THE UNIVERSITY OF CONNECTICUT
STORRS, CONNECTICUT

# RESEARCH REPORT
# ON
# STUDIES OF FROST ACTION IN SOILS AS A FUNCTION OF SELECTED SOIL PROPERTIES, CLIMATIC FACTORS, AND ELEVATION OF GROUND WATER TABLE

BY
EDWARD V. GANT
Professor of Civil Engineering

A cooperative research project sponsored by the
Connecticut State Highway Department and
The University of Connecticut

December 1963

**Technical Report Documentation Page**

**1.Report No.**
JHR 51-3-F

**2. Government Accession No.**
N/A

**3. Recipients Catalog No.**

**4. Title and Subtitle**
Studies of Frost Action in Soils as a Function of Selected Soil Properties, Climatic Factors, and Elevation of Ground Water Table

**5. Report Date**
December 1963

**6. Performing Organization Code**
JH 51-3

**7. Author(s)**
Edward V. Gant

**8. Performing Organization Report No.**
JHR 51-3-F

**9. Performing Organization Name and Address**

University of Connecticut
Civil Engineering Department
Storrs, CT 06269

**10. Work Unit No. (TRIS)**
N/A

**11. Contract or Grant No.**
N/A

**13. Type of Report and Period Covered**

Final Report

**12. Sponsoring Agency Name and Address**

Then, Connecticut State Highway Department
Now, Connecticut Department of Transportation
280 West Street, Rocky Hill, CT 06067

**14. Sponsoring Agency Code**
JH 51-3

**15. Supplementary Notes** A cooperative research project sponsored by the Connecticut State Highway Department and the University of Connecticut. Present day program is the Connecticut Cooperative Transportation Research Program, http://www.cti.uconn.edu/chwrp

**16. Abstract**

This report explains an investigation of controlling factors involved in frost action in frost-susceptible pavement subgrade soils, including soil properties, climatic conditions, and elevation of water table.

Beginning in 1952, field tests were conducted in two frost-susceptible soils: silt from the town of Glastonbury and glacial till from the town of Storrs. Field studies were completed in 1957, resulting in data from five successive winters. Over the five winters, the Duration of Freezing Index at the test sites was from 60 to 120 days each winter.

Both the silt and till were classified as frost susceptible, since 46 percent of the silt particles were smaller than 0.02 mm and 22 percent of the till particles were smaller than 0.02 mm. The Corps of Engineers classifies soils as frost susceptible if more 15 percent of particles are finer that 0.02 mm.

Analyses of frost penetration are based on applications of the Stefan Equation (the form referred to as the St. Paul equation) and Modified Berggren Equation for layered systems. Soil temperature and frost penetration computations are presented and discussed. Average maximum frost penetration depths were about the same in the two test pits. The maximum frost penetration for one winter was 38 inches at the test site. There was fairly good agreement between experimental and computed frost depths, where computed values from both equations are larger for the glacial till than for the silt. Heave and moisture migration consistently reflected changes in daily temperature with a time lag of two to three days.

In order to develop design depths of non-frost susceptible materials and to set the elevation of underdrainage, the maximum depth of frost penetration at a particular site must be known. The maximum frost penetration for design purposes should be obtained through the use of long range weather records for a particular site. In some areas, it may be necessary to begin to collect weather information for use in future design of pavement structures.

Researchers conclude that the total thickness of pavement structure, including all non-susceptible materials, should be at least as large as the maximum depth of frost penetration. However, researchers acknowledge and identify some techniques that may be used to design thinner pavement sections through the use of sand wedges, heat-insulating layers under the subbase, use of porous and impervious insulating layers and chemical stabilizers.

Results were applied to specific field problems with highway pavements encountered by engineers in ConnDOT's Division of Soils and Foundations.

**17. Key Words**
soil, geotechnical, frost susceptible soils, pavement subgrade design, glacial till, silt

**18. Distribution Statement**

**19. Security Classif. (Of this report)**
Unclassified

**20. Security Classif.(Of this page)**
Unclassified

**21. No. of Pages**
77

**20. Price**
N/A

**Form DOT F 1700.7 (8-72)** **Reproduction of completed page authorized**

# TABLE OF CONTENTS

Page

# LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

LIST OF FIGURES (Cont'd)

RESEARCH REPORT

on

# STUDIES OF FROST ACTION IN SOILS AS A FUNCTION OF SELECTED SOIL PROPERTIES, CLIMATIC FACTORS, AND ELEVATION OF GROUND WATER TABLE

## 1. INTRODUCTION

When air temperatures fall below freezing for a significant period moist soils freeze with the result that ice crystals are developed and additional moisture, if available, is attracted from lower elevations. The mechanism of moisture transfer is exceedingly complex. However, it is well known that where a source of moisture is available ice segregation in the freezing zone of certain types of soil produces a volumetric change, or "heave", in excess of the dimensional change which can be attributed to the expansion of water on freezing. Furthermore, the increased moisture content of the soil caused by ice segregation results in a loss of bearing strength when thaw of the upper boundary occurs and lower frozen levels prevent drainage of the excess moisture. To diminish the detrimental effects of frost action beneath highways it is common practice to use non-frost-susceptible materials beneath the pavement and also to install subgrade drainage where needed to intercept water or otherwise control the elevation of the ground water table.

Ideally, the total thickness of non-frost-susceptible materials - pavement, base, and subbase - should be at least equal to the maximum depth of frost penetration. With less than this ideal thickness some amount of frost action will occur in the upper part of a subgrade of frost-susceptible material unless there is no transfer of moisture to the freezing zone. In some soils a source of moisture will not exist within certain critical limits.(1) In other soils it may be possible to lower a ground water table sufficiently by means of underdrains to avoid, or limit, frost action in the subgrade. The fact that thermal gradients and duration of freezing temperatures in the lower part of the frost zone are generally smaller than at higher levels is also favorable in terms of reduced frost action in the subgrade.

For some subgrade soils with high capillarity it is not practical

---

(1) The Corps of Engineers (1) states that a water supply within 5 feet of the frost zone in frost-susceptible materials may be troublesome. Also, when the depth to the water table is in excess of 15 feet, a source of water for substantial ice segregation is usually not present.

to prevent moisture transfer by lowering the ground water table. Thus, in some soils, moisture can enter the frost zone through capillarity from a remote water table. In order to study quantitatively and qualitatively some of the controlling factors (including soil properties, climatic conditions, elevation of water table) involved in frost action in frost-susceptible subgrade soils, a series of field tests and analytical studies were carried out at the University of Connecticut over a period of several years.(2) Some principal features and results of these investigations are described in the following.

## 2. GENERAL DESCRIPTION OF FIELD TESTS

The field tests were conducted on two frost-susceptible soils - silt from Glastonbury, Connecticut and glacial till from the vicinity of Storrs, Connecticut - (see Figure 1). Special soil test pits were installed on the campus of the University of Connecticut at Storrs, with the elevation of the water table for each pit subject to independent control, Figure 2. Initially 6 pits of 30 inches inside diameter and 6 pits of 18 inches inside diameter were installed with silt in half of each size and till in the other half. However, it was found (Figure 3) that there was a definite size effect in the heave results for the 18 inch pits and after one year these pits were abandoned. Therefore, the results in this report, except for Figure 3, are based on the 30 inch diameter pits.

The pits were installed on a bench of a gentle slope (about 1 in 6) facing north. The pit area was selected so as to be removed from steam lines, sewer lines, and similar heat sources. The pit covers were set initially at approximately the same elevation. For each soil type, depths to the controlled water table, Figure 2, of 2.5 ft., 4.0 ft., and 5.5 ft. were used. The water table elevations were maintained by adding or subtracting water through the 3/4 inch plastic pipe inlets to the reservoirs, Figure 2. As a rule daily adjustments in the water levels were required during the frost season.

---

(2) Some aspects of the investigations were described in the Master's theses of Leonard (2) and Cuomo (3).

At the start of the tests the soil was compacted in the pits in layers of approximately 2 inches, with in-place average moisture and density values as shown in Tables 1 and 2. During the 1952 - 1953 winter, temperature measurements were made in the pits by means of thermometers lowered through plastic tubes to selected levels. Prior to the 1953 - 1954 winter the soil was removed and electric resistance moisture-temperature gages(3) were installed at predetermined levels as the soil was placed and compacted. The soil in the pits was not disturbed after the start of the 1953 - 1954 frost season until the field studies were discontinued in 1957.

TABLE 1

INITIAL DATA FOR SOILS AND TEST PITS - 1952

| | Till | | | Silt | | |
|---|---|---|---|---|---|---|
| Pit Number | 1 | 2 | 3 | 4 | 5 | 6 |
| Ave. moisture content (%) | 8.3 | 8.8 | 8.8 | 17.0 | 19.6 | 18.9 |
| Wet weight soil (lbs.) | 1446 | 2354 | 3264 | 1200 | 2046 | 2852 |
| Dry weight soil (lbs.) | 1335 | 2163 | 3000 | 1026 | 1711 | 2399 |
| Dry Density (pcf) | 125 | 126 | 124 | 100 | 99 | 98 |
| Cover bearing pressure(psf) | 91 | 89 | 88 | 87 | 89 | 92 |
| Diameter of pit (in.) | 29.35 | 29.38 | 29.25 | 29.44 | 29.33 | 29.34 |
| Depth of soil (ft.) | 2.27 | 3.64 | 5.18 | 2.18 | 3.68 | 5.19 |
| Depth to Water Table (ft.) | 2.5 | 4.0 | 5.5 | 2.5 | 4.0 | 5.5 |

TABLE 2

MOISTURE CONTENT AND DENSITY - 1953

| | Till | | | Silt | | |
|---|---|---|---|---|---|---|
| Pit Number | 1 | 2 | 3 | 4 | 5 | 6 |
| Ave. Moisture content (%) | 10.5 | 11.9 | 10.5 | 24.2 | 24.1 | 24.8 |
| Dry Density (pcf) | 119 | 118 | 115 | 97 | 97 | 98 |

Daily frost heave readings were taken by measuring the change in elevation of the concrete covers with an engineers level. Readings were taken on four rivets embedded in each concrete cover, with

---

(3) Because of the low order of discrimination of moisture contents near saturation most moisture content readings were deemed unsatisfactory.

an average computed for each pit. A permanent base for the level and a benchmark were provided in the pit area.

## 3. SOIL PROPERTIES

The silt used in the tests was from Glastonbury, Connecticut and the glacial till was representative of the soil occurring in the vicinity of the University of Connecticut in Storrs. Grain size curves, Figure 1, show that the silt is a fairly uniform soil with about 80 percent of the grains in the silt range. On the other hand the till has a much more even gradation with grain sizes ranging from clay to fine gravel. According to the classic Casagrande (4) criterion uniform soils are frost susceptible if they contain more than 10% of grains smaller than 0.02 mm., and non-uniform soils are frost susceptible if they contain more than 3% of particles smaller than the 0.02 mm. Therefore, both the silt and till are classified as frost susceptible since for the silt 46% of the particles were smaller than the 0.02 mm. size while 22% of the till particles were smaller than 0.02 mm. The two soils are also seen to be frost-susceptible from the Corps of Engineers (1) Table 3.(4)

TABLE 3

FROST-SUSCEPTIBLE SOIL GROUPS - CORPS OF ENGINEERS (1)

| Group | Description |
|---|---|
| F1 | Gravelly soils containing between 3 to 20 percent finer than 0.02-mm. by weight. |
| F2 | Sands containing between 3 and 15 percent finer than 0.02-mm. by weight. |
| F3 | (a) Gravelly soils containing more than 20 percent finer than 0.02-mm. by weight. (b) Sands, except very fine silty sands, containing more than 15 percent finer than 0.02-mm. by weight. (c) Clays with plasticity indexes of more than 12. (d) Varved clays existing with uniform subgrade conditions. |
| F4 | (a) All silts including sandy silts. (b) Very fine silty sands containing more than 15 percent finer than 0.02-mm. by weight. (c) Clays with plasticity indexes of less than 12. (d) Varved clays existing with nonuniform subgrade conditions. |

---

(4) Linell, Hennion, and Lobacz (5) have suggested a modification of the groupings shown in Table 3.

Additional soil properties are listed in Table 4, and moisture-tension relationships for the two soils are shown in Figure 4. Moisture-density relationships for the till and silt are shown in Figures 5 and 6, respectively.

TABLE 4

PROPERTIES OF SOILS IN TEST PITS

| | Storrs Till | Glastonbury Silt |
|---|---|---|
| Specific Gravity | 2.72 | 2.75 |
| Liquid Limit | 22 | 24 |
| Plastic Limit | 19 | 20 |
| Plastic Index | 3 | 4 |
| % finer than 0.02mm | 22 | 46 |
| Proctor Density (pcf) | 117 | 104 |

## 4. AIR TEMPERATURES - FREEZING INDEX

Since air temperature is a controlling factor in frost action it is common practice in frost studies to calculate a freezing index, based on average, or mean, daily temperatures, as a measure of the climatic conditions at a site during the freezing season.(5) As defined by the Corps of Engineers (5), (6), (7) the freezing index is a measure of the combined duration and magnitude of below-freezing air temperatures occurring during any given winter and therefore is related to the depth of frost penetration. Numerically, the index is equal to the maximum ordinate of the cumulative degree days (in $^{o}$F.) versus time curve (Figure 7). For any one day the number of degree days is equal to the difference between the average air temperature and 32$^{o}$F. The degree days are taken as positive when the average temperature is below 32$^{o}$F, and negative when the average temperature is above 32$^{o}$F. The cumulative degree days-time curve is a plot of the cumulative degree days by days, starting usually with the first day for which the average temperature is equal to or below 32$^{o}$F. The period for which the average daily temperatures tend to be below freezing and the cumulative value has a fairly con-

---

(5) Average daily temperature is the average of the maximum and minimum temperatures for one day or the average of several temperature readings taken at equal time intervals during one day. Mean daily temperature is the average of the average daily temperature for a given day for several years.

tinuous growth from minimum to maximum value is termed "Duration of Freezing Index", Figure 7, (7).

Cumulative degree day curves for the Storrs test site for the years 1952-1957 are shown in Figure 8 where the cumulative values are derived from the separate plots of average daily air temperatures in Figures 9, 10, 11, 12, 13. From Figure 8 it can be seen that the general character of the winters during the test period varied considerably with the freezing index ranging from a low of about 220 to a high of 585 and the Duration of Freezing Index ranging from 60 to 120 days. In comparison with these values for the test period, the Corps of Engineers (1) has found from a study of long term weather records that the "mean freezing index"(6) for Storrs is about 325, with a range for the whole State from a low of 100 degree days (along the coast) to 500 degree days (in the northwest corner). Similarly the Corps of Engineers (7) has found the long-term Duration of Freezing Index for Connecticut to range from about 70 days along the coast to 90 in the northwestern part of the State with a value of 80 for Storrs.

TABLE 5

| Winter | First date for which average daily temperature was at or below 32°F. | Beginning date when average daily temperatures tended to be below 32° | Date of maximum positive cumulative degree days | Duration of Freezing Index(days) |
|---|---|---|---|---|
| 1952-53 | Nov. 8 | Dec. 12 | Mar. 12 | 90 |
| 1953-54 | Nov. 6 | Dec. 15 | Feb. 14 | 60 |
| 1954-55 | Nov. 10 | Dec. 1 | Feb. 15 & Mar. 10 | 100 |
| 1955-56 | Nov. 19 | Dec. 1 | Apr. 1 | 120 |
| 1056-57 | Nov. 10 | Dec. 17 | Feb. 22 & Mar. 12 | 85 |

In addition to the difference in freezing index for the winters of the test period there were also differences, as shown in Table 5, in the dates on which the cumulative degree days were a maximum and in the Duration of Freezing Index. Further, as shown in Table 5, the date on

---

(6) Mean freezing index is based on mean temperatures computed for a period of 10 to 30 years.

which frost action in the soil might be assumed to begin to build up (not start) varied from the first to the 17th of December. There is a possibility, of course, that some soil freezing takes place whenever the air temperature first drops below 32°F. (at Storrs, ordinarily in October but sometimes in September). However, even after the air temperature first falls below 32°F there usually will be many days with minimum air temperatures above freezing and hence freezing temperatures do not penetrate below a thin boundary layer of the soil. Certainly deep penetration of below freezing temperature does not occur until average daily temperatures are fairly consistently below freezing. This was borne out at the test site where ground temperatures (Figures 14, 15, 16) show that freezing at a depth of 6 inches did not occur until two or more weeks after the date when average air temperatures tended to be at or below 32°F. Over-all, the period corresponding to the Duration of Freezing Index (Figure 7), when cumulative degree days arein general increasing, would appear to be the most significant period for frost action.

For design for frost the Corps of Engineers (1) utilizes a "design freezing index" which is the freezing index of the coldest winter in the latest 10-year period of record or the average of the three coldest winters in the latest 30 years of record. From a statistical study by the Corps of Engineers (1), (5) of the relationship between the mean freezing index, computed for a term of 30 years, and the design freezing index it appears that the design freezing index for Storrs would be about 800 with a range of 500 to 1000 for the whole State of Connecticut.

## 5. FROST PENETRATION - GENERAL

The depth to which freezing temperatures penetrate in a soil mass is a function chiefly of air temperatures and thermal properties of the soil. However, other factors including surface cover and exposure conditions can also affect frost penetration. From extensive field investigations of frost penetration under airfield pavements, the Corps of Engineers (1), (6), (7) found a good correlation between frost penetration and mean freezing index. These investigations produced an empirical curve, Figure 17, which was found to apply satisfactorily to all pavement types with bases of non-insulating and non-frost-susceptible materials. After further refinements the original curve was presented as a design curve, Figure 18, for total thickness of pavement and base as a function of the design freezing index. More recently, Linell, Henion, and Lobacz (5) have published additional curves for frost penetration as a function of the freezing index and selected soil properties.

Figure 17 as presented by the Corps of Engineers is applicable to materials with thermal characteristics falling within a narrow range and does not apply for wet, fine-grained soils for which frost penetration depths generally will be less than indicative by the curve, (1). Therefore, in order to obtain frost penetration depths for conditions which differ from those assumed it is necessary to utilize analytical methods in which provision can be made for the conditions which actually exist. Two of the principal analytical methods(7) used in frost penetration studies

---

(7) A good description of analytical methods for computing frost penetration is given by Jumikis (8). Aldrich (9) discusses the Stefan equation and gives the development of the modified Berggren equation. Additional information is contained in the references (5) through (13).

are:

**The Stefan Equation:** $$h = \sqrt{\frac{48knF}{L}} \qquad (1)$$

**The Modified Berggren Equation:** $$h = \lambda\sqrt{\frac{48knF}{L}} \qquad (2)$$

where: $h$ = depth of frost penetration, in feet

$k$ = soil thermal conductivity(8), in Btu per hour per sq. ft. per deg. F per ft.

$L$ = latent heat, in Btu per cu. ft. = $1.434\ w\ \gamma_d$ per hr. (3)

$\gamma_d$ = dry density, lb. per cu. ft.

$w$ = water content, per cent

$F$ = freezing index, degree days F.

$n$ = surface correction factor(9)

$\lambda$ = dimensionless correction factor given by Sanger (12), Figure 21 and Aldrich (9), Figure 5, as a function of two dimensionless parameters $\alpha$ and $\mu$ :

Thermal ratio, $$\alpha = \frac{V_o}{V_s} = \frac{V_o t}{F} \qquad (4)$$

Fusion parameter, $$\mu = \frac{C}{L} V_s = \frac{CF}{Lt} \qquad (5)$$

and $V_o$ = mean annual temperature, deg. F minus 32°F.

$V_s$ = surface freezing index, deg. F, divided by the duration of freezing period, $t$ . ($V_s = \frac{F}{t}$ )

$C$ = volumetric heat, in Btu per cu. ft. per deg. F.

$= \frac{C_f + C_u}{2}$ the average of the values for the frozen and unfrozen states

$$C_u = \gamma_d\left(0.17 + \frac{w}{100}\right) \quad C_f = \gamma_d\left(0.17 + \frac{0.5w}{100}\right) \qquad (6)$$

---

(8) Often taken as $1/2\ (k_f + k_u)$, the average of the values for the frozen and unfrozen states, Aldrich (9)

(9) Kersten and Johnson found good agreement between observed and calculated values of frost depth with $n = 0.8$ in a form of the Stefan Equation. (The St. Paul Equations). Sanger (12) refers to studies which show that good results are obtained for $n = 0.9$ in the Modified Berggren Equation.

For a layered system the Stefan Equation has been placed in the following form referred to as the St. Paul Equations by Kersten (11):

St. Paul Equations:

$$F_1 = \frac{L_1 d_1}{24} \quad \frac{R_1}{2} \qquad (7)$$

$$F_2 = \frac{L_2 d_2}{24} \left( R_1 + \frac{R_2}{2} \right)$$

$$F_n = \frac{L_n d_n}{24} \left( \Sigma \; R_{n-1} + \frac{R_n}{2} \right)$$

where: $F_1$ = surface freezing index required to freeze layer 1, degree days F

$L_1$ = latent heat, Btu per cu. ft. for layer 1

$d_1$ = thickness of layer 1 in ft.

$R_1$ = thermal resistance of layer 1 = $\frac{d_1}{k_1}$

$k_1$ = thermal conductivity of layer 1, in Btu per sq. ft. per deg. F per ft. per hr.

Aldrich (9) has given the following form of the Modified Berggren Equation for layered systems:

$$h = \lambda \sqrt{\frac{48nF}{(\frac{L}{k})_{eff.}}} \qquad (8)$$

$$\text{where: } (\tfrac{L}{k})_{\text{effective}} = \frac{2}{h^2} \left[ \frac{d_1}{k_1} \left( \frac{L_1 d_1}{2} + L_2 d_2 + \dots L_n d_n \right) + \frac{d_2}{k_2} \left( \frac{L_2 d_2}{2} + L_3 d_3 + \dots L_n d_n \right) + \dots + \frac{d_n}{k_n} \left( \frac{L_n d_n}{2} \right) \right] \qquad (9)$$

h = estimated depth of frost penetration = $d_1 + d_2 + \dots d_n$

$C_{wt}$ = weighted value of volumetric heat

$$= \frac{C_1 d_1 + C_2 d_2 + \dots\dots C_n d_n}{h} \qquad (10)$$

$L_{wt}$ = weighted value of latent heat

$$= \frac{L_1 d_1 + L_2 d_2 + \cdots L_n d_n}{h} \qquad (11)$$

$$\mu = \frac{C_{wt}\ F}{L_{wt}\ t} \qquad (12)$$

## 6. FROST PENETRATION COMPUTATIONS

### A. Soil Temperature Measurements

At the Storrs test site the maximum observed depth of soil freezing (taken at 32°F) varied from a minimum of 12 inches for the 1952-53 winter to a maximum of 38 inches for the 1956-57 winter. For the three winters 1953-54, 1954-55, 1955-56 for which ground temperatures are shown in Figures 14, 15, 16 the average maximum depth of freezing temperature was 26 inches. For these same three winters the average air freezing index was 510 degree days F and the average duration of freezing index was 95 days.

### B. Frost Penetration Computations

The computed depth of frost penetration in the soil pits for the three winters, 1953-54, 1954-55, 1955-56, for which the foregoing averages of observed values are given, can be obtained as follows:

Average Air Freezing Index: 510 degree days F
Average Duration of Freeze: 95 days
Mean Annual Air Temperature: 47°F
4 inch concrete cover (9): k = 0.54 Btu/sq. ft./deg.F/ft./hr.
C = 30.0 Btu/cu. ft./deg.F

Data for the till and silt is as follows:

| | Till | Silt |
|---|---|---|
| Dry density, $\gamma d$, pcf : | 118 | 97 |
| Moisture Content, w, percent: | 16 | 27 |
| Thermal conductivity(10), Btu/sq. ft./deg. F/ft./hr. | | |
| Unfrozen soil, $k_u$ : | 1.17 | 0.83 |
| Frozen soil, $k_f$ : | 1.25 | 1.17 |
| $1/2\ (k_u + k_f)$ : | 1.2 | 1.0 |
| Volumetric heat, C. Btu/cu. ft./deg. F | | |
| $C_\mu = \gamma_d\ (0.17 + \frac{w}{100}$ : | 39.0 | 42.6 |
| $C_f = \gamma_d\ (0.17 + \frac{w(0.5)}{100}$ : | 29.5 | 29.5 |
| $1/2\ (C_\mu + C_f)$ : | 34.25 | 36.05 |
| Latent heat, L. Btu/cu. ft. | | |
| $1.434\ w\gamma_d$ : | 2710 | 3760 |

---

(10) Values given are estimated from charts prepared by Kersten (<u>14</u>). For both the till and the silt a value of 1.0 Btu/sq. ft./deg. F/ft./hr. was obtained by test as the average of the values for the unfrozen and frozen states.

## 1. Examples of Frost Penetration Computations Using St. Paul Equations

### For Layered System:

4 inch concrete cover = layer 1
Till or silt = layer 2
$L_1 = 0$, $R_1 = \frac{0.33}{0.54} = 0.611$

From equations (7), if $L_1 = 0$, $F_1 = 0$

For a surface correction factor of $n = 0.8$, $F_2 = 510 \times .8 = 40$

**Penetration in Till:**

$$408 = \frac{2710\, d_2}{24} \left[ 0.611 + \frac{d_2}{1.2 \times 2} \right]$$

$d_2 = 2.31$ ft. and $h = 0.33 + 2.31 = 2.64$ ft. from top of cover to bottom of frost in till

**Penetration in Silt:**

$$408 = \frac{3760\, d_2}{24} \left[ 0.611 + \frac{d_2}{1.0 \times 2} \right]$$

$d_2 = 1.75$ ft. and $h = 0.33 + 1.75 = 2.08$ ft. from top of cover to bottom of frost in silt.

## 2. Examples of Frost Penetration Computations Using Modified Berggren Equations for Layered System:

**Penetration in Till:**

To start with, it is necessary to make some estimate of the frost penetration to use in Equation (9). For Storrs the mean freezing index, as mentioned earlier in the report, is about 325 and from Figure 17 the depth of frost in non-frost-susceptible materials would be about 27 inches or 2.25 ft. In fine grained moist soils the frost depth would be less and a value of 2.0 ft. can be assumed for h ($d_2 = 1.67$ ft.). From equation (9), $\left(\frac{L}{k}\right)$ eff. $=$

$$\frac{2}{2.0^2} \left[ \frac{0.33}{0.54} (0 + 2710 \times 1.67) + \frac{1.67}{1.2} \left( \frac{2710 \times 1.67}{2} \right) \right] = 2950$$

from Equation (10) $C_{wt} = \frac{30 \times 0.33 + 34.25 \times 1.67}{2} = 33.6$

from Equation (11) $L_{wt} = 2710 \times \frac{1.67}{2} = 2260$

from Equation (12) $\mu = \frac{33.6 \times 510}{2260 \times 95} = 0.0799$

from Equation (4) $\alpha = \frac{(47-32)95}{510} = 2.8$

from Figure 21 in Ref. (12) or Figure 5 in Ref. (9), $\lambda = 0.71$

from Equation (8) $h = 0.71 \sqrt{\frac{48 \times .9 \times 510}{2950}} = 1.94$ ft. from top of cover to bottom of frost in till.

Penetration in Silt

Assume $h = 1.6$ ft. ($d_2 = 1.27$ ft.)

$$\left(\frac{L}{k}\right)_{eff.} = \frac{2}{(1.6)^2} \left[ \frac{0.33}{0.54} \left( 0 + 3760 \times 1.27 \right) + \frac{1.27}{1.0} \left( \frac{3760 \times 1.27}{2} \right) \right] = 4660$$

$$C_{wt} = \frac{30 \times 0.33 + 36.05 \times 1.27}{1.6} = 34.8$$

$$L_{wt} = 3760 \times \frac{1.27}{1.60} = 2980$$

$$\mu = \frac{34.8 \times 510}{2980 \times 95} = 0.0627$$

$$\alpha = 2.8$$

$$\lambda = 0.72$$

$$h = 0.72 \sqrt{\frac{48 \times .9 \times 510}{4660}}$$

$= 1.57$ ft. from top of cover to bottom of frost in silt

## TABLE 6

### SUMMARY OF FROST PENETRATION DEPTHS OBTAINED FOR TEST PITS BASED ON WINTERS OF 1953-54, 1954-55, 1955-56

| Method | | Soil | |
|---|---|---|---|
| | | Till | Silt |
| Based on measured soil temperatures: | | 2.16 ft. | 2.16 ft. |
| Computed from St. Paul Equations : | n = 0.8 | 2.64 | 2.08 |
| | n = 0.6 | 2.26 | 1.78 |
| Computed from Modified Berggren Equations: | n=0.9 | 1.94 | 1.57 |
| | n=1.0 | 2.05 | 1.65 |

Corps of Engineers (Fig 17) value for non-frost-susceptible material = 2.25 ft.

Comparison of frost penetration values for the pits, obtained from average conditions over 3 years Table 6, shows fairly good agreement between experimental and computed frost depths. Computed values are in each case larger for the till than for the silt. However, temperature measurements in the till and silt indicated that the average maximum frost penetration depths were about the same in the two soils. In this connection it should again be noted that the maximum observed frost penetration for one winter was 38 inches at the test site.

### 3. Application to Highways

At the test site the 4 inch concrete cover rested directly on the potential subgrade materials and frost penetration computations were carried out for a two-layered system. However, a highway pavement profile usually consists of several separate layers. For example, the profile might consist of:

3-1/2 in. bituminous concrete
3 in. penetration macadam
4 in. broken stone base
10-1/2 in. sub-base
12 in. selected subgrade material
the subgrade

Using known climatic factors and tabulated or laboratory values of the thermal characteristics of the several layers, the frost penetration could be computed. The design depths could then be varied depending on the ground water conditions, traffic characteristics, and other factors.

## 7. FROST HEAVE AND MOISTURE MIGRATION

Throughout the period of test, records were kept on both the vertical movement of the covers and the amount of water which entered or left the soil from the controlled level reservoirs(11) (Figure 2). The daily changes are plotted as heave and moisture migration for the five winters 1952-1957 in Figures 19-48. Pits 1, 2, 3 contained till with depths to the water table of 2.5 ft., 4.0 ft. and 5.5 ft. respectively. Pits 4,5, 6 contained silt with depths to the water table of 2.5 ft., 4.0 ft., and 5.5 ft., respectively. Equilibrium was not reached in 1952-53 and 1953-54

---

(11) Both pits 2 and 5 developed leaks as can be seen from the moisture migration curves for these pits.

prior to freezing and the moisture varriations for these two winters do not depend simply on temperature changes. For the other years moisture equilibrium in the soil generally was reached before freezing occurred.

Figures 19-48 show that heave and moisture migration are closely related, with daily fluctuations in one value fairly consistently reflecting the daily fluctuations in the others. Further, comparison of the day to day variations in heave and moisture migration with the variations in average daily temperatures, Figures 9-13, shows that heave and moisture migration consistently reflect changes in average daily temperature with a time lag of from one to two or three days. Thus, a decrease in average daily air temperatures on a given day consistently produced a moisture migration to the soil a day or two later. Conversely, an increase in average daily air temperature on a given day led to a moisture transfer back to the water reservoir (Figure 2) a day or two later. Usually both the cumulative heave and cumulative moisture migration to the soil in a pit were maximum near the date of maximum cumulative degree days for a winter. An exception was when cumulative degree days were maximum in late winter.

For a given depth of ground water table the net moisture migration during the main period of frost action tended to be larger in the till than in the silt. On the other hand, the maximum cumulative heave tended to be slightly larger in the silt. In general, the net moisture migration increased with an increase of depth to the water table. However, there was not a clear variation of heave with depth to the water table, possibly because of the high susceptibility of both soils to frost action.

Figure 49 illustrates the influence of the duration and magnitude of below freezing temperatures, as measured by the air freezing index, on the average maximum heave of the soil in the pits. The average maximum heave was computed as the average of the maximum heaves for all six pits in a given year. The period covered, 1953-1956, corresponds to the period during which the soil in the pits was not disturbed.

## 8. CONCLUSIONS AND RECOMMENDATIONS

A. Both the glacial till and silt used in the frost studies exhibit characteristics of soils highly susceptible to frost action. Thus both soils heave during periods of freezing with a migration of moisture upwards which results in increased moisture contents in upper regions of the soils, remaining even after late winter warming sets in. In practice the detrimental effects of these characteristics is found in non-uniform heaving during winter and decreased bearing strength during the later winter and early spring when thaw occurs.

B. Within the limits studied, the elevation of the ground water table has almost no influence on the possible detrimental effects of frost action in glacial till and silt. Thus, there was little difference in the heaving of the soils for depths to the ground water table of 2.5, 4, and 5 feet. Probably, greater depths to the water table - at least within practical limits - would not eliminate the frost effects in the two soils.

C. Since both till and silt are highly susceptible to frost action and, as a practical matter, lowering of the ground water table does not provide relief from frost action, the soils should be replaced by non-frost-susceptible materials when they occur within the frost penetration zone beneath a pavement.

D. Non-frost-susceptible materials within the frost penetration zone should be kept free of moisture. Therefore, in all cases underdrains should be provided to intercept side hill drainage and in general to lower the elevation of the ground water table below the frost penetration zone.

E. In order to develop design depths of non-frost-susceptible materials and to set the elevation of underdrainage, the maximum depth of frost penetration at a particular site must be known. Good correlation was obtained between measured and computed values of frost penetration at the test site from both the St. Paul Equations for Layered Systems and the Modified Berggren Equations for Layered Systems. The maximum frost penetration for design purposes should be obtained through the use of long range weather records for a particular site. Actual measurements of frost penetration for one year or even a few years are useful to provide a check on analytical methods.

F. There is a considerable variation in climatic factors through the State of Connecticut. Therefore, in order to apply analytical methods to the determination of design frost penetration depths for different areas of the state, required information must be developed from existing weather records. In some areas of the state, it may be necessary for the Highway Department to begin to collect weather information which in coming years will be useful in the design of pavement structures.

G. Different judgements exist on the relation between depth of frost penetration and the depth of non-frost-susceptible materials to use over soils such as till or silt. Erickson (15) reports that in the western states two states use one-half of the frost penetration for the total thickness of pavement structure unless the soil strength calls for a greater thickness. In addition, Colorado has a table of factors which determines thickness requirements depending upon the frost penetration and moisture conditions.

Ideally the total thickness of pavement structure, including all non-frost-susceptible materials should be at least as large as the maximum depth of frost penetration. However, for reasons of economy it may not be practical to provide the ideal thickness particularly where soil bearing strength does not control. Rengmark (16) has reported on several measures used in Sweden in frost areas to reduce detrimental frost action. These measures include:

insertion of sand wedges in areas of transaction from rocks to frost susceptible soil; insertion of heat-insulation layers under the sub-base(12); use of porous and impervious insulating layers; chemical stabilization.

---

(12) Rengmark (16) comments on the longitudinal frost cracks developed along the center line of newly built roads early in the frost period as the result of a greater depth of frost penetration at the center than at the sides, where snow provides insulation. Thorough snow clearing at the sides or use of a heat-insulating layer at the center is recommended to eliminate the cracking in cases where non-frost-susceptible material cannot be provided over the full frost depth.

## BIBLIOGRAPHY

(1) Corps of Engineers, U. S. Army, EM 1110 - 345 - 306, Airfield Pavement Design, Frost Conditions, October 1954.

(2) Leonard, Roy J., A Study of the Effect of the Depth of Water Table on Frost Action in Soils, Master's Dissertation, University of Connecticut, 1954.

(3) Cuomo, Paul V., A Study of Moistures Migration in Freezing Soils, Master's Dissertation, University of Connecticut, 1956.

(4) Casagrande, Arthur, Discussion on Frost Heaving, Proceedings of the Highway Research Board 11 : 168-172.

(5) Linell, K. A., F. B. Hennion and E. F. Lobacz. Current Corps of Engineers Practices Related to Design of Pavements in Areas of Seasonal Frost. Presented at the Annual Meeting of the Highway Research Board, Washington, D. C., January 1963.

(6) Corps of Engineers, War Department, New England Division, Boston, Massachusetts; Report on Frost Investigation 1944-1945, April 1947.

(7) Corps of Engineers, U. S. Army, New England Division, Boston, Massachusetts, Addendum No. 1 1945-1947 To Report on Frost Investigation 1944-1945, October 1949.

(8) Jumikis, Alfreds R., The Frost Penetration Problem in Highway Engineering, Rutgers University Press, New Brunswick, New Jersey, 1955.

(9) Aldrich, Harl P. Jr., Frost Penetration Below Highway and Airfield Pavements, Bulletin 135 Highway Research Board, 1956.

(10) Kersten, Miles S. and Rodney W. Johnson, Frost Penetration Under Bitumenous Pavements, Bulletin 111, Highway Research Board, 1955.

(11) Kersten, Miles S., Frost Penetration: Relationship to Air Temperatures and Other Factors, Bulletin 225, Highway Research Board, 1959.

(12) Sanger, Frederick J., Discussion of Frost Penetration, Bulletin 225, Highway Research Board, 1959.

(13) Aldrich, Harl P. Jr., Discussion of Frost Penetration, Bulletin 225, Highway Research Board, 1959.

(14) Kersten, Miles S., Thermal Properties of Soils, Special Report No. 2, Highway Research Board, 1952, 161-166.

(15) Erickson, L. F., Frost Effects Considerations for Highway Pavement Design in the Western United States, Annual Meeting of the Highway Research Board, Washington, D. C., January 1963.

(16) Rengmark, Folke, Highway Pavement Design in Frost Areas in Sweden, Annual Meeting of the Highway Research Board, Washington, D. C., January 1963.

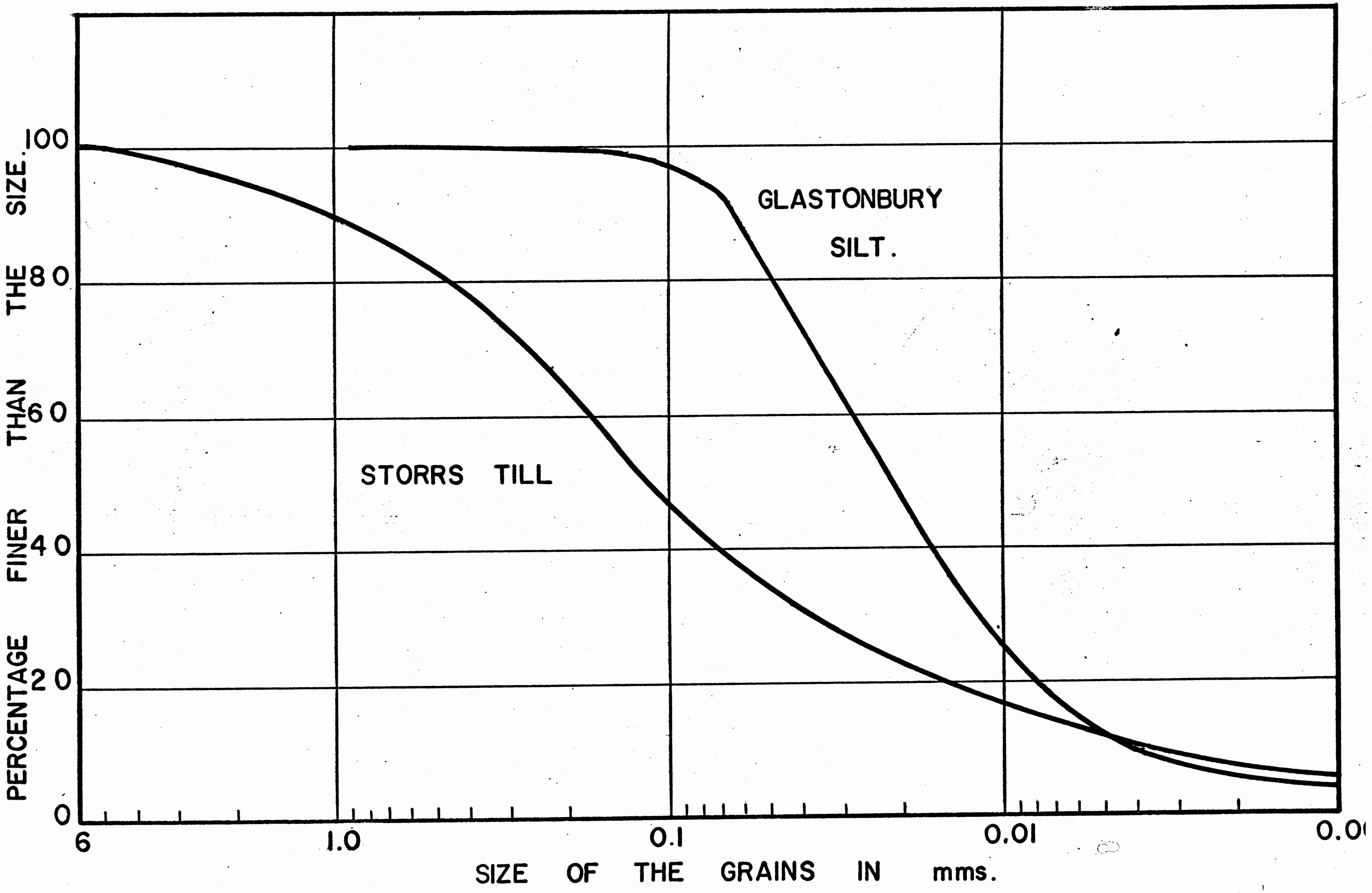

PERCENTAGE FINER THAN THE SIZE.
100
80
60
40
20
0
GLASTONBURY SILT.
STORRS TILL
6
1.0
0.1
0.01
0.0
SIZE OF THE GRAINS IN mms.

FIGURE 1

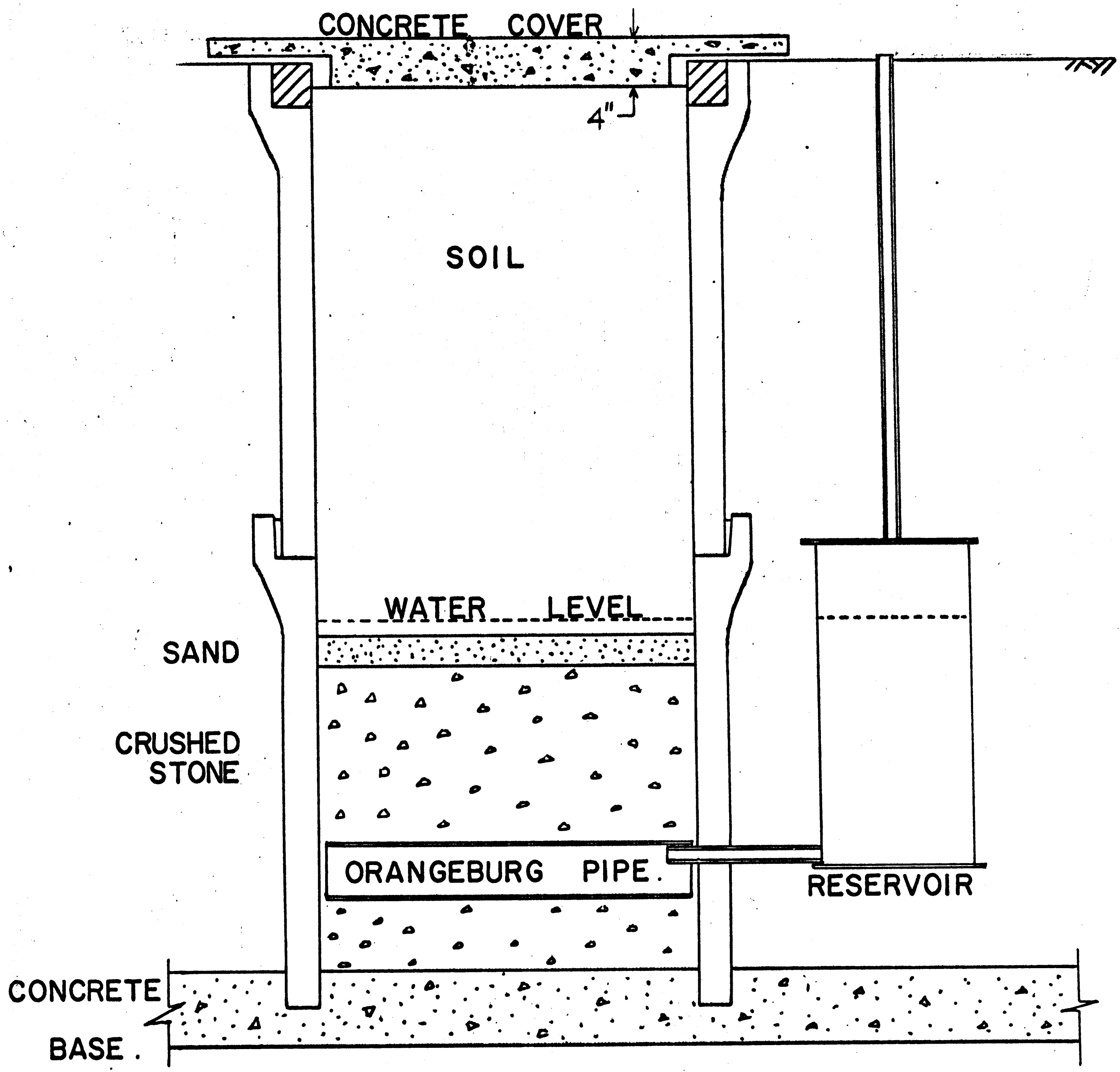
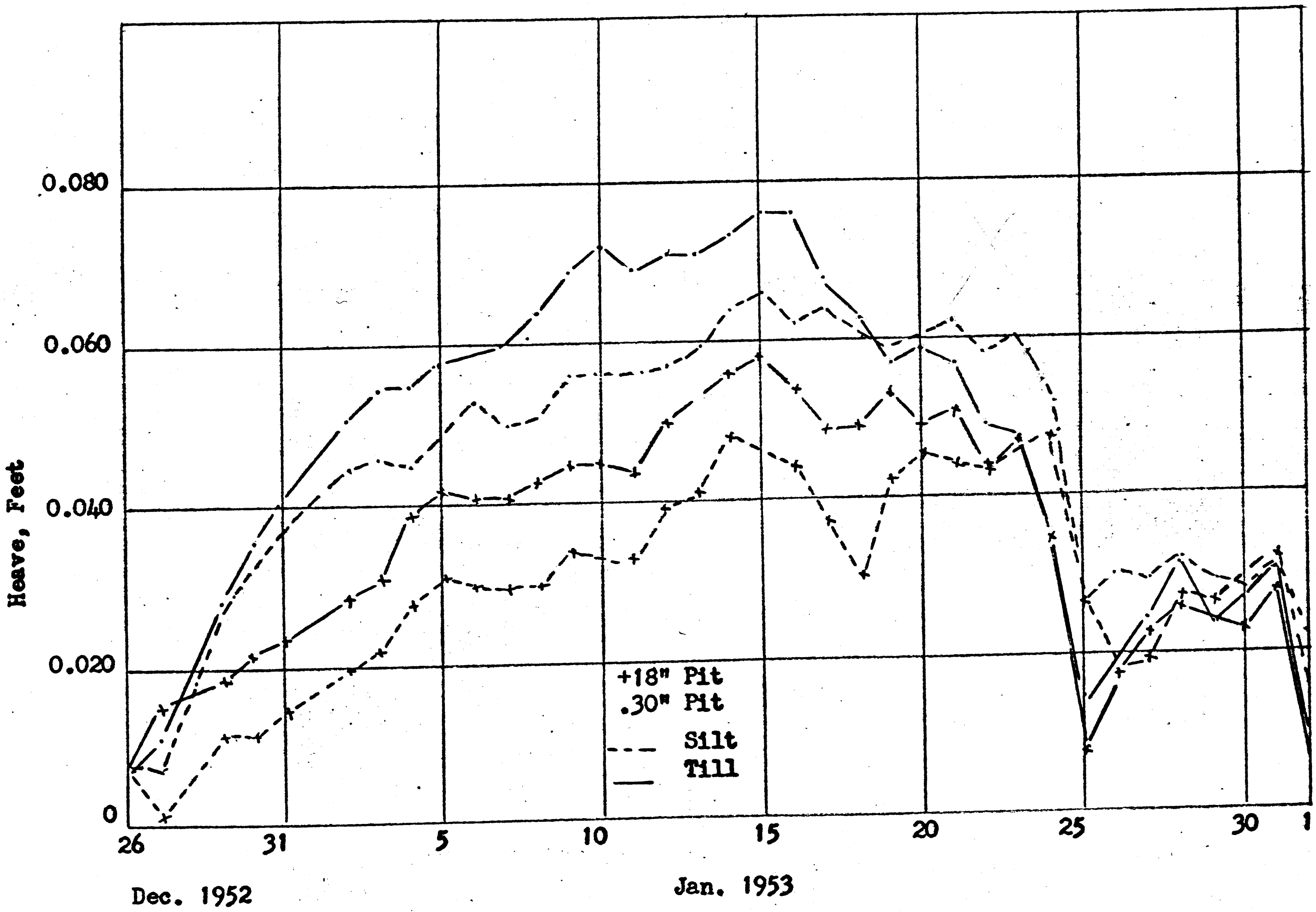

CONCRETE COVER
4"
SOIL
WATER LEVEL
SAND
CRUSHED STONE
ORANGEBURG PIPE.
RESERVOIR
CONCRETE BASE.

FIGURE 2

FIGURE 3



Depth to Ground Water Table = 2.5 ft.

LEONARDS
MS Pg 36

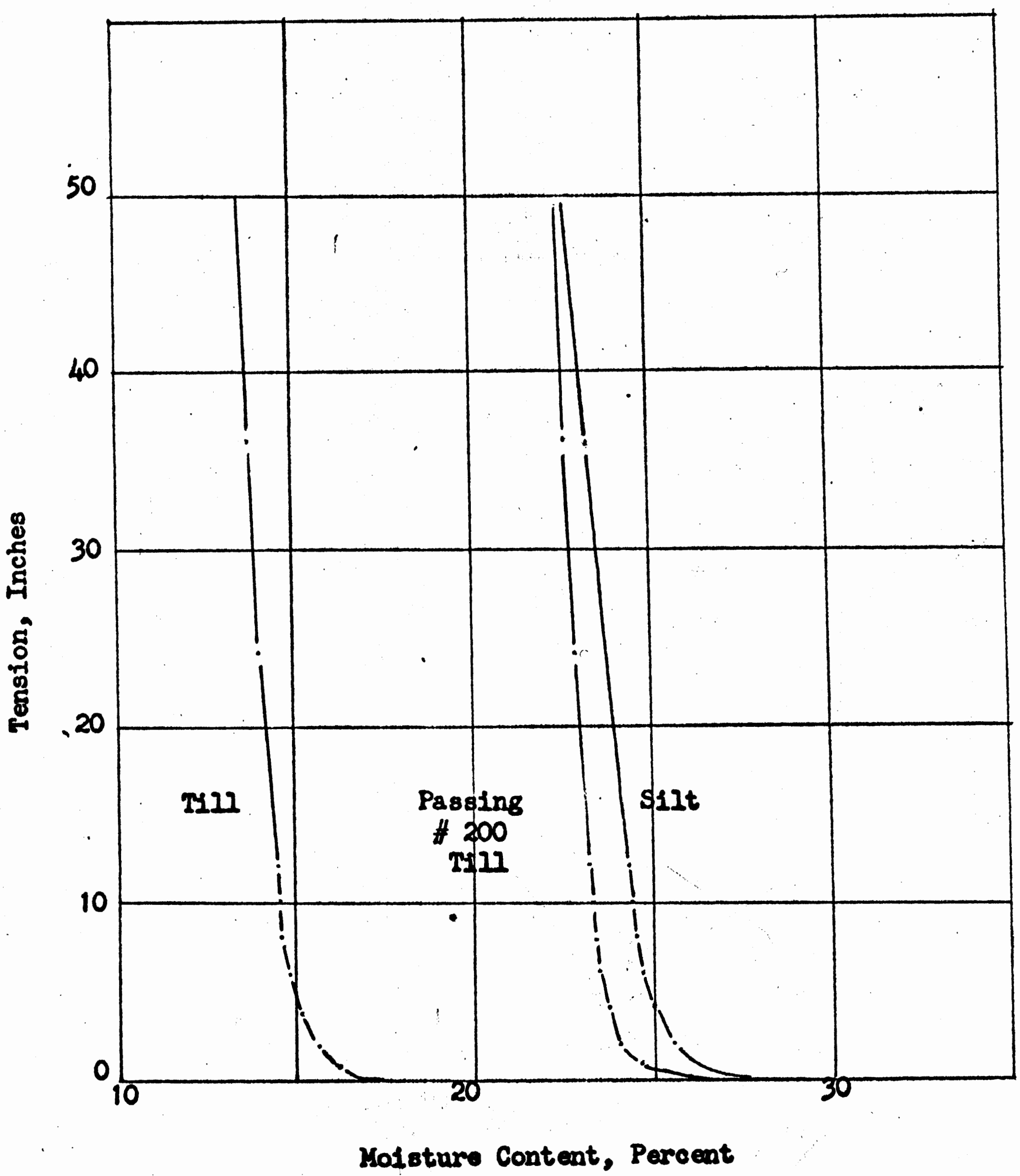


FIGURE 4

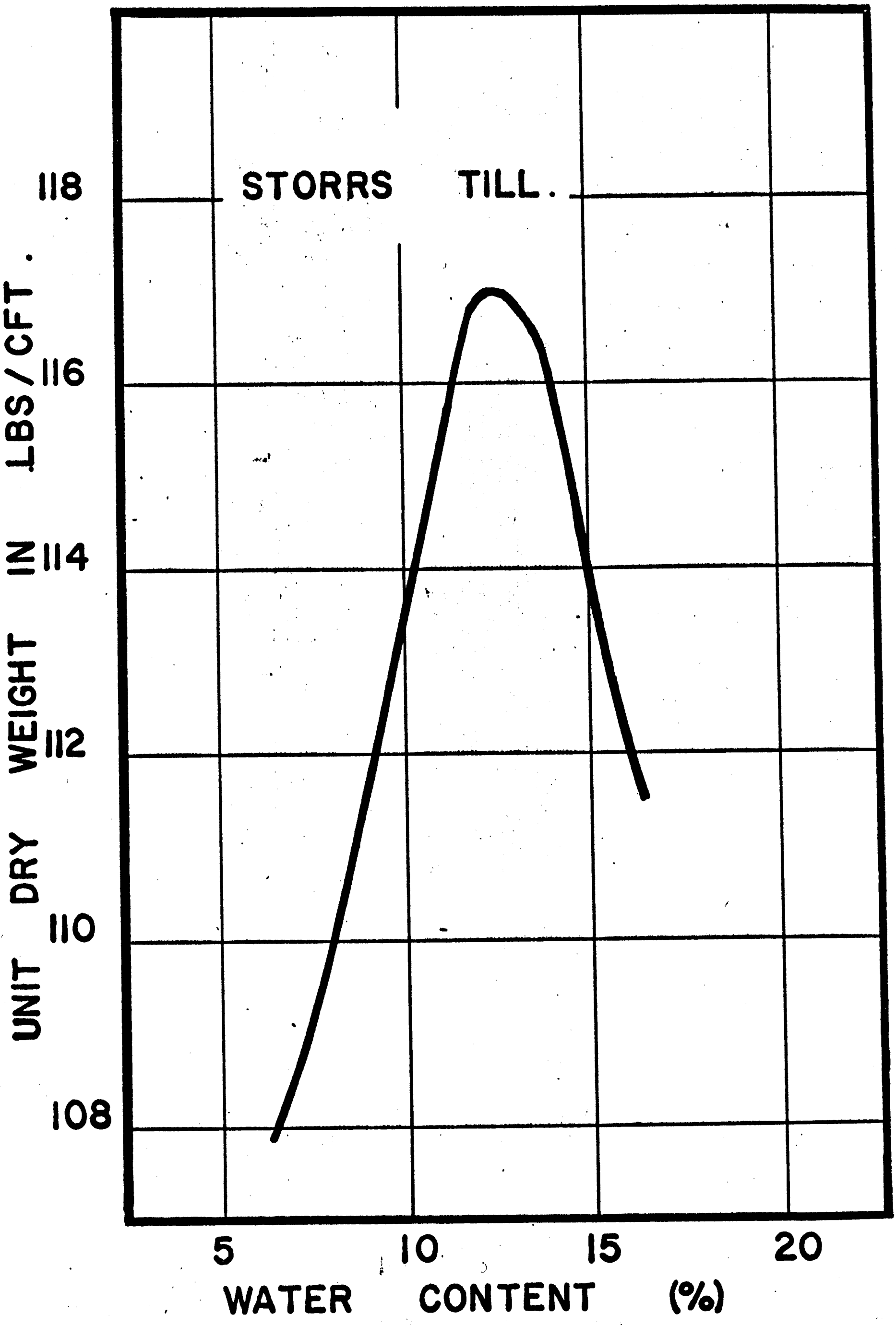

STORRS TILL.
118
116
114
112
110
108
UNIT DRY WEIGHT IN LBS/CFT.
5
10
15
20
WATER CONTENT (%)

FIGURE 5

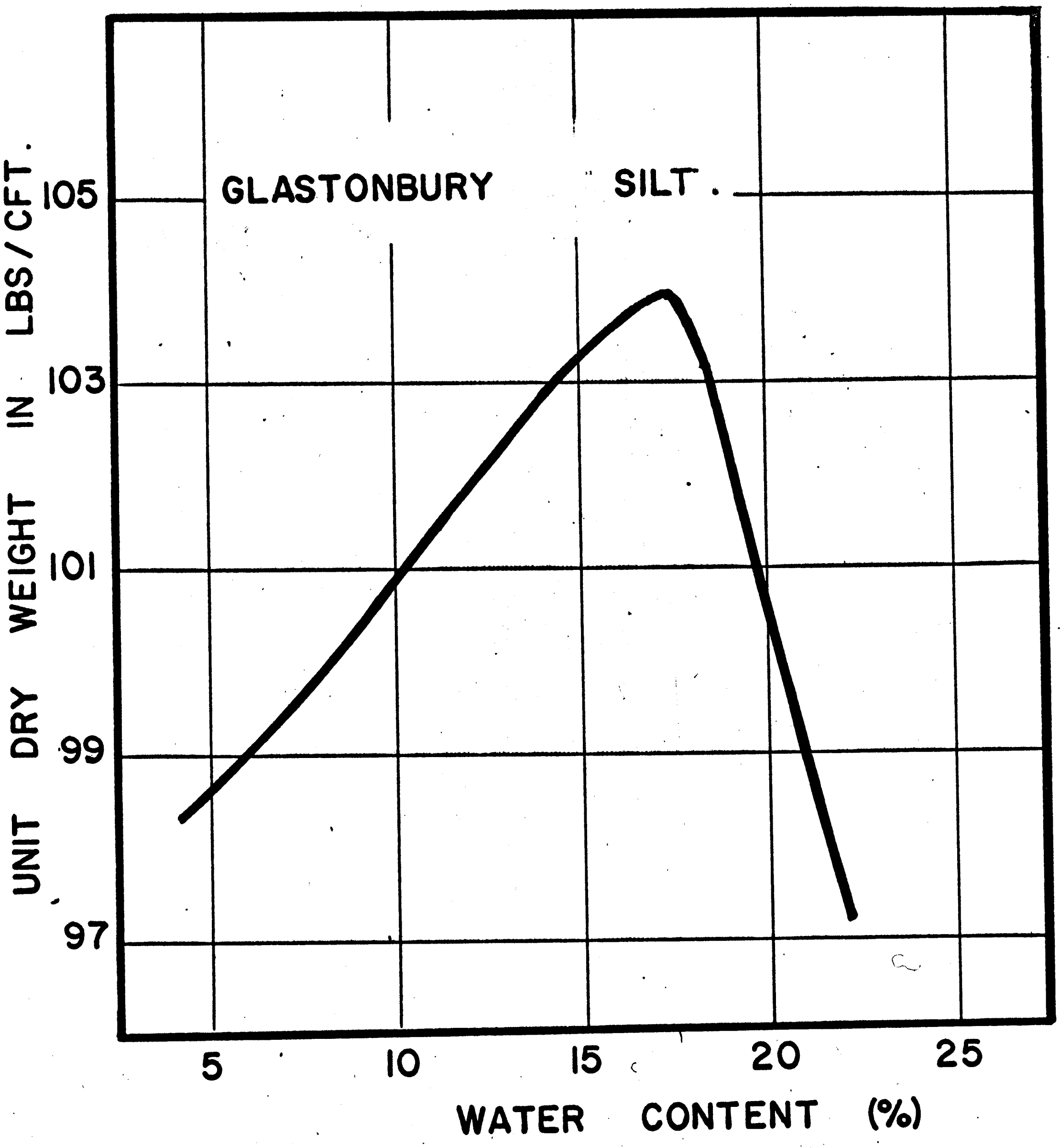

GLASTONBURY SILT.
UNIT DRY WEIGHT IN LBS/CFT.
105
103
101
99
97
5
10
15
20
25
WATER CONTENT (%)

FIGURE 6

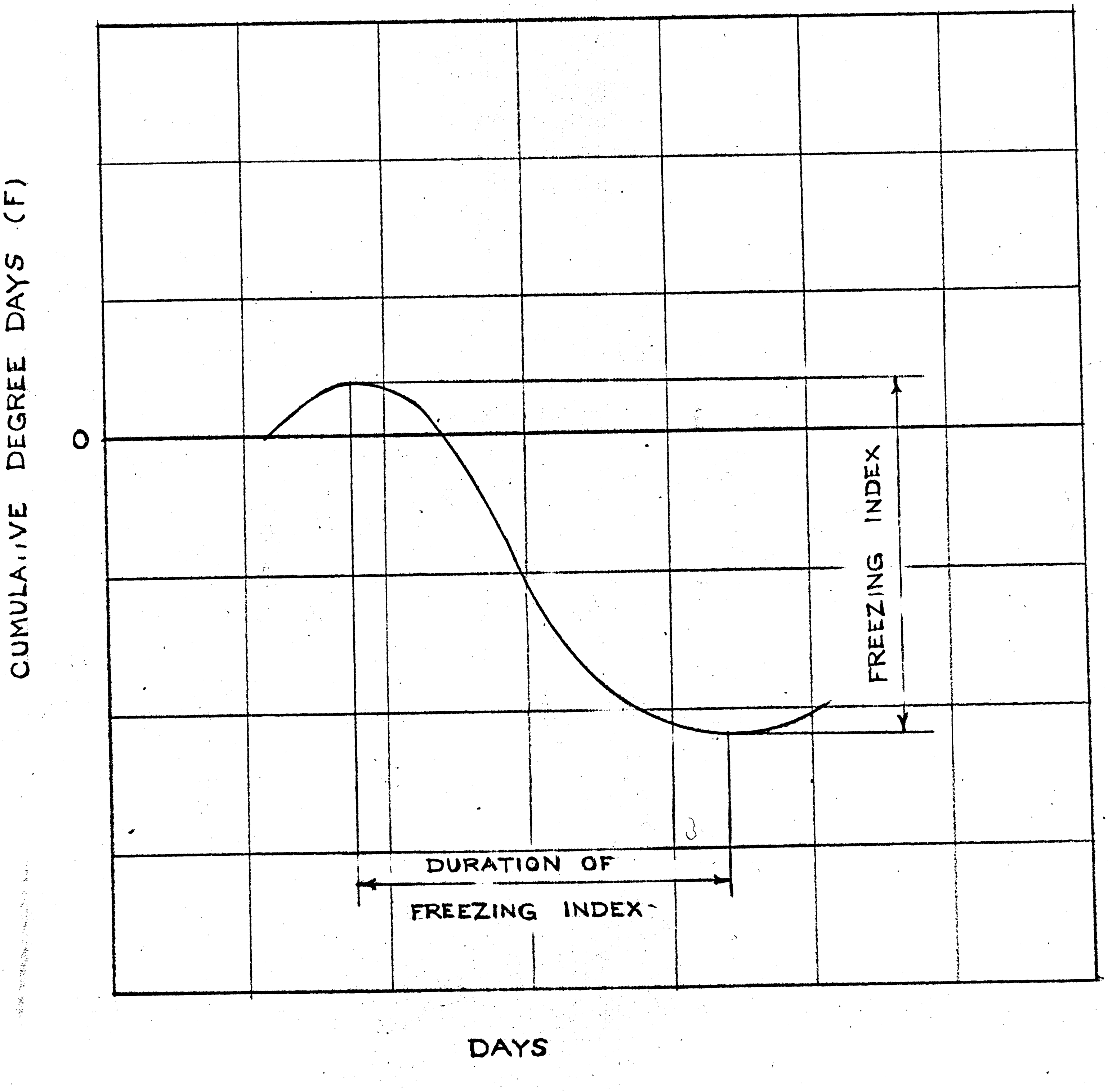

CUMULATIVE DEGREE DAYS (F)
0
FREEZING INDEX
DURATION OF FREEZING INDEX
DAYS

FIGURE 7

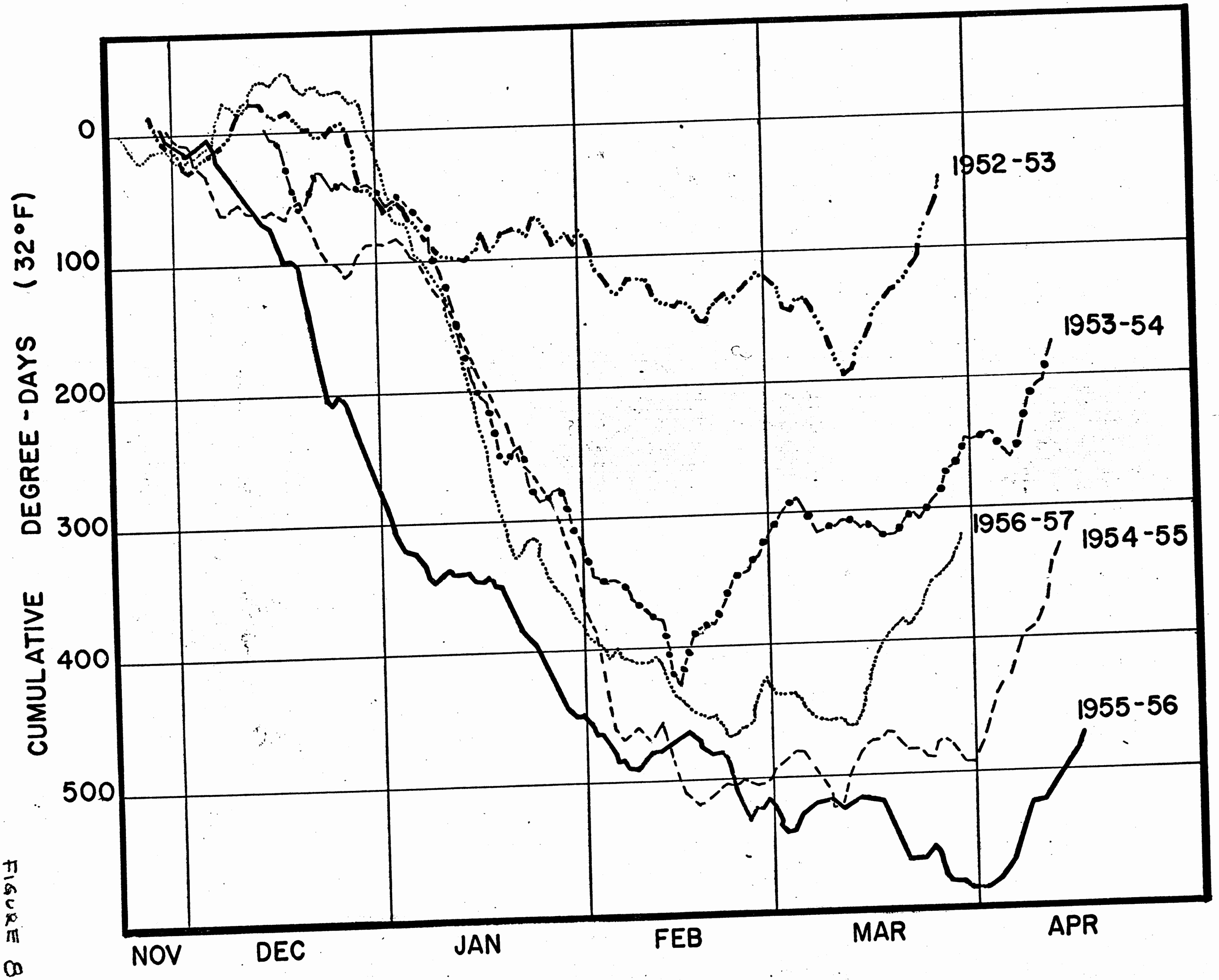

0
100
200
300
400
500
CUMULATIVE DEGREE - DAYS (32°F)
NOV
DEC
JAN
FEB
MAR
APR
1952-53
1953-54
1956-57
1954-55
1955-56

FIGURE 8

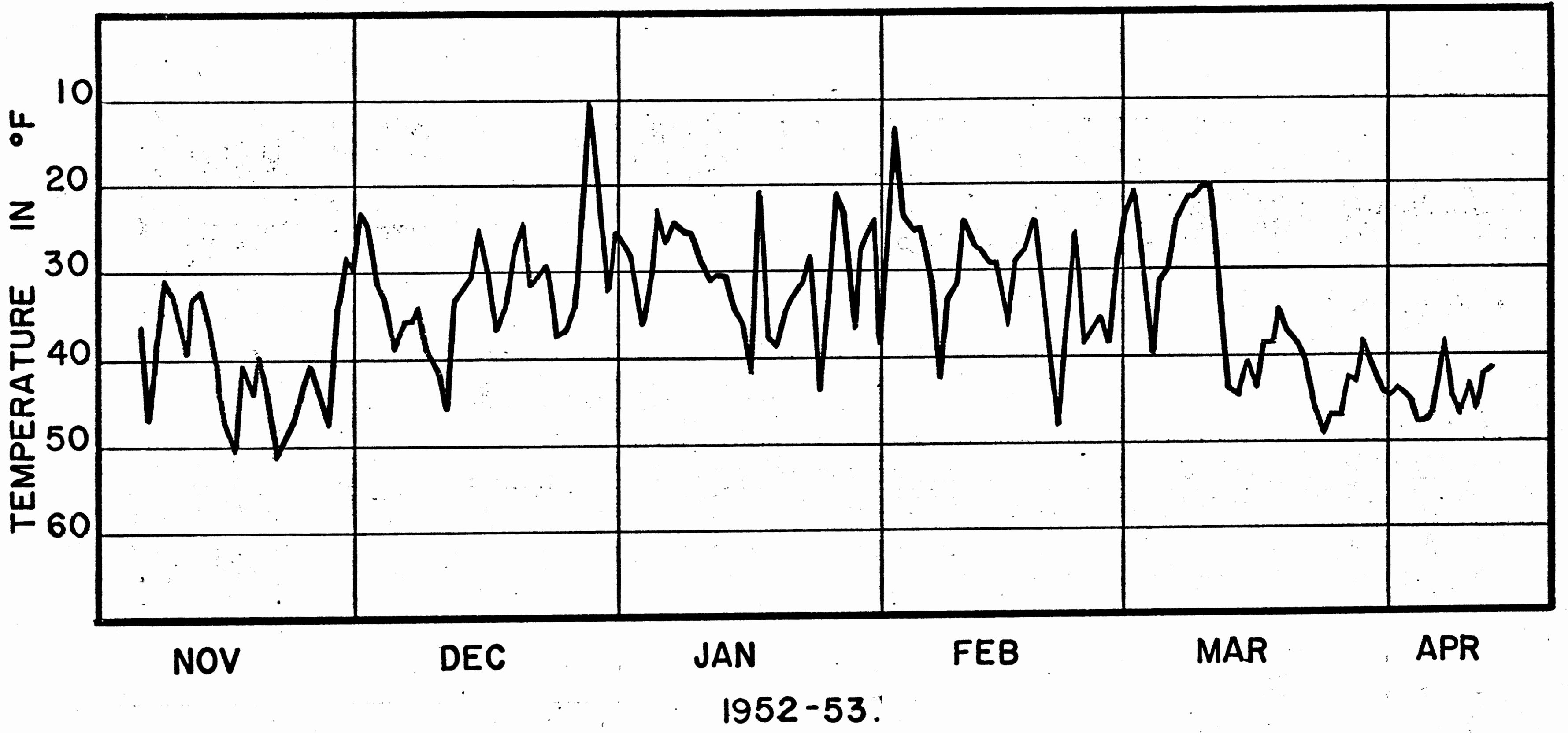

10
20
30
40
50
60
TEMPERATURE IN °F
NOV
DEC
JAN
FEB
MAR
APR
1952-53.

FIGURE 9

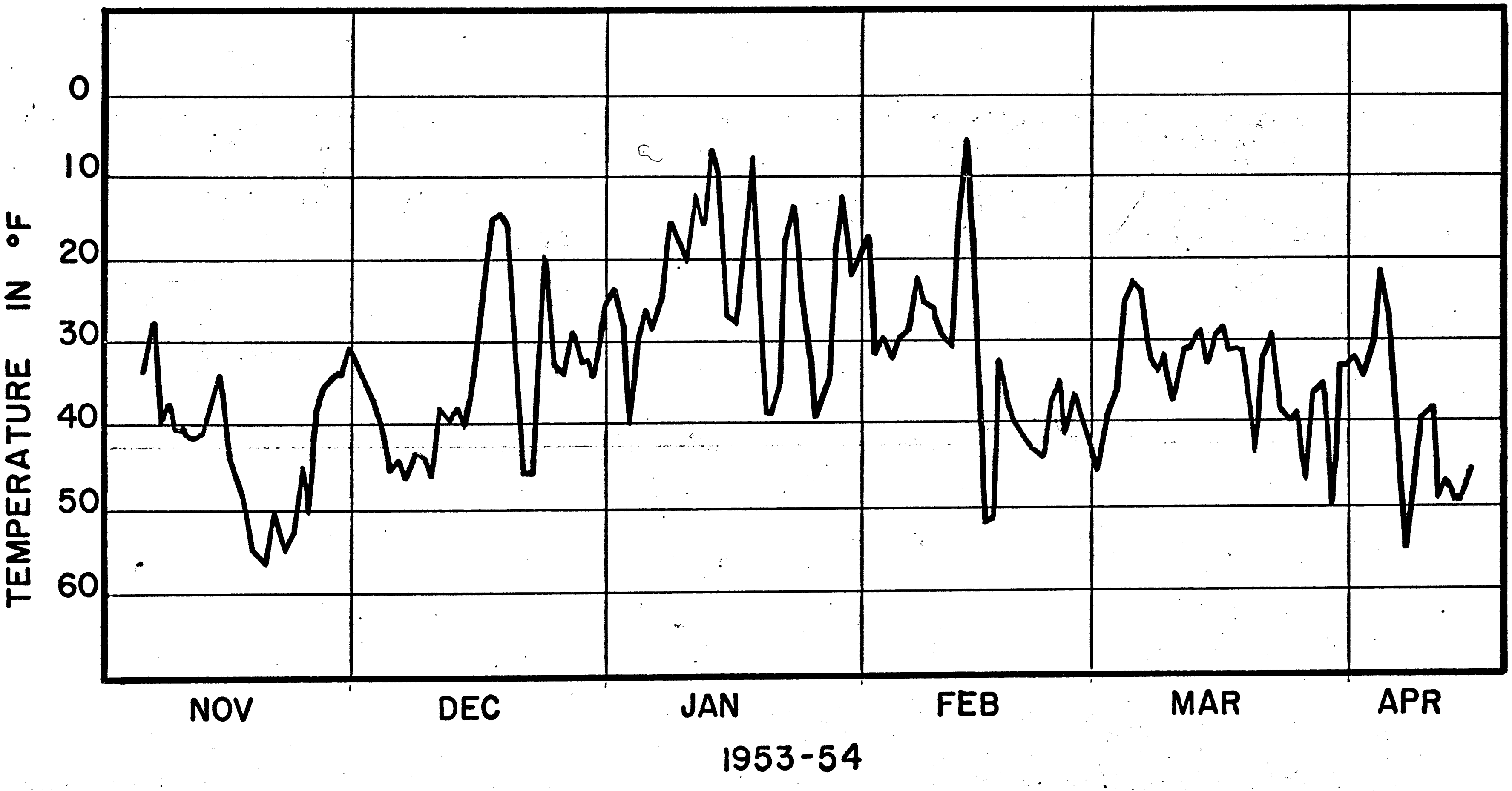

0
10
20
30
40
50
60
TEMPERATURE IN °F
NOV
DEC
JAN
FEB
MAR
APR
1953-54

FIGURE 10

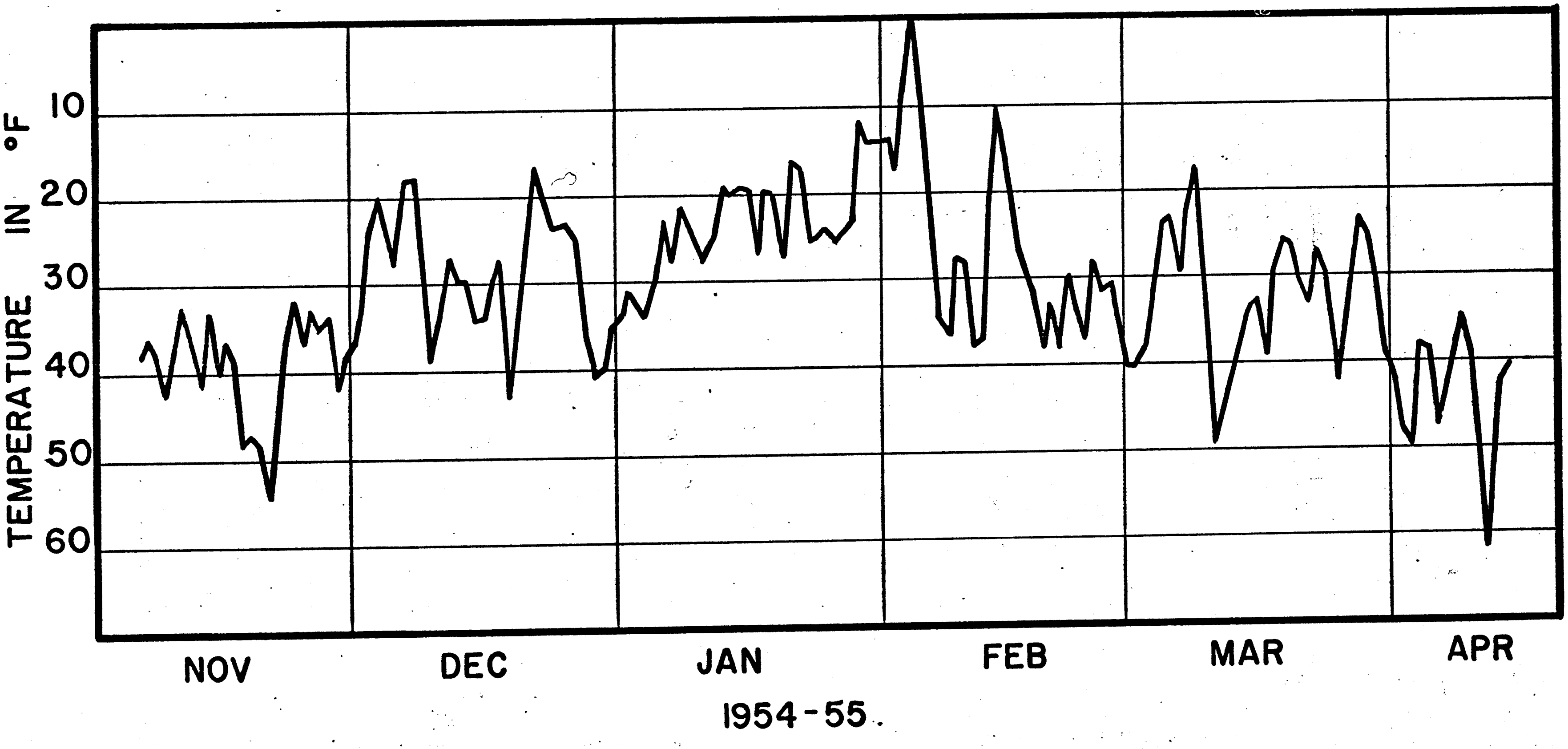

TEMPERATURE IN °F
10
20
30
40
50
60
NOV
DEC
JAN
FEB
MAR
APR
1954-55.

FIGURE 11

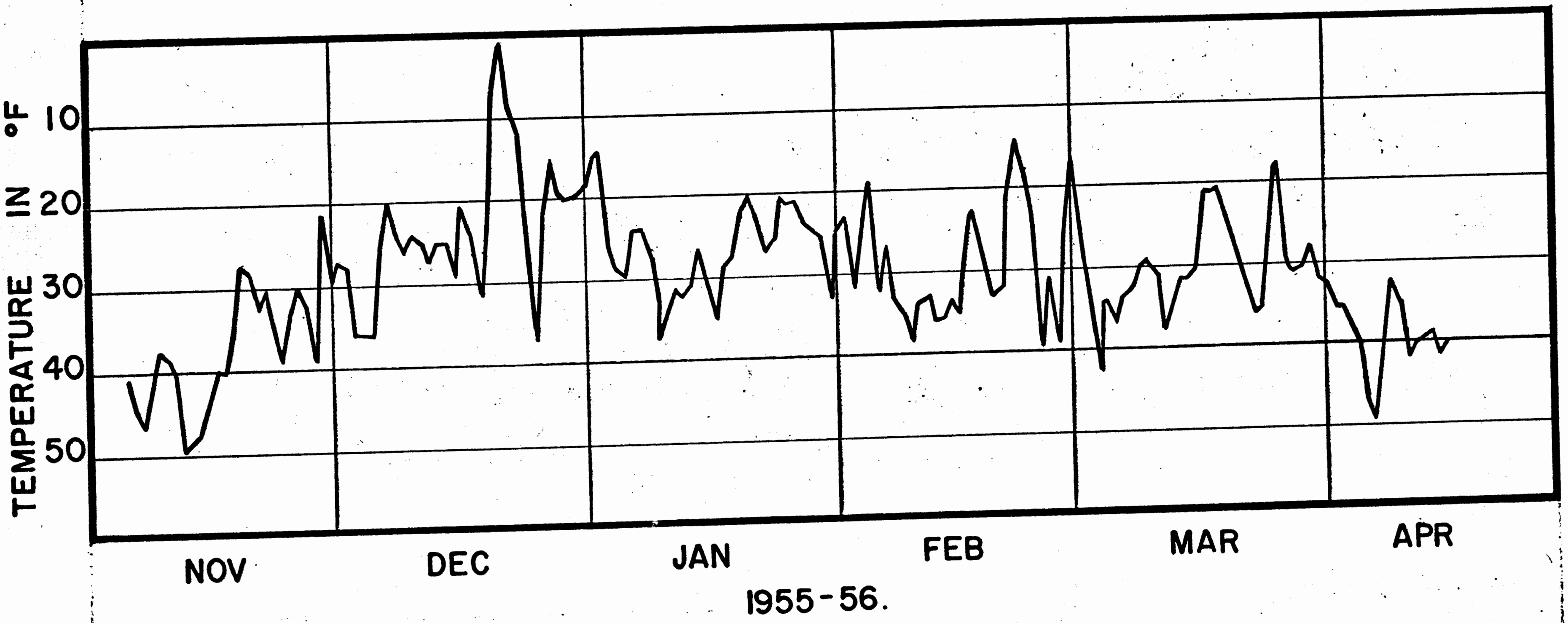


FIGURE 12

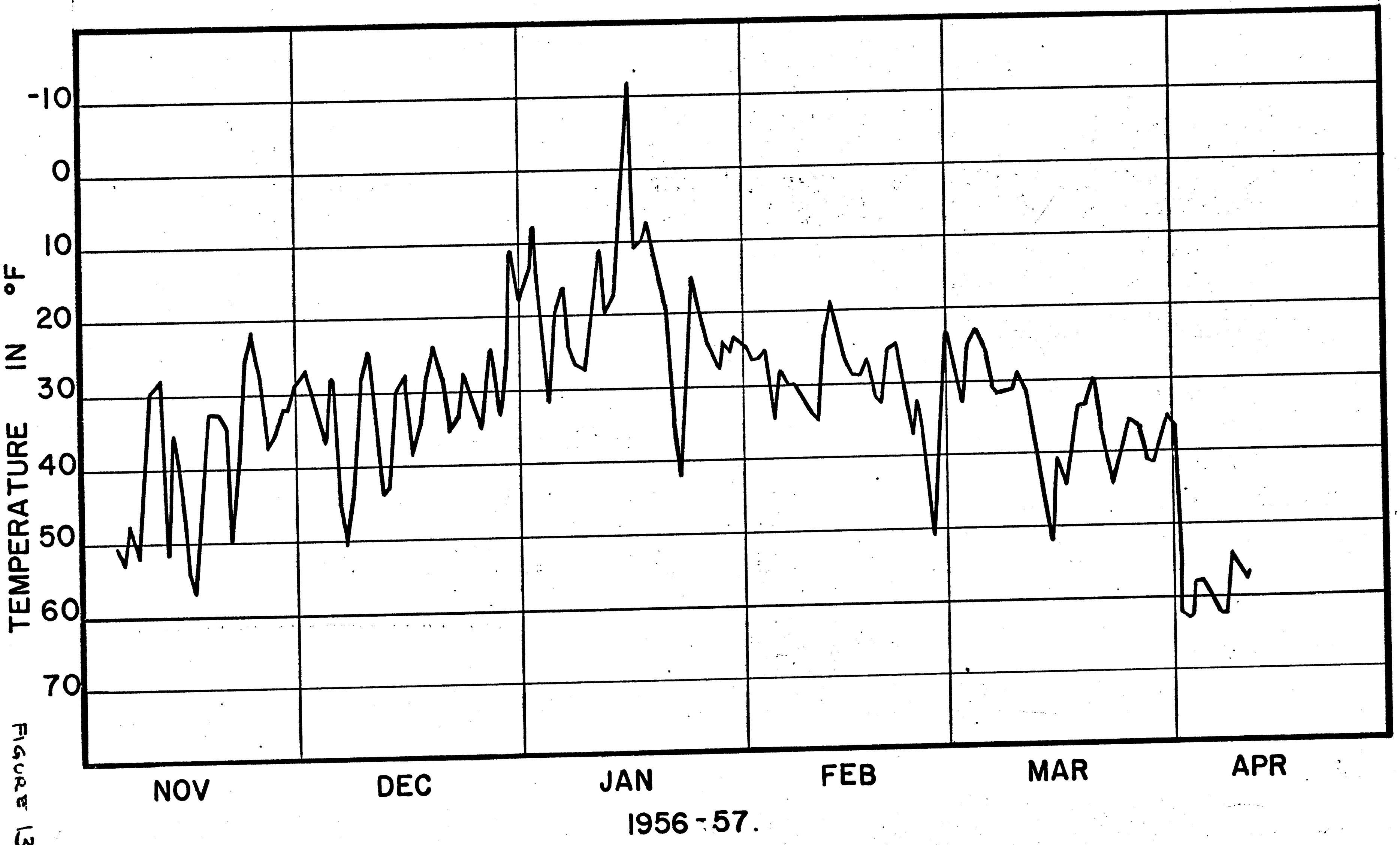

-10
0
10
20
30
40
50
60
70
TEMPERATURE IN °F
NOV
DEC
JAN
FEB
MAR
APR
1956-57.

FIGURE 13

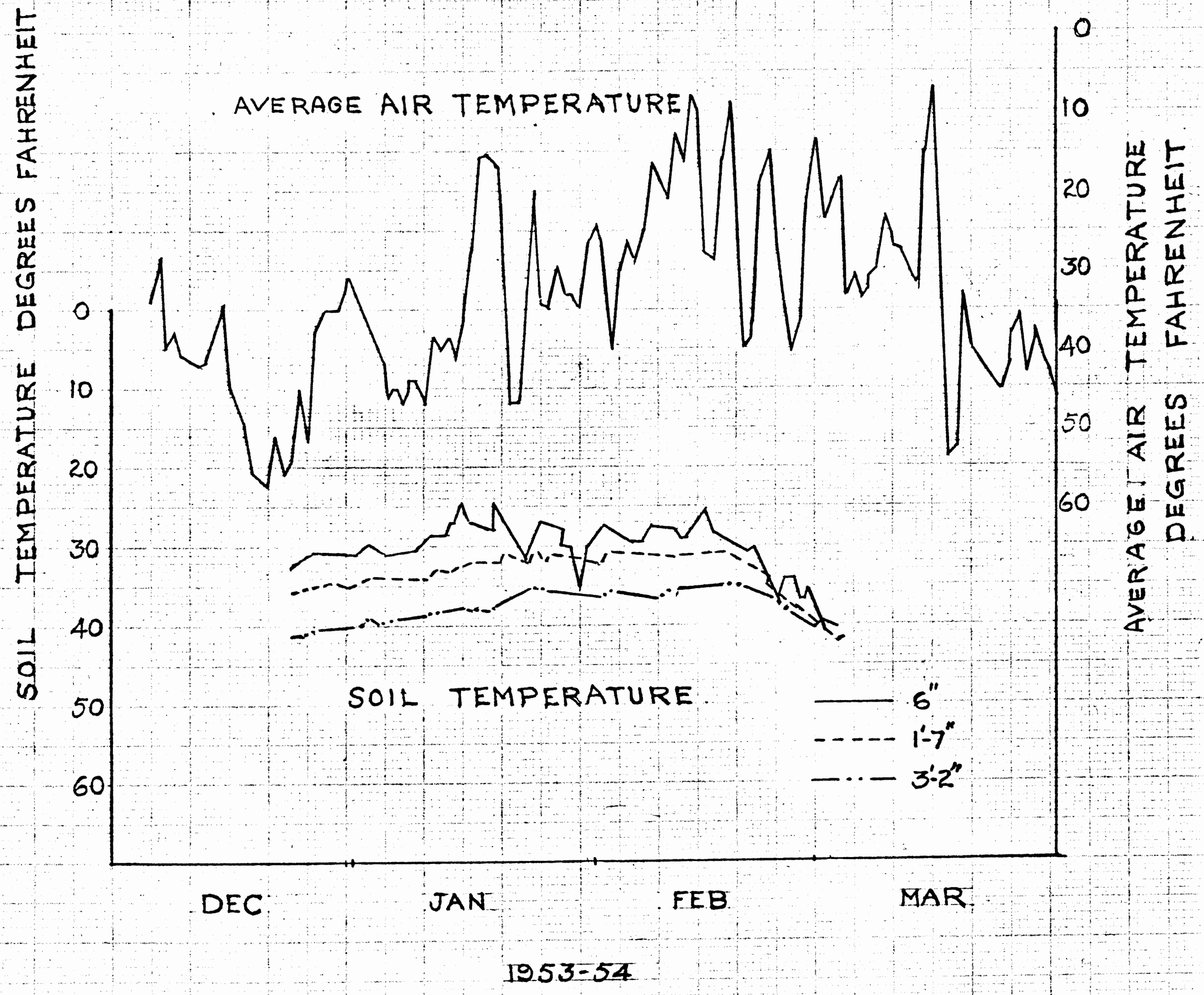

AVERAGE AIR TEMPERATURE
SOIL TEMPERATURE DEGREES FAHRENHEIT
0
10
20
30
40
50
60
AVERAGE AIR TEMPERATURE DEGREES FAHRENHEIT
0
10
20
30
40
50
60
SOIL TEMPERATURE
6"
1'-7"
3'-2"
DEC
JAN
FEB
MAR
1953-54

FIGURE 14

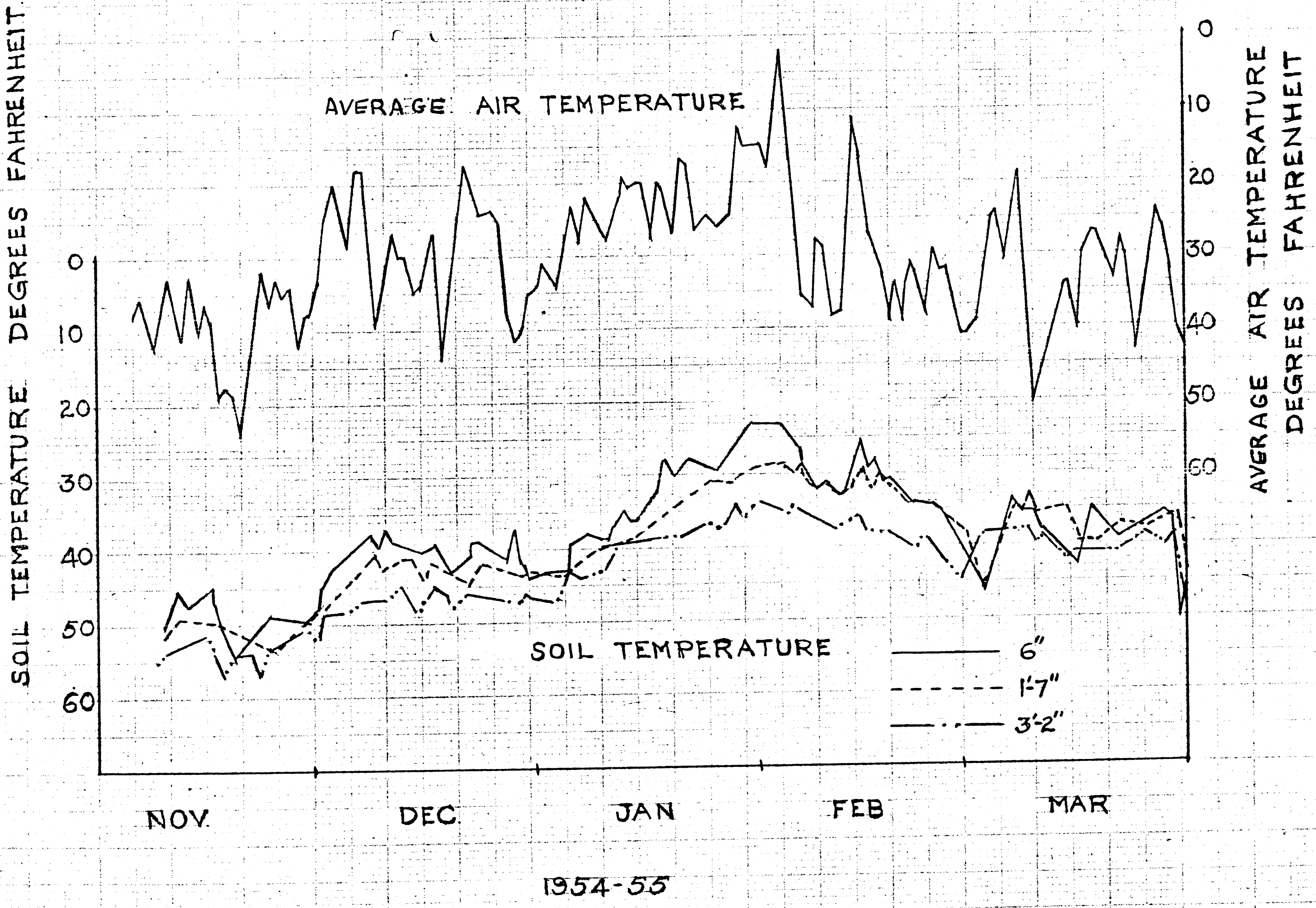
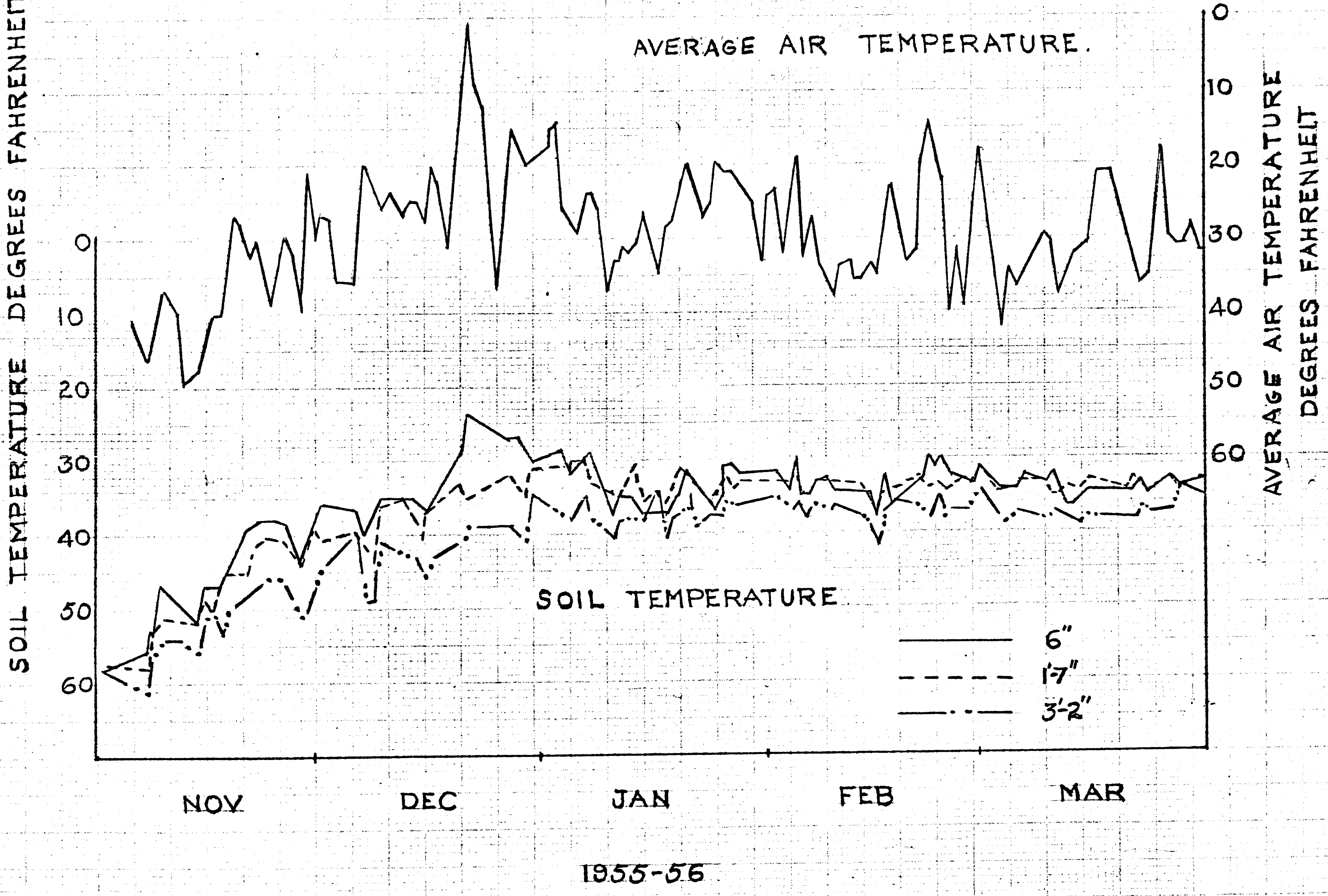
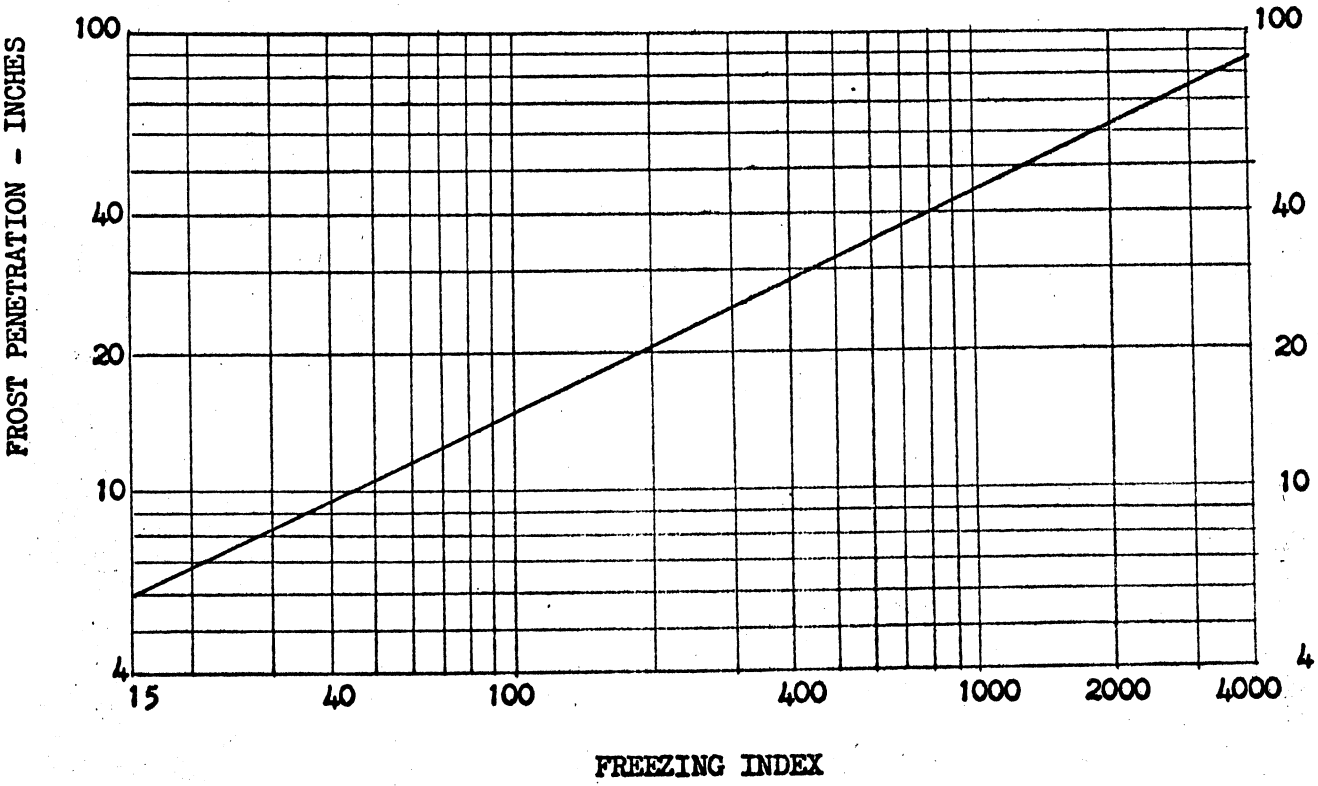

AVERAGE AIR TEMPERATURE
SOIL TEMPERATURE DEGREES FAHRENHEIT
0
10
20
30
40
50
60
AVERAGE AIR TEMPERATURE DEGREES FAHRENHEIT
0
10
20
30
40
50
60
SOIL TEMPERATURE
6"
1'-7"
3'-2"
NOV.
DEC.
JAN
FEB
MAR
1954-55

FIGURE 15

FIGURE 16


AVERAGE AIR TEMPERATURE.
SOIL TEMPERATURE DEGREES FAHRENHEIT
0
10
20
30
40
50
60
AVERAGE AIR TEMPERATURE DEGREES FAHRENHEIT
0
10
20
30
40
50
60
SOIL TEMPERATURE
6"
1'7"
3'2"
NOV
DEC
JAN
FEB
MAR
1955-56



FROST PENETRATION - INCHES
100
40
20
10
4
100
40
20
10
4
15
40
100
400
1000
2000
4000
FREEZING INDEX

FIGURE 17

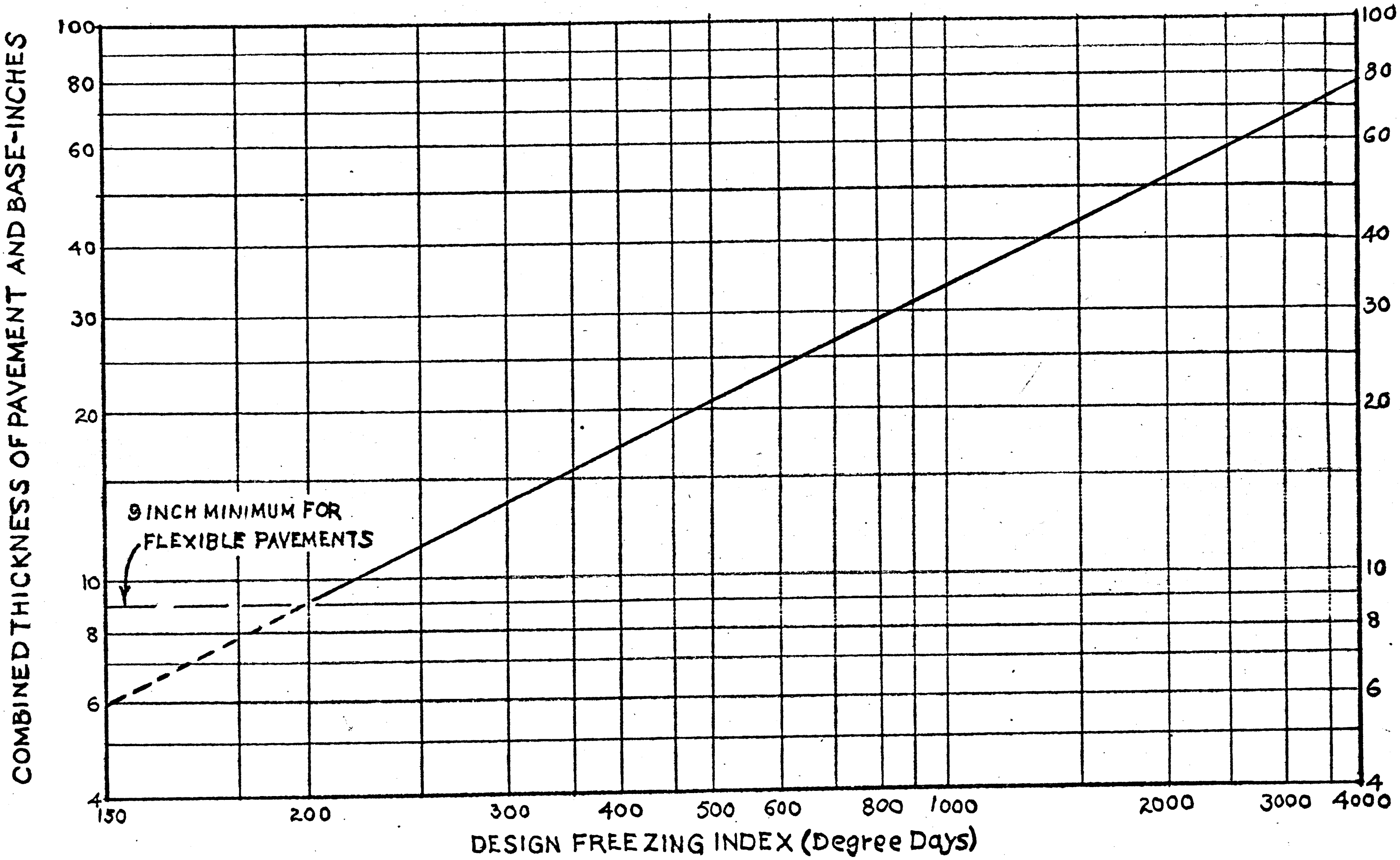

COMBINED THICKNESS OF PAVEMENT AND BASE-INCHES
100
80
60
40
30
20
10
8
6
4
9 INCH MINIMUM FOR
FLEXIBLE PAVEMENTS
150
200
300
400
500
600
800
1000
2000
3000
4000
DESIGN FREEZING INDEX (Degree Days)

FIGURE 18

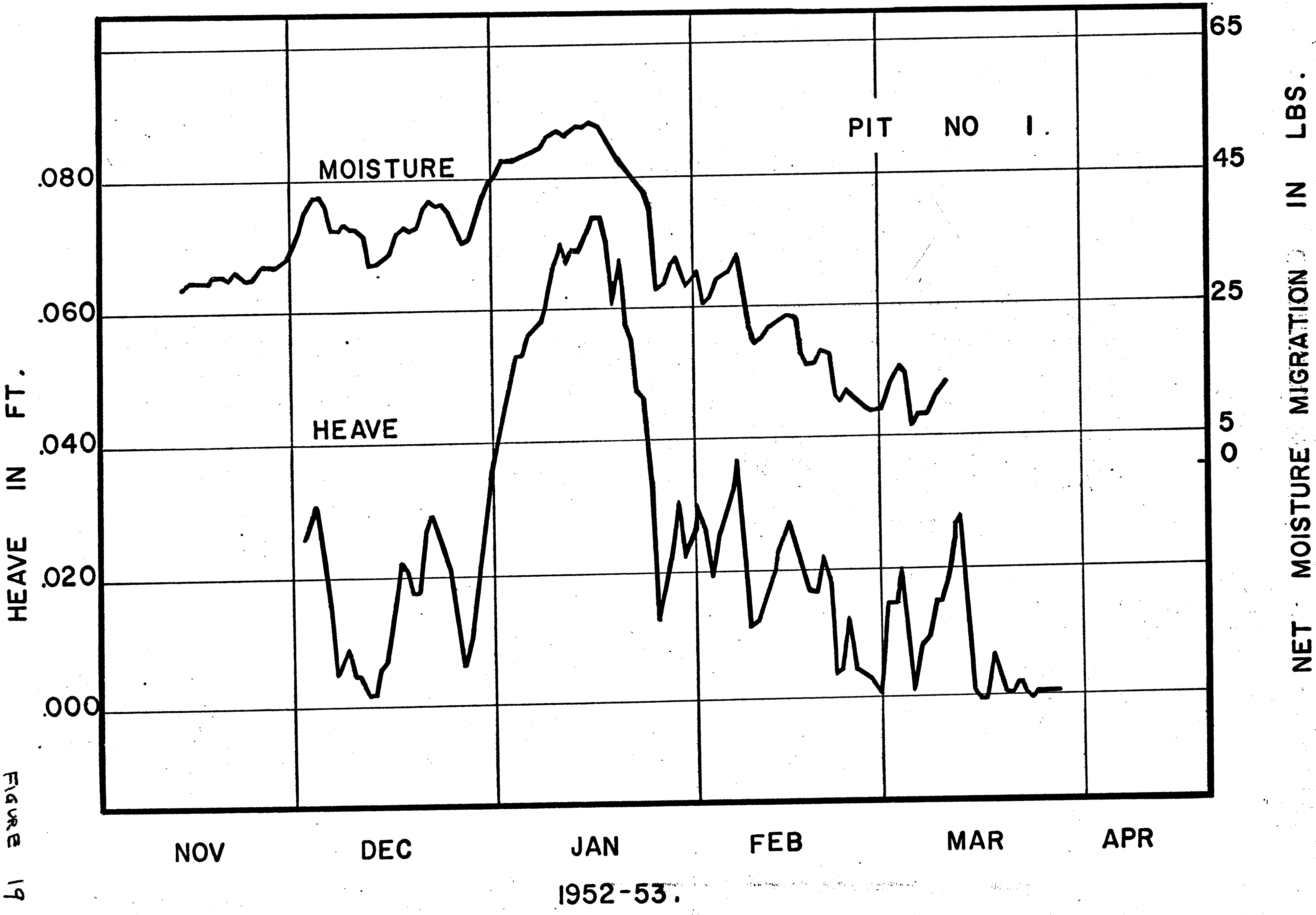

PIT NO 1.
MOISTURE
HEAVE
HEAVE IN FT.
.080
.060
.040
.020
.000
NET MOISTURE MIGRATION IN LBS.
65
45
25
5
0
NOV
DEC
JAN
FEB
MAR
APR
1952-53.

FIGURE 19

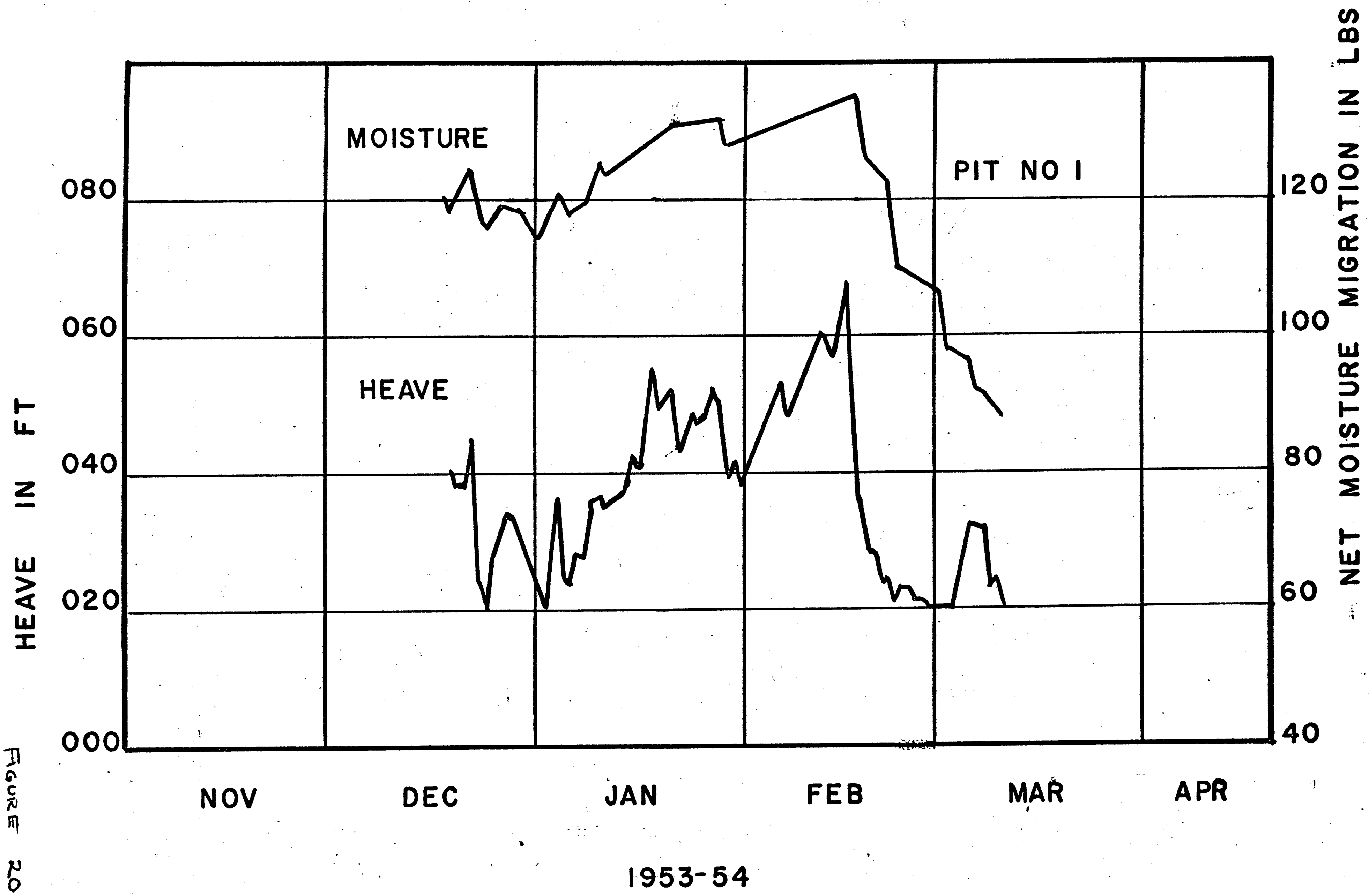

MOISTURE
PIT NO I
HEAVE
HEAVE IN FT
080
060
040
020
000
NET MOISTURE MIGRATION IN LBS
120
100
80
60
40
NOV
DEC
JAN
FEB
MAR
APR
1953-54

FIGURE 20

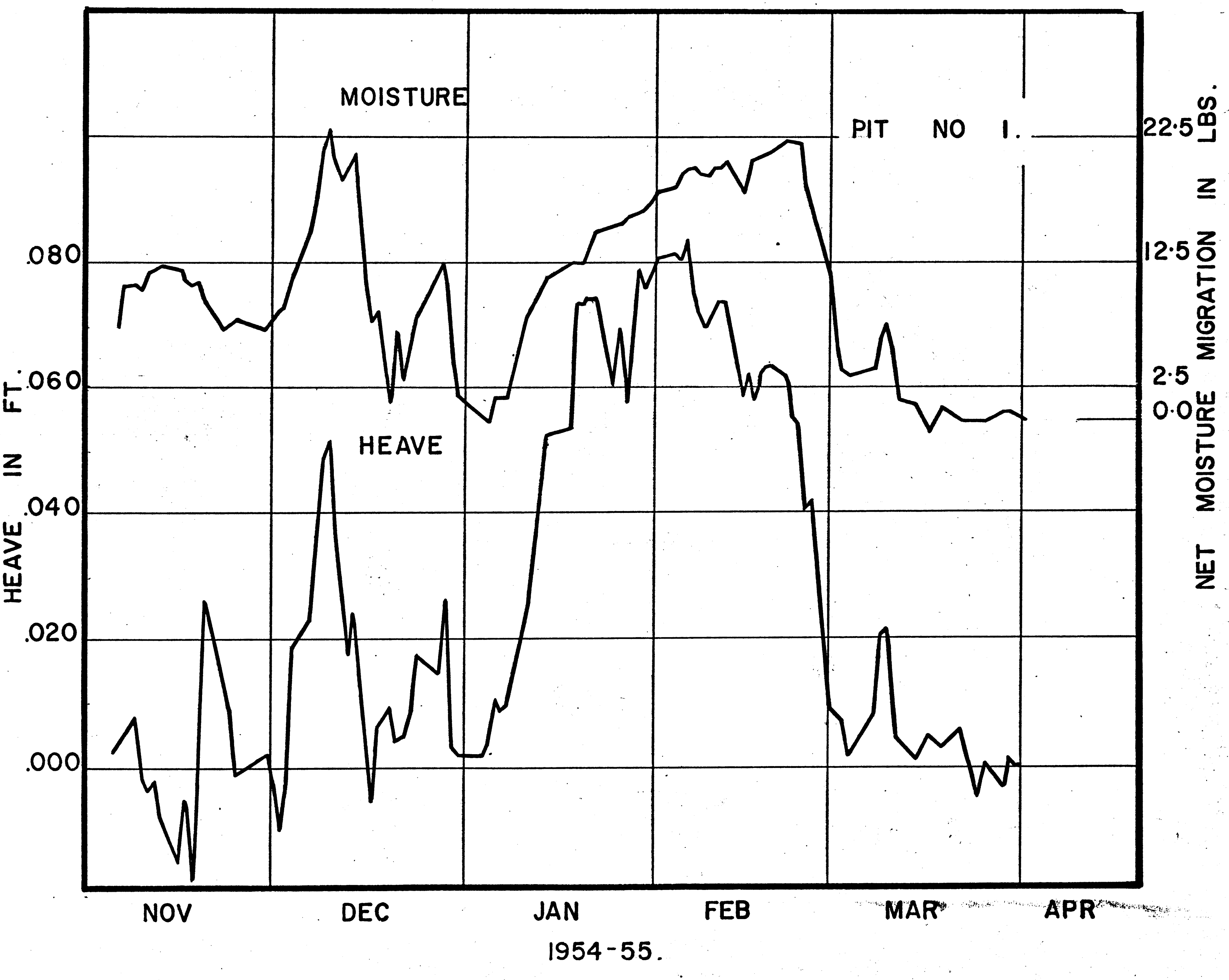

MOISTURE
PIT NO 1.
HEAVE
HEAVE IN FT.
.080
.060
.040
.020
.000
NET MOISTURE MIGRATION IN LBS.
22·5
12·5
2·5
0·0
NOV
DEC
JAN
FEB
MAR
APR
1954-55.

FIGURE 21

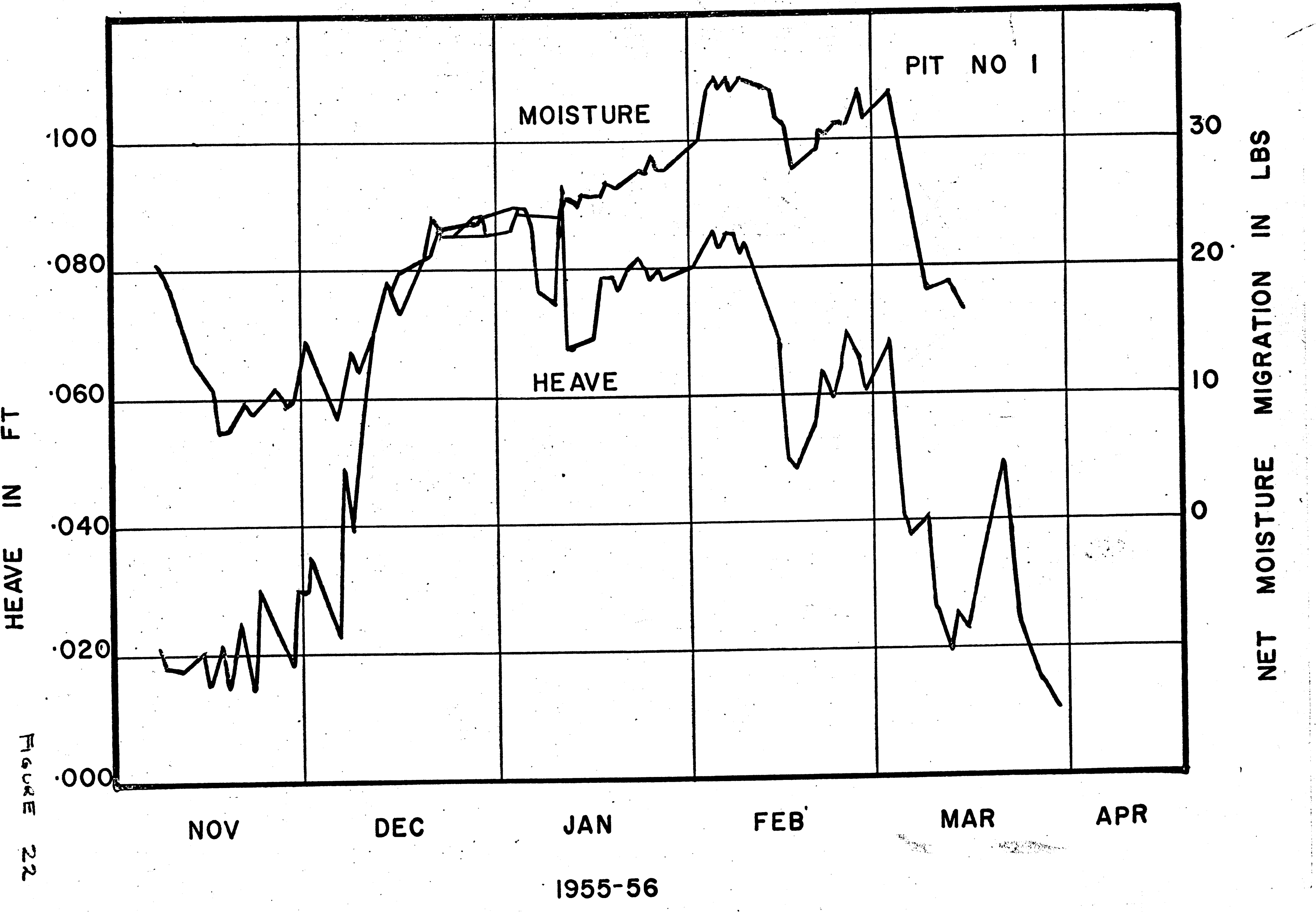

PIT NO 1
MOISTURE
HEAVE
HEAVE IN FT
·100
·080
·060
·040
·020
·000
NET MOISTURE MIGRATION IN LBS
30
20
10
0
NOV
DEC
JAN
FEB
MAR
APR
1955-56

FIGURE 22

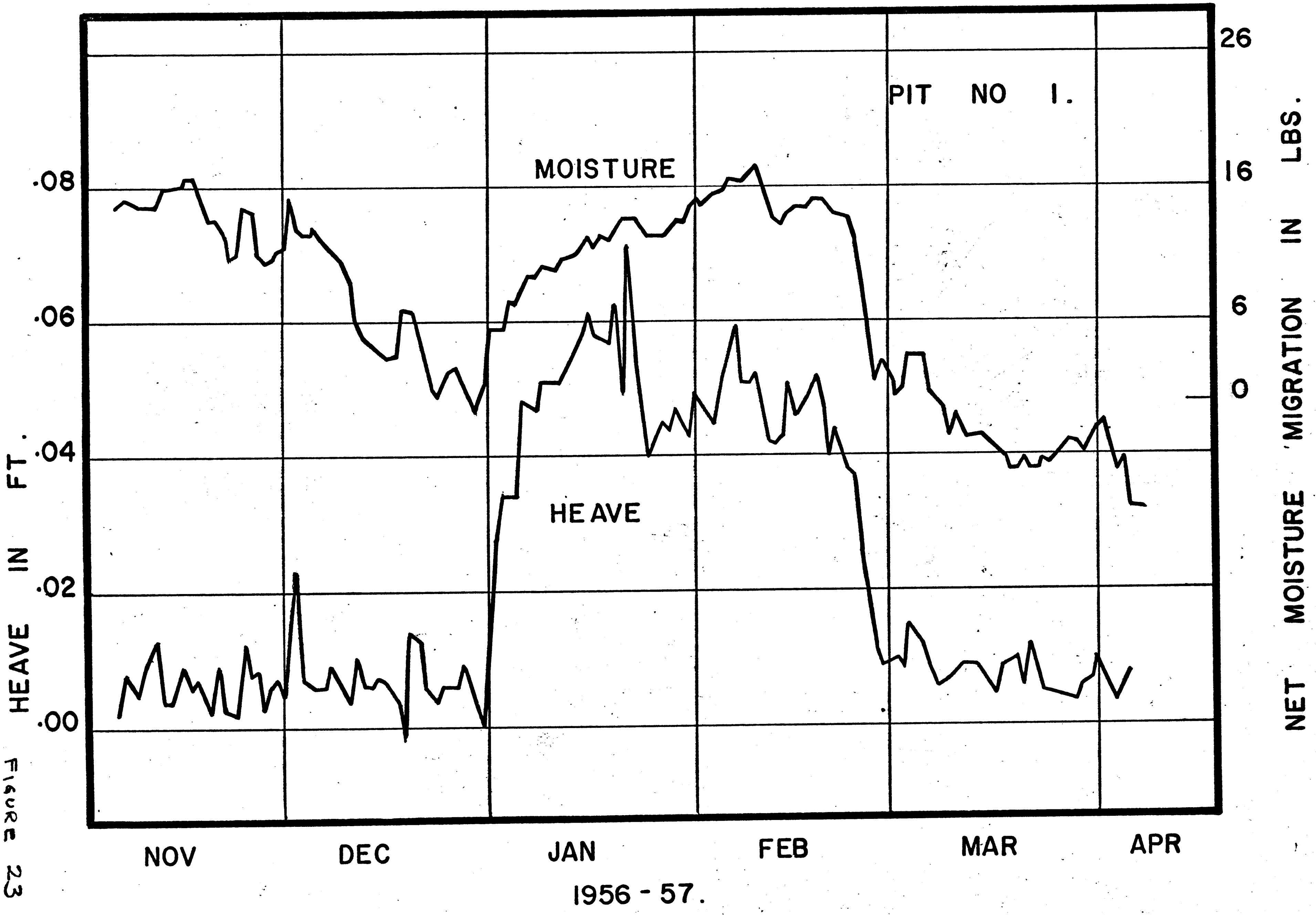

PIT NO 1.
MOISTURE
HEAVE
HEAVE IN FT.
·08
·06
·04
·02
·00
NET MOISTURE MIGRATION IN LBS.
26
16
6
0
NOV
DEC
JAN
FEB
MAR
APR
1956 - 57.

FIGURE 23

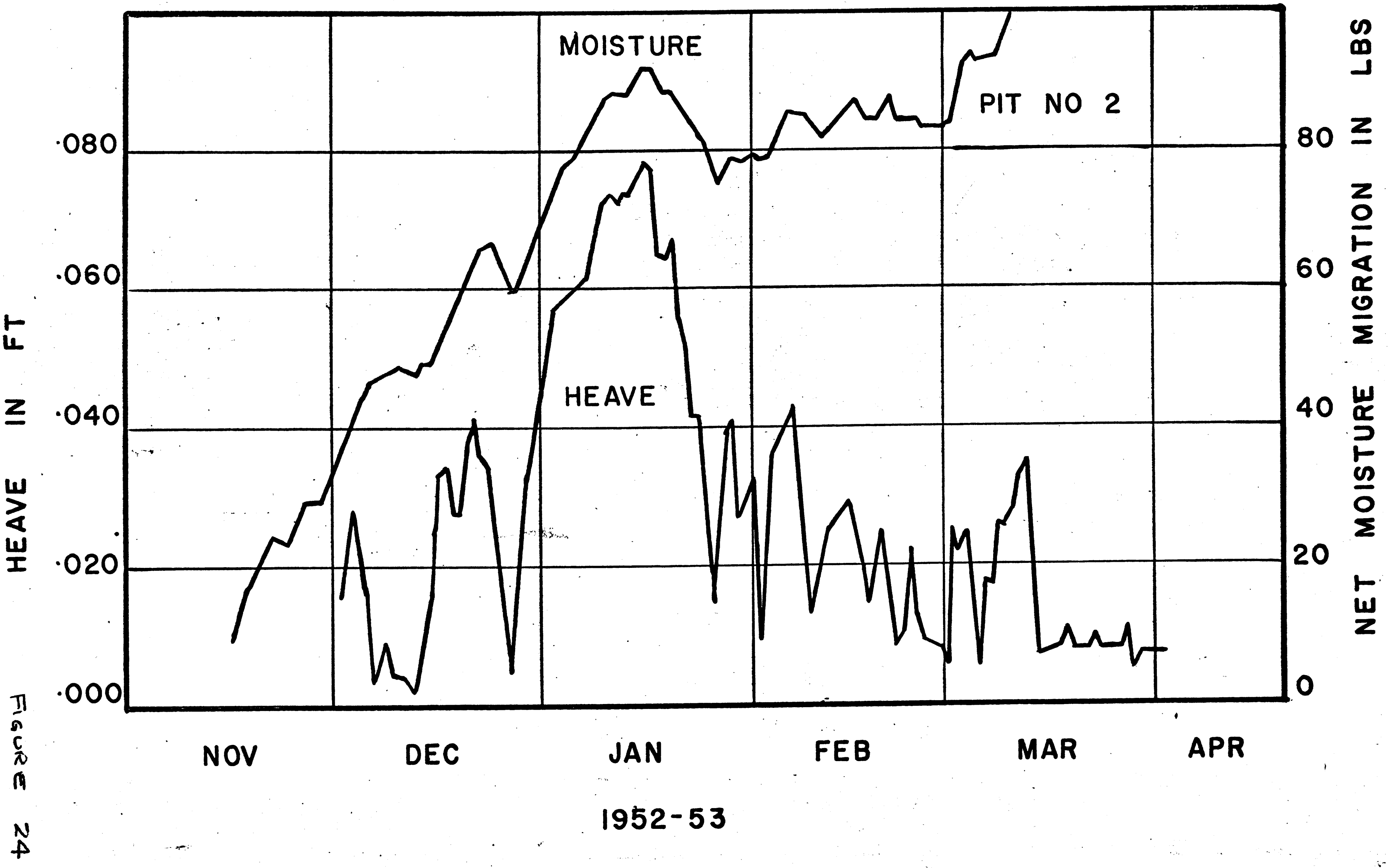

MOISTURE
PIT NO 2
HEAVE
HEAVE IN FT
·000
·020
·040
·060
·080
NET MOISTURE MIGRATION IN LBS
0
20
40
60
80
NOV
DEC
JAN
FEB
MAR
APR
1952-53

FIGURE 24

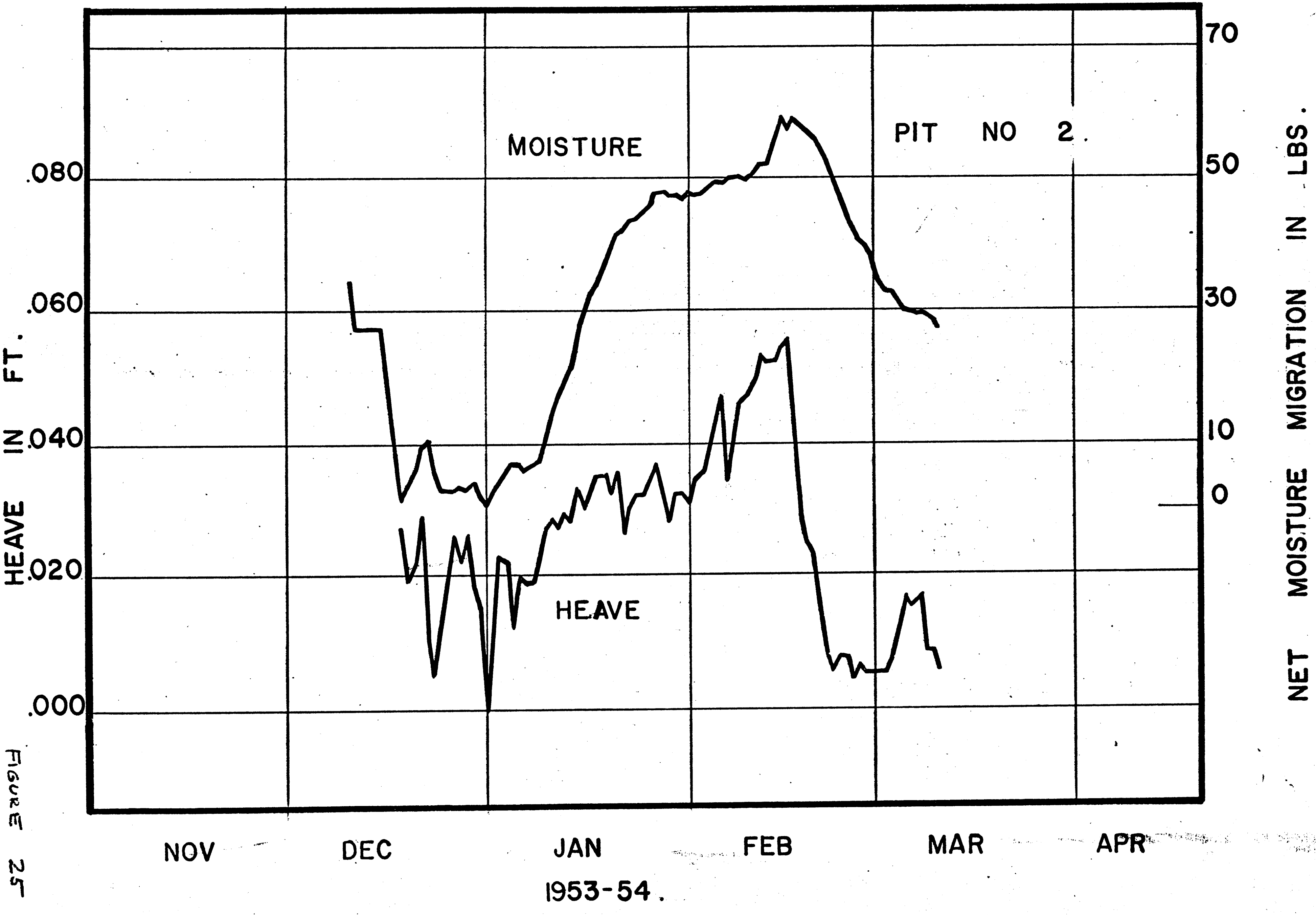

MOISTURE
PIT NO 2.
HEAVE
HEAVE IN FT.
.080
.060
.040
.020
.000
70
50
30
10
0
NET MOISTURE MIGRATION IN LBS.
NOV
DEC
JAN
FEB
MAR
APR
1953-54.

FIGURE 25

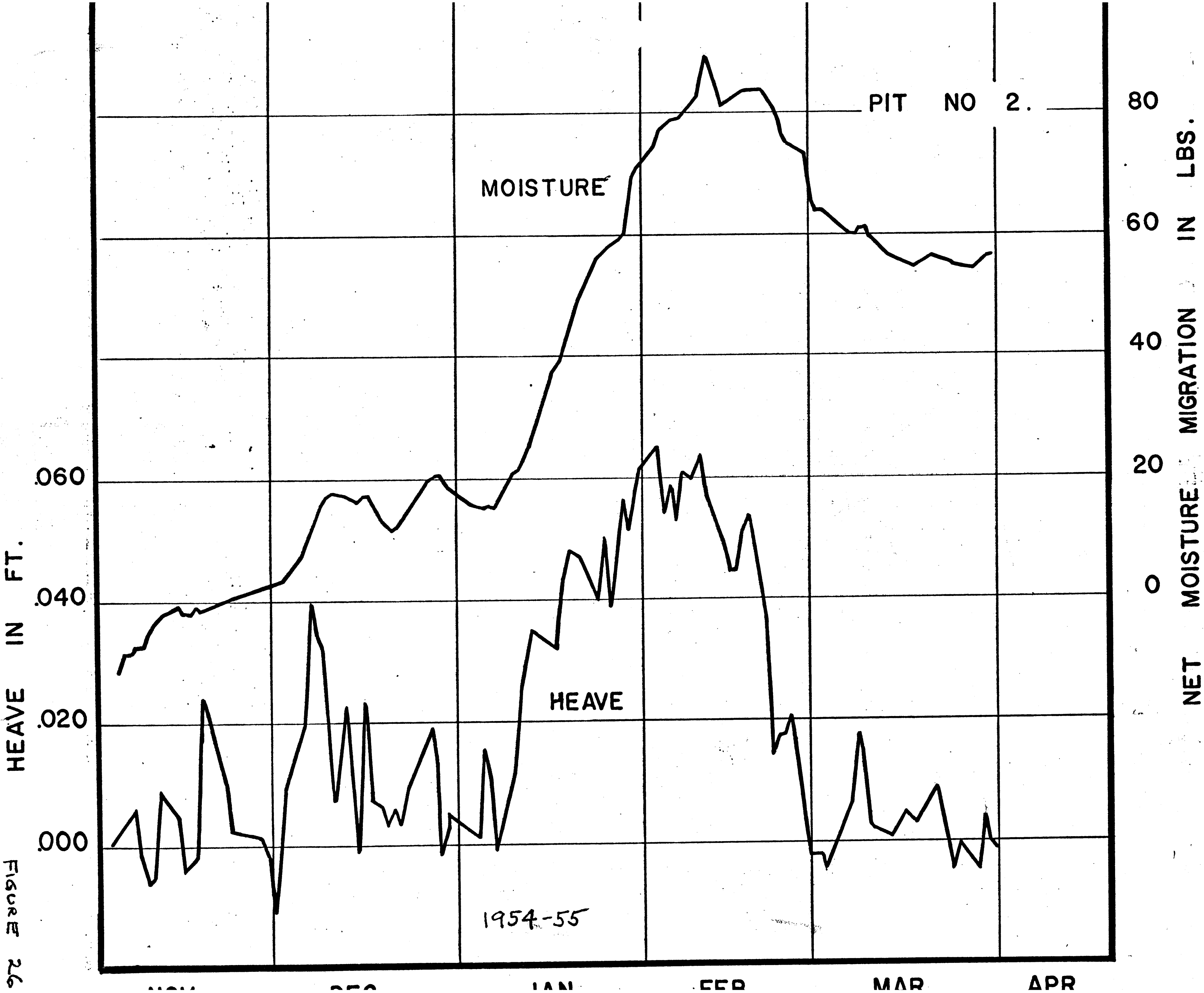

PIT NO 2.
MOISTURE
HEAVE
1954-55
HEAVE IN FT.
.060
.040
.020
.000
NET MOISTURE MIGRATION IN LBS.
80
60
40
20
0
NOV
DEC
JAN
FEB
MAR
APR

FIGURE 26

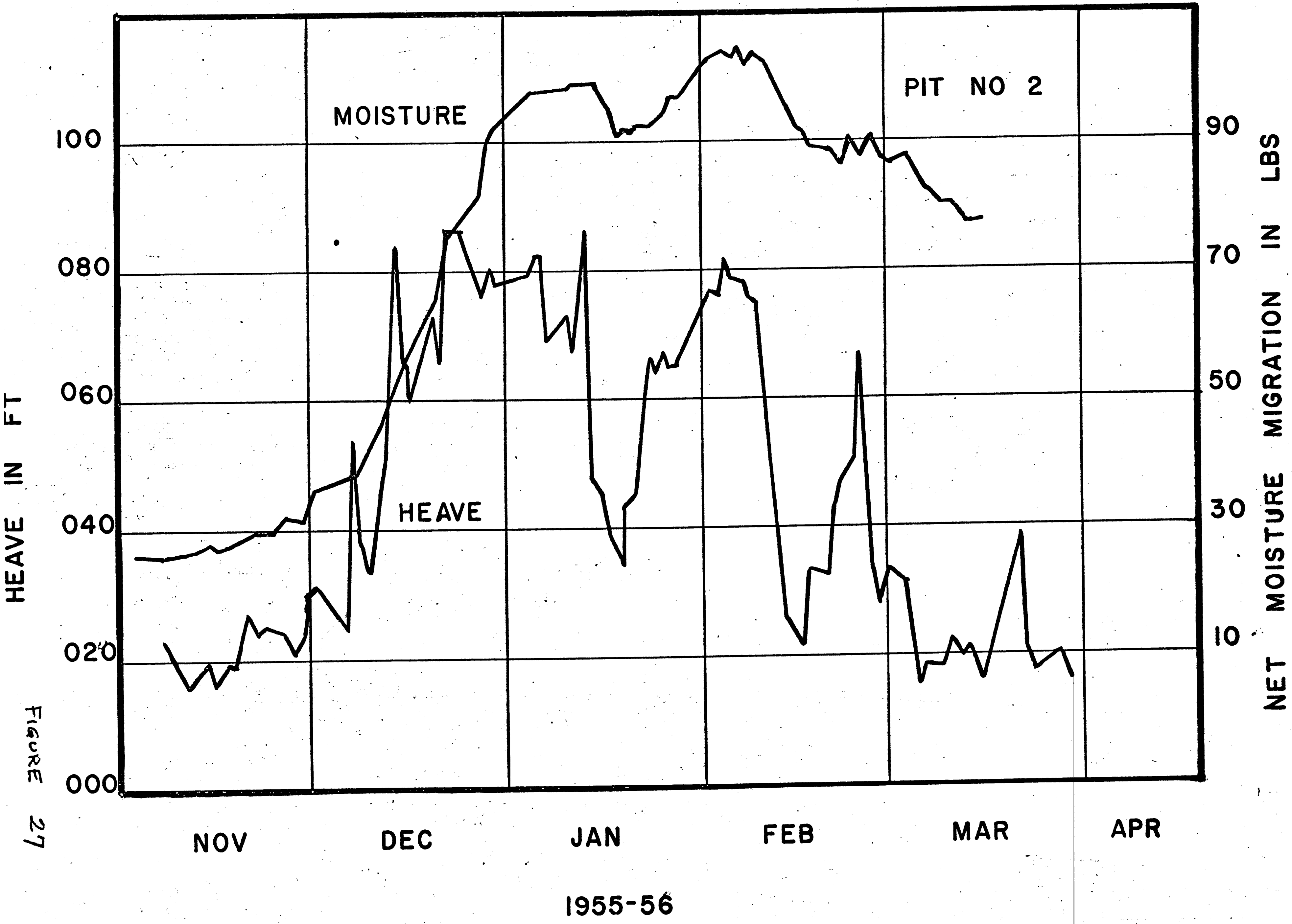

PIT NO 2
MOISTURE
HEAVE
HEAVE IN FT
100
080
060
040
020
000
NET MOISTURE MIGRATION IN LBS
90
70
50
30
10
NOV
DEC
JAN
FEB
MAR
APR
1955-56

FIGURE 27

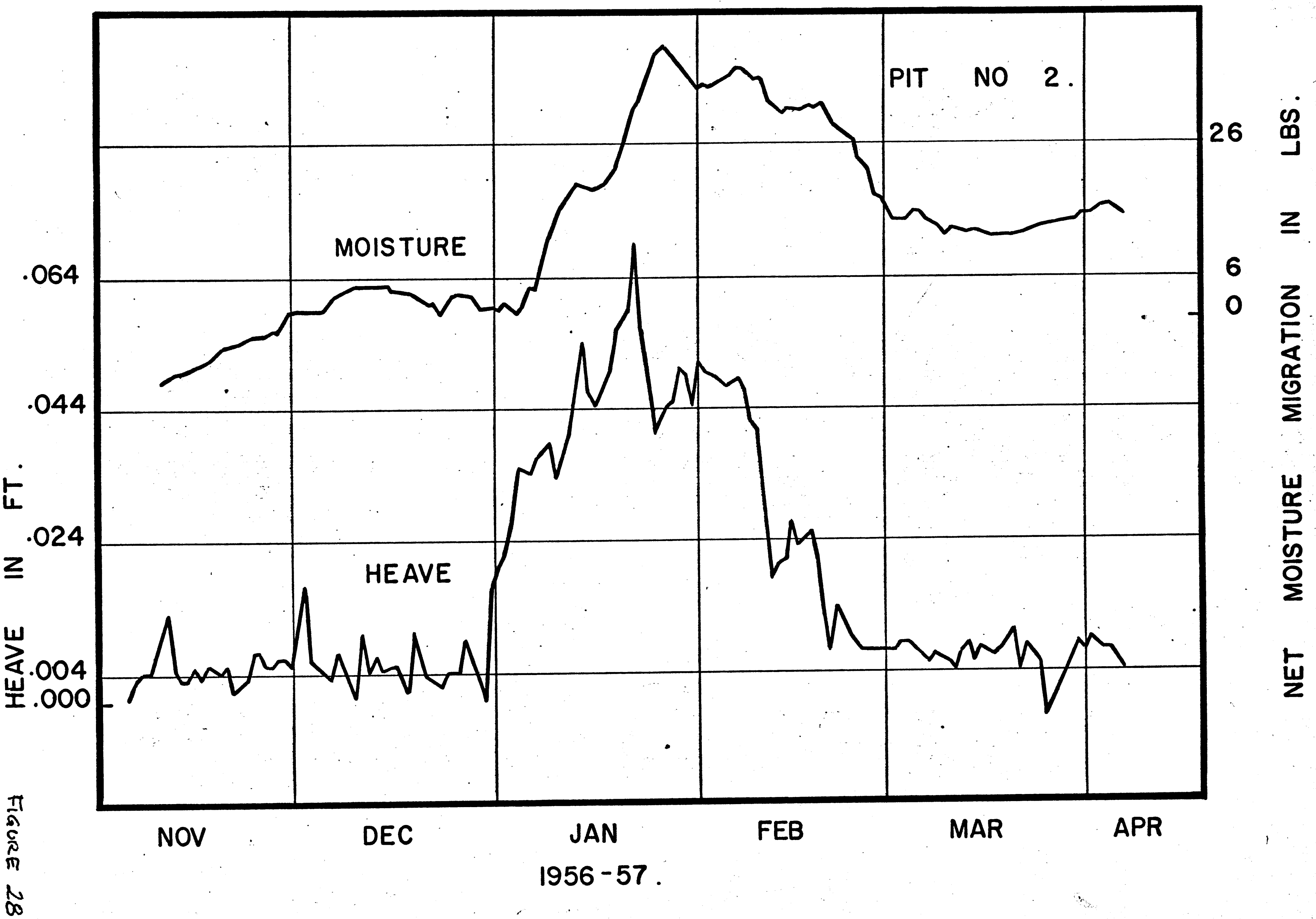

PIT NO 2.
MOISTURE
HEAVE
HEAVE IN FT.
·064
·044
·024
·004
.000
NET MOISTURE MIGRATION IN LBS.
26
6
0
NOV
DEC
JAN
FEB
MAR
APR
1956-57.

FIGURE 28

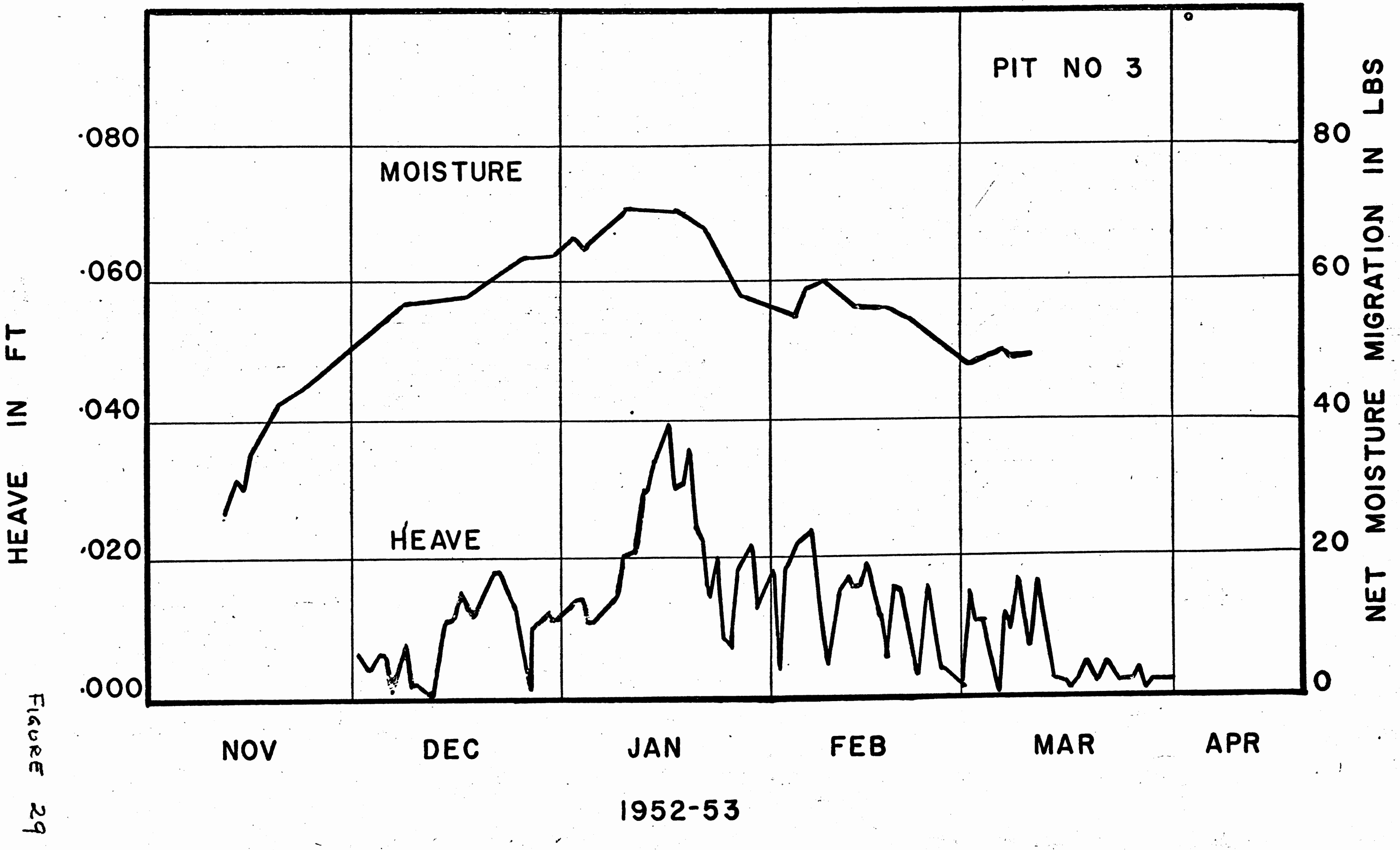

PIT NO 3
MOISTURE
HEAVE
HEAVE IN FT
·080
·060
·040
·020
·000
NET MOISTURE MIGRATION IN LBS
80
60
40
20
0
NOV
DEC
JAN
FEB
MAR
APR
1952-53

FIGURE 29

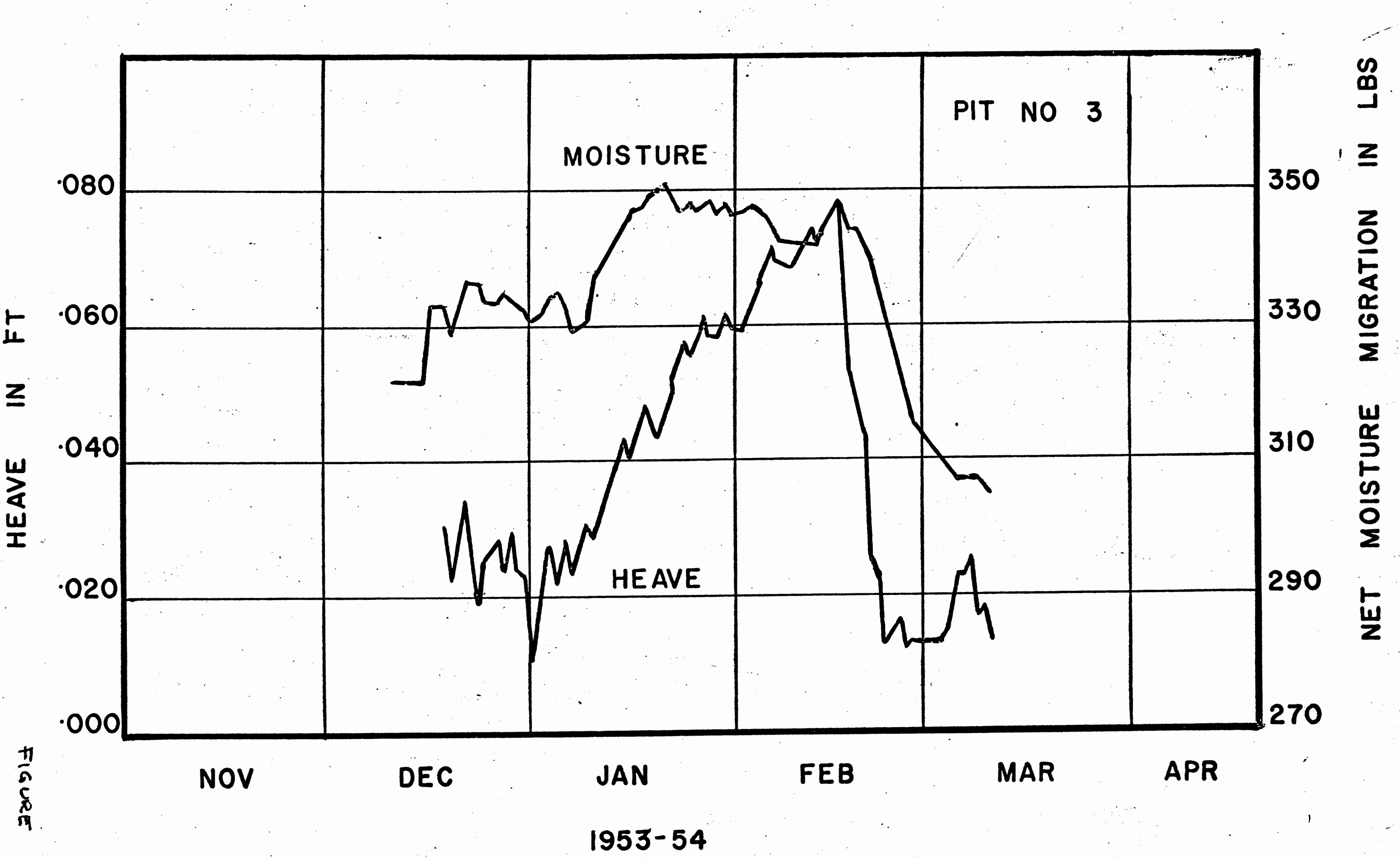

PIT NO 3
MOISTURE
HEAVE
HEAVE IN FT
·080
·060
·040
·020
·000
NET MOISTURE MIGRATION IN LBS
350
330
310
290
270
NOV
DEC
JAN
FEB
MAR
APR
1953-54

FIGURE 30

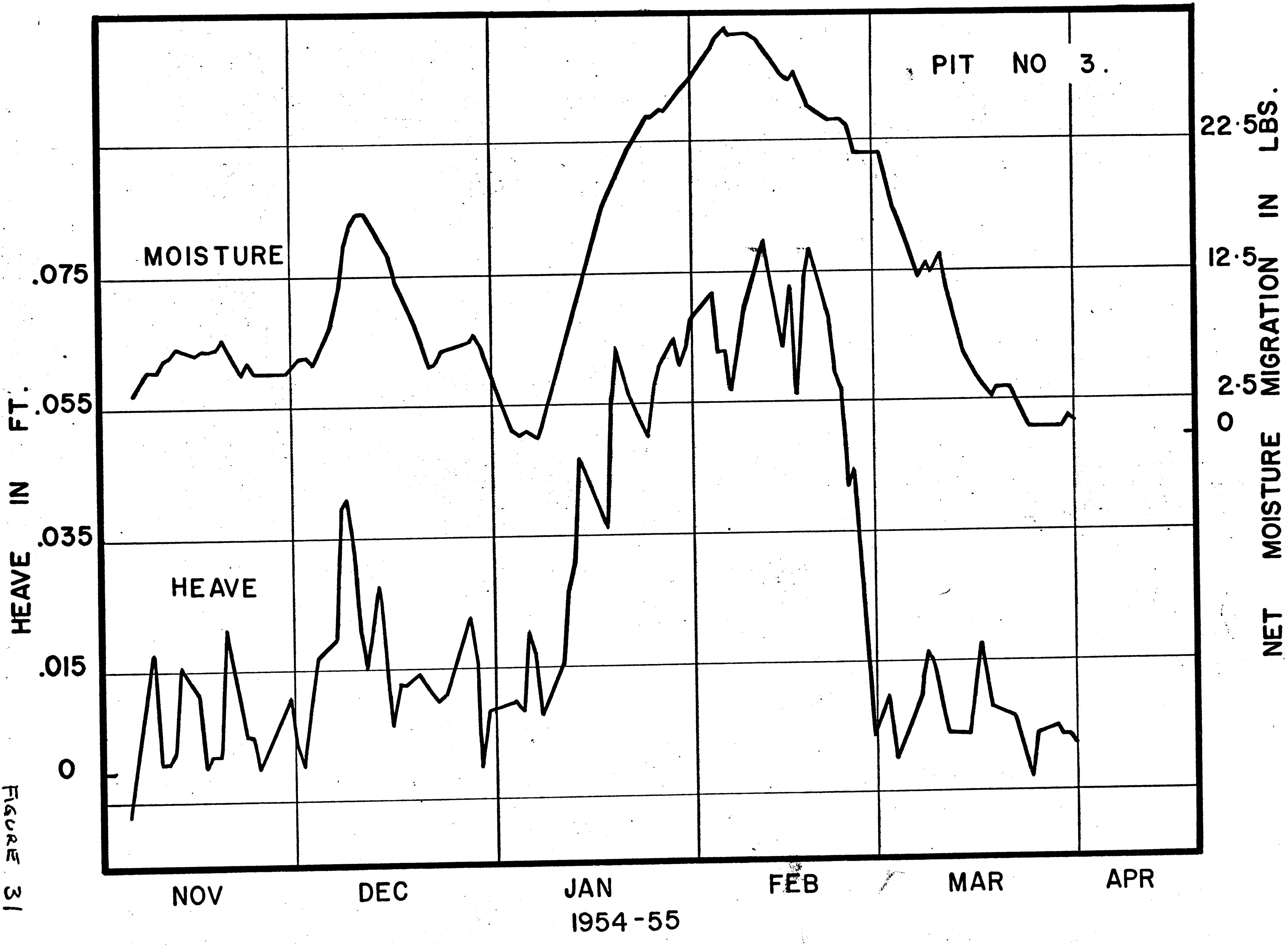

PIT NO 3.
MOISTURE
HEAVE
HEAVE IN FT.
.075
.055
.035
.015
0
NET MOISTURE MIGRATION IN LBS.
22·5
12·5
2·5
0
NOV
DEC
JAN
FEB
MAR
APR
1954-55

FIGURE 31

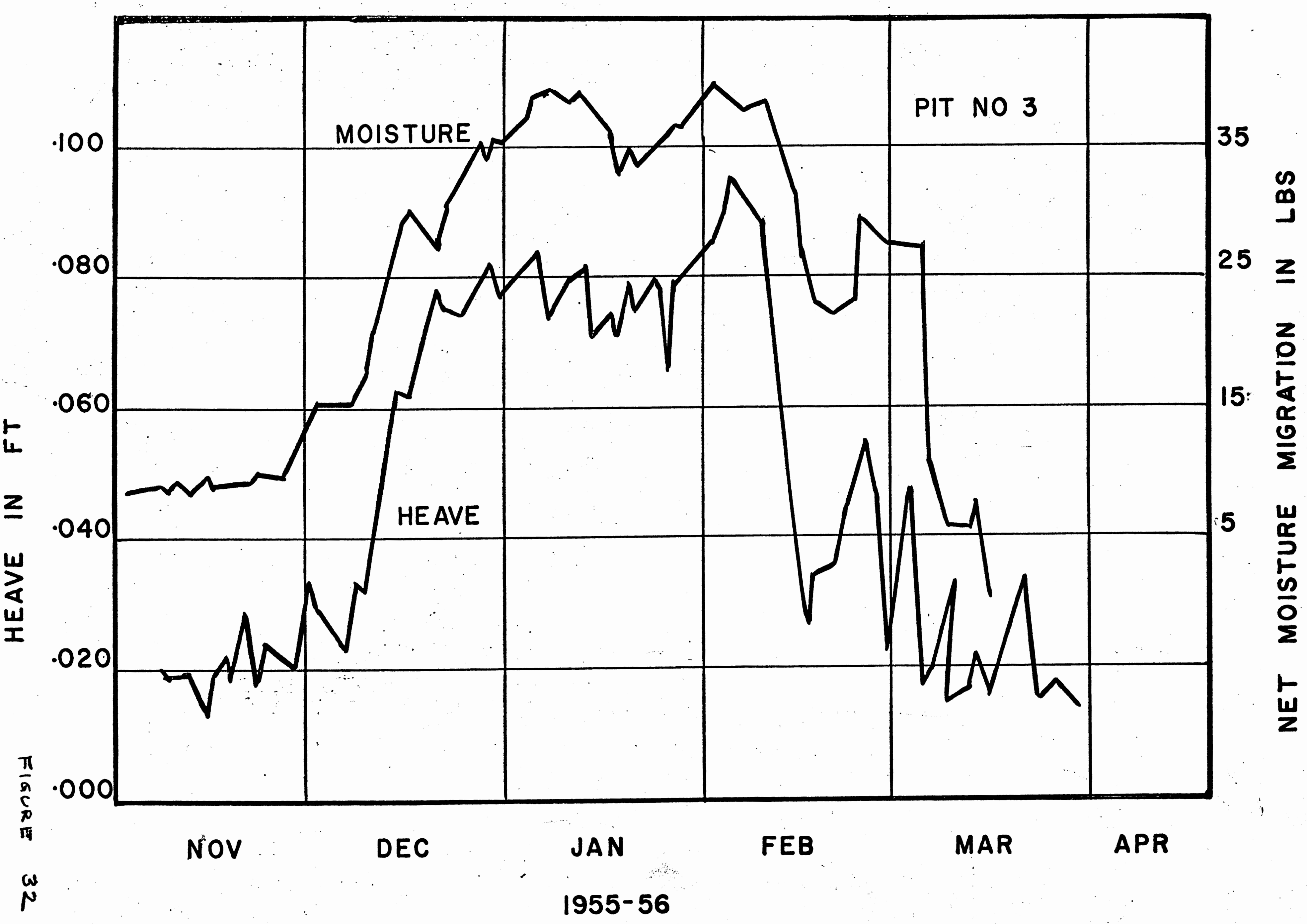

PIT NO 3
MOISTURE
HEAVE
HEAVE IN FT
·100
·080
·060
·040
·020
·000
NET MOISTURE MIGRATION IN LBS
35
25
15
5
NOV
DEC
JAN
FEB
MAR
APR
1955-56

FIGURE 32

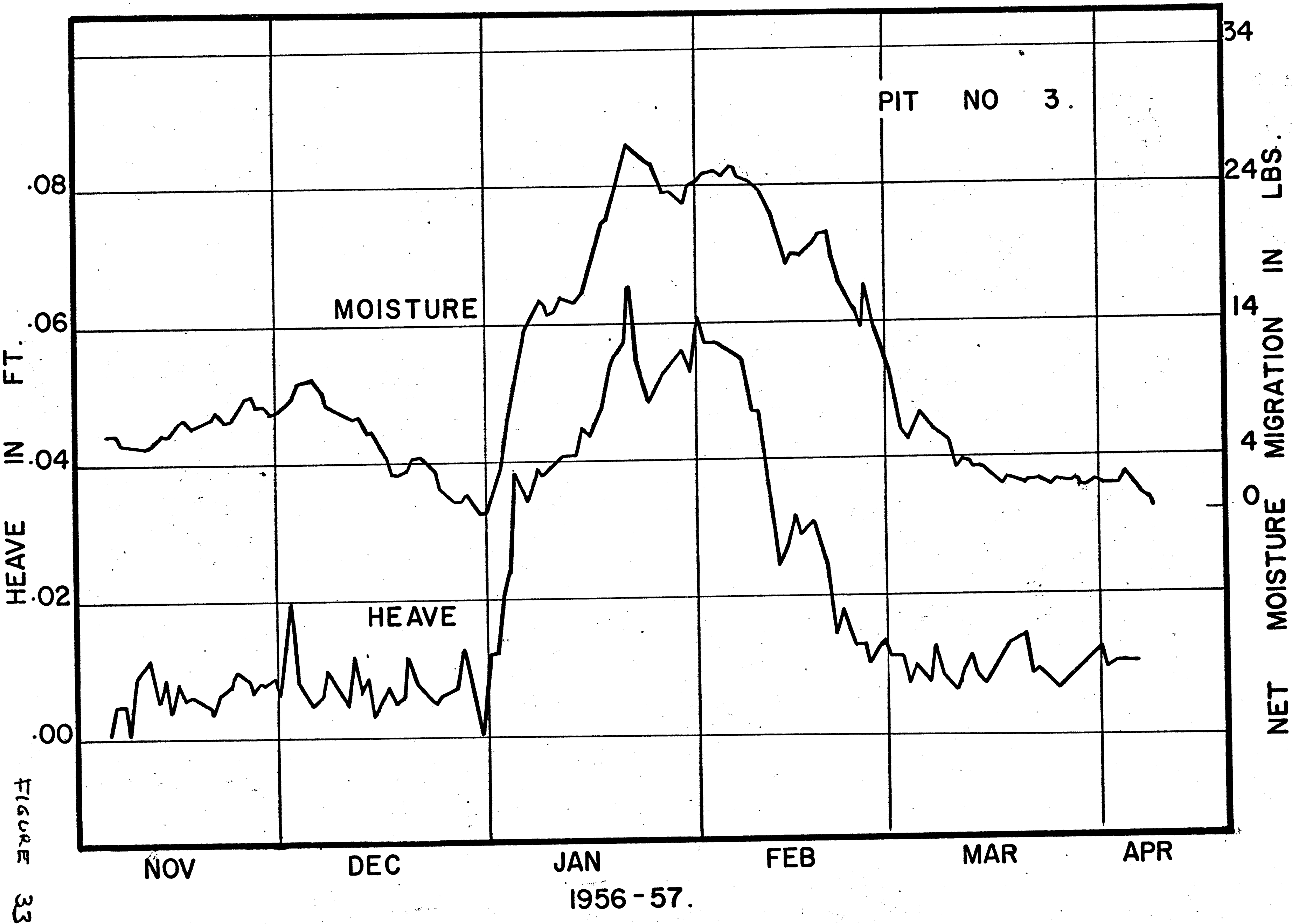

PIT NO 3.
MOISTURE
HEAVE
HEAVE IN FT.
·08
·06
·04
·02
·00
NET MOISTURE MIGRATION IN LBS.
34
24
14
4
0
NOV
DEC
JAN
FEB
MAR
APR
1956 - 57.

FIGURE 33

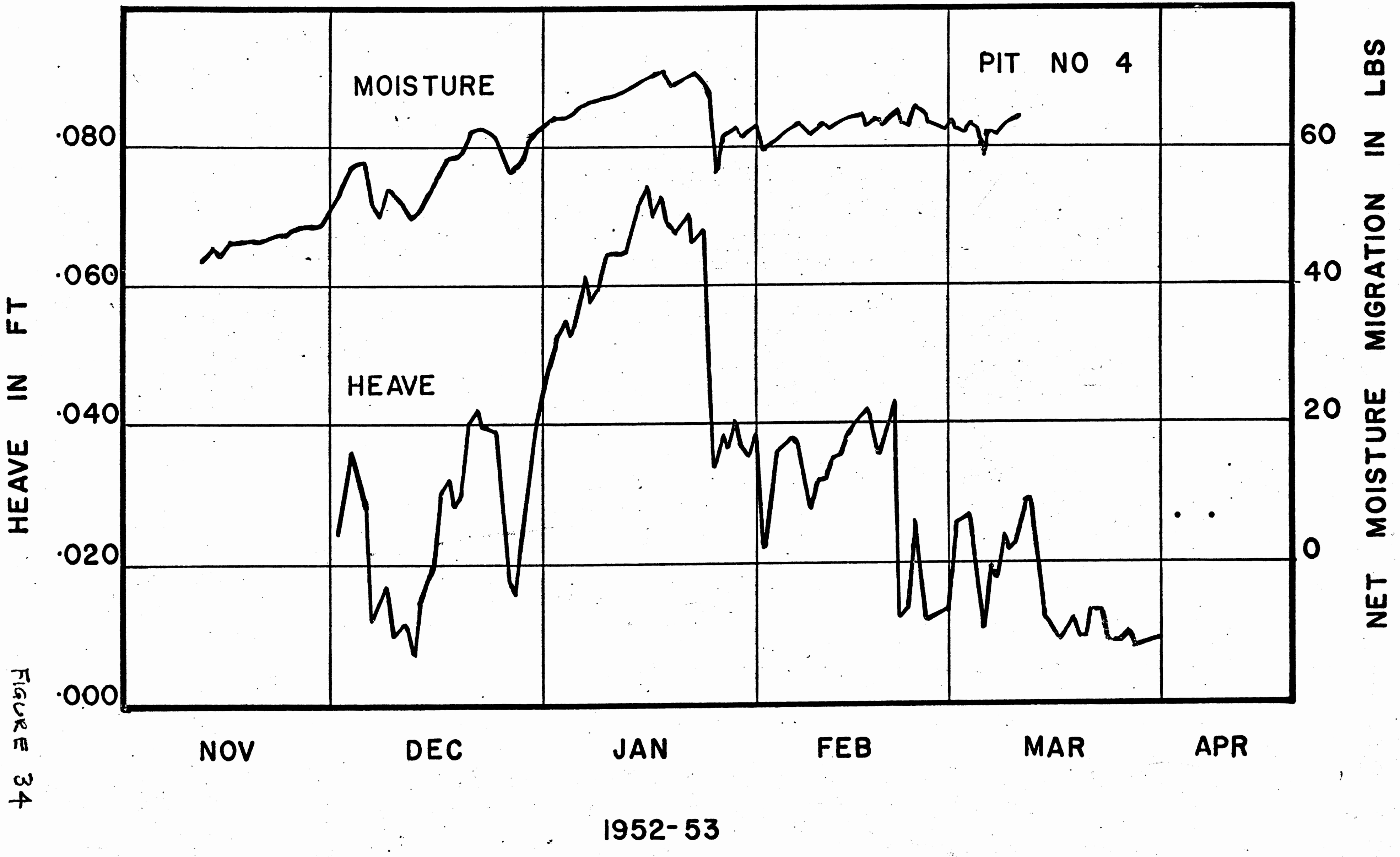

MOISTURE
PIT NO 4
HEAVE
·080
·060
·040
·020
·000
HEAVE IN FT
60
40
20
0
NET MOISTURE MIGRATION IN LBS
NOV
DEC
JAN
FEB
MAR
APR
1952-53

FIGURE 34

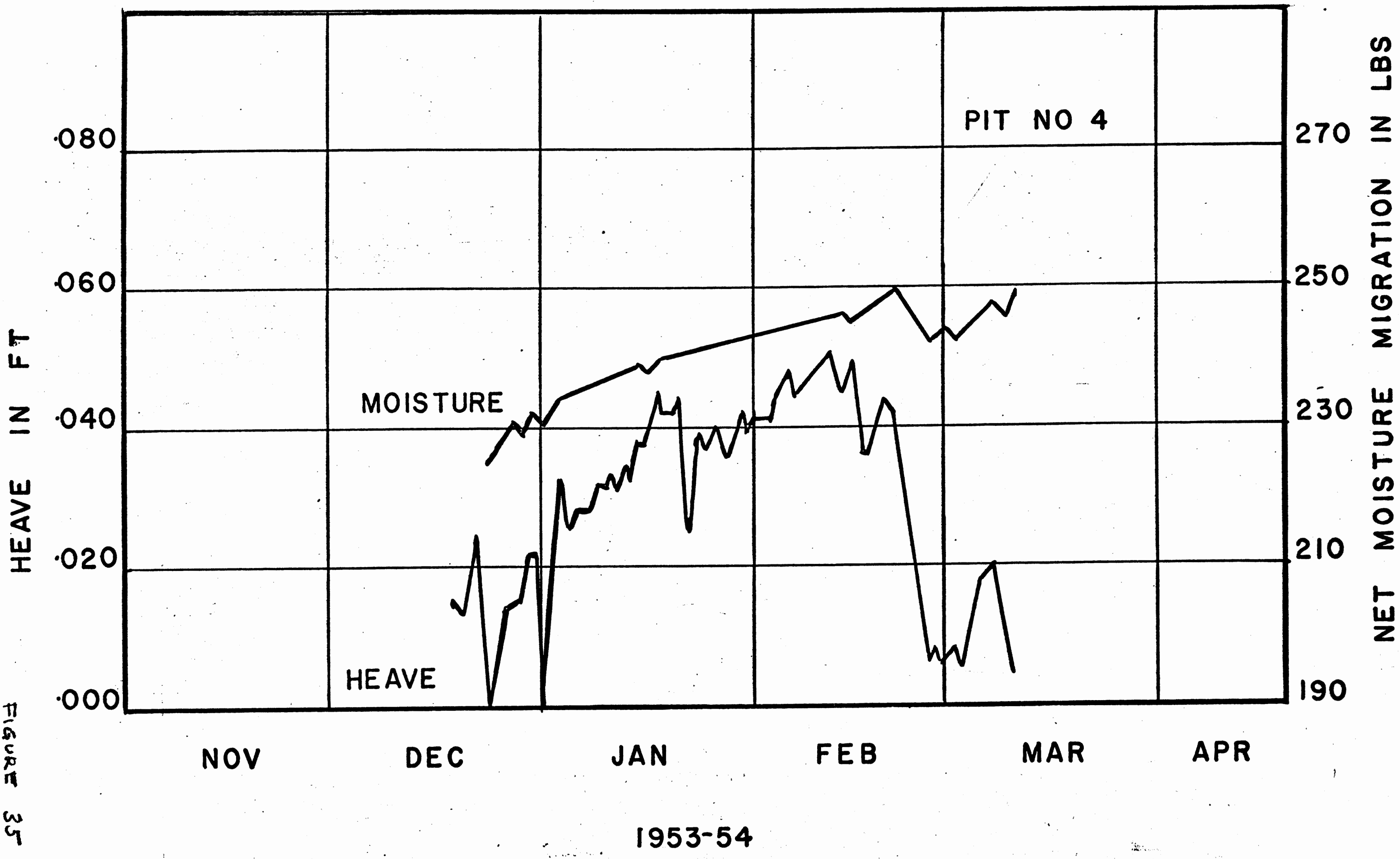

PIT NO 4
MOISTURE
HEAVE
HEAVE IN FT
·080
·060
·040
·020
·000
NET MOISTURE MIGRATION IN LBS
270
250
230
210
190
NOV
DEC
JAN
FEB
MAR
APR
1953-54

FIGURE 35

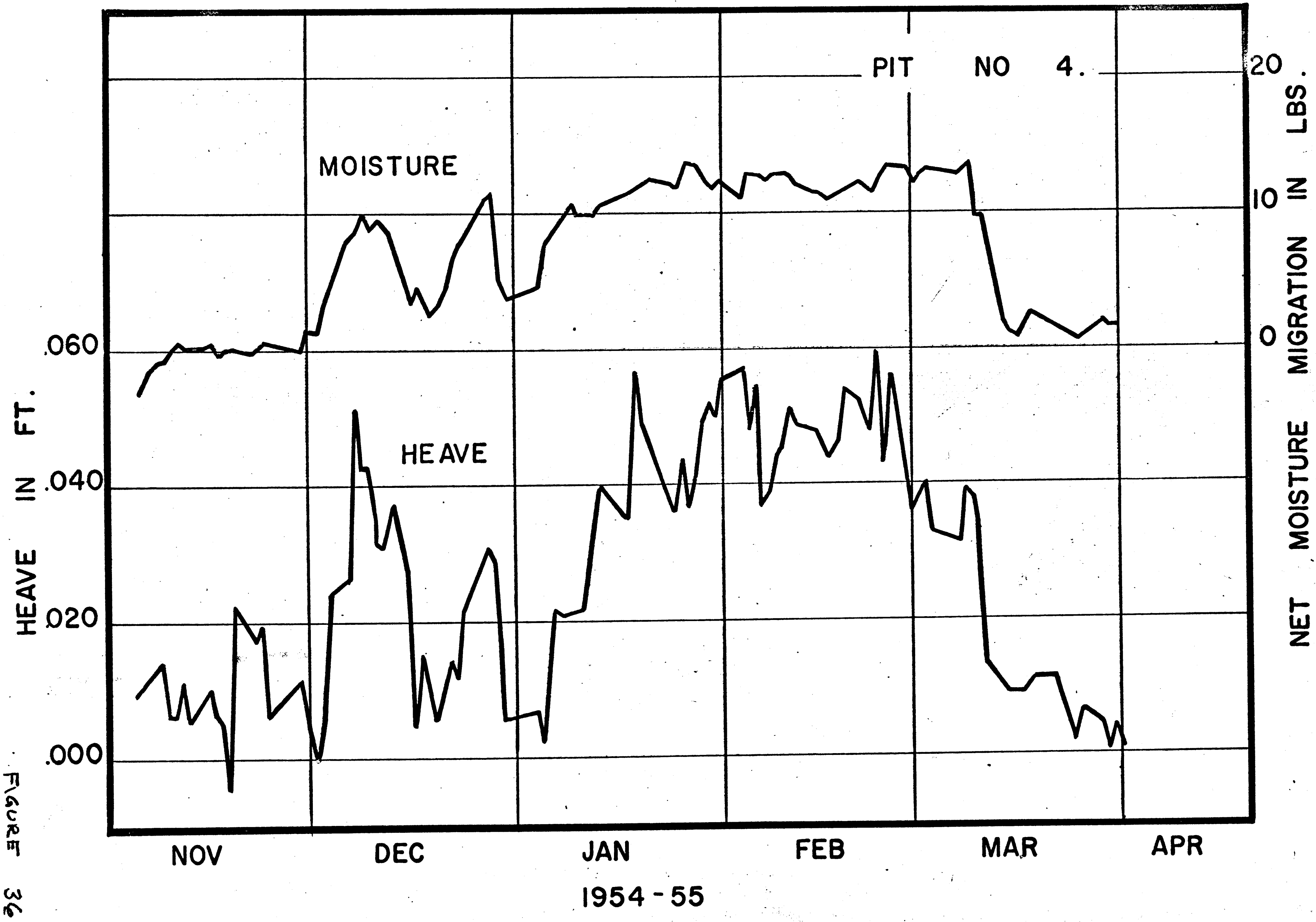

PIT NO 4.
MOISTURE
HEAVE
HEAVE IN FT.
.060
.040
.020
.000
NET MOISTURE MIGRATION IN LBS.
20
10
0
NOV
DEC
JAN
FEB
MAR
APR
1954 - 55

FIGURE 36

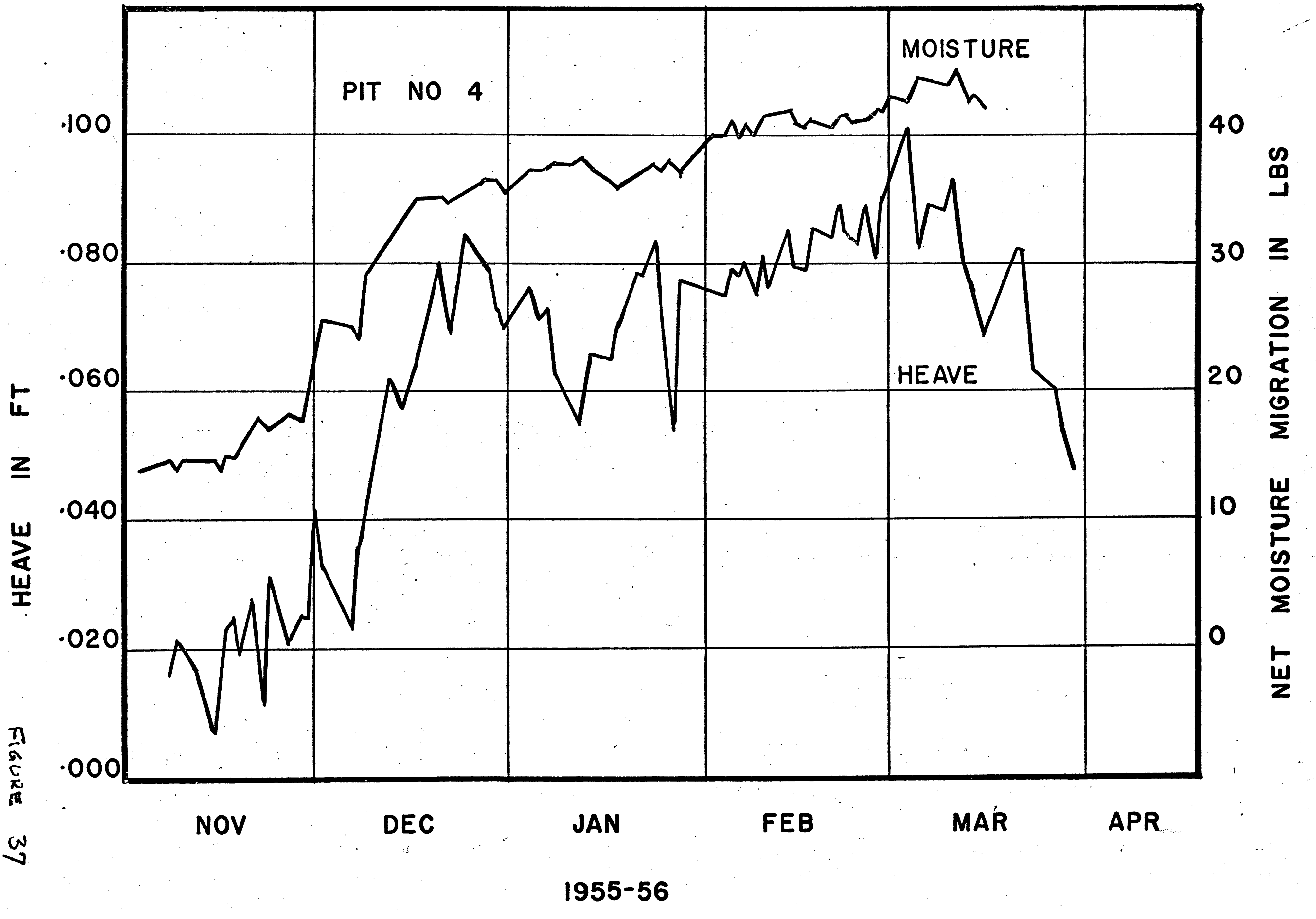

PIT NO 4
MOISTURE
HEAVE
HEAVE IN FT
·000
·020
·040
·060
·080
·100
NET MOISTURE MIGRATION IN LBS
0
10
20
30
40
NOV
DEC
JAN
FEB
MAR
APR
1955-56

FIGURE 37

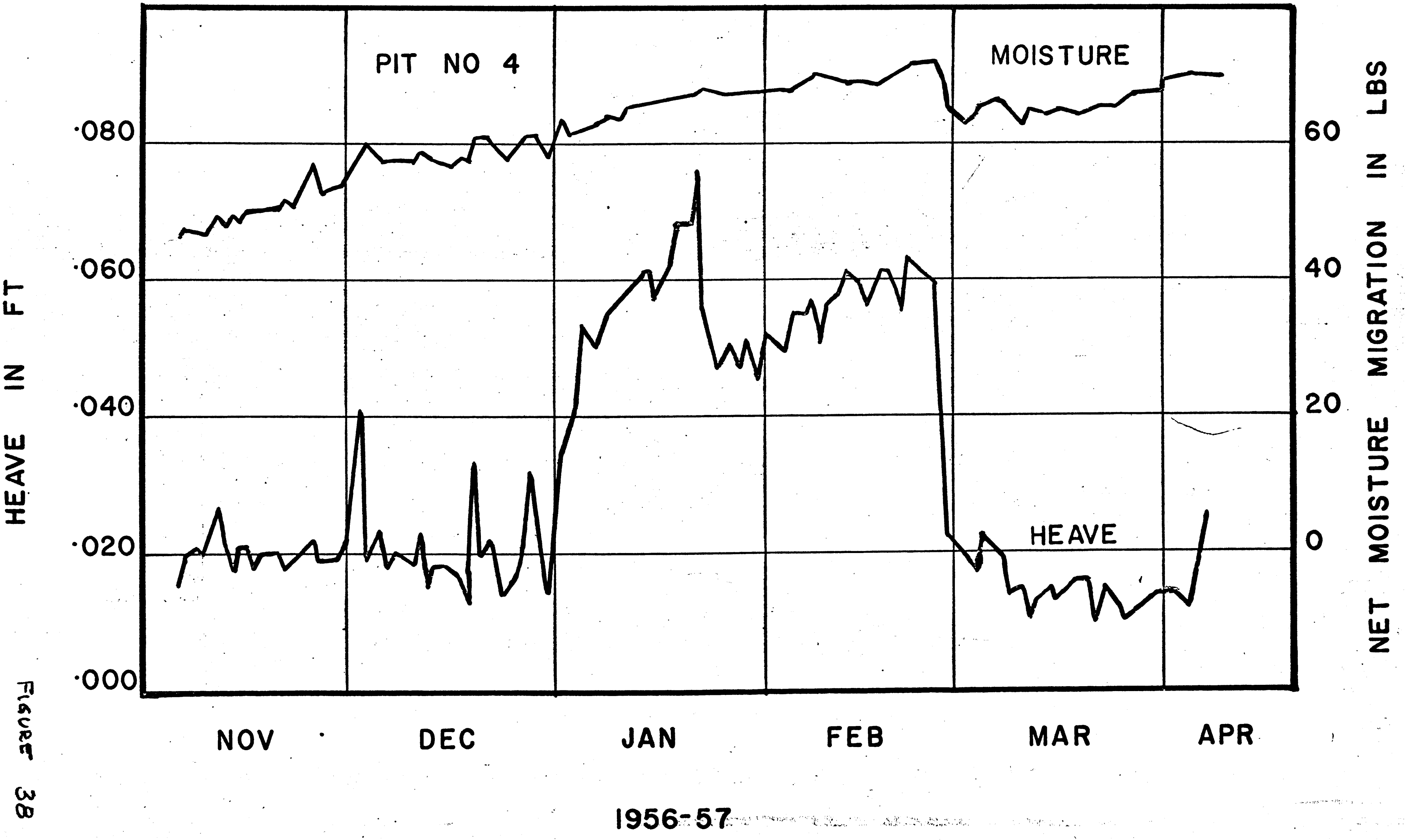

PIT NO 4
MOISTURE
HEAVE
HEAVE IN FT
·080
·060
·040
·020
·000
NET MOISTURE MIGRATION IN LBS
60
40
20
0
NOV
DEC
JAN
FEB
MAR
APR
1956-57

FIGURE 38

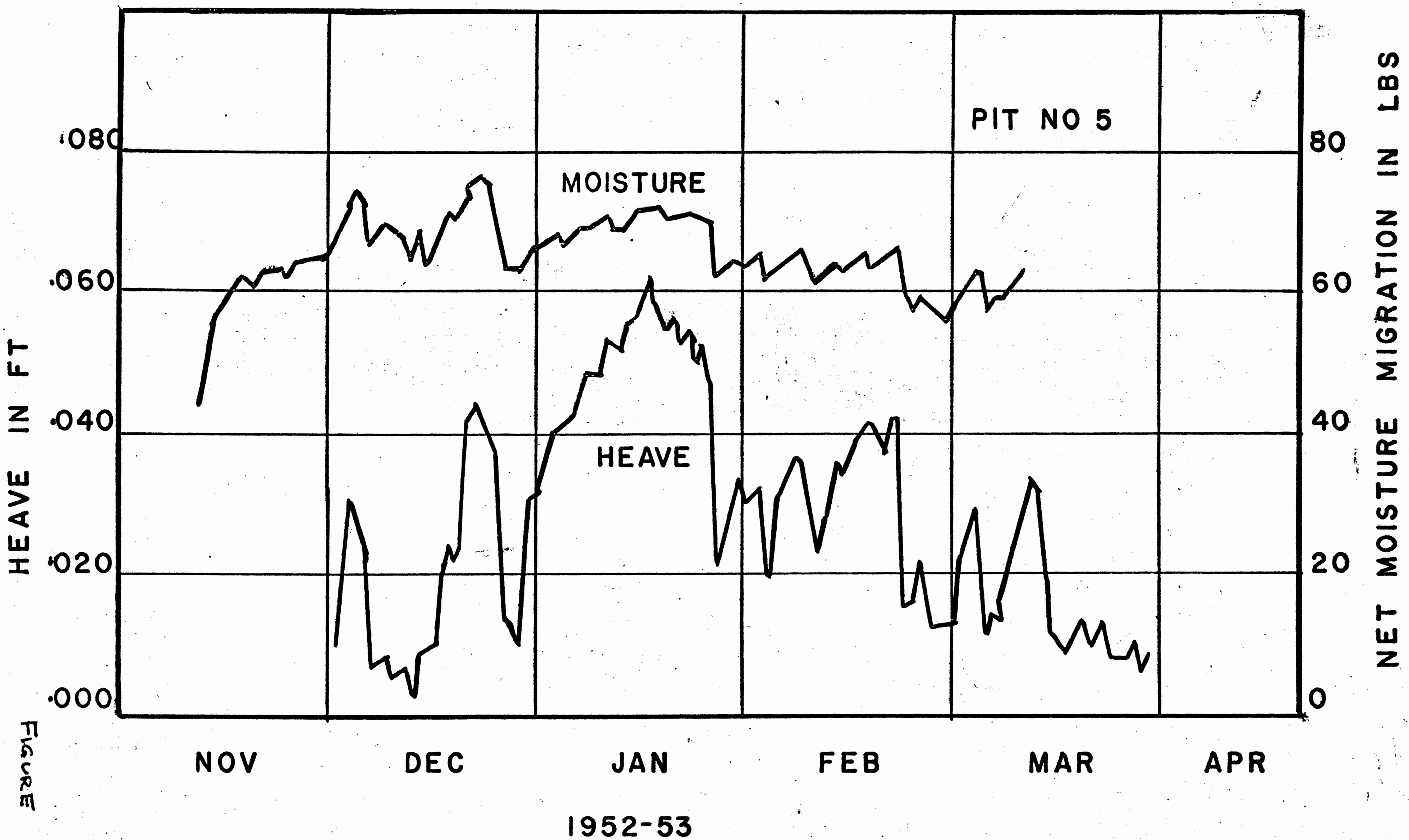

PIT NO 5
MOISTURE
HEAVE
HEAVE IN FT
·080
·060
·040
·020
·000
NET MOISTURE MIGRATION IN LBS
80
60
40
20
0
NOV
DEC
JAN
FEB
MAR
APR
1952-53

FIGURE 39

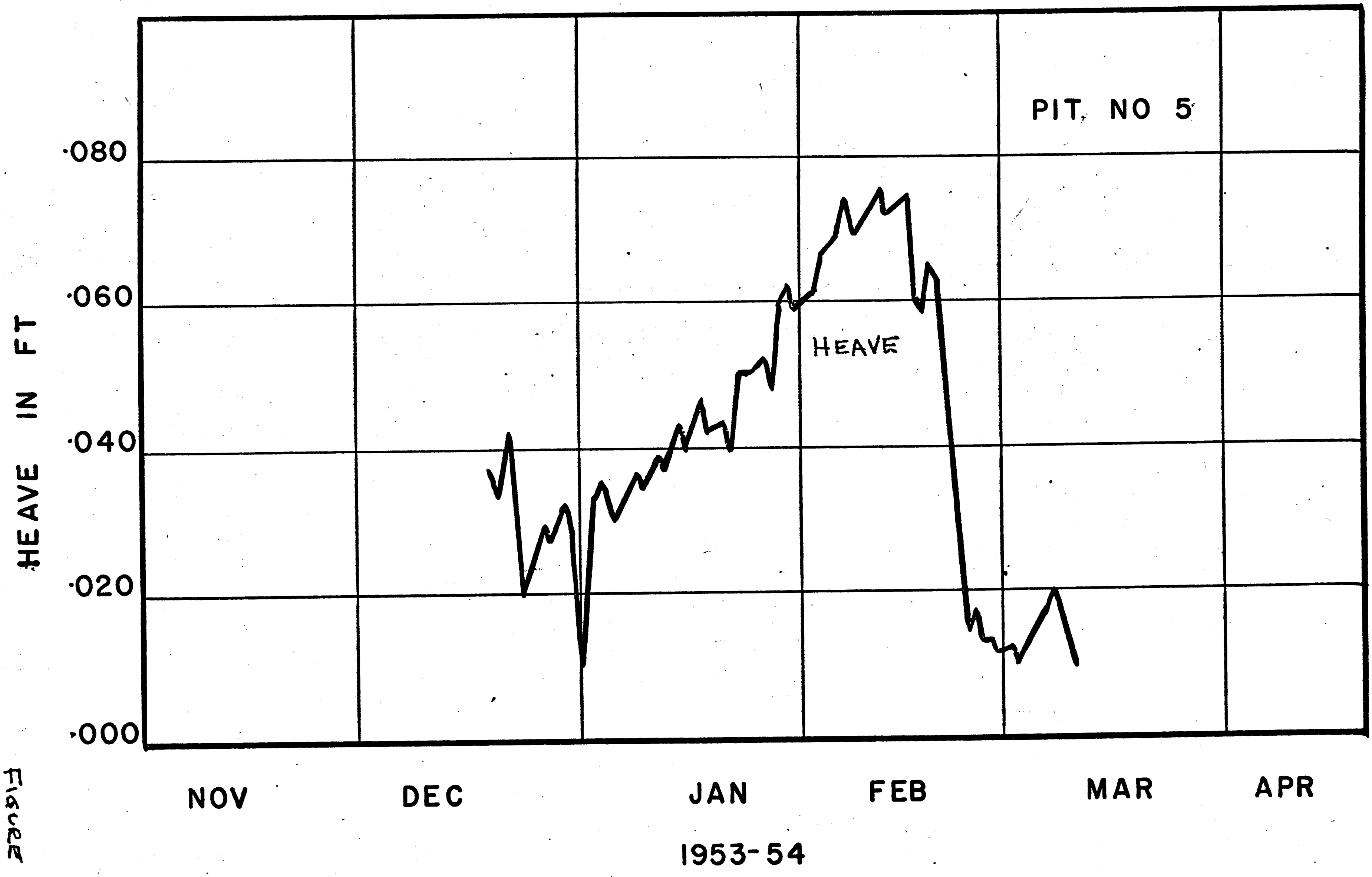

PIT NO 5
HEAVE
HEAVE IN FT
·080
·060
·040
·020
·000
NOV
DEC
JAN
FEB
MAR
APR
1953-54

FIGURE 40

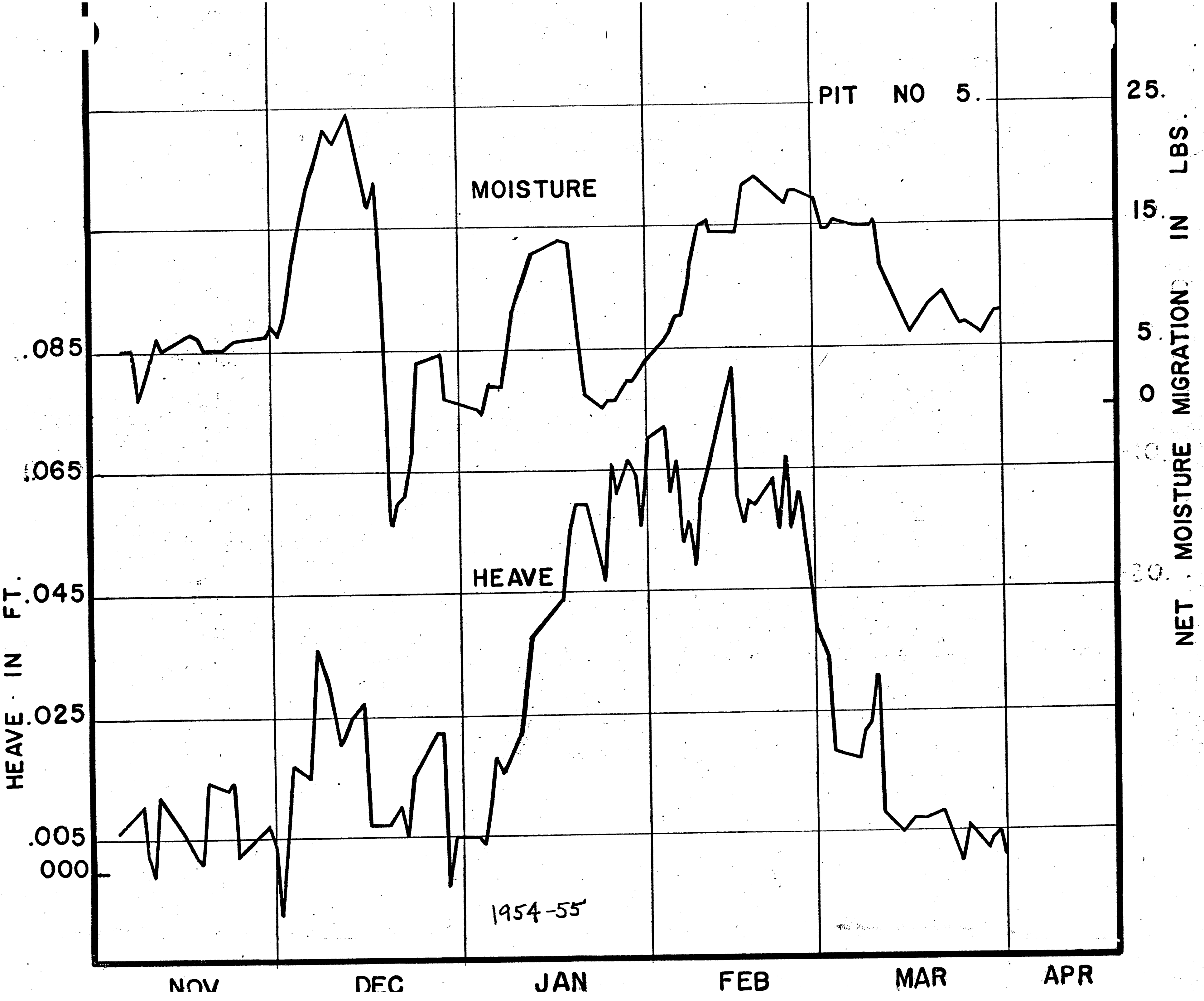

PIT NO 5.
MOISTURE
HEAVE
1954-55
HEAVE IN FT.
.085
.065
.045
.025
.005
.000
NET MOISTURE MIGRATION IN LBS.
25.
15.
5.
0
10.
20.
NOV
DEC
JAN
FEB
MAR
APR

FIGURE 41

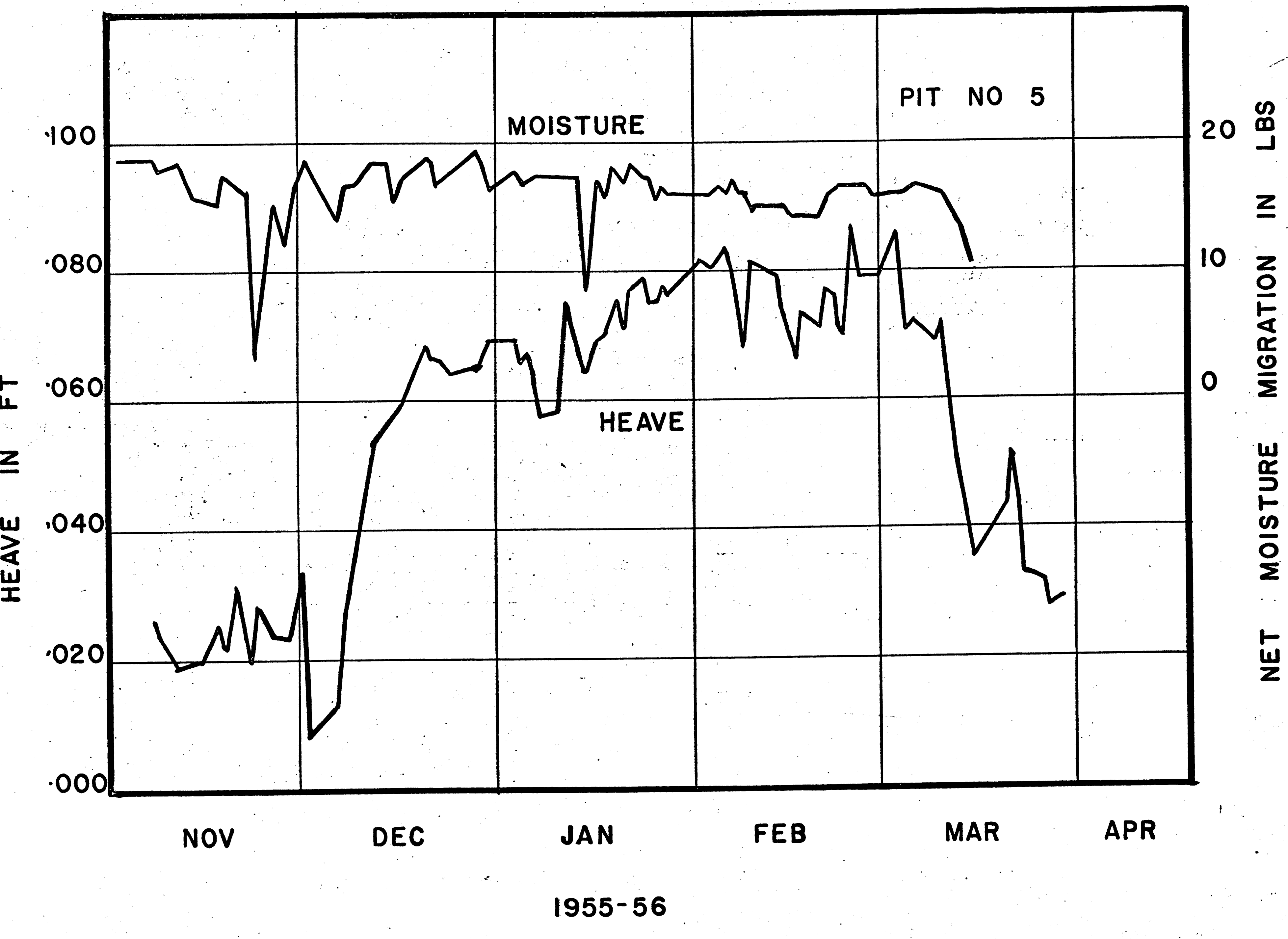

PIT NO 5
MOISTURE
HEAVE
·100
·080
·060
·040
·020
·000
HEAVE IN FT
20
10
0
NET MOISTURE MIGRATION IN LBS
NOV
DEC
JAN
FEB
MAR
APR
1955-56

FIGURE 42

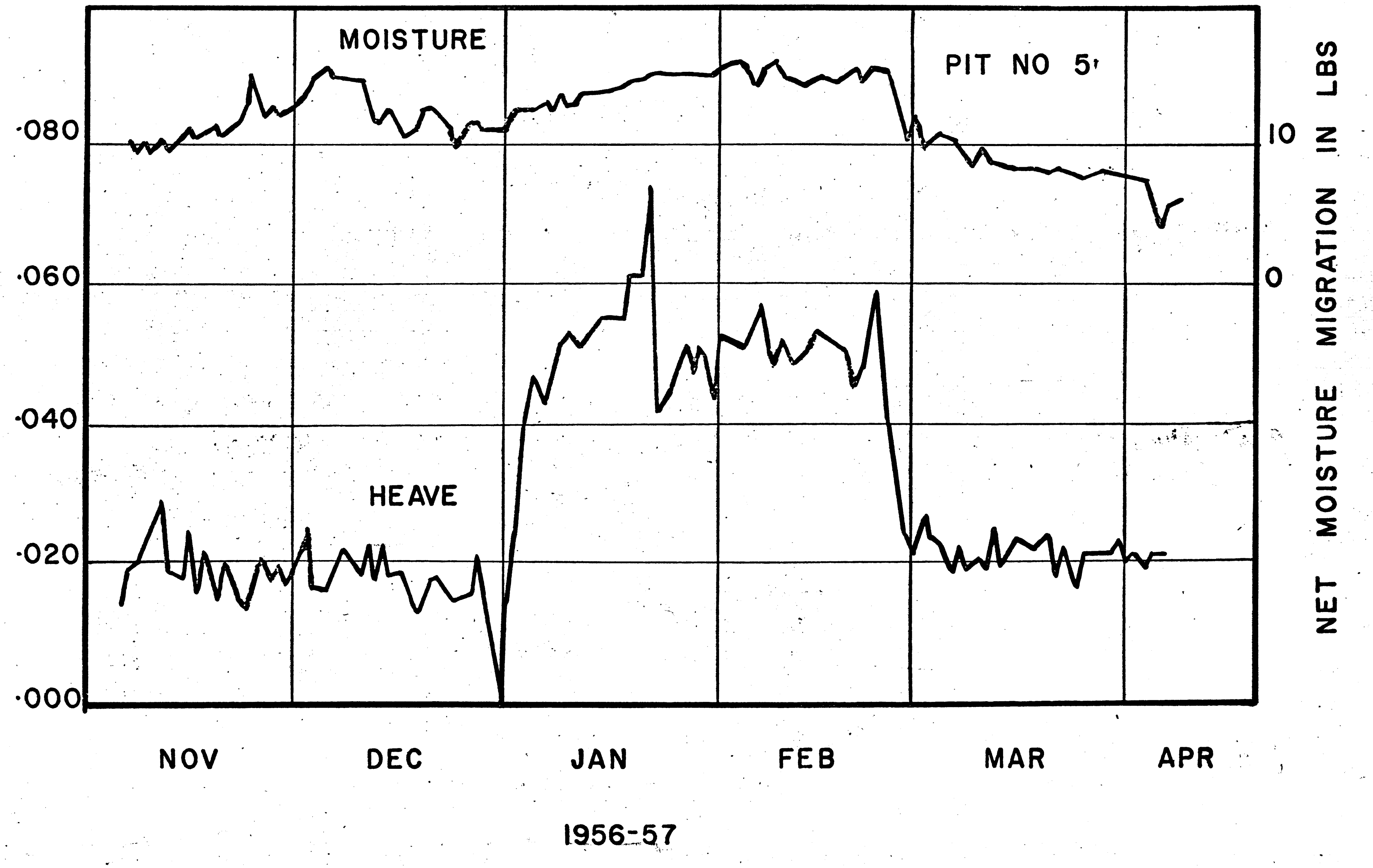

MOISTURE
PIT NO 5'
HEAVE
HEAVE IN FT
·080
·060
·040
·020
·000
NET MOISTURE MIGRATION IN LBS
10
0
NOV
DEC
JAN
FEB
MAR
APR
1956-57

FIGURE 43

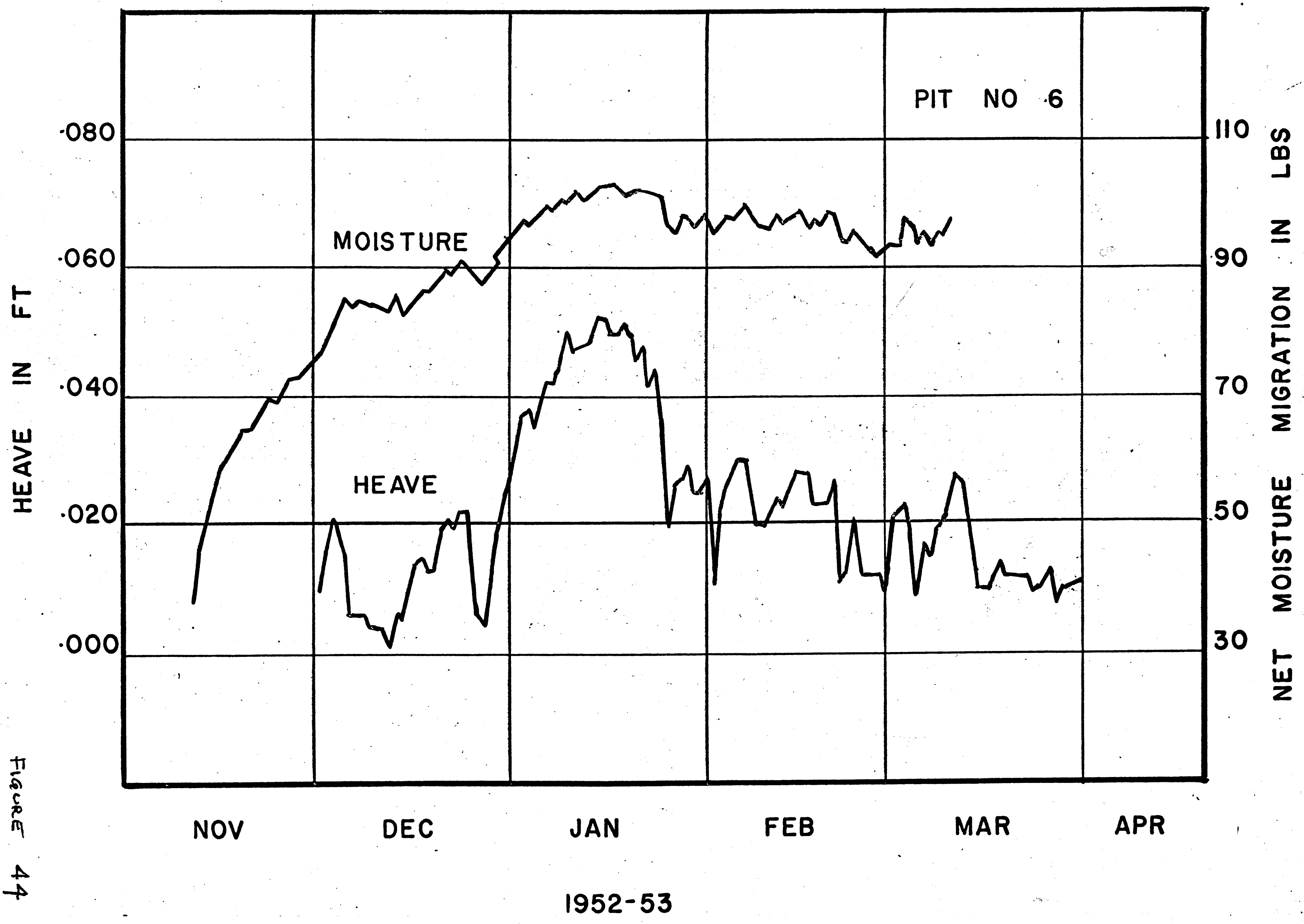

PIT NO 6
MOISTURE
HEAVE
HEAVE IN FT
·080
·060
·040
·020
·000
NET MOISTURE MIGRATION IN LBS
110
90
70
50
30
NOV
DEC
JAN
FEB
MAR
APR
1952-53

FIGURE 44

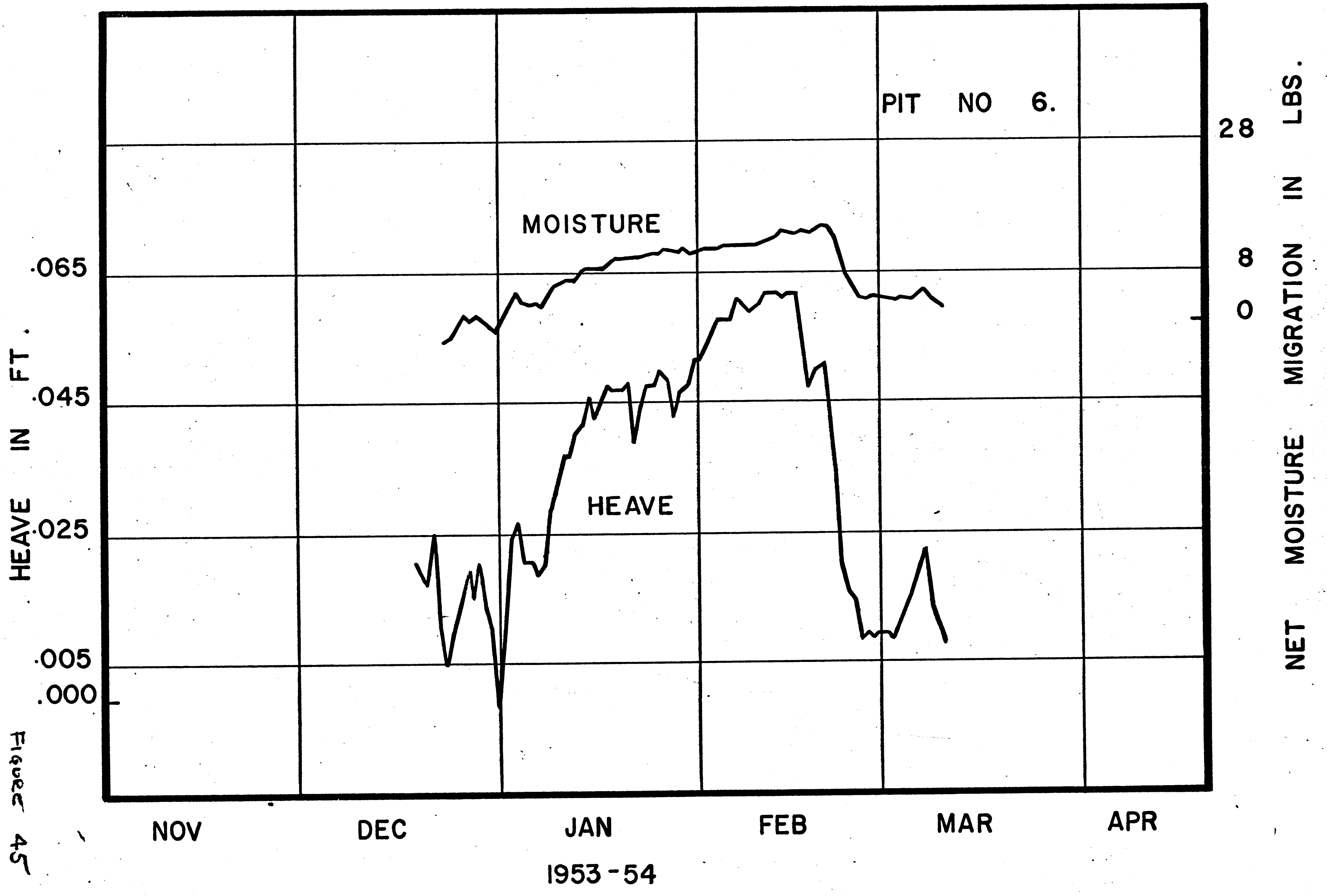

PIT NO 6.
MOISTURE
HEAVE
HEAVE IN FT.
·065
·045
·025
·005
.000
NET MOISTURE MIGRATION IN LBS.
28
8
0
NOV
DEC
JAN
FEB
MAR
APR
1953-54

Figure 45

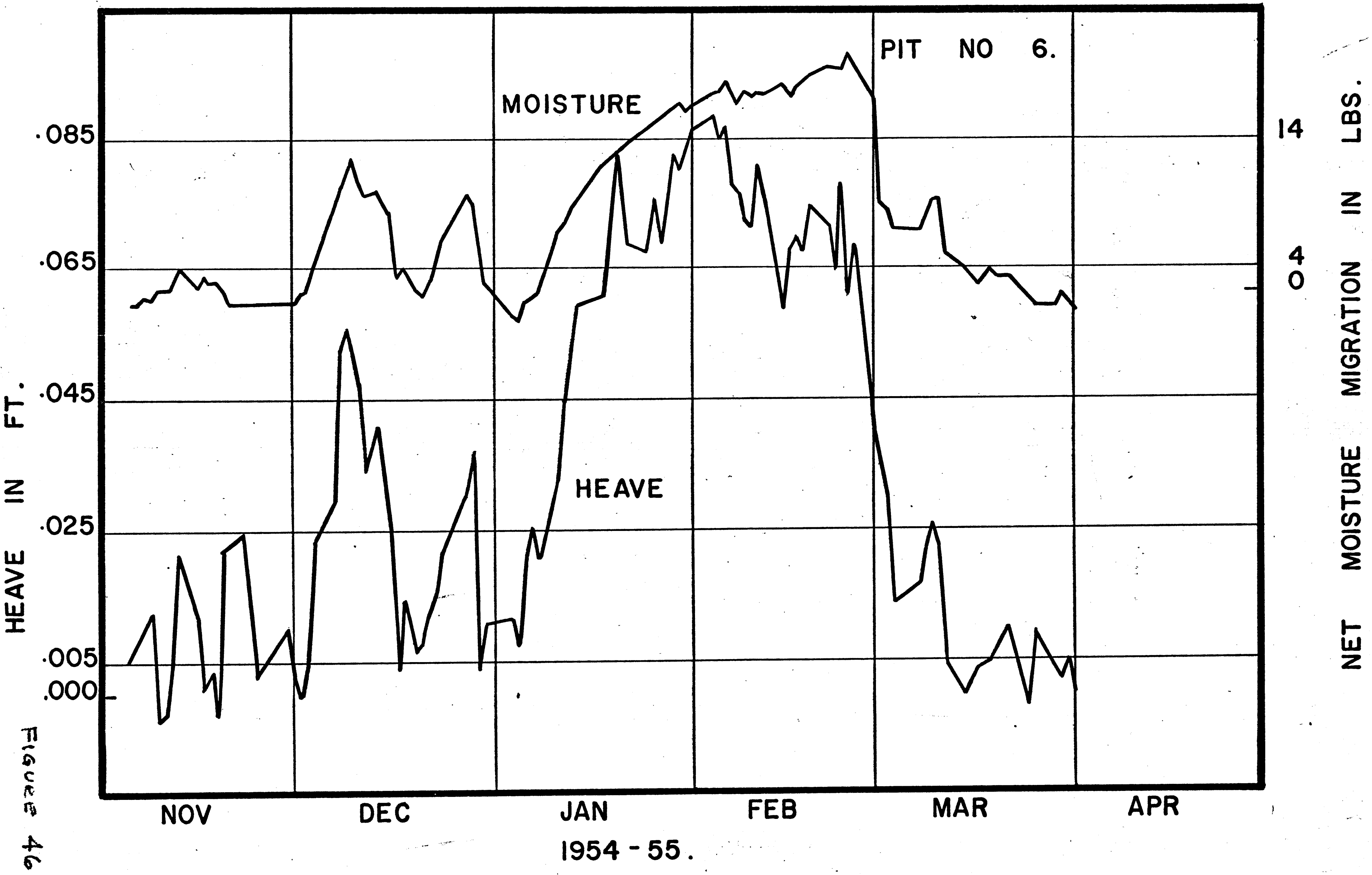

PIT NO 6.
MOISTURE
HEAVE
HEAVE IN FT.
·085
·065
·045
·025
·005
.000
NET MOISTURE MIGRATION IN LBS.
14
4
0
NOV
DEC
JAN
FEB
MAR
APR
1954 - 55.

Figure 46

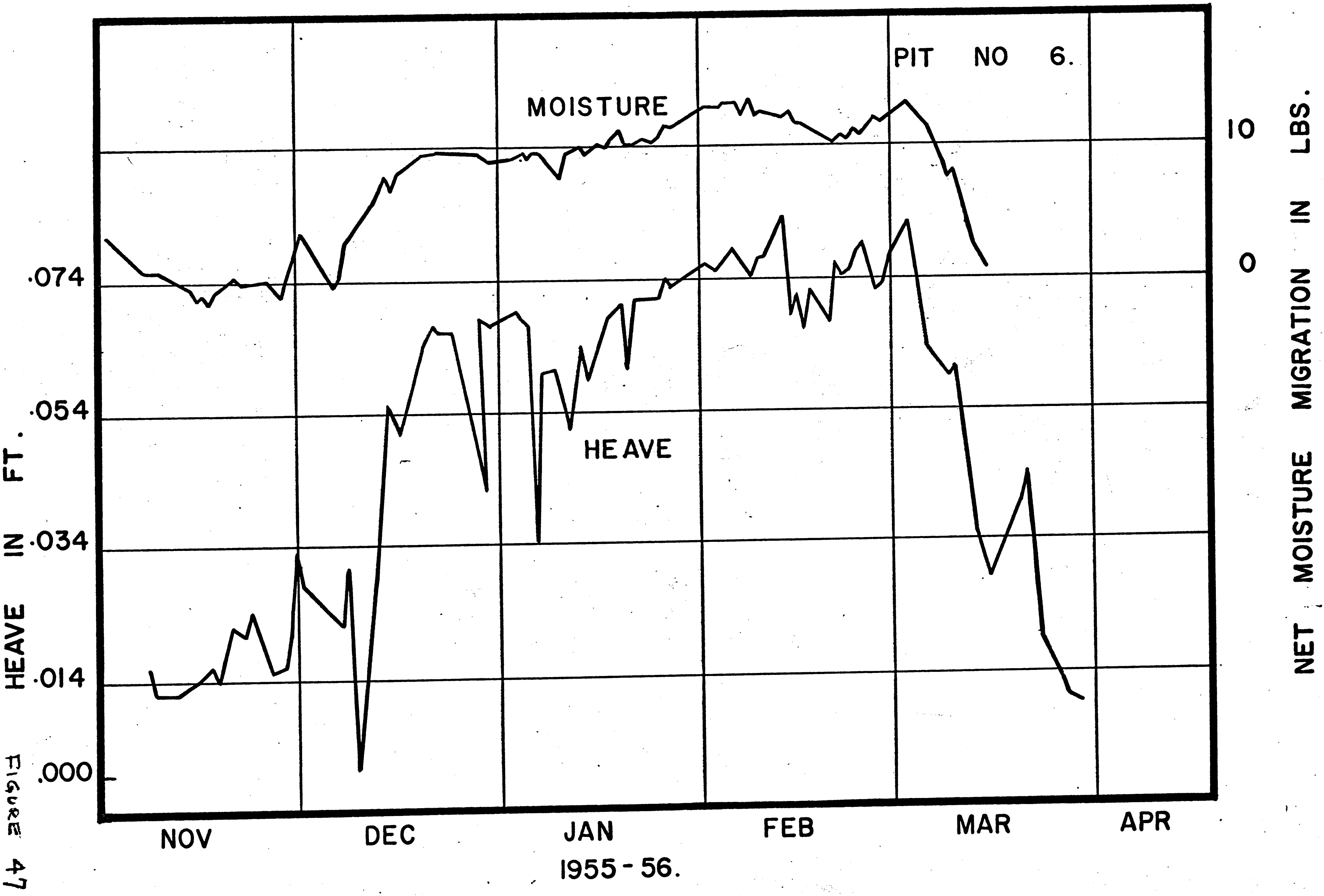

PIT NO 6.
MOISTURE
HEAVE
HEAVE IN FT.
·074
·054
·034
·014
.000
NET MOISTURE MIGRATION IN LBS.
10
0
NOV
DEC
JAN
FEB
MAR
APR
1955 - 56.

FIGURE 47

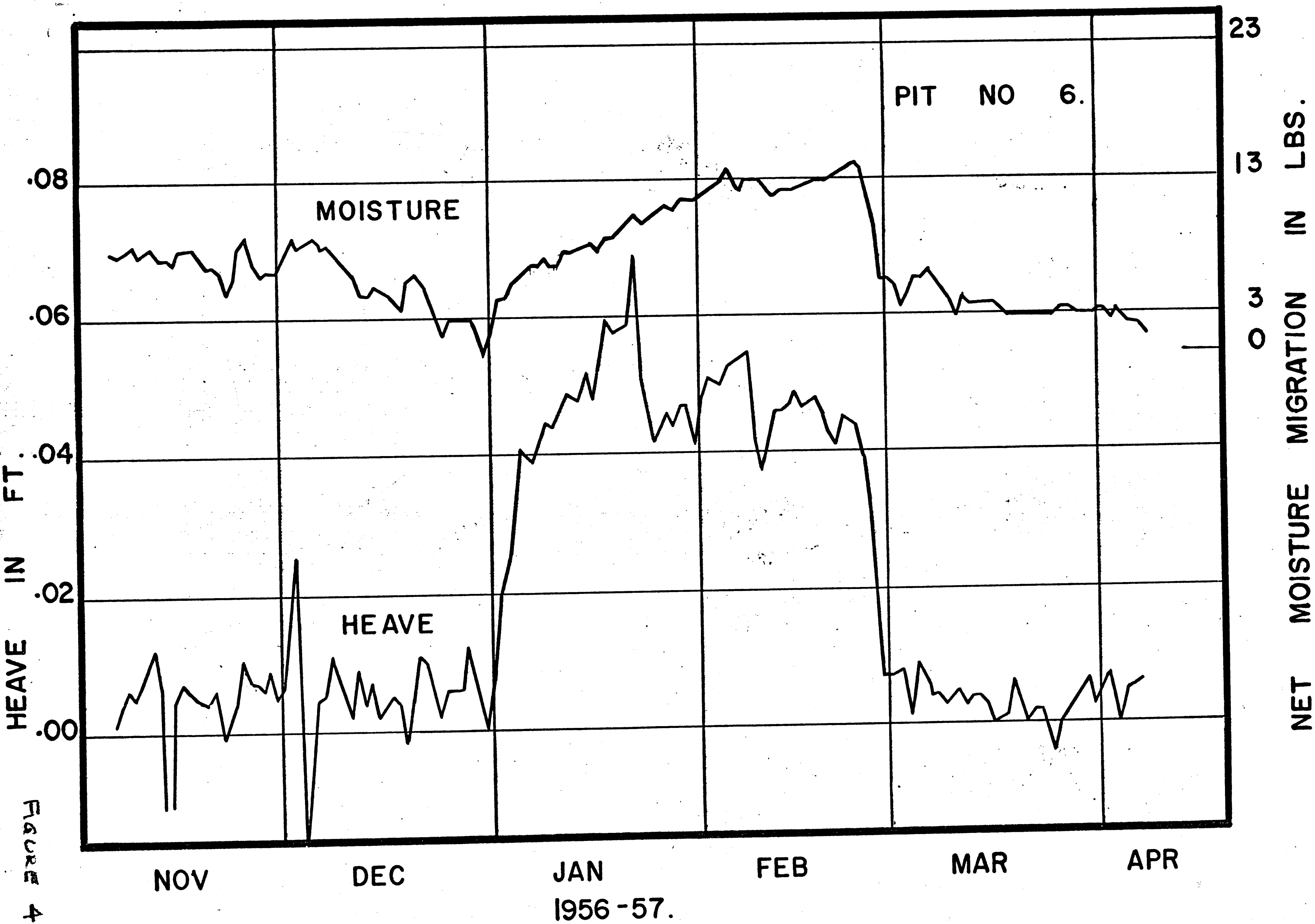
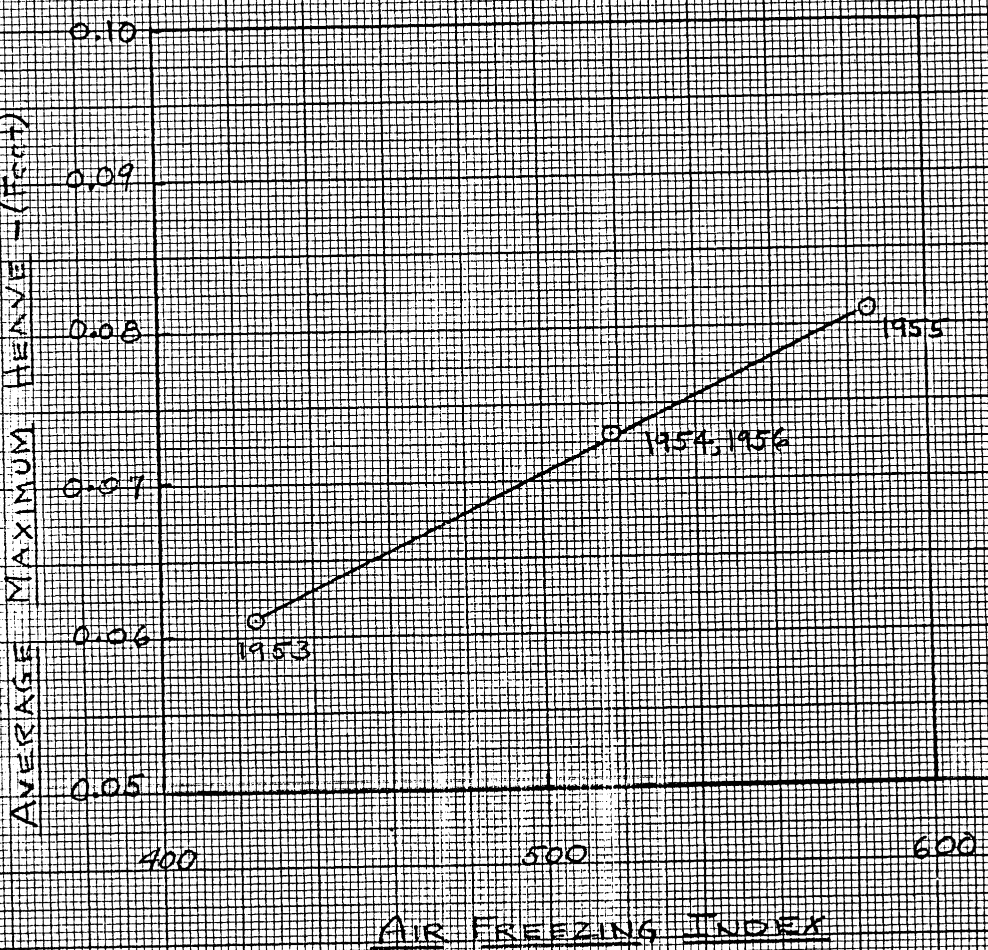

PIT NO 6.
MOISTURE
HEAVE
HEAVE IN FT.
.08
.06
.04
.02
.00
NET MOISTURE MIGRATION IN LBS.
23
13
3
0
NOV
DEC
JAN
FEB
MAR
APR
1956-57.

FIGURE 4B



Relationship Between Air Freezing Index and Average Maximum Heave for Soil Pits

Figure 49