can be used on existing structures or on new structures without requiring gage placement before pouring.

22. When fast neutrons enter a substance, either of two reactions occur; they are either absorbed into the nuclei of the material or they are scattered as a result of elastic collisions. Energy losses occurring on collision between neutrons and nuclei are the greatest when the masses of the two particles are most nearly equal. Since hydrogen has approximately the same mass as the neutrons, it releases the greatest amount of energy and is the most efficient atomic nuclei in reducing the velocity of neutrons. Since the moisture in concrete is composed mainly of hydrogen and oxygen atoms, this technique adapts readily to the measurement of moisture movement in concrete.

23. The measuring apparatus consists of a fast neutron source of high energy adjacent to a detector of low energy, or thermal neutrons. Thus, the number of neutrons reduced to thermal energy and diffused back

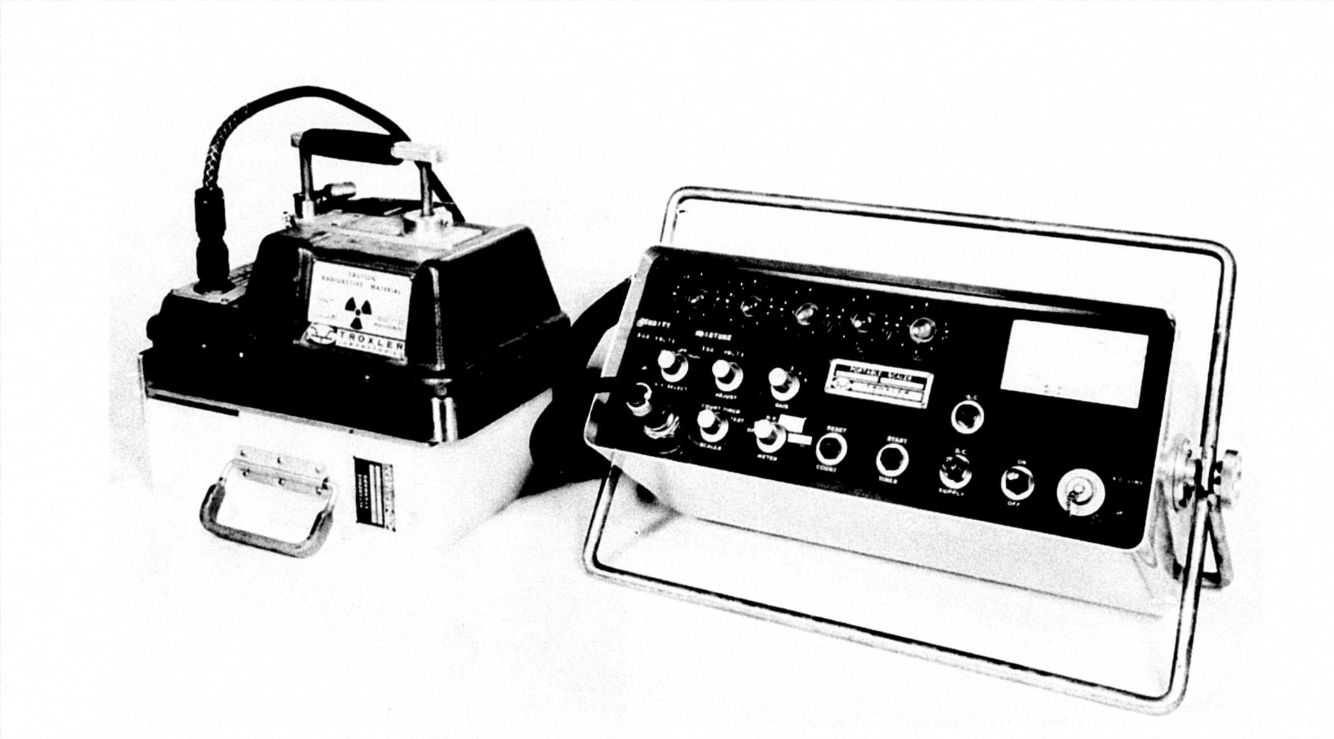

Figure 6. Nuclear surface backscatter gage, standard count block, and scaler

to the detector will be a function of the number of hydrogen nuclei in the vicinity of the meter. The "nuclear count" is measured on a nuclear scaler connected to the meter.

Fabrication Procedure

24. After individual tests on various gages determined what type of gages would be tested, a copper specimen mold was fabricated to allow evaluation of all gages using a common concrete specimen. The box was made from 16-gage copper and measured 12 by 12 by 18 in. long. All the seams of the box were soldered to prevent moisture loss and a top 12 by 18 in. was made to be soldered on after the concrete was poured into the box.

25. Holes were cut in the sides of the box to allow the various gages to be inserted in the sides of the form. Figures 7 and 8 show the orientation of the gages. On the north side of the box, two OWL gages were inserted one above the other with connections for the input frequencies and the readout crystal detectors. One soil moisture gage

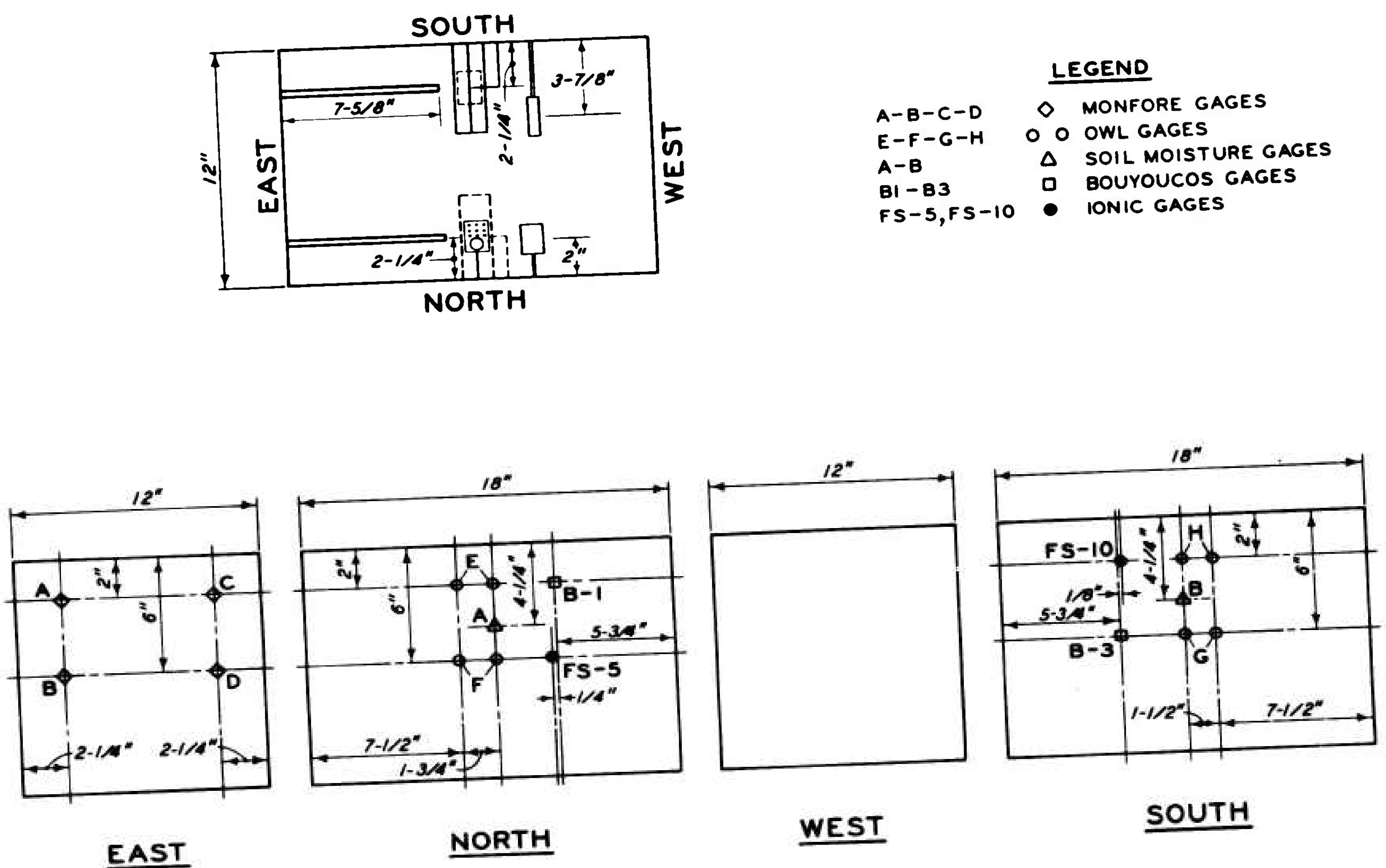

Figure 7. Orientation of gages in copper box

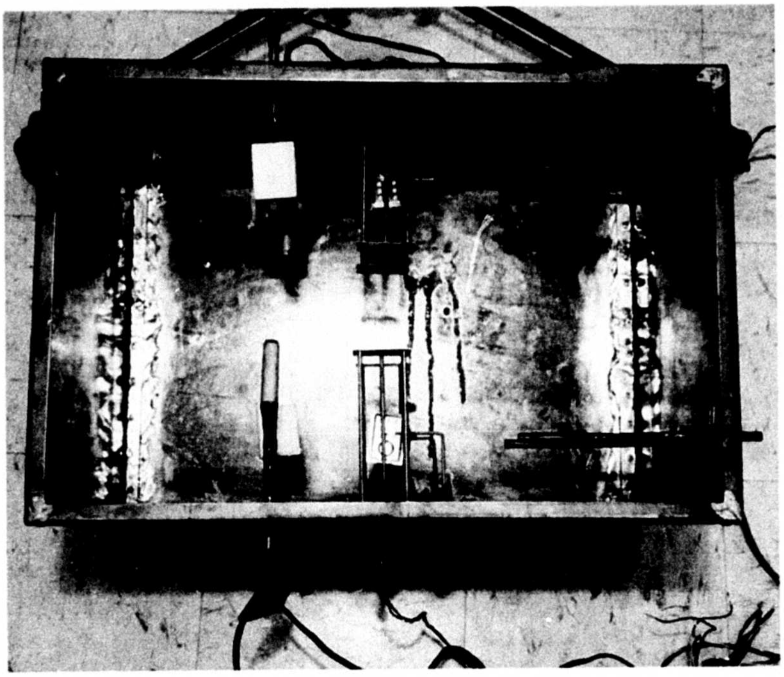

Figure 8. Specimen mold immediately prior to concrete casting (top view)

was positioned between the upper and lower OWL gages on both the north and south sides of the form. To the right of the OWL gages on the north side, one Bouyoucos gage was mounted at the same elevation as the upper OWL gage and an ionic barrier moisture meter was mounted at the same elevation as the lower OWL gage. The orientation of the OWL gage and the soil moisture gage on the south side was the same as that on the north side, but the ionic barrier moisture gage on this side was located next to the upper OWL gage and the Bouyoucos gage was located at the same elevation as the lower OWL gage. On the east end of the copper box, the four wells for the Monfore gages were located: two at the top and two at the bottom.

26. The four OWL gages were soldered into place in the box while, because of the type of lead wires, the Bouyoucos, ionic barrier moisture, and soil moisture gages were epoxied into place to prevent heat damage to the gages and lead wire. Subsequently, all the gages were labeled and the copper box was readied for placement of the concrete.

27. When all the gages were secured in the form and the preliminary testing (described in the next section) was completed, the concrete was

placed. The placing operation was very delicate. The concrete had to be placed without disturbing or displacing the gages. Small hand scoops were used to put the concrete in the copper box so that it was kept away from the gages. When enough concrete was placed to bring the level up close to the lower gages, small hand vibrators were used to vibrate the concrete in and around the lower gages. This procedure was used until the copper box was filled. When the final layer had been vibrated, the top rim of the box was cleaned and the cover was soldered on to prevent the loss of any moisture from the top surface.

Testing Procedure

28. After the gages were assembled in the copper box, and for a 2-week period before the concrete was poured into the box, three of the types of test gages were monitored, first for 2 days in air and then for the remainder of the 2 weeks submerged underwater. The gages monitored were the ionic, Bouyoucos, and soil moisture gages. The gages were read in air for 2 days, the box was then filled with water and the gages were read at intermittent intervals for the remainder of the 2 weeks, thus keeping the gages saturated until the time of the placement of concrete.

29. After 2 weeks of preliminary readings, the concrete was placed in the box and the top sealed onto the box. To prevent possible humidity changes from ambient conditions, the box was placed in a constant relative humidity room; the room humidity was kept at 50 percent relative humidity. The box was weighed and the gages were read immediately. On the day the concrete was placed, the gages were read twice in the morning and once in the afternoon to determine the initial movement of moisture. They were read twice on the second day and daily from then until the sixteenth day. After the gages stabilized from initial moisture changes, the gages were read at intermittent intervals for the remainder of the testing period.

30. At the end of 194 days of testing, the top of the copper box was removed from the specimen to allow moisture to migrate uniaxially

through one surface of the specimen. The gages were again read daily for a period of 3 weeks. Once the readings had stabilized, they were again read periodically for the remainder of this portion of the testing.

31. At the end of 520 days of testing, the copper box was stripped from the concrete block to allow moisture to migrate to or from the concrete from all faces. When the box was removed, the concrete block was weighed and the gages were read at intermittent intervals.

32. At the completion of 722 days of testing in the 50 percent relative humidity atmosphere, the specimen was moved to a 100 percent relative humidity atmosphere and the testing continued. The specimen was loosely covered with clear plastic to eliminate pools of water forming on the surface of the specimen; the specimen was removed from the 100 percent relative humidity atmosphere for purposes of weighing and reading the gages only.

PART III: RESULTS AND DISCUSSION

33. The results of the 800-day testing of the six types of moisture measuring gages are shown in Plates 1-33. The test data have been plotted in two groups, 60- and 800-day graphs.

34. Each plate is a time plot of some moisture dependent characteristic of the gage. The Monfore gage readings are plotted as percent relative humidity versus time, while the OWL gage readings are plotted as refractive indices versus time. A plot of the nuclear moisture count ratio versus time is the representation of the data for the nuclear backscatter gage, and the data from the Bouyoucos, soil moisture, and ionic barrier moisture gages all result in plots of gage resistance versus time.

35. In some of the plates moisture content can be measured directly, and in others a property (such as resistance) can be converted to percent relative humidity, either from a correlation graph or by mathematical calculations. Since the objective of this investigation is to evaluate each gage for its stability and accuracy of measuring moisture for prolonged periods of time, and is not to make a comparison of gages, the results of testing need not be reported in a uniform manner (i.e., it is not necessary to have all the results plotted as a function of one variable with respect to time). Each set of plates for a particular type of gage can be evaluated and compared with the general results of moisture loss obtained from periodic weighing of the specimen. Comparisons are made among the gages that report results in a similar manner to determine consistency in measurement and variation of moisture content with distance from the exposed surface of the concrete.

36. The results are presented in two types of plots for each gage. The first of these types is moisture measurement for a period of 0 to 60 days. This set of plots is intended to indicate gage behavior during the major portion of the specimen hydration process. During hydration, the specimen is fully sealed from the surrounding atmosphere and moisture cannot enter or leave the specimen. Any fluctuations during this time indicate a migration of moisture to or from one point within the specimen to another, or a change from free moisture to combined moisture.

37. The second type of plot is a measure of moisture movement for 800 days. During this time, the specimen was subject to physical changes. Initially the specimen was sealed; after 194 days the top of the copper box was removed and the specimen was exposed to air of 50 percent relative humidity. At 520 days into the test, the sides and bottom of the copper box were removed exposing the entire specimen to 50 percent relative humidity. At the end of 722 days of testing, the stripped sample was put under a plastic cover and placed in a 100 percent relative humidity atmosphere and was removed only for measurement purposes. The purpose of these procedures was to evaluate gage sensitivity to environmental changes and to determine the stability of the gage over extended periods of testing.

38. Plate 1 is a plot of specimen weight loss versus time from 195 to 800 days. At 194 days the cover of the box was removed and one face of the specimen was exposed to an exchange with the surrounding atmosphere. The plate shows that there is a linear loss of moisture through this face up to 520 days. At this point the copper jacket was entirely removed, exposing five additional faces to the air. The plate shows that the moisture loss curve became a polynomial function of the six exposed faces of the block as opposed to the linear one-face relation from 195 to 520 days.

Monfore Relative Humidity Gages

39. Plates 2-5 are 60-day plots of relative humidity versus time for Monfore gages A-D, respectively. As shown in Figure 7, gages A and C are located on the east side of the box 2 in. from the top and 2-1/4 in. from the north and south faces and gages B and D are directly below gages A and C and 6 in. from the top of the box.

40. During the first 60 days, all four Monfore gages registered approximately constant relative humidity. The actual data ranged from 93 to 100 percent relative humidity with an average of approximately 96 percent for the first 35 days. Beginning at 20 days, the average humidity began to rise, and between 40 and 60 days three of the gages (A, C,

and D) registered 100 percent relative humidity. All four gages registered slight decreases in relative humidity from 57 to 60 days.

41. In the initial stages of hydration, there is an excess of free water in the mixture. This free water, when concentrated around the tip of the Monfore humidity well, promoted a 100 percent relative humidity atmosphere within the well. Even though much of the free water in the mixture was taken into the combined state during the early days of hydration, the Monfore wells continued to measure close to saturation as long as the humidity in the well indicated free water surrounding the well. This accounted for the gage's insensitivity to the initial moisture change caused by combination with the cement.

42. Plates 6 and 7 show 800-day plots of relative humidity versus time for the average of gages A and C and B and D, respectively. Paragraph 40 describes the results for the first 60 days. Subsequent to this period, the average relative humidity for the gages began to decrease from 95 percent at 60 days to 77 percent at 730 days. During this time, the readings fluctuated but showed a linear relationship of relative humidity versus time for the 670 days. The graphic results of gages A and C were continually below those of B and D during this time.

43. The moderate drop of 18 percent relative humidity in a linear fashion indicated that the Monfore gages react slowly to sudden changes in environmental conditions. The removal of the top of the copper box at 194 days did not produce any immediate change in the rate of moisture loss. Similarly, at 520 days, the moisture loss remained linear even when the entire box was removed exposing all faces to the atmosphere.

44. Gages A and C were located nearer to the top of the box than B and D, so when the top was removed, the moisture lost through the top face was "sensed" more by the top gages than the bottom ones. This trend continued until the entire jacket was removed and gages B and D recorded greater rates of moisture loss than A and C until 700 days when they were approximately equal.

45. At 722 days, the stripped specimen was placed in a 100 percent relative humidity room. Both sets of gages showed an immediate rise in relative humidity and a continued rise until the 800 days.

46. Part of the difficulty with the accuracy of the Monfore gages is due to the location of the moisture sensing thread at the end of a metal tube or well that is functioning as a direct channel to the atmosphere surrounding the specimen. Consequently, the air next to the thread (at whatever humidity the surrounding atmosphere contains) will influence the relative humidity indication of the gage. This has been partially remedied by inserting rubber stoppers in the tubes when measurements are not being taken to allow the air in the tube to equalize to the moisture content of the surrounding concrete.

47. The Dacron thread at the tip of the Monfore gage is subject to moisture corrosion from acids and salts that may be present in the moisture at the base of the well. This may not have an effect on the thread in the early phases of testing, but could lead to inaccurate measurements in long-term testing.

48. These gages must also be periodically calibrated before being used, thus making reading time longer.

Soil Moisture Gages

49. Plates 8 and 9 are 60-day plots of resistance versus time for the soil moisture gages. Both gages were located 4-1/4 in. below the top of the box midway between the top and bottom OWL gages (see Figure 7 for location). These gages recorded the amount of moisture present using the amount of resistance encountered when a current of known value is passed between the two electrodes of the gage. Since moisture is a conductor of electricity, the ore moisture present between the electrodes of the gage, the lower the resistivity.

50. Both gages measured approximately the same resistance for the first 60 days, with gage A (Plate 8) taking 50 days to reach its peak loss of moisture and gage B (Plate 9) reaching its maximum at 40 days. These gages can distinguish between free and combined water since they register a moisture loss during the part of the test when the copper box was completely sealed.

51. Plates 10 and 11 show the behavior of soil moisture gages A and

B, respectively, for the 800-day period. These graphs show that the maximum moisture loss recorded for the first 60 days was not, in fact, a maximum at all but actually less than 20 percent of the total moisture loss. The rate of moisture loss continued to increase closely between the two gages A and B until the top of the box was removed at 194 days. Both gages showed increases in moisture loss at this time, gage B beginning to show increase in approximately 10 days and gage A within 30 days. The moisture loss measured by gage A was higher than that measured by gage B from 260 days until the specimen was placed in the 100 percent relative humidity atmosphere.

52. At 520 days, when the sides and bottom of the box were removed, gage A again registered a slightly increased rate of moisture loss, but gage B did not show any reaction to this change. Its rate of moisture loss did not change. At 722 days, the specimen was placed in the 100 percent relative humidity environment and both gages showed increases in moisture content. Gage A began to register moisture gain immediately while B continued to show moisture loss until 750 days before it indicated gain of moisture. From that point, both gages indicated a continued gain of moisture to the end of the test.

53. In this test, gage A indicated a reaction to all environmental changes during the 800 days of testing. Gage B reacted insignificantly to changes except when the specimen was put in 100 percent relative humidity environment. While it may seem that both gages showed relatively linear moisture losses, gage A showed slight increases in the rate of moisture loss both at 194 days and again at 520 days. Since both of these gages were located at the same elevation in the specimen, their reaction patterns should have been similar. Since gage A reacted to the change in environment more as it was expected, this gage behaved properly and gage B did not. This could indicate a lack of sensitivity in the functioning of the gage with extended time intervals.

54. A limitation of the soil moisture gage is its lack of a means to prevent salt corrosion from entering the gage. The salt ions present in the moisture between the electrodes can corrode the leads and can cause resistance readings to be in error. The Bouyoucos gage has a

calibration chart to account for this, and membranes in the ionic gage prevent salt ions from touching the gage.

Ionic Barrier Moisture Gages

55. The ionic barrier moisture gages were located on opposite sides of the box. Gage FS-5 was mounted in the north face approximately 6 in. from the top of the box and 6 in. from the west face. Gage FS-10 was mounted in the south face approximately 2 in. from the top and 6 in. from the west face.

56. Both gages reacted very similarly during the 60-day plots of resistance versus time. Both gages reached an initial moisture loss peak at approximately 23 days and then began to register a small gain in moisture. From 23 days to 60 days their behavior was not as similar as in the first 23 days but the trend was the same (see Plates 12 and 13).

57. Comparison of Plates 14 and 15 shows that the moisture losses registered by gages FS-5 and FS-10 are nearly identical for the first 210 days and compared with the total moisture loss, the losses during this time were relatively small. At 210 days gage FS-5, the gage farther from the open surface, showed a very moderate increase in the rate of moisture loss while FS-10, at this time, indicated a large increase in the rate of moisture loss.

58. Both gages reacted to the second change at 520 days by showing increases in the rate of moisture loss; however, with respect to the rate of change during the period after the top was removed, the increase shown by gage FS-5 was greater than that by FS-10. This is the result of a greater transfer of moisture from the interior through the newly opened faces than through the top that had been exposed 326 days previously.

59. The gages both reacted simultaneously to being placed in 100 percent relative humidity atmosphere and showed an immediate gain of moisture at 722 days. They continued to register moisture gain to the end of the test. A comparison of Plates 14 and 15 shows that at 800 days they were at almost the same moisture level.

60. Gage reaction to change of environment was relatively rapid and the stability of measurement was good. At the points in the testing when the box was altered, the gage indicated the change immediately. The stability of the measurements is shown by the smooth line of the graph and the absence of the "saw-tooth" type of graph that indicates fluctuations in the measurement of moisture loss.

Bouyoucos Gages

61. Plates 16 and 17 show plots of resistance versus time for Bouyoucos gages B-1 and B-3, respectively, for the initial 60 days. Gage B-1 was located above ionic moisture gage FS-5, 2 in. from the top of the box on the north face and 6 in. from the west face. Gage B-3 was below gage FS-10, 6 in. from the top of the box on the south side and 5-3/4 in. from the west face.

62. These plates show that both gages recorded similar moisture migrations for the first 60 days. Both gages reached a peak moisture loss at 21 days with B-1 slightly lower in resistance than B-3 between 5 and 30 days. Between 30 and 60 days B-1 was slightly higher in resistance.

Discussion of Soil Moisture, Ionic Barrier, and Bouyoucos Gage Results

63. Plates 18 and 19 plot the 800-day readings of resistivity versus time for gages B-1 and B-3, respectively. Comparison of these two plates shows that the two gages measured approximately the same moisture movement for the first 200 days. At this point, B-1 indicated a rapid nonlinear increase in resistivity, showing high moisture loss from 200 to 300 days and a less rapid rate from 400 to 500 days. Gage B-3 also showed an increase in resistivity, but it was much milder and appeared to be essentially linear from 200 to 500 days.

64. At 520 days, when the copper box was removed, both gages indicated loss of moisture in the form of an increase of resistance. Both

gages showed polynomic increases, with that of gage B-3 being more pronounced than that of B-1. Both polynomic increases were rapid at first and mild toward the end of the curve. Gage B-1 reached its greatest moisture loss at 634 days, while B-3 peaked at 721 days. At 721 days both gages indicated a rapid decrease in resistance, an immediate increase, and then a decrease to the end of the test period indicating immediate moisture gain.

65. The three gage types that measure moisture change by resistance can be discussed together because their results were similar in some important respects.

66. The first and most obvious observation is that the gage of each type (soil moisture, ionic barrier, and Bouyoucos) embedded at the lower elevation showed a lower loss of moisture. This is obvious because, between 195 and 519 days, the greatest moisture loss should have been at or near the free surface (i.e., the top surface). The gage nearer the top would experience the greater change of moisture content. The lower gage would also show moisture loss but would show less loss between 195 and 519 days than the upper gage, mainly because of the redistribution of the remaining free moisture throughout the specimen.

67. Two of the three gages (ionic and Bouyoucos) were oriented as described above. The third gage, the soil moisture gage, was oriented on opposite sides of the form, at the same elevation. Although they show different moisture losses, the difference is not due to the abovementioned reasons but to some characteristic of the gage.

68. One characteristic of the soil moisture gage is that the plot of resistance is determined from an interpretation graph furnished by the gage manufacturer. The soil moisture gage readings are in microamps from 0 to 200 μA. Microamps are converted to resistance by using the interpretation graph. Since the graph was established for use with soil, its use for concrete moisture measurements could lead to errors due to differences in the properties of the two materials.

69. When the moisture loss to the atmosphere is through only one face of the specimen, the rate at which this moisture is lost would be fairly constant (see Plates 10 and 11 and 14 and 15). Between 194 and

519 days, the soil moisture gages and the ionic barrier moisture gages both reflected a relatively linear loss of moisture to the atmosphere. With respect to the ionic barrier moisture gages alone, gage FS-5 was closer to a linear moisture loss than the upper gage, FS-10. This was to be expected since this gage was much farther from the exposed surface.

70. One of the Bouyoucos gages did not reflect this relationship. Gage B-3, in the period from the time the top was removed until the time the entire box was removed, showed a linear moisture loss. When the box was removed at 520 days, its plot became polynomic as expected; but gage B-1 at 195 days into the test showed a plot that was polynomic, indicating major moisture loss immediately and minor moisture loss in the later stages of the test (375 to 519 days). When the box was removed at 520 days, the plot of gage B-1 became more polynomic and continued thus until 722 days.

71. All three gages register the moisture used in the process of hydration as moisture lost. Plate 20 is a normalized plot of 60-day moisture versus time. Each plot is a graph of the percentages of the individual data points to the maximum moisture loss for that gage. It can be seen from this graph that the Bouyoucos gage indicates the conversion of free water to combined water most rapidly, followed by the ionic gage and the soil moisture gage.

72. All three types of gages showed close correlation between readings of the two gages until 30 days when they begin to deviate from each other. The Bouyoucos gages remained the closest together, followed by the ionic and the soil moisture.

73. Plate 21 is a normalized plot of 800-day moisture movement versus time. This plot shows that both Bouyoucos gages showed higher moisture loss at an earlier age than did either ionic gage. Both ionic and Bouyoucos gages were at the same elevation in the test specimen. The soil moisture gages, which were at an elevation between the ionic and Bouyoucos gages, were also between the extremes of these two gages in this plate and were fairly similar to each other in moisture loss.

74. Plates 22 and 23 are, respectively, normalized plots of 60- and 800-day moisture movement versus time. They are similar to Plates 20 and 21. However, they are plotted with respect to the maximum reading for each gage type, i.e. each point is a percentage of the maximum resistance reading recorded for that gage type. For the 60-day plots, Bouyoucos gage B-1 reached 98 percent of the maximum reading gage B-3 reached; soil moisture gage A reached 96.5 percent of the maximum reading gage B reached; and ionic gage FS-5 reached 100 percent of the maximum reading gage FS-10 reached. All of these readings were made while the box was sealed and therefore are measurements of moisture loss through hydration. The relative closeness of all maximum readings to the maximum recorded for the gage type indicates that all gages were functioning properly and measuring moisture loss through chemical combination with the cement. For the 800-day plot, Bouyoucos gage B-3 reached 68.7 percent of the maximum reading gage B-1 reached; soil moisture gage B reached 80.5 percent of the maximum reading gage A reached; and ionic gage FS-5 reached 16.4 percent of the maximum reading gage FS-10 reached. Both gages B-3 and FS-5 were located at the bottom of the specimen and reflected lower moisture losses, 68.7 and 16.4 percent, respectively, than their associated gages located at the top of the specimen. Soil moisture gage B showed the smallest difference between associated gages, 80.5 percent of maximum, and this would be expected because the gages were located at the same elevation. Since gages B-3 and FS-5 were both located at the same elevation in the specimen and the normalized graph reports data as a percentage of maximum, the two percentages should be closer together than 68.7 and 16.4 percent. The difference arises from the fact that the ionic gage was located 3-7/8 in. from the north face and the Bouyoucos gage was only 2 in. from the south face of the block. The higher moisture loss of the Bouyoucos gage resulted from that gage's proximity to the surface of the block.

Open-Wire-Line Gage

75. There were four OWL gages used during the test, two located on

each side of the moisture box. Gages E and F were placed on the north side of the box and were located 2 and 6 in., respectively, from the top of the box and 9 in. from the east side. Similarly, gages G and H were placed on the south side 6 and 2 in., respectively, from the top of the box and 9 in. from the east side (see Figure 7 for details). These gages measure frequency at voltage nulls. The frequency at a voltage null at any given time is a measure of the moisture content of the specimen at that time: the lower the frequency, the lower the moisture content. Plates 24-31 are plots of refractive indices of the gage versus time The refractive index is the square of the quotient of the voltage null in air as calibrated for each gage divided by the average null calculated for each moisture reading. This refractive index gives a more relative plot of moisture movement with time for comparison between OWL gages.

76. Plates 24-27 show the trends of the OWL gages for the first 60 days. Gages E and H, the upper two gages, bear similar results. They both show rapid moisture loss between 0 and 10 days, and then relatively little loss until 30 days. Between 30 and 40 days the two gages differed. Gage E showed a drop in frequency from 4700 to 4350 Hz at 30 days and then showed no more moisture loss through the 60-day period. Gage H showed a drop in frequency from 4650 to 4350 Hz at 40 days and then no more moisture loss to the end of the 60-day period.

77. Gages F and G, the lower two OWL gages, have identical plots with the exception that they are separated by approximately 250 Hz throughout the first 60 days. Their general results were similar to those recorded for gages E and H. Both gages showed rapid moisture loss in the first 10 days and then very mild loss from 10 to 55 days. At 55 days both gages showed increased moisture loss to the end of the 60-day test.

78. Plates 28-31 are plots of refractive indices versus time for the 800-day plots of gages E, F, G, and H, respectively. Top gages E and H follow each other closely for the first 194 days. During this time, they appear to reflect a loss of a major portion of the moisture loss

during the entire test. Due to the fact that this type of gage does distinguish between free and combined moisture, this apparent loss during the first 50 days was moisture that had changed from free to combined water. At 194 days, gage E recorded rapid moisture loss to about 4000 Hz and then subsided until the next major change in atmospheric conditions. However, gage H, at 194 days, did not measure any radical moisture change but continued to lose moisture at a gradual rate until 520 days when the gages were approximately equal. When the copper box was removed at 520 days, gage H showed an increase in moisture loss, but gage E began to react as if it were recording a moisture gain and then reversed to a slight moisture loss.

79. Neither gage showed an increase in moisture content when the block was put in 100 percent relative humidity atmosphere. Only gage E registered a moisture gain 70 days after being put in 100 percent relative humidity at 790 days into the test.

80. Gages F and G, the lower two OWL gages, reacted very similarly throughout the 800-day tests as did gages E and H. Both gages showed the major portion of moisture lost between 0 and 150 days. This is due to the free water becoming combined water. Gage F measured consistently lower than gage G up to 600 days, similar to the movement between 0 and 60 days.

81. Neither gage showed any reaction to having the top removed (194 days), but this was expected since these gages were not in the vicinity of the physical change. However, at 520 days when the sides were removed, there should have been a more pronounced change in the rate of moisture loss than was actually recorded. Gage G did record a moisture loss at 520 days, but gage F dropped and subsequently rose again to the same level of moisture content.

82. Both gages should have recorded a moisture gain at 722 days. Gage F showed an increase at 742 days but returned to a decreasing moisture content at the next reading. The gage G reading increased temporarily at 770 days but also decreased at the next reading.

83. The frequency at which the moisture reading for the OWL gages is recorded is dependent on a voltage minimum or null. As the frequency

is varied over its range there is a voltage reading that is associated with each frequency. The minimum voltage or null voltage indicates either a short wave or half-wave frequency point at the center tapped point where the voltage is being measured. This half-wave frequency produces a sharp drop in voltage when it coincides with the measuring point. During the testing, at about 1 yr into the testing, these gages began to show two low voltage points and their corresponding frequencies. The frequency that was correct for the proper moisture content ranged between the two frequencies determined by the two voltage nulls, but the exact point could not be determined. This type of reading continued from 1 yr to the end of the testing, indicating that the embedded OWL probe had lost its sensitivity at approximately 1-yr testing.

Nuclear Moisture Gage

84. The nuclear meter was not embedded into the concrete but was placed on top of the box to make readings throughout the 800 days of testing. For each reading, a series of six nuclear backscatter counts were taken. The meter was placed on top of the specimen and aligned with the longitudinal axis; three readings were taken at 5-min intervals, then the meter was turned 180 deg and three more readings were taken. The moisture count ratio was considered a function of these six readings.

85. Plate 32 shows the results of the first 60 days of testing. From viewing this plate, it appears that there is an immediate loss of moisture followed by a gain between 12 and 16 days, and then another loss from 16 to 54 days. Actually, since the nuclear moisture gage does not make a distinction between free and combined water, there is not any loss or gain. These highs and lows are fluctuations in the gage readings.

86. Plate 33, the 800-day plot of moisture count ratio versus time, shows the gage fluctuation more clearly. From 0 to 194 days, the readings ranged from 0.538 to 0.506, averaging around 0.520 for the major part of the time. At 194 days, the top of the specimen was removed.

Immediately there was a large jump in the moisture count ratio indicating a large influx of moisture to the specimen. This jump in moisture count ratio was the result of an increased number of neutrons reaching the detector cells of the gage when the copper barrier was removed, rather than an actual increase in moisture content. A previous preliminary report on humidity indicators* states that, in preliminary tests, the moisture measurement on bare concrete and through a 0.008-in.-thick copper sheet made no difference in the measurement. The results of the present investigation indicated that the moisture count ratio taken over bare concrete, as was done subsequent to 194 days of testing, was indeed different from that taken through the copper sheet (0.0625-in. thickness) and, as reported, is a higher ratio. It seems that the thicker copper sheet used in this test absorbs or rereflects some of the backscatter radiation.

87. Immediately following the 194-day increase, the moisture count ratio began to drop, indicating a loss of moisture through the free surface. The moisture loss continued in a relatively linear fashion to 700 days. During this time the readings fluctuated above and below the linear trend in loss of moisture. At 520 days when the entire box was removed; there was no noticeable change in the rate of moisture loss from the specimen. The gage continued to show steady moisture loss until 700 days. At 722 days, after the specimen was put in 100 percent relative humidity, the moisture count ratio began to increase and continued to do so to the end of the test.

88. The nuclear backscatter gage measures neutron backscatter from hydrogen molecules in the concrete whether the molecules are free or combined; the gage does not make a distinction between the two. Thus, the measurements are not exact measurements of free moisture. One method of separating free from combined water is to drive all the free water from the specimen and measure the moisture count ratio for only combined water; the free moisture is the total moisture reading minus

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* J. E. McDonald, "Moisture Migration in Concrete," Technical Report C-75-1, May 1975, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

the combined water reading. This procedure is satisfactory for laboratory specimens or for small structures where the water can easily be driven off but becomes an impractical procedure in the case of large structures.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

89. From the observations made on the testing conducted over the 800-day test period, the following conclusions can be drawn.

90. Moisture loss from the specimen, as determined by weighing the concrete block, began at 220 days shortly after the top was removed from the copper box. The rate of moisture loss was linear from 220 days to 520 days. When the sides and bottom of the box were removed (520 days), the moisture rate became polynomic, reflecting the loss of moisture from all surfaces of the specimen. This weight loss continued to 722 days. At that point, the specimen began to gain weight from immersion in a 100 percent relatively humidity atmosphere. The total weight loss over the 2-yr period was 22 oz.

91. During the 60-day hydration period, two of the gages did not show a moisture loss; the remaining four gages did. The electrical resistance gages (soil moisture, ionic, and Bouyoucos gages) all showed a rapid loss of moisture and then a small gain in moisture. These three gages do not measure combined water, so the water that combined with the portland cement was sensed as lost moisture. The OWL gages also recorded a moisture loss without gain during the 60-day period. The two gages that showed no loss were the Monfore relative humidity probes and the nuclear moisture gage. During this period, the Monfore probe measured a constant humidity around 96 percent. The probe supposedly can make a distinction between free and combined water but did not behave as the electrical resistivity gages did. The nuclear backscatter gage, the one gage that makes no distinction between free and combined water, also showed a constant moisture content.

92. All six types of gages indicated moisture loss during the period of 194 to 722 days, when the specimen was partially or wholly exposed to a 50 percent relative humidity atmosphere. Subsequently, all gages, with the exception of the OWL gages, indicated a rise in the moisture content when the specimen was placed in the 100 percent relative humidity atmosphere.

93. The electrical resistivity gages (the soil moisture, the ionic

barrier moisture, and the Bouyoucos gages) produced results that indicated these gages were the most stable and reliable throughout the 800 days of testing. Their plots did not have the saw-tooth type of curve that indicates a fluctuation of gage reading around an average value. The other gages (Monfore, nuclear moisture backscatter, and OWL gages) registered this saw-tooth pattern.

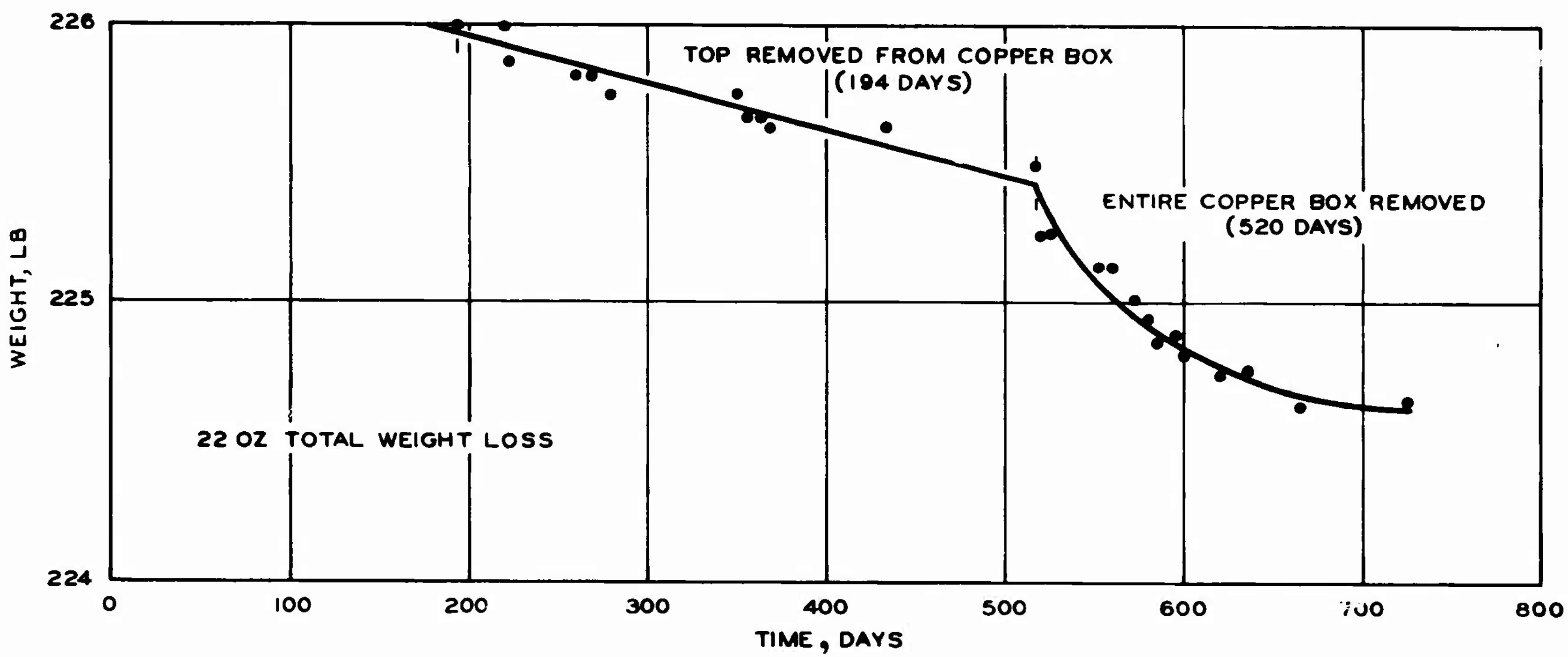
94. The OWL gages and the Monfore relative humidity gages indicated no sensitivity to environmental changes. Their plots showed rather steady moisture losses from the time the top was removed to the time the specimen was put into 100 percent relative humidity. These gages did not indicate any change in rate of moisture loss or gain due to changes in specimen conditions. The OWL gages became defective after 1 yr; they gave two readings of voltage null where there should have been only one. When the top and sides of the box were removed, the ionic barrier moisture gages reacted quickest to the change of atmosphere and indicated an increase in moisture loss. Also, when placed in a 100 percent relative humidity atmosphere, these gages indicated a moisture gain immediately. The Bouyoucos gages also reacted rapidly, showing good reaction to environmental changes.

95. The Monfore relative humidity gages use a Dacron thread to measure changes in relative humidity. This thread is susceptible to corrosion from salts in the humidity well, a cause of inaccurate readings. The Bouyoucos gages are also sensitive to salt corrosion, but have a corrective chart to allow for these inaccuracies. The ionic gages eliminate the salt from the solution that is allowed to reach the gage by the use of two permeable selective membranes, thereby eliminating the erosion problem. As mentioned before, the OWL gages produced inaccurate readings after 1 yr when two voltage nulls were recorded for one humidity state. Soil moisture gage readings are adjusted using correction charts for different types of soils, but the readings obtained in the tests reported herein may be in error because the gages were installed in concrete and readings were adjusted using correction charts for soil.

96. Two gages outperformed the rest. The ionic barrier moisture

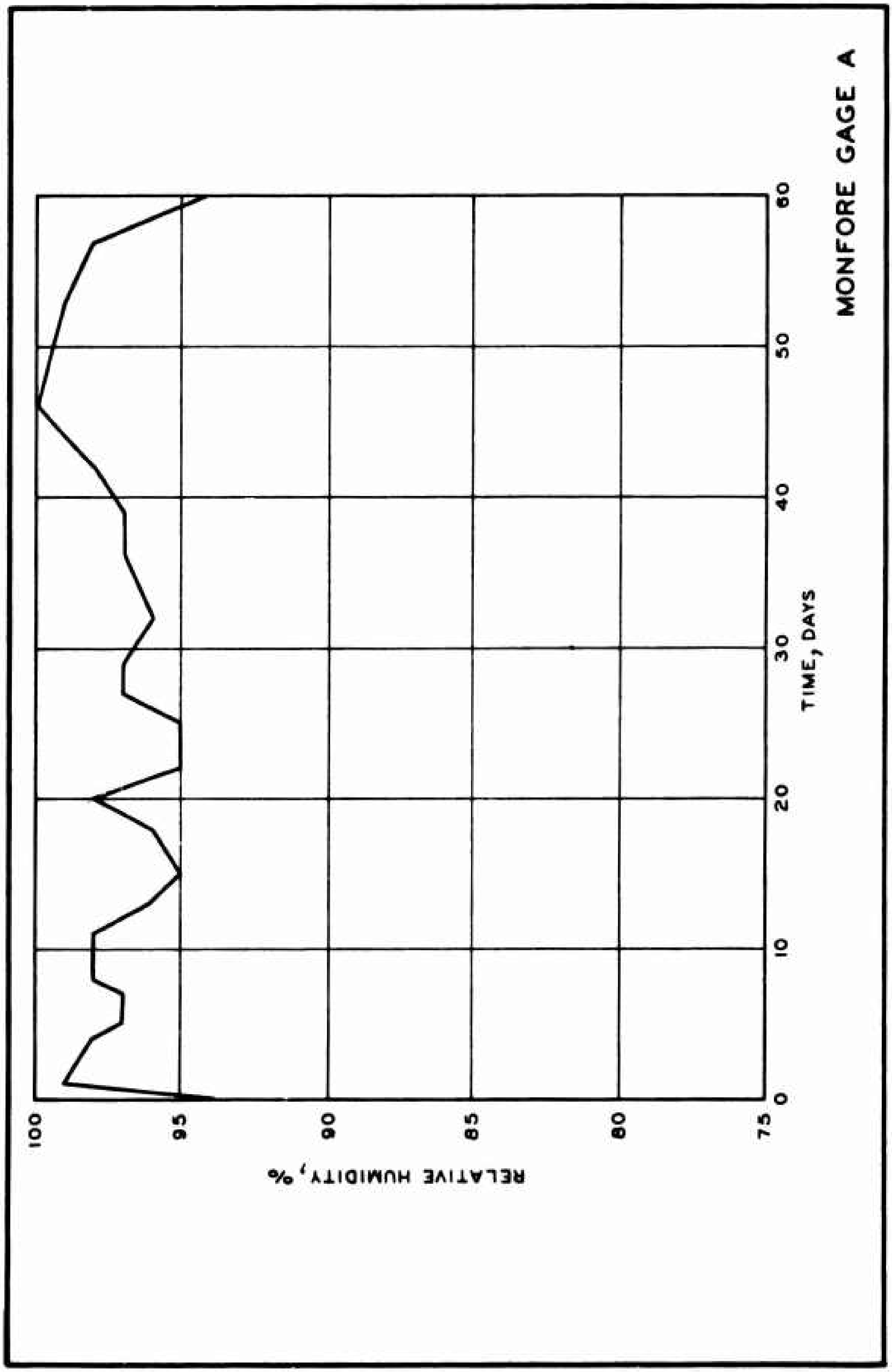
gages produced results that were smooth and stable, and reactive to changes in moisture flow over the entire 800-day test period. The Bouyoucos gages also produced results indicative of stability and long-range response to moisture change. The Bouyoucos gage is commercially available; the other is not.

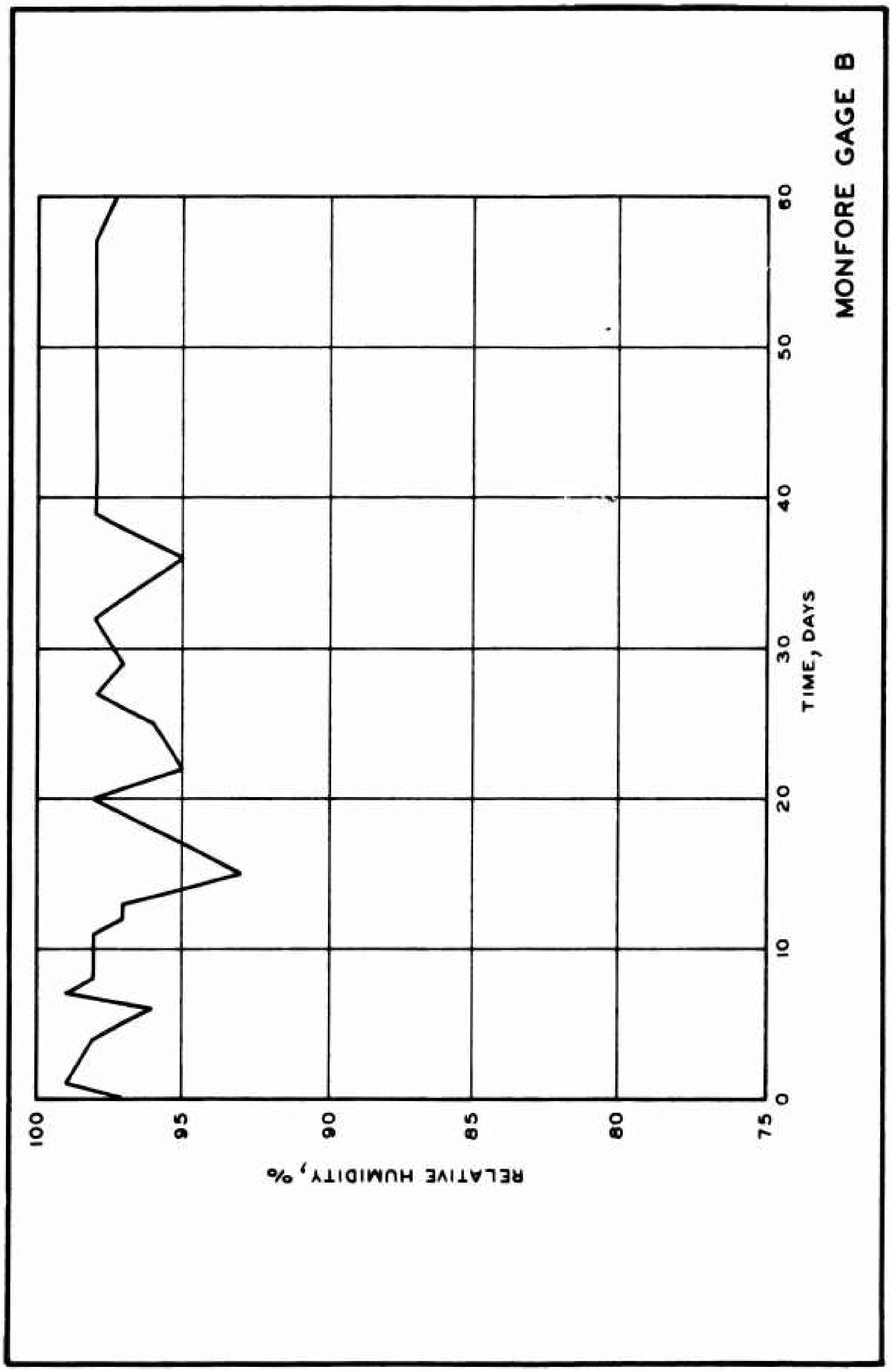
97. As a result of the tests and observations, it is recommended that these two gages be considered as reliable and stable moisture measuring instruments. It should also be noted here that the third type of electrical resistance gage, the soil moisture gage, produced graphs that were stable. Their resistance values were obtained, however, from conversion charts for soil. These gages could possibly be used advantageously to measure moisture movement in hardened concrete if they had accompanying conversion charts that were designed for concrete.



SPECIMEN WEIGHT LOSS VS TIME
195-800 DAYS

PLATE 1


MONFORE GAGE A
RELATIVE HUMIDITY, %
TIME, DAYS
100
95
90
85
80
75
0
10
20
30
40
50
60



MONFORE GAGE B

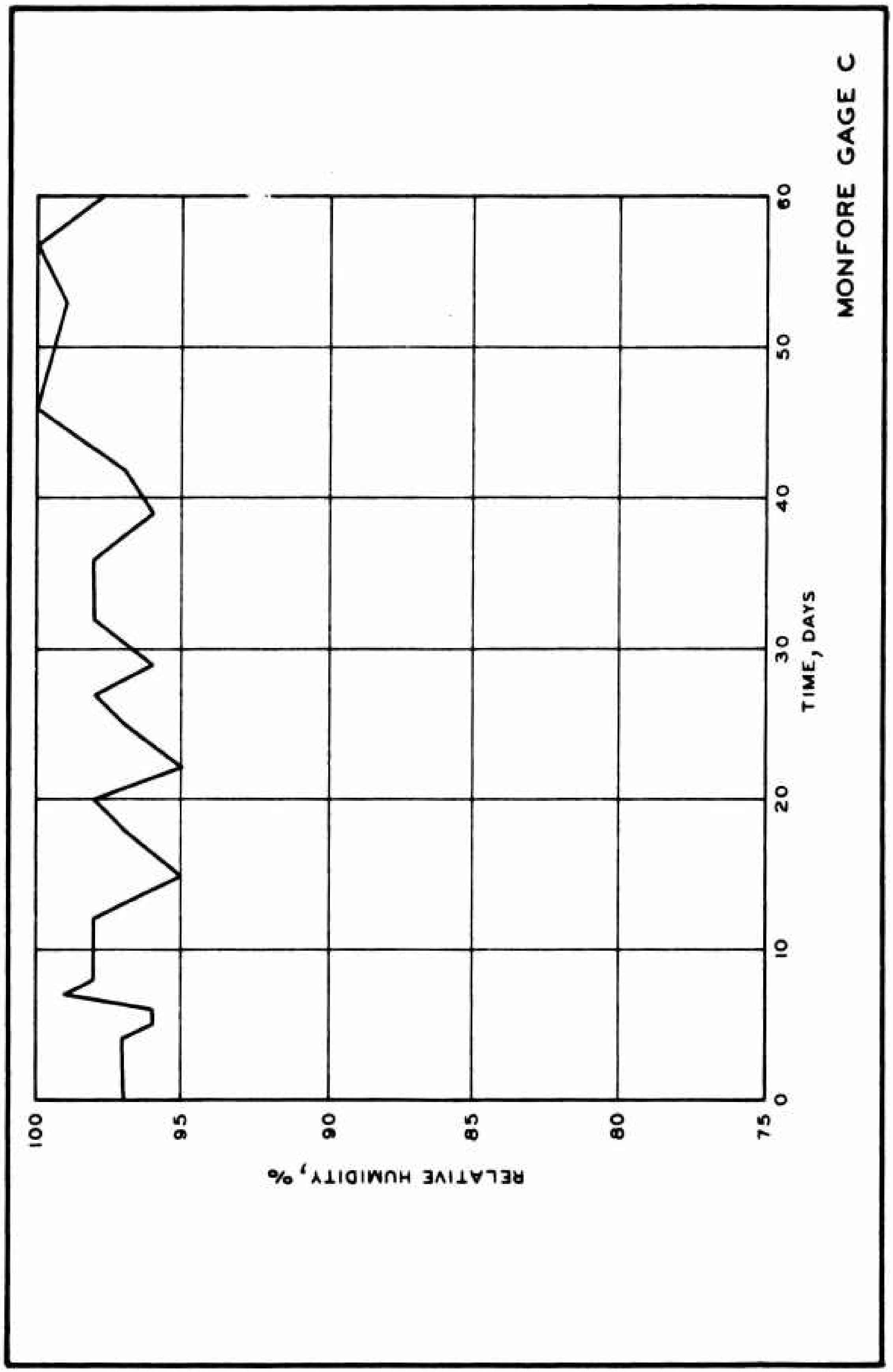

MONFORE GAGE C
RELATIVE HUMIDITY, %
100
95
90
85
80
75
TIME, DAYS
0
10
20
30
40
50
60

PLATE 4

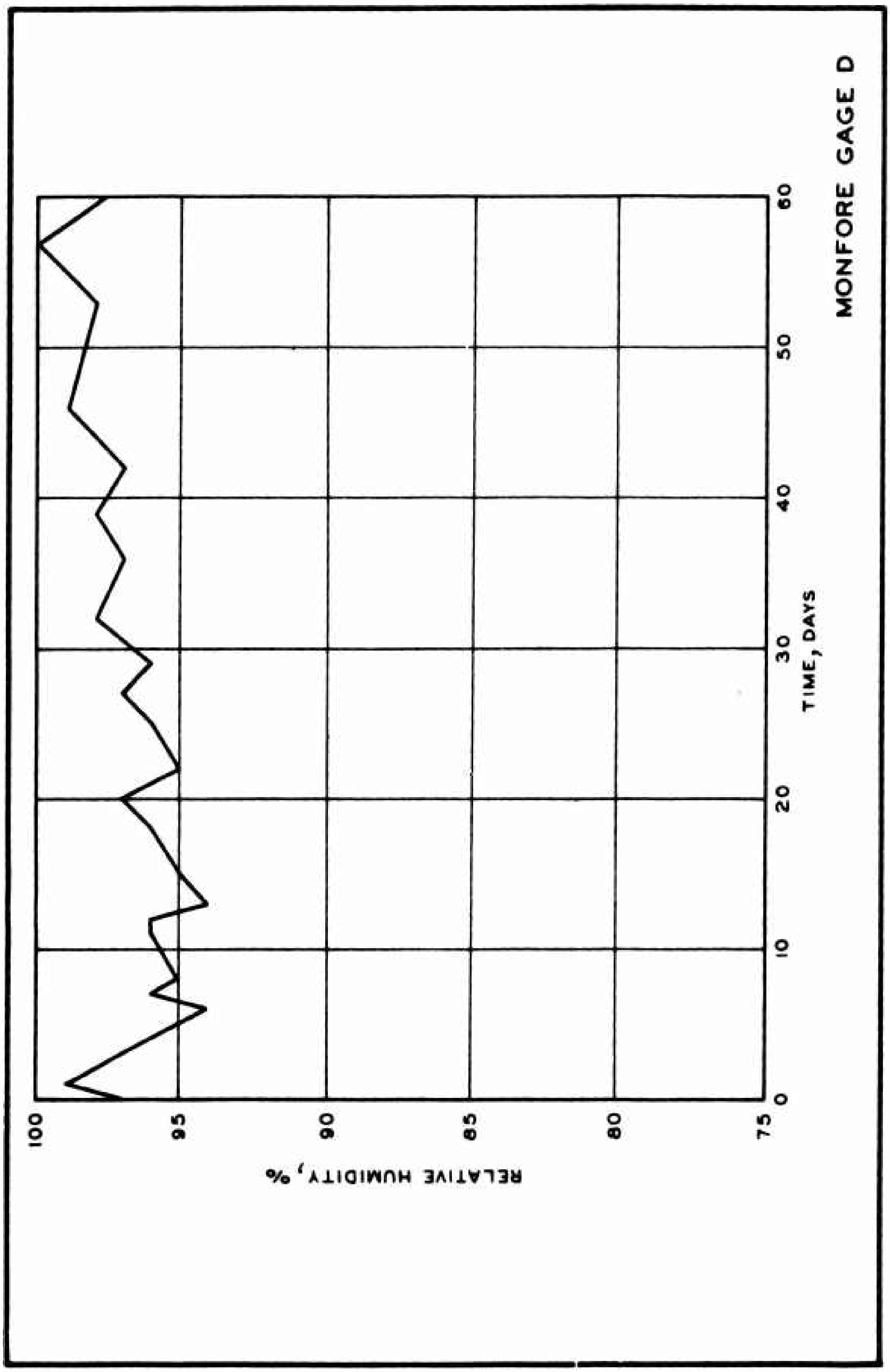

MONFORE GAGE D
RELATIVE HUMIDITY, %
100
95
90
85
80
75
TIME, DAYS
0
10
20
30
40
50
60

PLATE 5

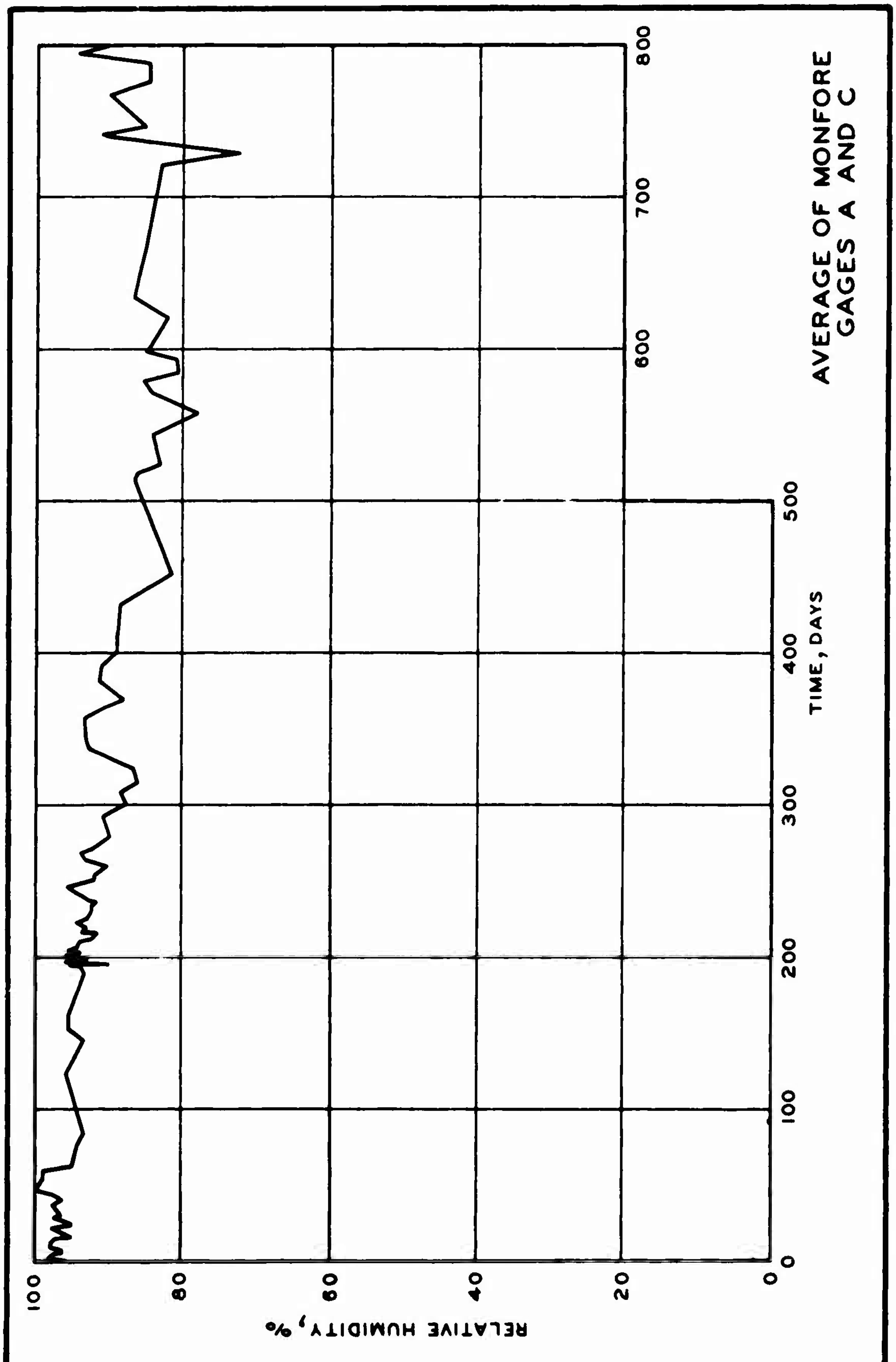
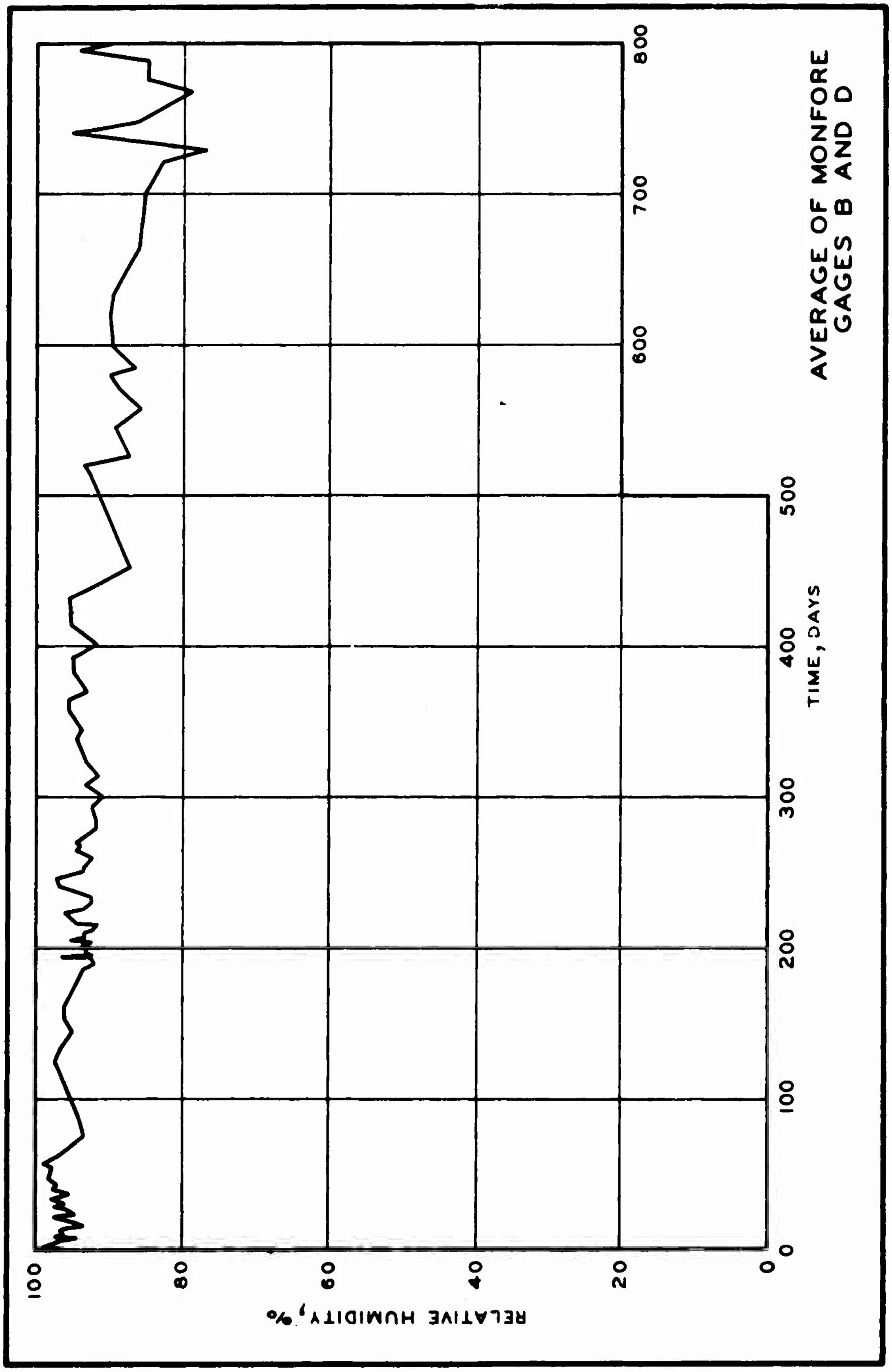
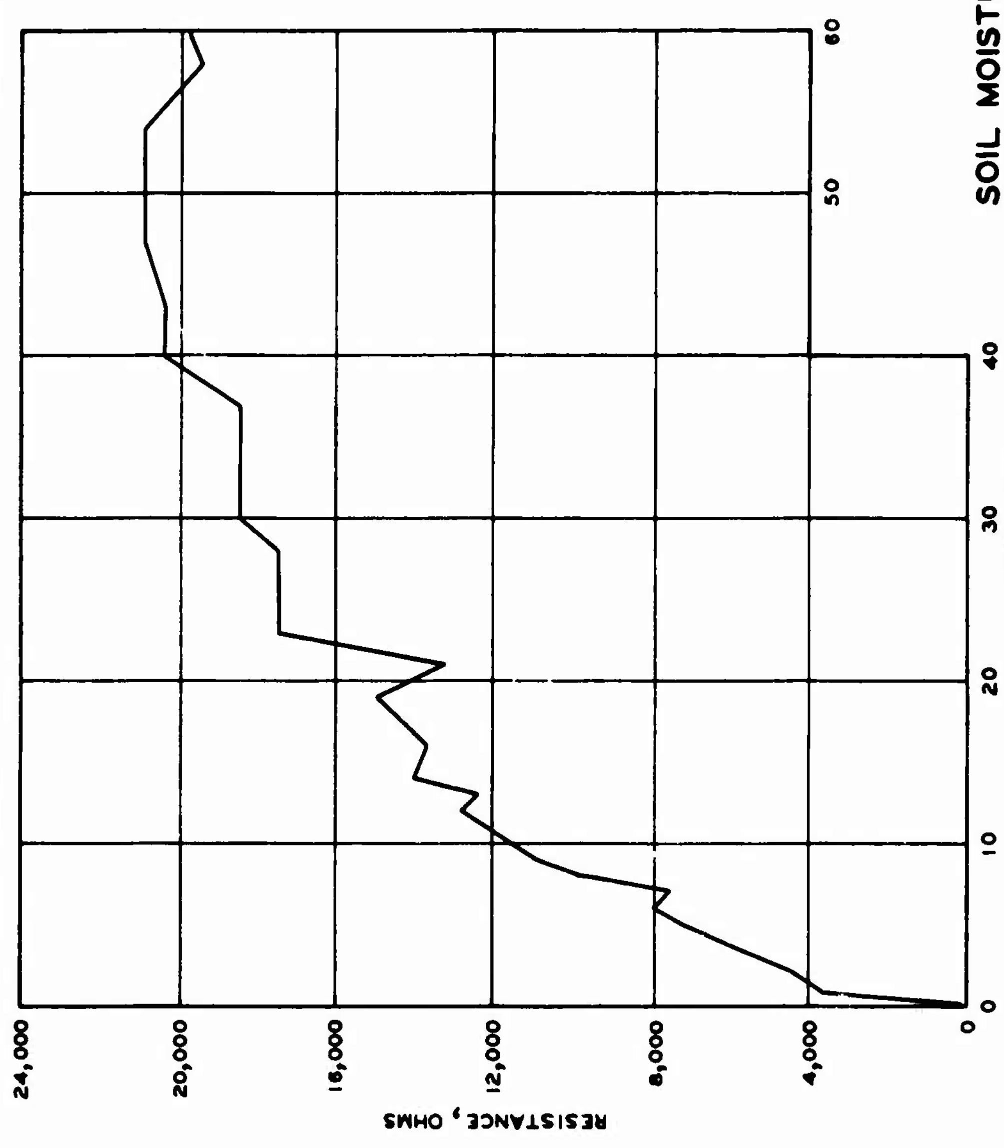

RELATIVE HUMIDITY, %
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800
TIME, DAYS
AVERAGE OF MONFORE
GAGES A AND C

PLATE 6

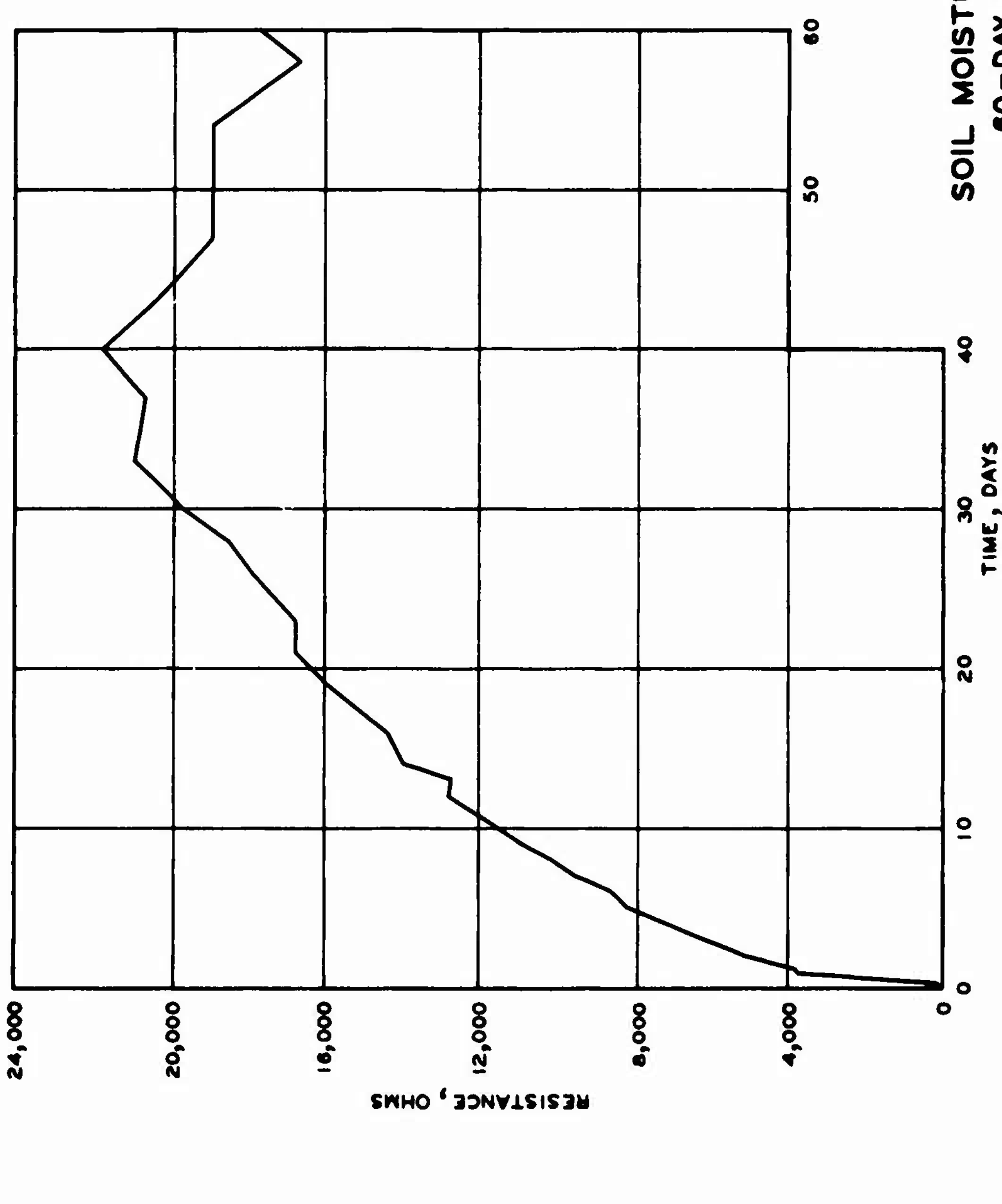


RELATIVE HUMIDITY, %
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800
TIME, DAYS
AVERAGE OF MONFORE
GAGES B AND D

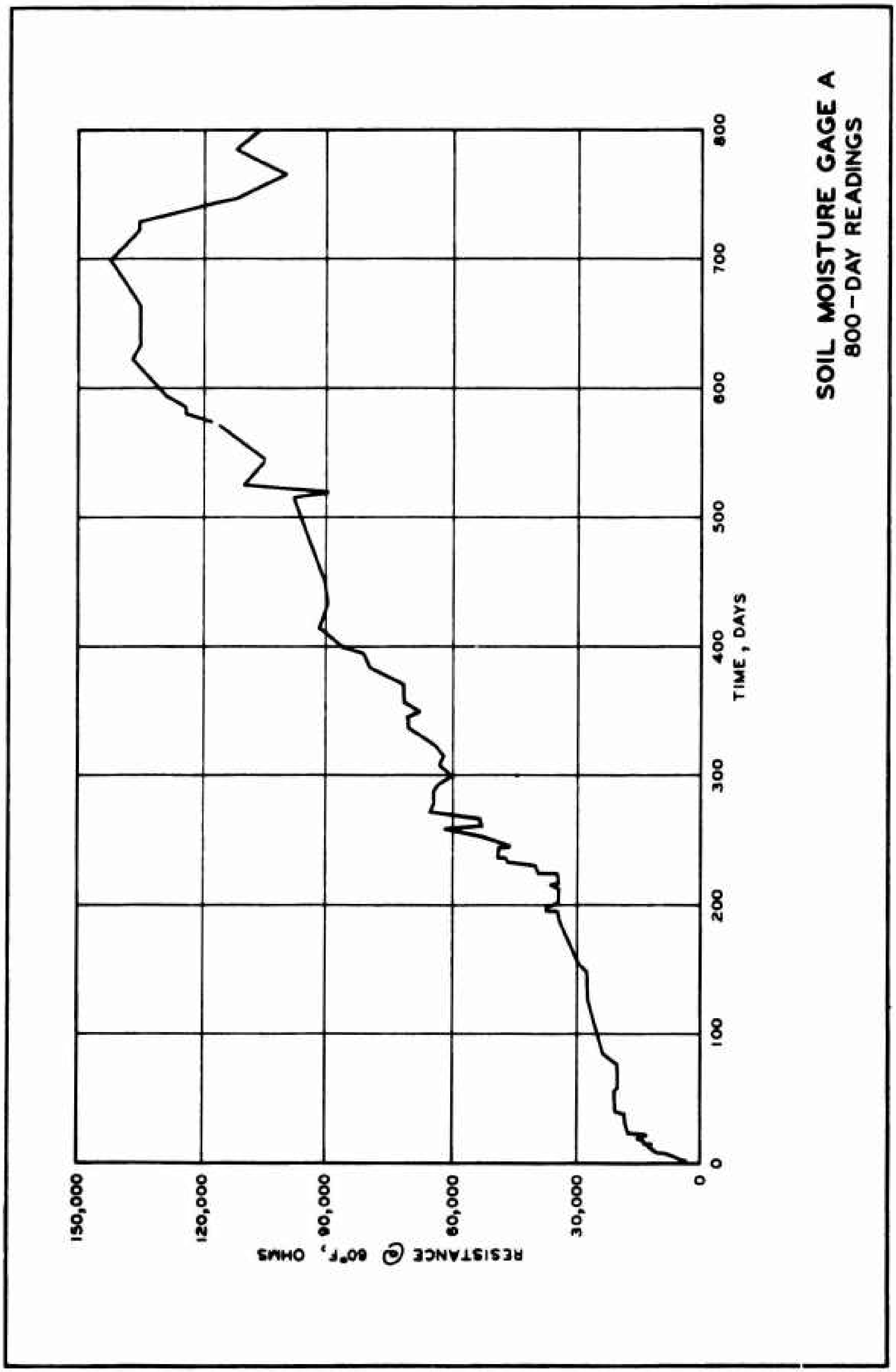
PLATE 7



SOIL MOISTURE GAGE A
60-DAY READINGS

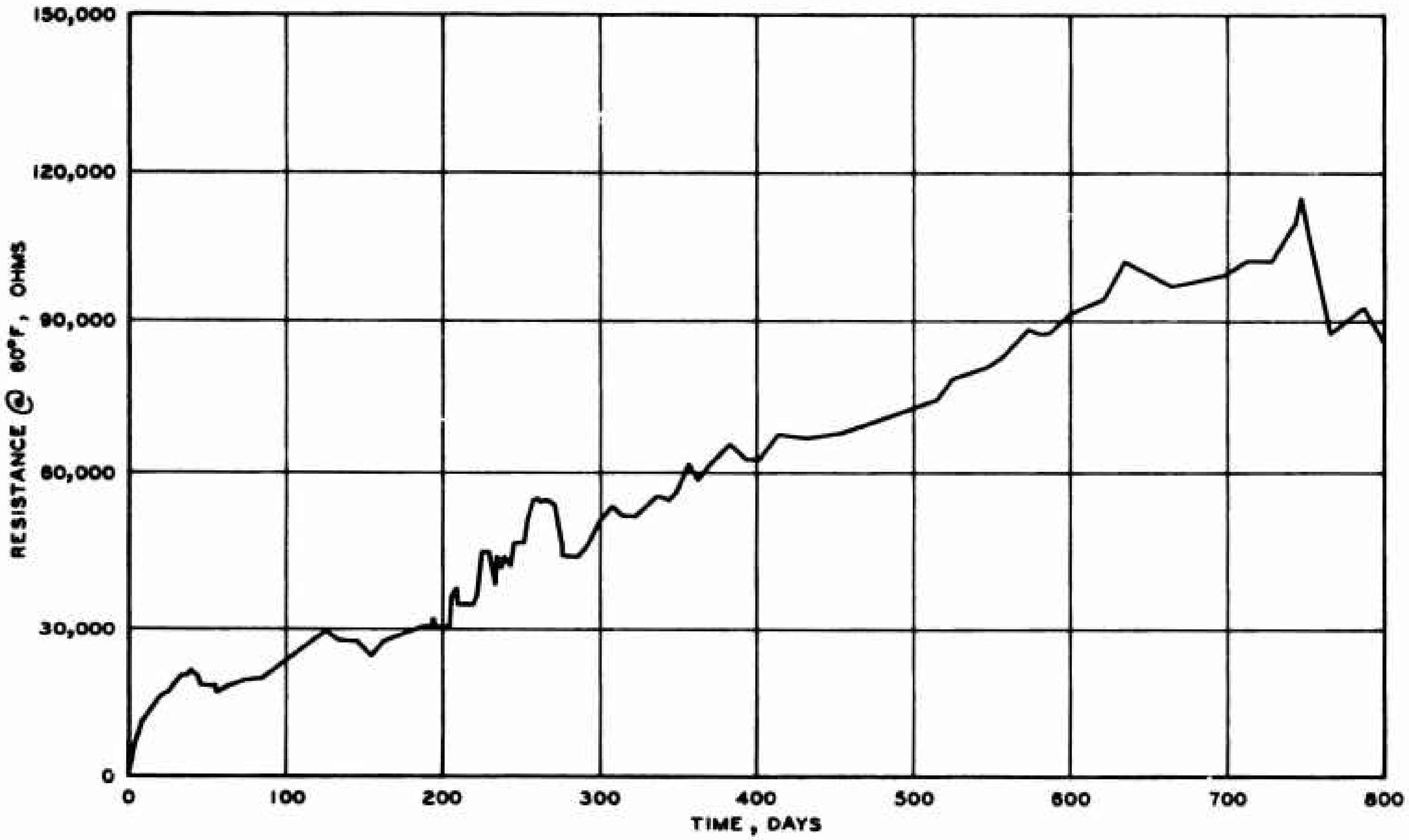


SOIL MOISTURE GAGE B
60-DAY READINGS



SOIL MOISTURE GAGE A
800-DAY READINGS

PLATE 10



SOIL MOISTURE GAGE B
800-DAY READINGS

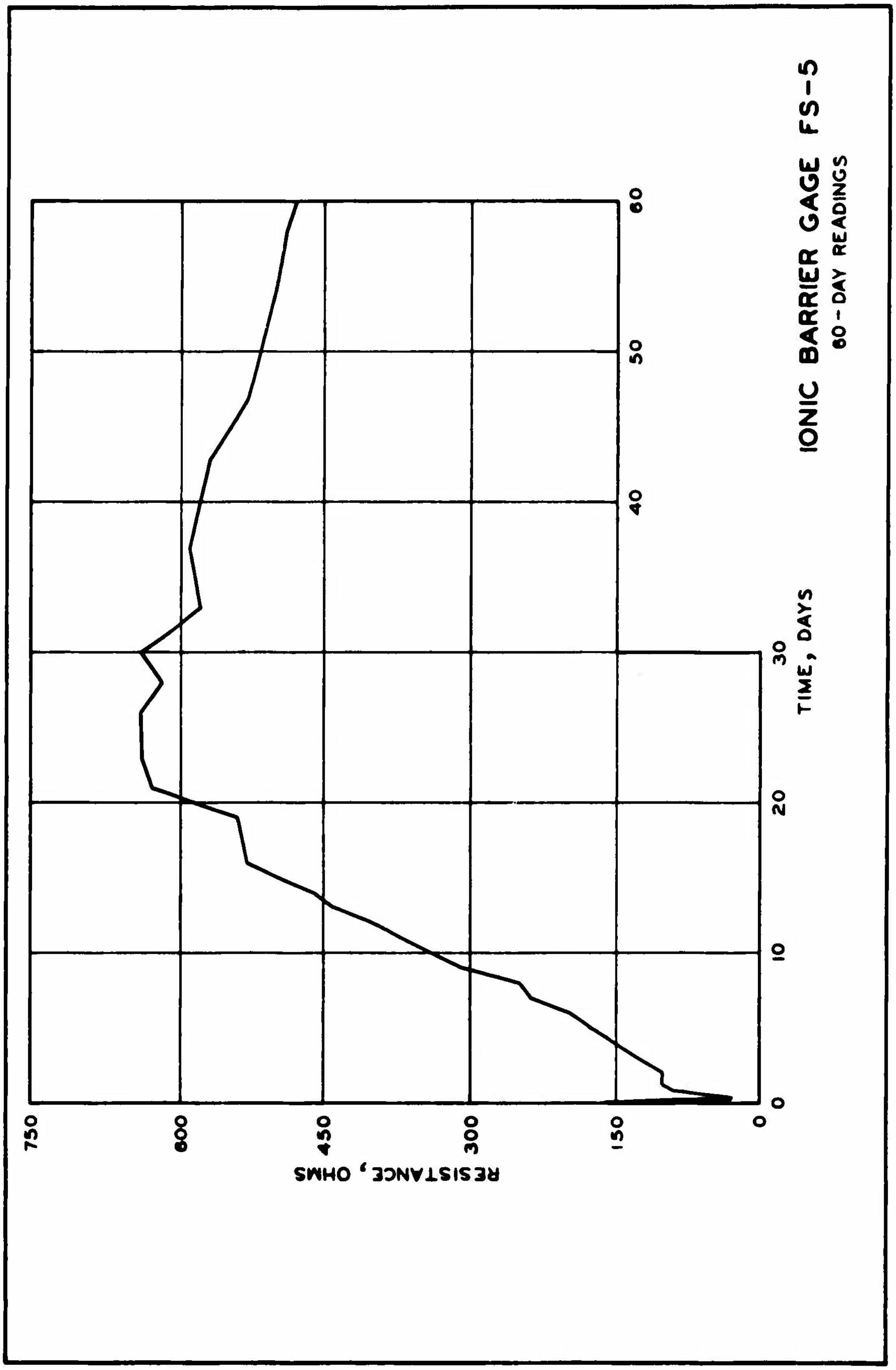
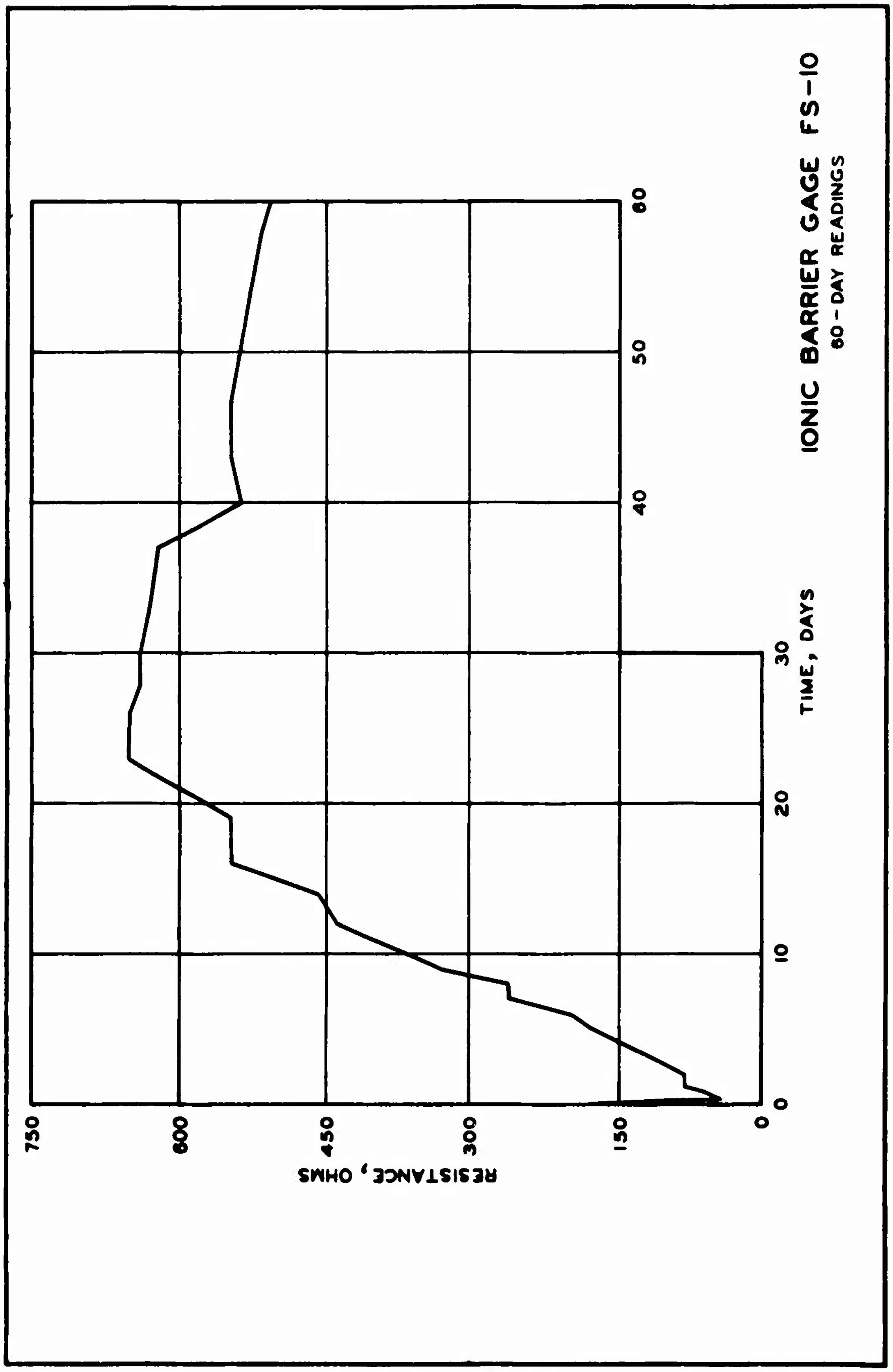
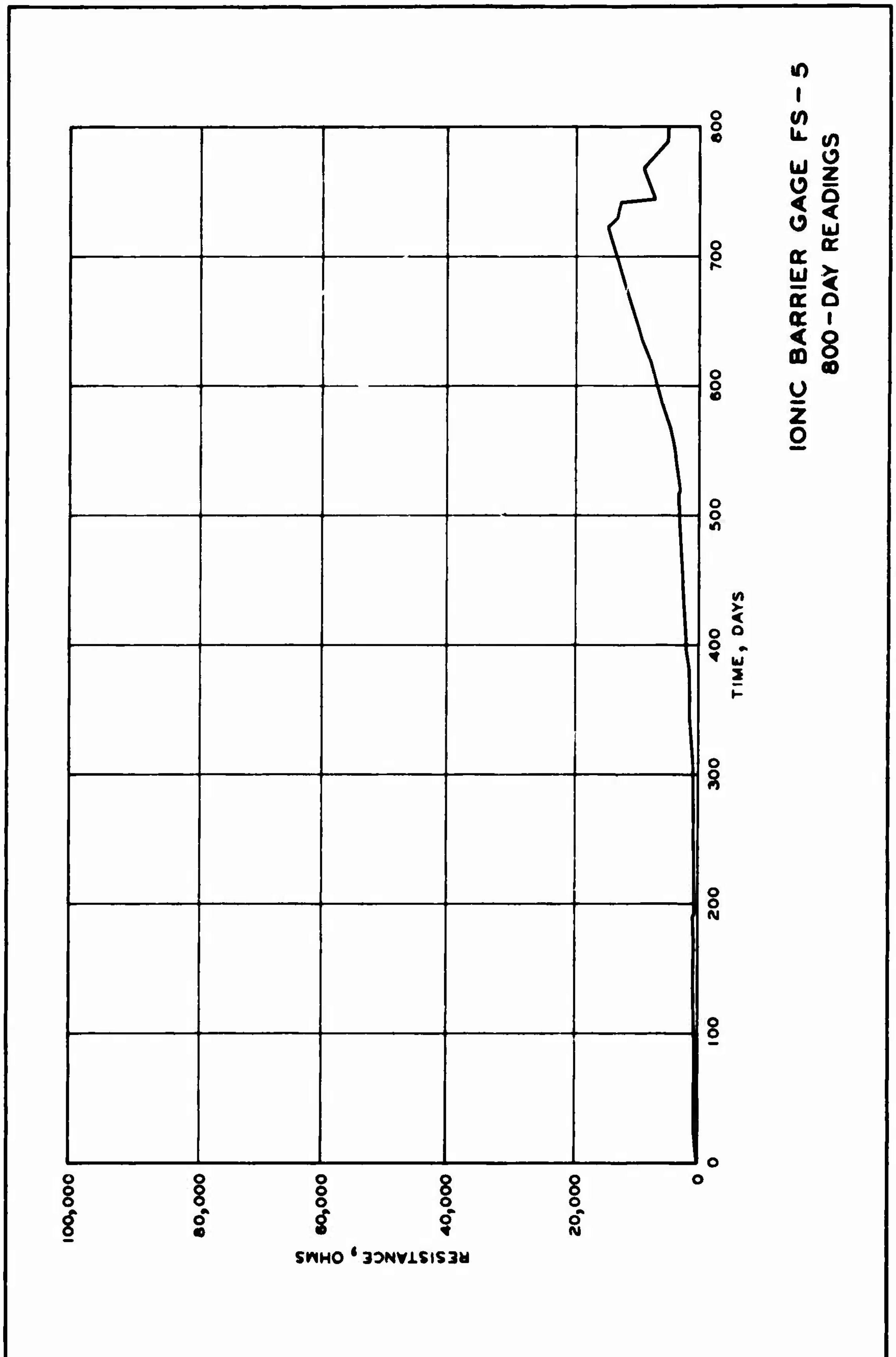

IONIC BARRIER GAGE FS-5
60-DAY READINGS
RESISTANCE, OHMS
0
150
300
450
600
750
TIME, DAYS
0
10
20
30
40
50
60

PLATE 12

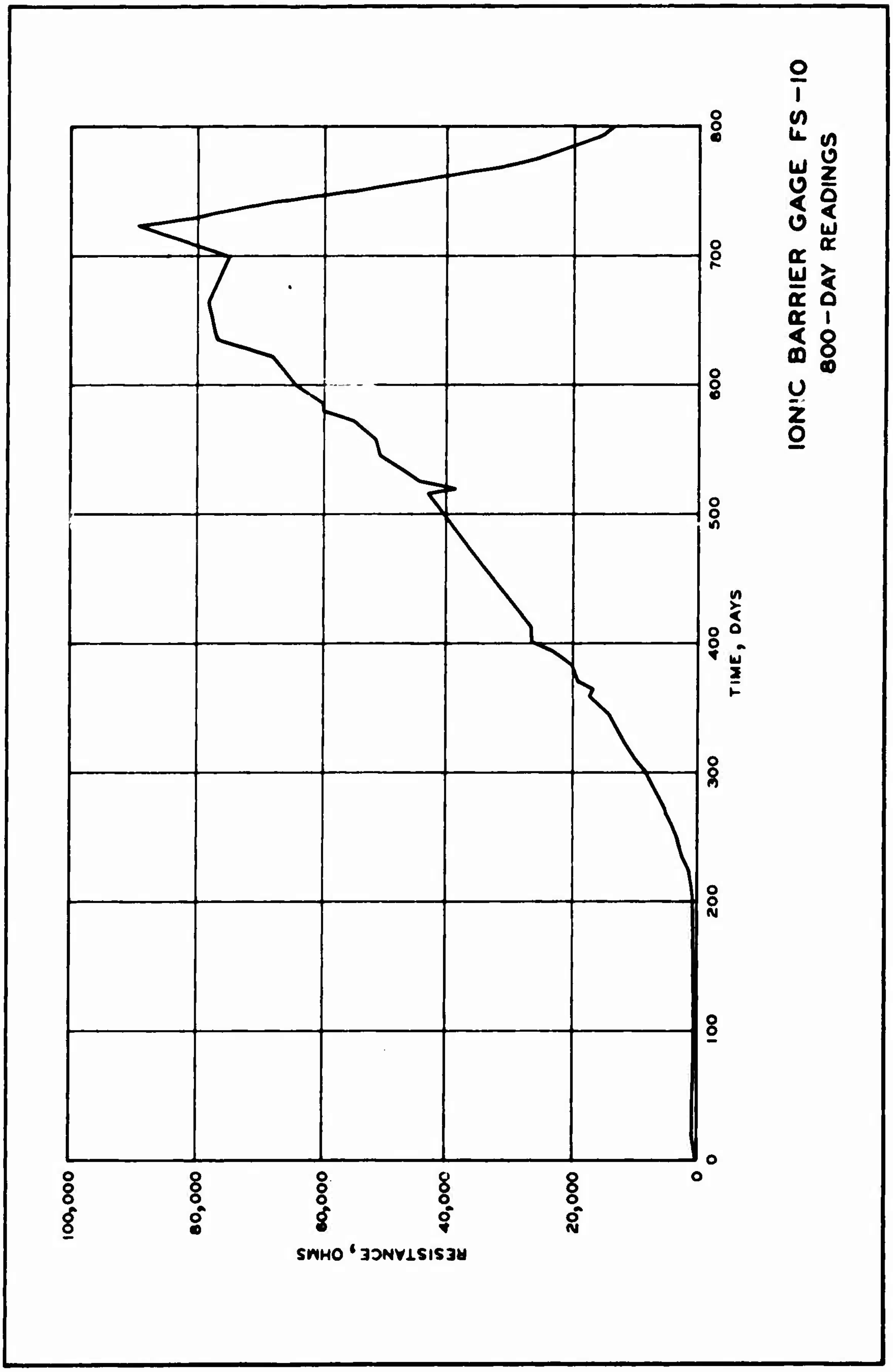


IONIC BARRIER GAGE FS-10
60-DAY READINGS



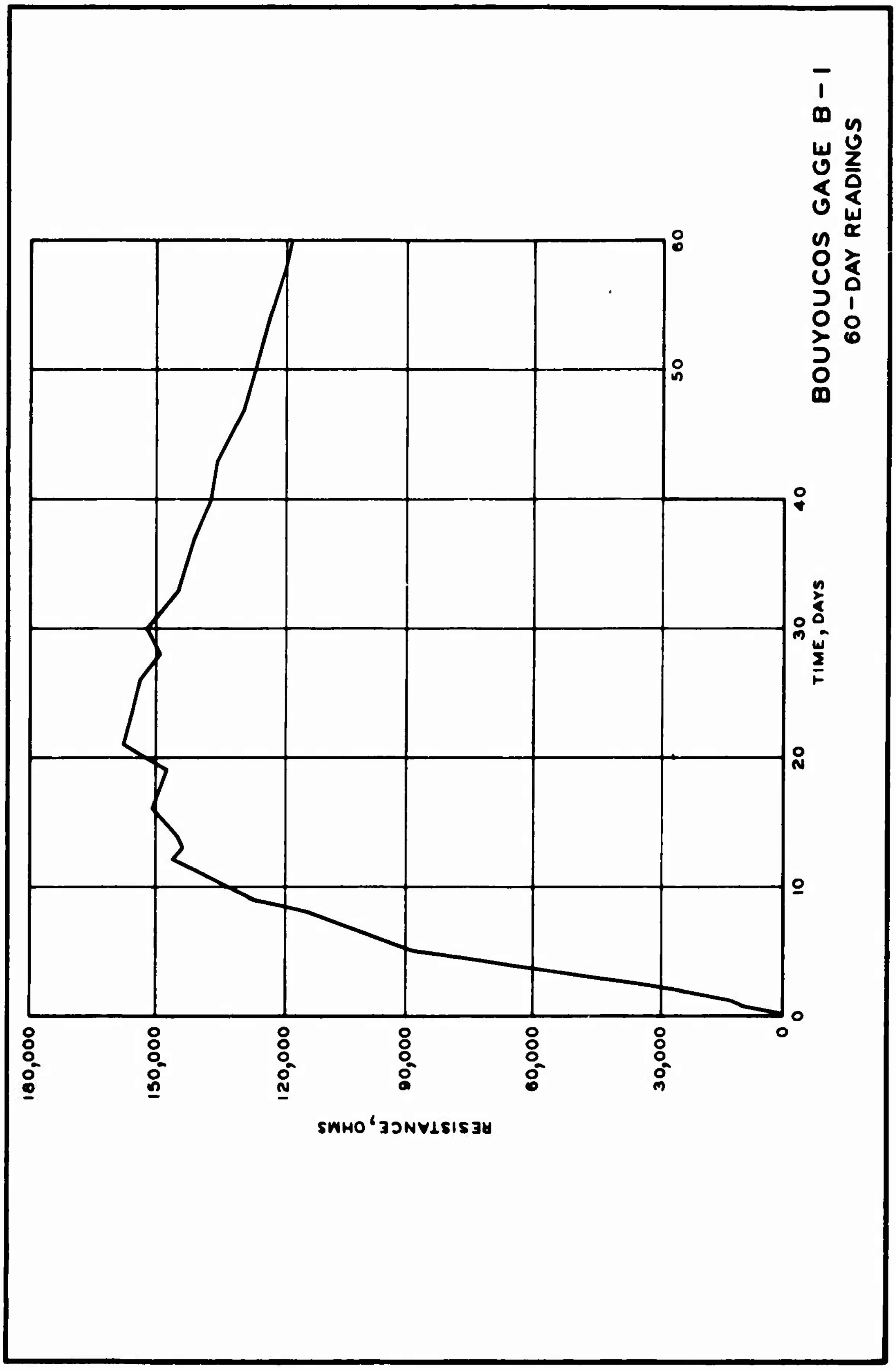
IONIC BARRIER GAGE FS-5
800-DAY READINGS
RESISTANCE, OHMS
100,000
80,000
60,000
40,000
20,000
0
TIME, DAYS
0
100
200
300
400
500
600
700
800

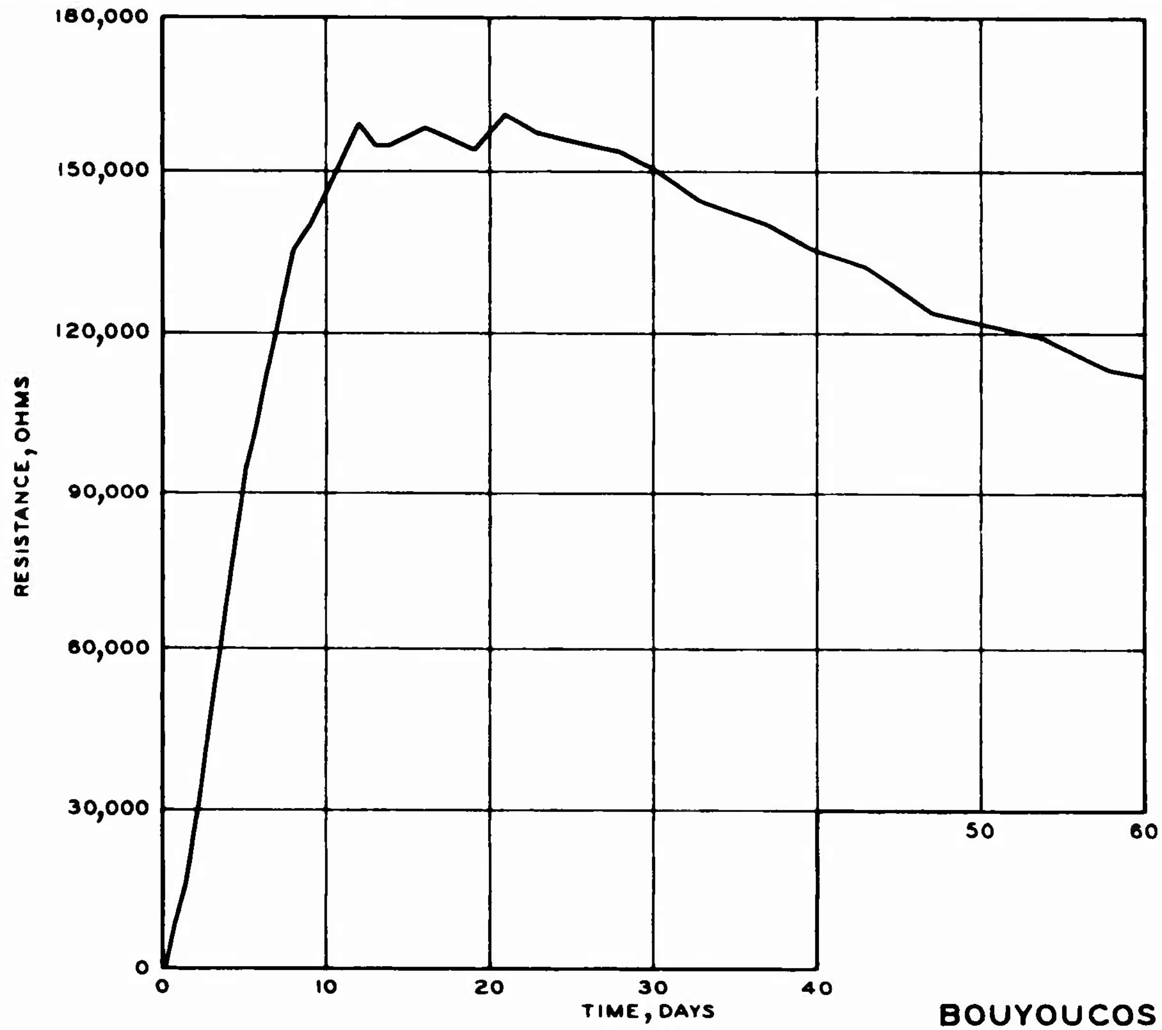
PLATE 14



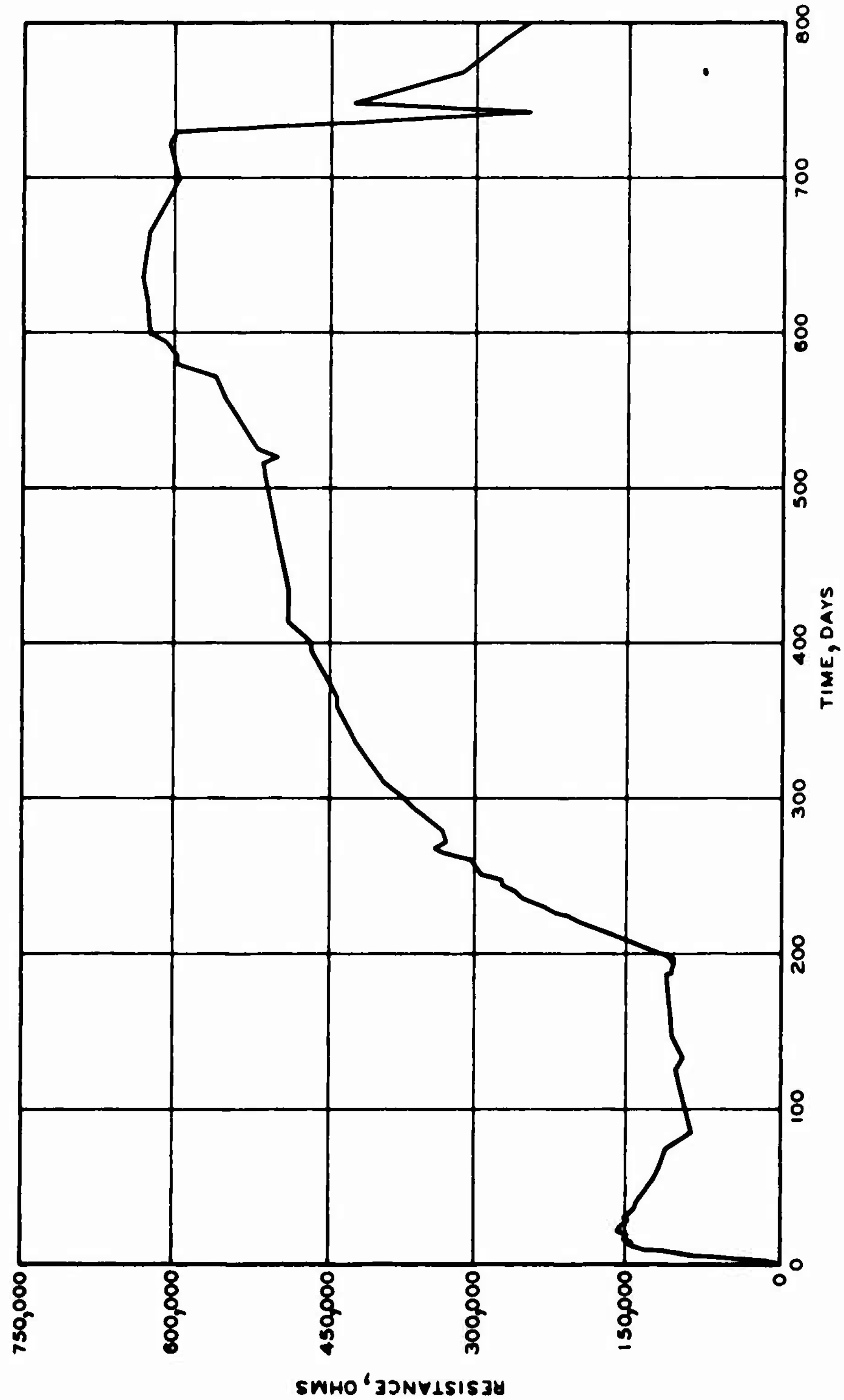
IONIC BARRIER GAGE FS-10
800-DAY READINGS

PLATE 15


BOUYOUCOS GAGE B-1
60-DAY READINGS
RESISTANCE, OHMS
180,000
150,000
120,000
90,000
60,000
30,000
0
TIME, DAYS
0
10
20
30
40
50
60

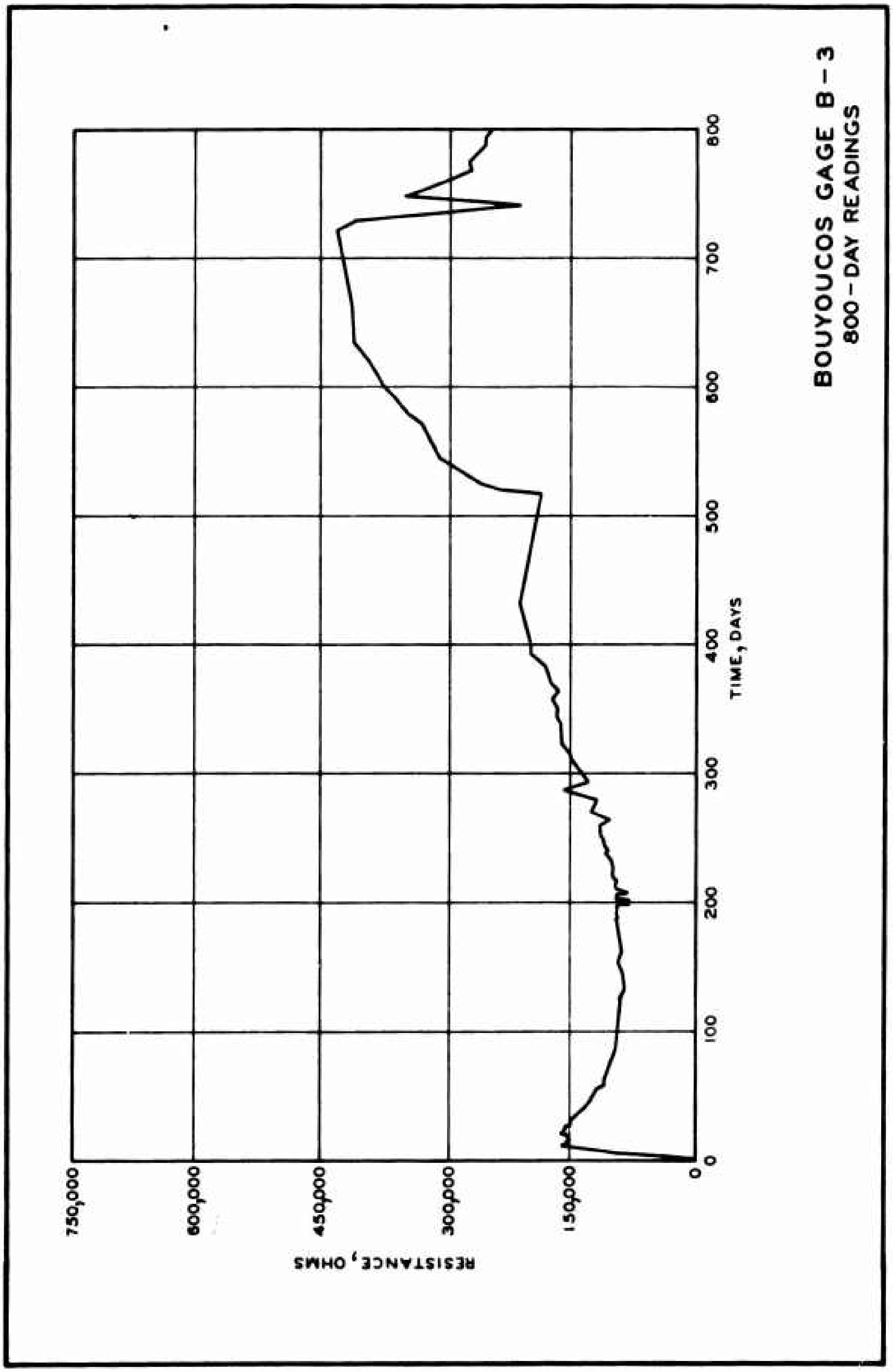


BOUYOUCOS GAGE B-3
60-DAY READINGS

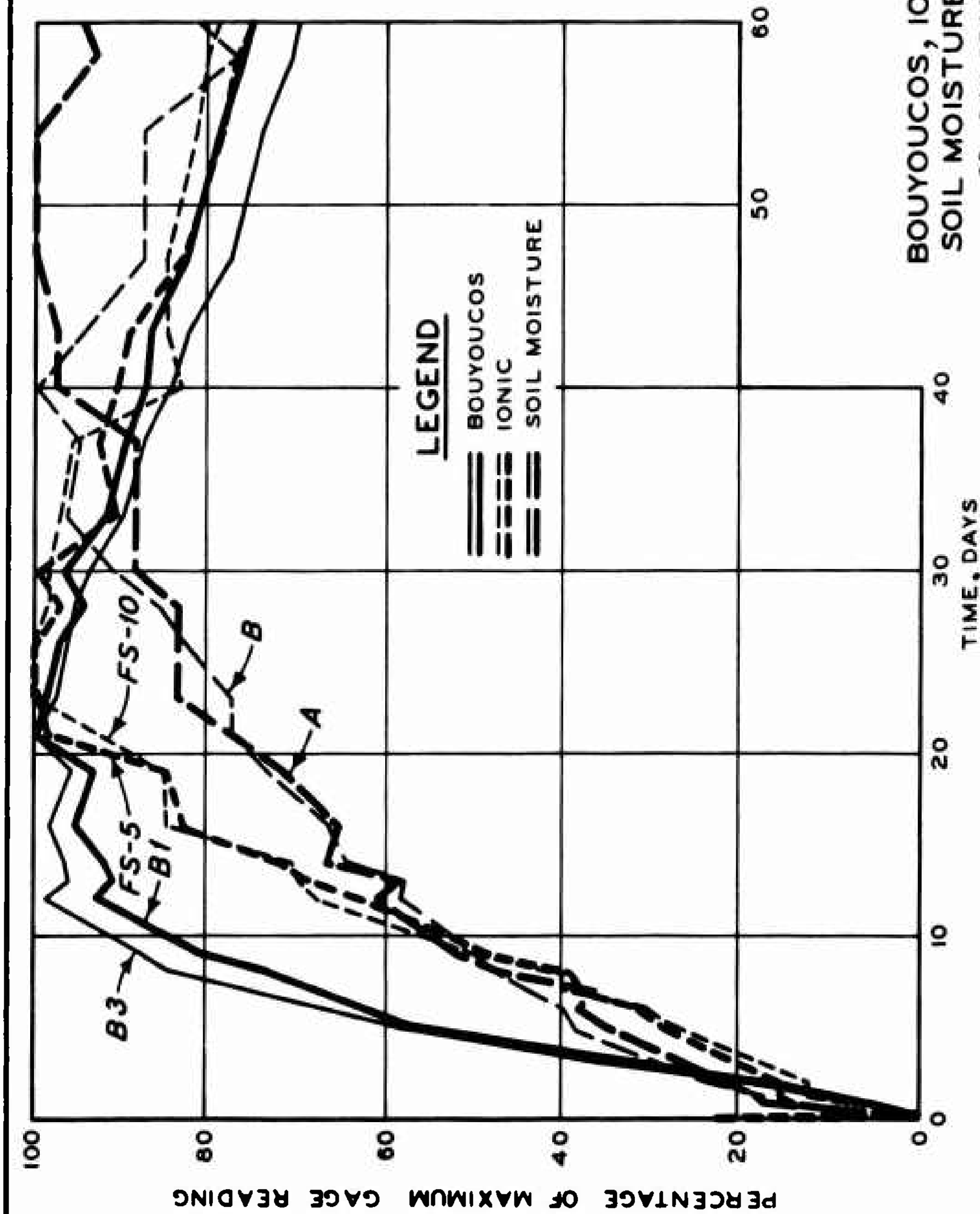


BOUYOUCOS GAGE B-1
800-DAY READINGS

PLATE 18

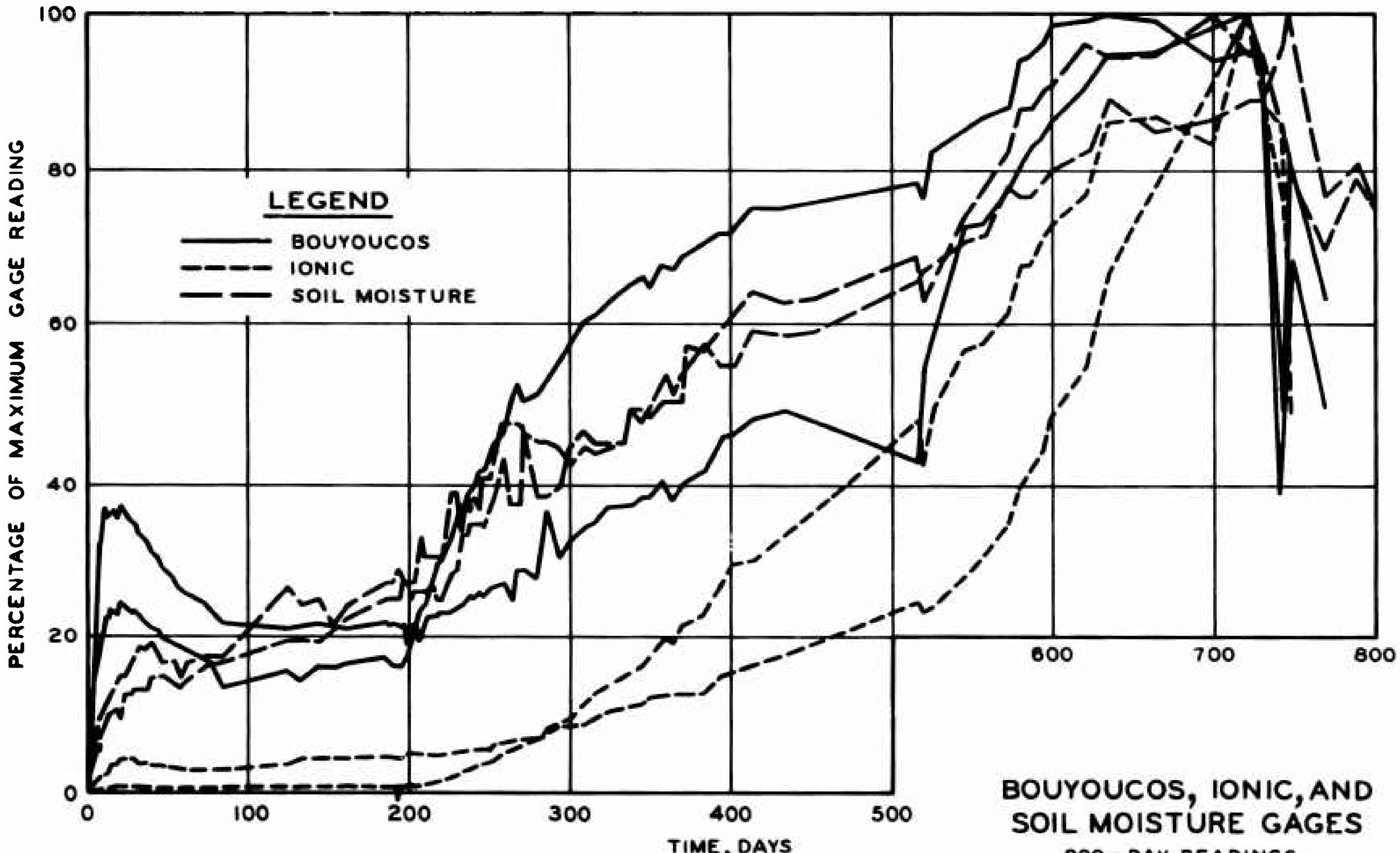


BOUYOUCOS GAGE B – 3
800 – DAY READINGS



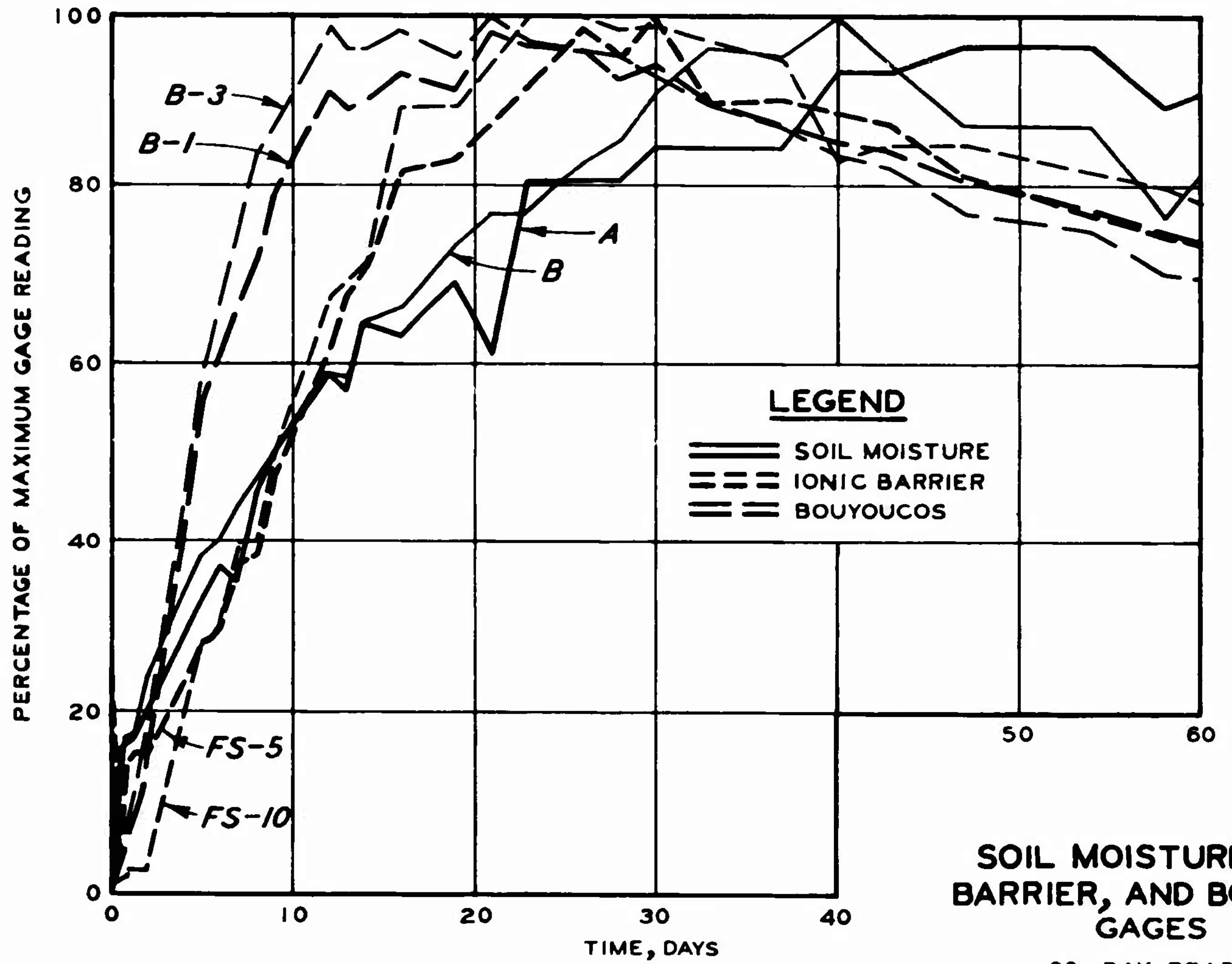
BOUYOUCOS, IONIC, AND SOIL MOISTURE GAGES

60-DAY READINGS NORMALIZED TO EACH GAGE



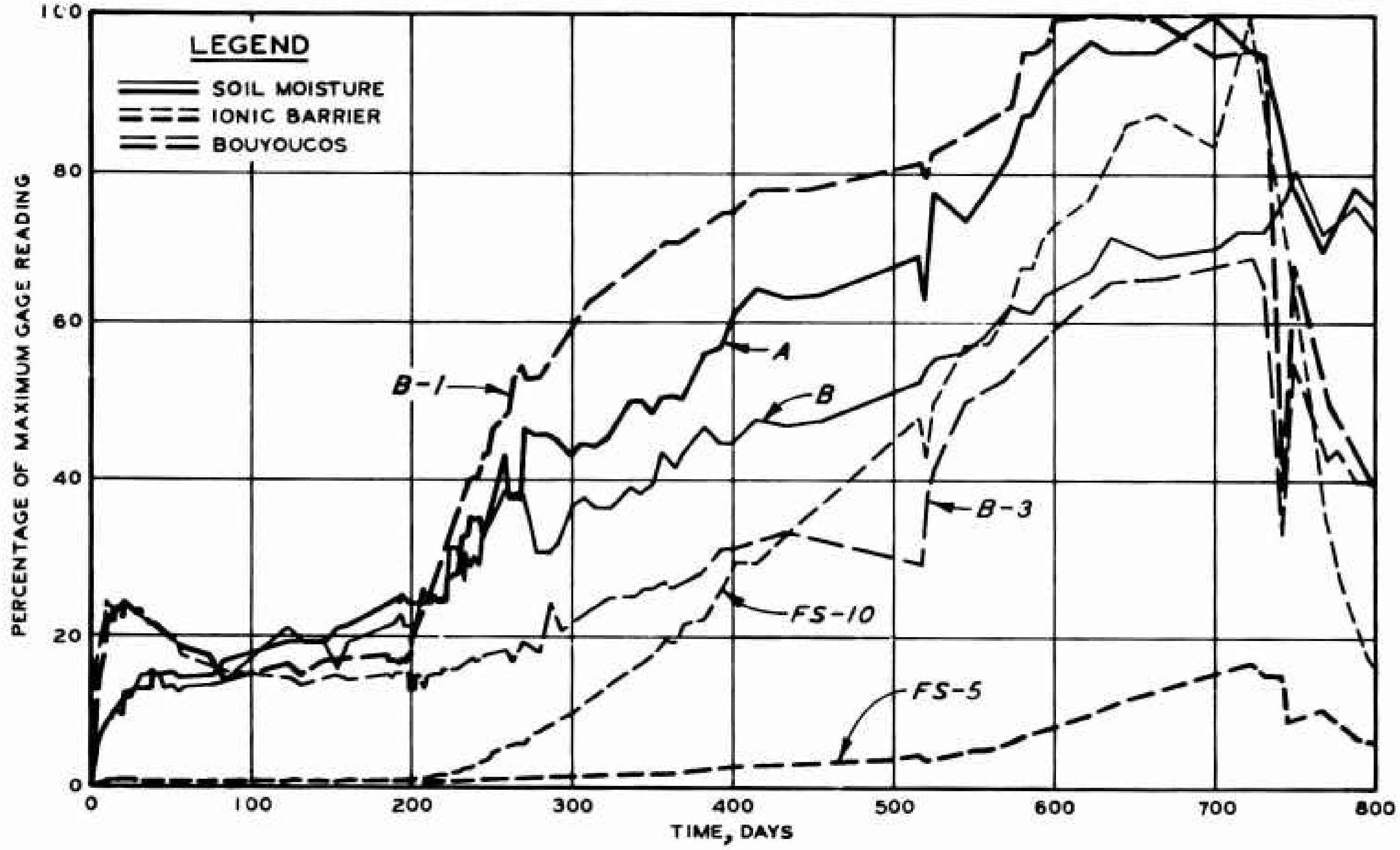
BOUYOUCOS, IONIC, AND SOIL MOISTURE GAGES

800-DAY READINGS NORMALIZED TO EACH GAGE



SOIL MOISTURE, IONIC BARRIER, AND BOUYOUCOS GAGES

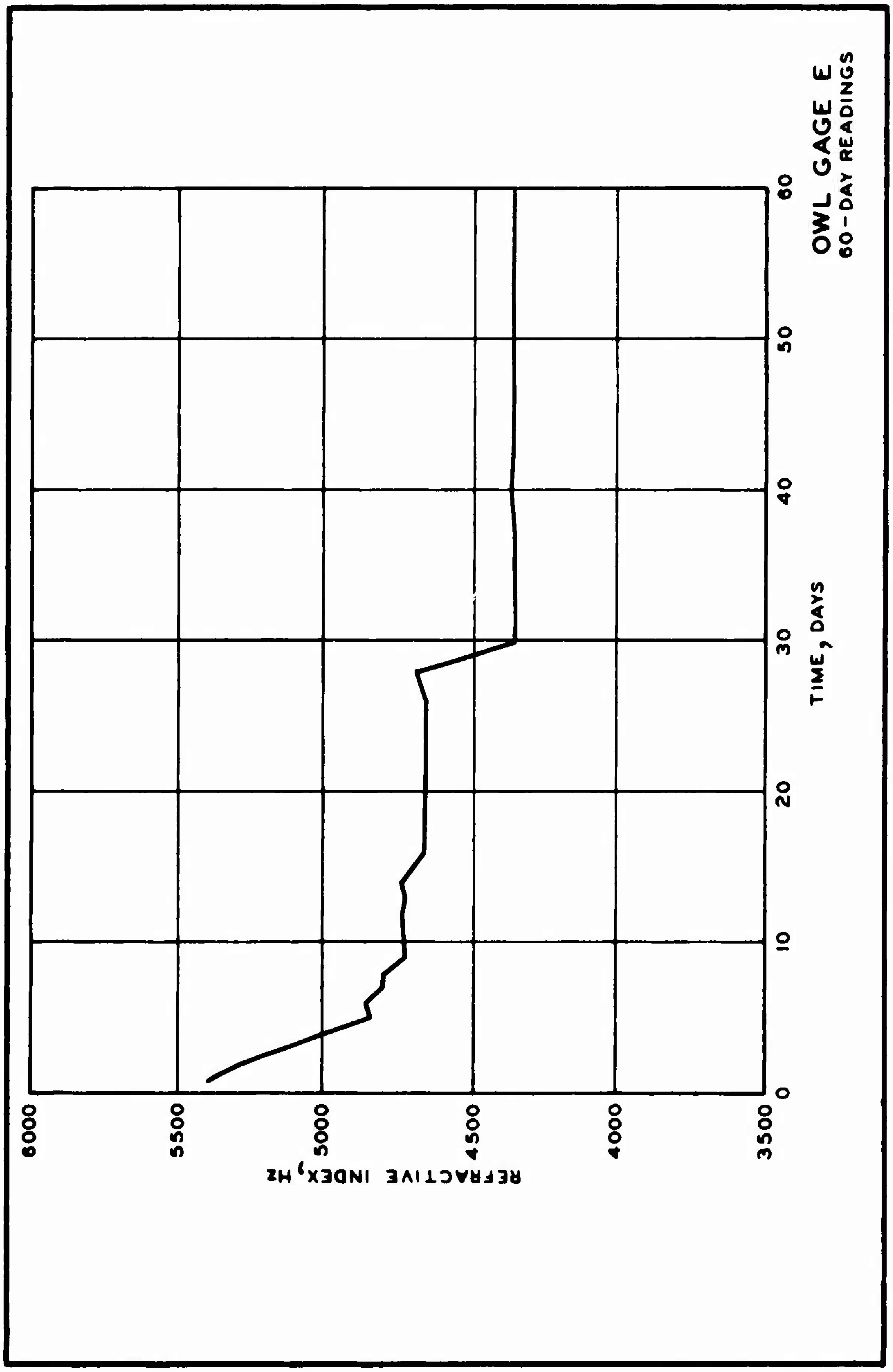
60-DAY READINGS
NORMALIZED TO GAGE TYPE

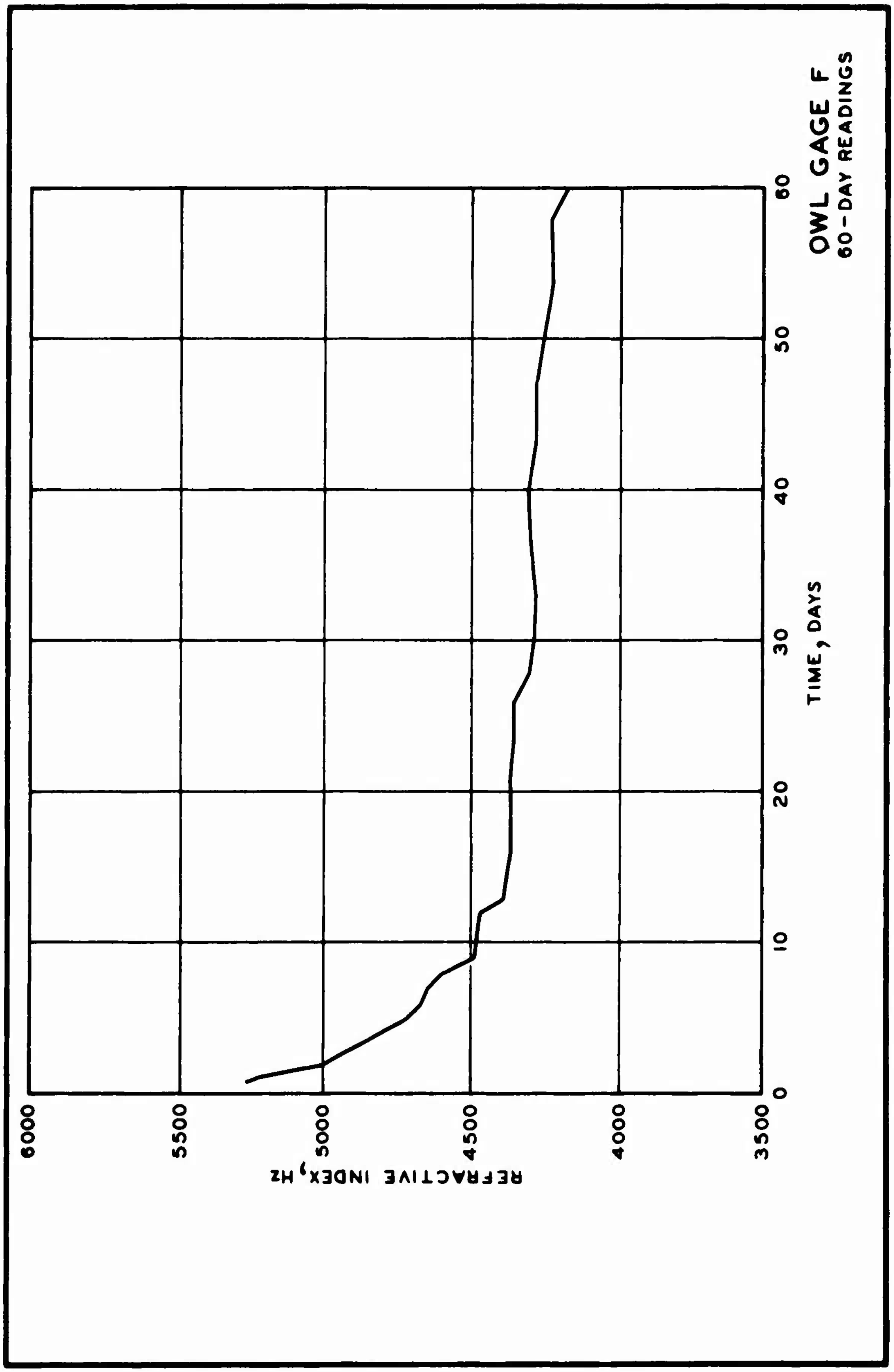


SOIL MOISTURE, IONIC BARRIER, AND BOUYOUCOS GAGES

800-DAY READINGS

NORMALIZED TO GAGE TYPE


OWL GAGE E
60-DAY READINGS
TIME, DAYS
REFRACTIVE INDEX, HZ
0
10
20
30
40
50
60
3500
4000
4500
5000
5500
6000


OWL GAGE F
60-DAY READINGS
TIME, DAYS
REFRACTIVE INDEX, Hz
0
10
20
30
40
50
60
3500
4000
4500
5000
5500
6000

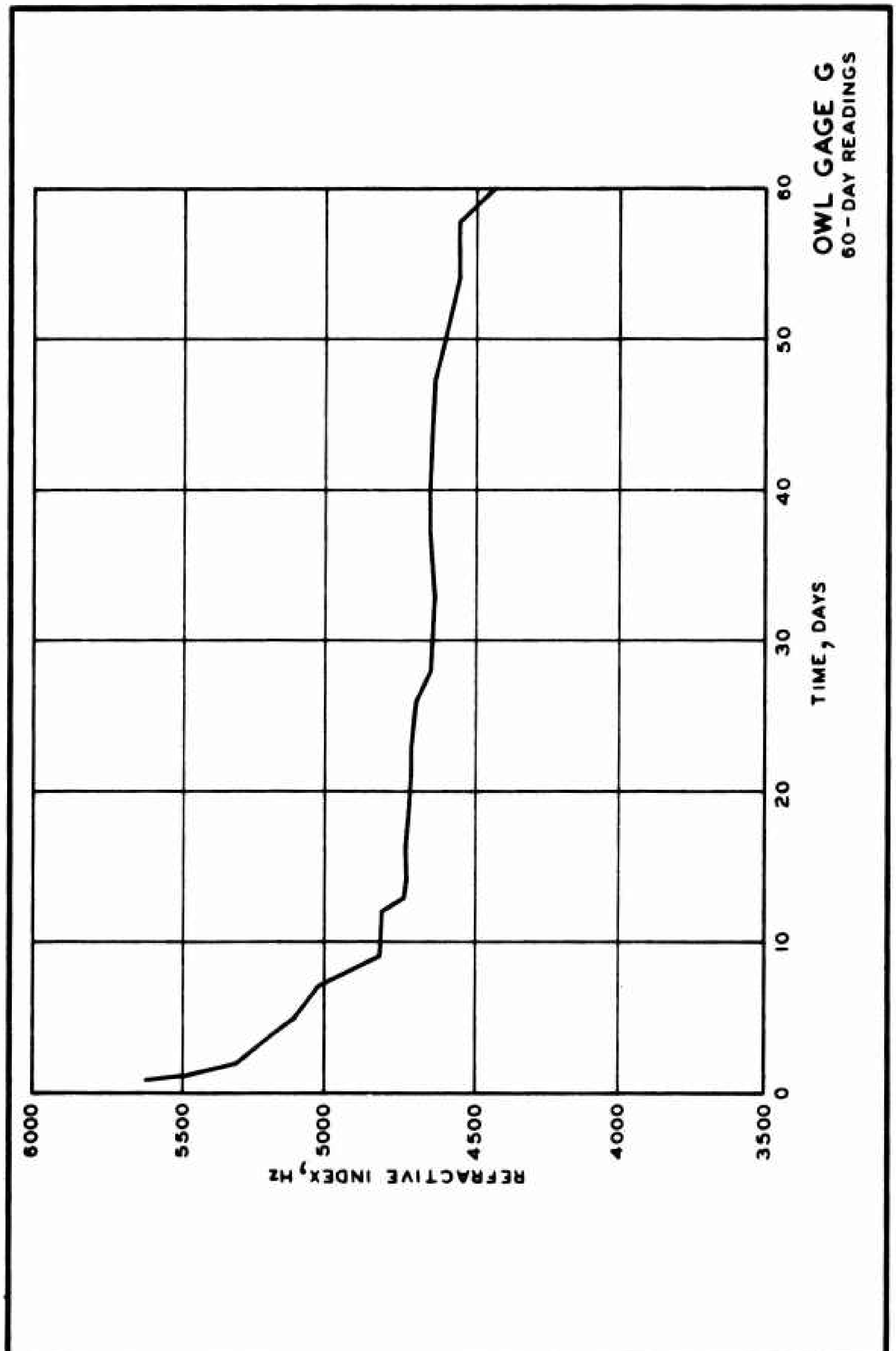

OWL GAGE G
60-DAY READINGS
TIME, DAYS
REFRACTIVE INDEX, HZ
0
10
20
30
40
50
60
3500
4000
4500
5000
5500
6000

PLATE 26

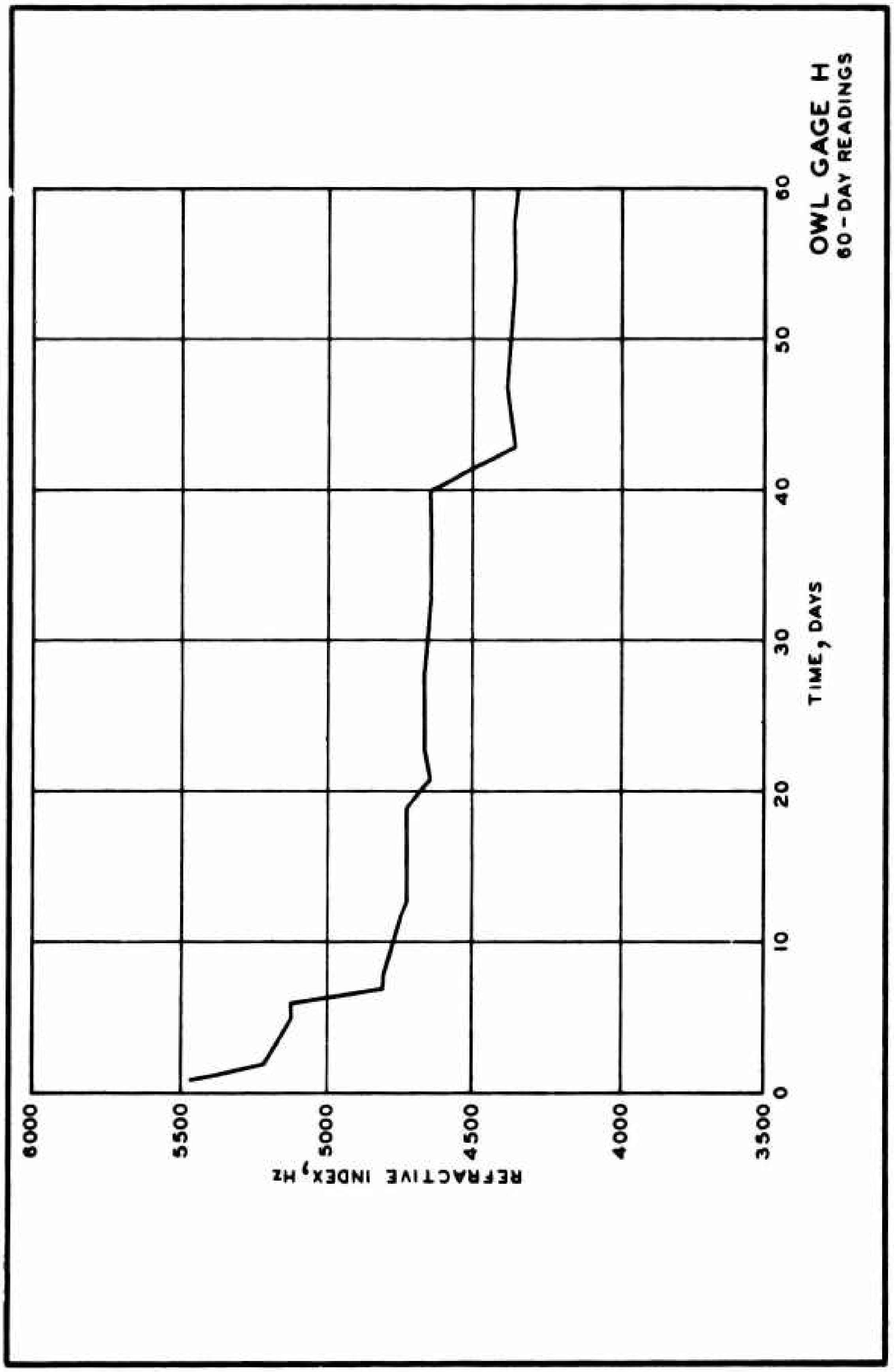

OWL GAGE H
60-DAY READINGS
TIME, DAYS
REFRACTIVE INDEX, HZ
0
10
20
30
40
50
60
3500
4000
4500
5000
5500
6000

PLATE 27

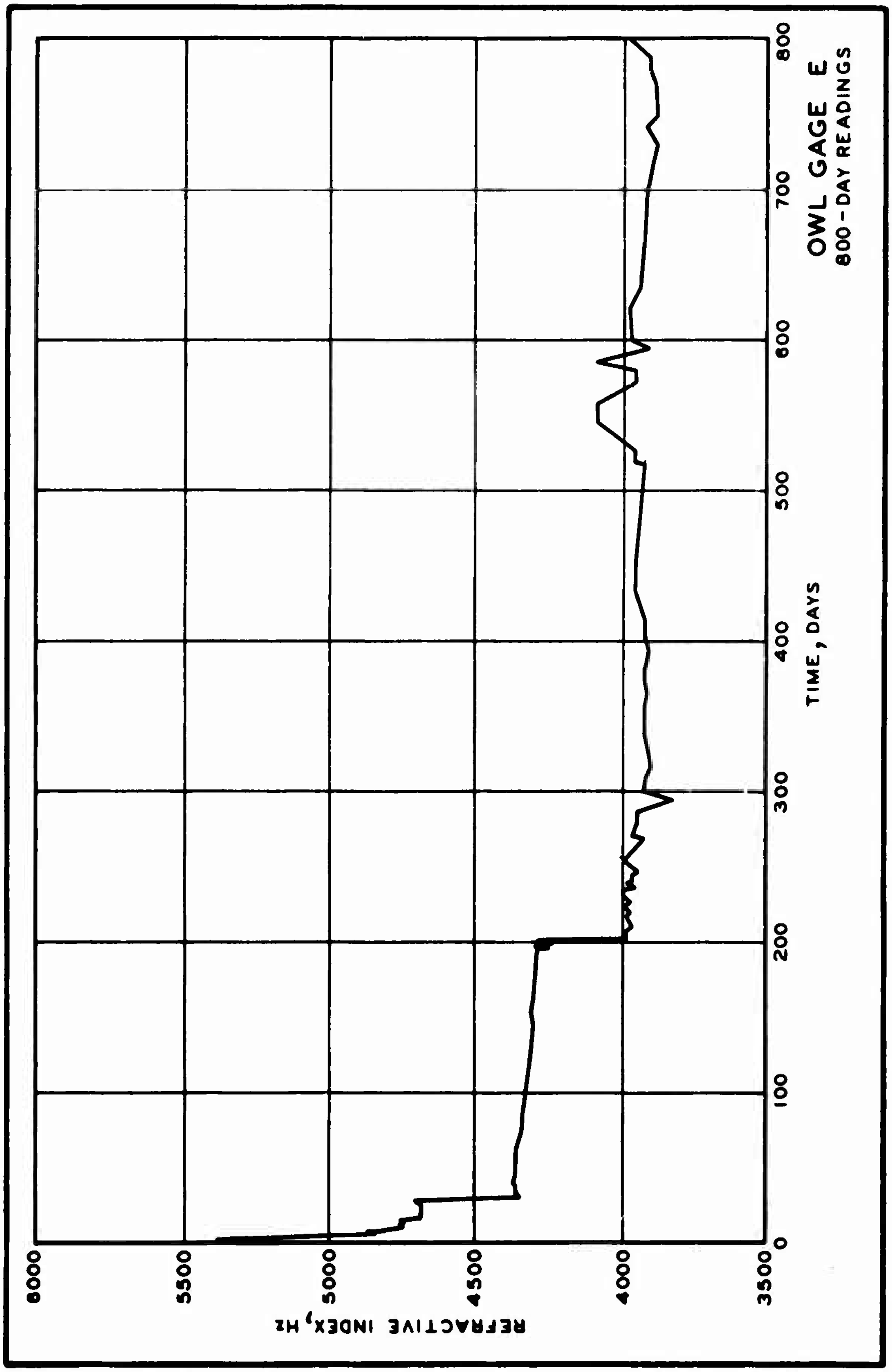
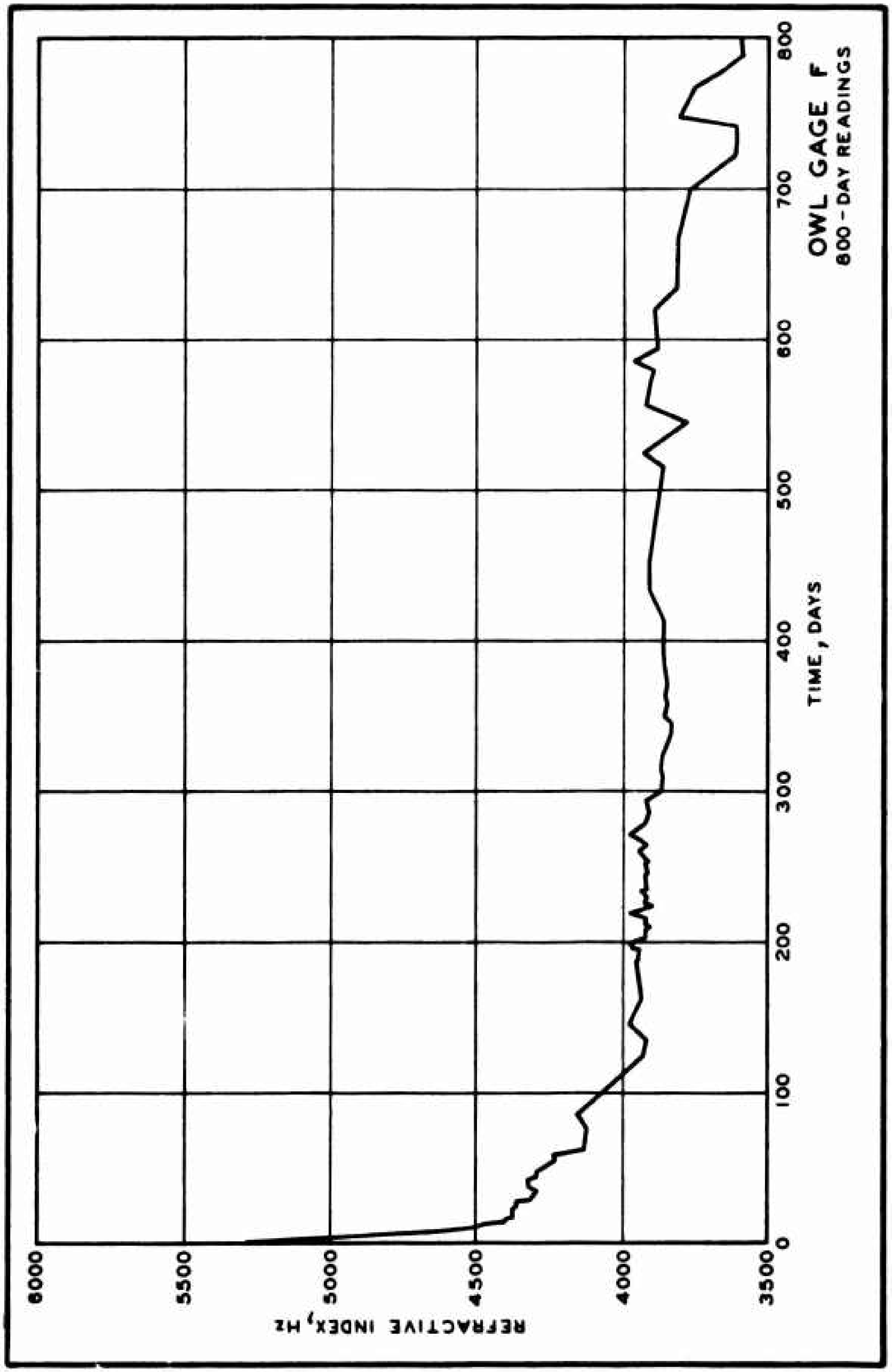

OWL GAGE E
800-DAY READINGS
TIME, DAYS
REFRACTIVE INDEX, HZ
0
100
200
300
400
500
600
700
800
3500
4000
4500
5000
5500
6000

PLATE 28


OWL GAGE F
800 - DAY READINGS
TIME, DAYS
REFRACTIVE INDEX, Hz
0
100
200
300
400
500
600
700
800
3500
4000
4500
5000
5500
6000

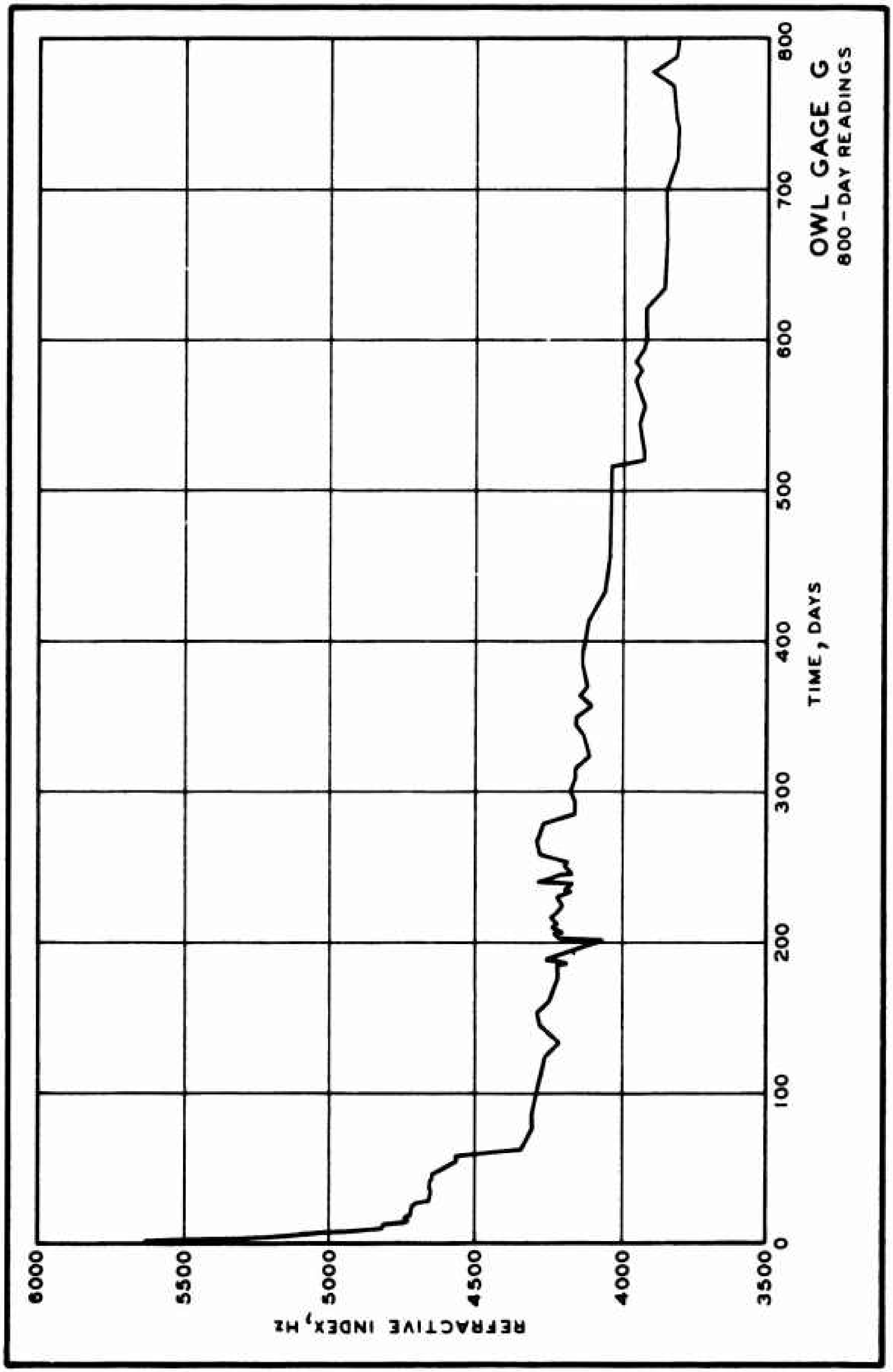
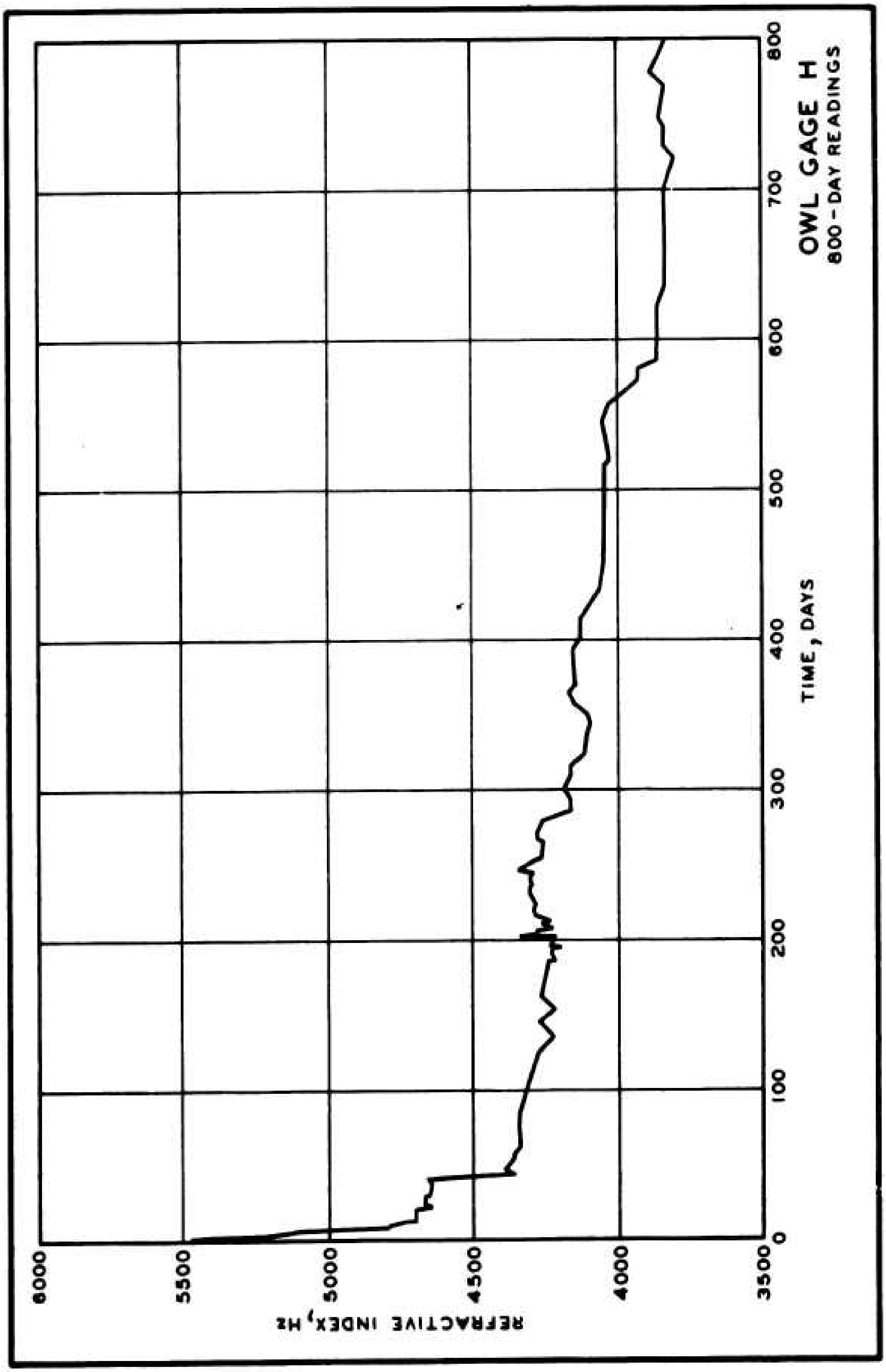
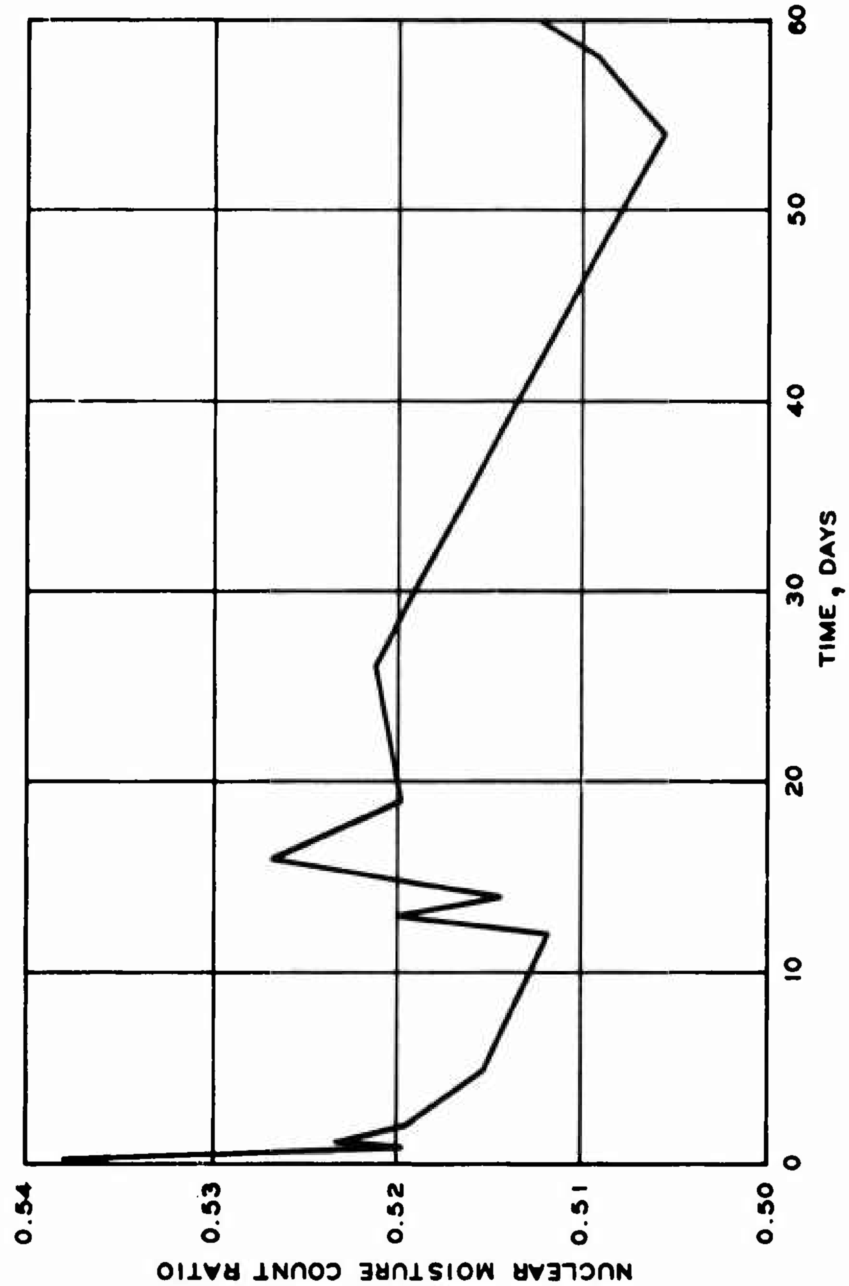

OWL GAGE G
800-DAY READINGS
TIME, DAYS
REFRACTIVE INDEX, HZ
0
100
200
300
400
500
600
700
800
3500
4000
4500
5000
5500
6000

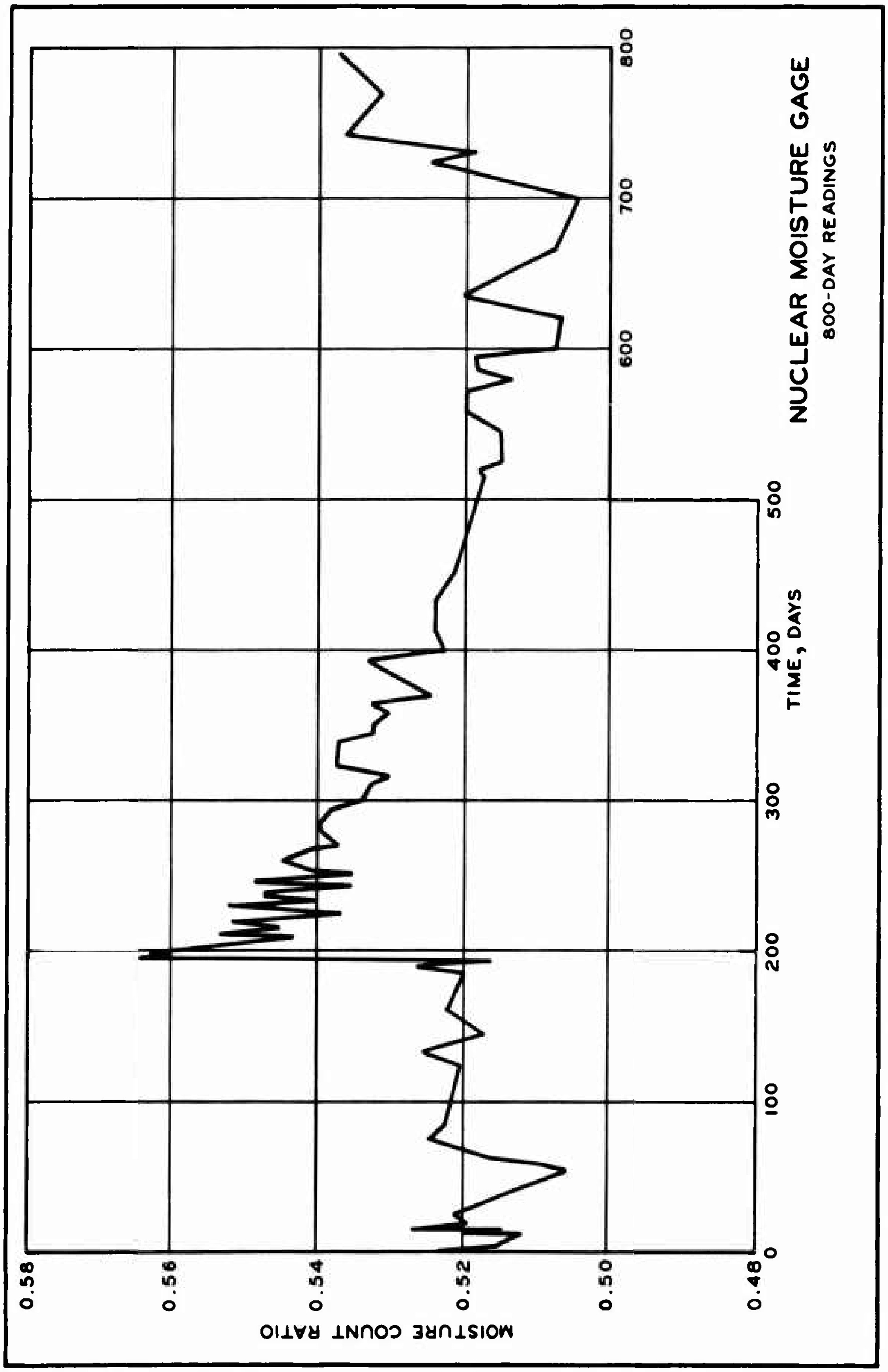
PLATE 30



OWL GAGE H
800-DAY READINGS
TIME, DAYS
REFRACTIVE INDEX, HZ
0
100
200
300
400
500
600
700
800
3500
4000
4500
5000
5500
6000



NUCLEAR MOISTURE GAGE
60-DAY READINGS


NUCLEAR MOISTURE GAGE
800-DAY READINGS
MOISTURE COUNT RATIO
0.48
0.50
0.52
0.54
0.56
0.58
TIME, DAYS
0
100
200
300
400
500
600
700
800

In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

O'Neil, Edward F
An evaluation of selected instruments used to measure the moisture content of hardened concrete, by Edward F. O'Neil [and] James E. McDonald. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1976.
1 v. (various pagings) illus. 27 cm. (U. S. Waterways Experiment Station. Technical report C-76-1)
Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under WU 31138.

1. Concretes. 2. Measuring instruments. 3. Moisture content. I. McDonald, James E., joint author. II. U. S. Army. Corps of Engineers. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Technical report C-76-1)
TA7.W34 no.C-76-1