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NEW ENGLAND DIVISION
CORPS OF ENGINEERS, U. S. ARMY
BOSTON, MASSACHUSETTS

ADDENDUM NO. 1

1945 - 1947

TO REPORT ON

FROST INVESTIGATION

1944 - 1945

FROST EFFECTS LABORATORY
OCTOBER 1949
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TO
REPORT ON FROST INVESTIGATION, 1944-1945

1. SYNOPSIS.

The frost investigation program was authorized by the Office, Chief of Engineers during the summer of 1944. A summary of the results of the investigations conducted during fiscal year 1944-1945 was published in a report entitled "Frost Investigation, 1944-1945" dated April 1947. The investigational program was continued during the fiscal years 1945-1946 and 1946-1947 for the purpose of extending and augmenting these studies in order to substantiate the design criteria in the Engineering Manual or to recommend revisions. A summary of the investigations and studies made during the period July 1945 through June 1947 with analyses of the results is presented in this addendum to the original report. Analyses are based on these additional data and the data presented in the original report; however, repetition of data contained in the original report has been avoided. Based on these studies and investigations revisions to Chapter 4, Part XII of the Engineering Manual are being recommended. Recommendations for continued studies are also included.

2. INTRODUCTION.

a. Authorization. The continuance of the frost investigation program was authorized by the Chief of Engineers during the fiscal year 1945-1946 by letter to the Division Engineer, New England Division, dated 4 August 1945, subject: "Frost Investigation during Fiscal Year 1945-1946", and subsequent indorsements, and during the fiscal year 1946-1947 by letters dated 5 July 1946 and 12 August 1946, subject: "Funds for Investigational Projects for Fiscal Year 1947". The Frost Effects Laboratory, established at the Boston District by direction of the Chief of Engineers, by circular letter No. 3221, dated 11 August 1944, was continued.

b. Purpose. The purpose of this report is to present the results of studies made and data obtained during the frost investigation program for the fiscal years 1945-1946 and 1946-1947 and to recommend warranted revisions to Chapter 4, Part XII of the Engineering Manual entitled "Frost Conditions". This report has been prepared as an addendum to the "Report on Frost Investigation, 1944-1945" dated April 1947, hereinafter referred to as the original report.

c. Scope. A summary and analyses of the studies, observations, and tests which were made to accomplish the following phases of the investigation are included in this addendum:

(1) Field investigations and testing of the effect of frost action during the winters of 1945-1946 and 1946-1947 under paved and turfed airfield areas. These included tests for soil classification, availability of ground water, soil temperatures, and ice segregation.

(2) Plate Bearing Tests on rigid and flexible pavements during normal and frost melting periods.

(3) Traffic Tests at Selfridge Field, Michigan, during frost melting period, March 1946.

(4) Studies of soil properties influencing freezing. These include the performance of laboratory tests to determine the thermal conductivity of frozen cohesionless materials with different densities and water contents under controlled temperatures.

(5) Mathematical studies to predict the rate and depth of frost penetration and correlate with field observations.

(6) A study of airfield pavement failures to which frost action was a contributing cause.

(7) A summary study of airfield pavements at permanent Air Force installations constructed on subgrades subject to frost action.

(8) Laboratory studies of methods of making frost-susceptible soils non-frost-susceptible by the use of admixtures and studies of methods to prevent leaching of salt admixtures.

(9) An investigation of the rate of frost penetration in pavements and non-frost-susceptible base construction materials and of the effect of density, water content, degree of saturation, and water table on ice segregation in frost susceptible materials in a test embankment at Dow Field, Bangor, Maine.

d. Presentation of Report. This report is presented as a main report with two appendices. The appendices which are presented at the end of this report are as follows:

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Appendix A - Mathematical Studies of Thermal Properties of Soils.

Appendix B - Summary Tabulation of Airfield Pavements at Air Force Installations Constructed on Frost Susceptible Subgrades.

e. Definitions. The description of tests and analysis of results involves a specialized use of certain terms and words which are defined in paragraph 2d, of the original report. Revised and additional definitions are contained in the "Glossary" at the end of this addendum.

f. Bibliography. Additional references obtained since compiling the bibliography for the original report are appended to this addendum.

g. Acknowledgments. In addition to consultants acknowledged in original report, Dr. L. A. Pipes of Harvard University assisted in the mathematical studies.

Acknowledgment is made to the U. S. Weather Bureau for weather data furnished and to the Post Engineers at the various airfields for continued assistance in performing tests.

3. FIELD INVESTIGATIONS - GENERAL. The observations and testing of the effect of frost action under paved and turfed areas were made at ten airfields during 1945-1946 and five airfields during 1946-1947. These airfields are located in the northern part of central and eastern United States as shown on Plate 1.

The following eight airfields of the 15 studied during 1944-1945 were selected for further study during 1945-1946:

(1) Dow Field, Bangor, Maine

(2) Presque Isle Airfield, Presque Isle, Maine

(3) Truax Field, Madison, Wisconsin

(4) Pierre Airfield, Pierre, South Dakota

(5) Sioux Falls Airfield, Sioux Falls, South Dakota

(6) Watertown Airfield, Watertown, South Dakota

(7) Fargo Municipal Airfield, Fargo, North Dakota

(8) Great Bend Airfield, Great Bend, Kansas

The field investigations consisted of weather observations, heave measurements, subsurface temperature measurements, and ground water observations, which were supplemented at some of the sites with periodic observations of variations in water content, density, and ice lens formations in base and subgrade materials. At a few selected sites plate bearing tests on rigid and flexible pavements and on bases beneath rigid pavements were made to determine the supporting capacity of the pavements.

Two additional airfields, Bedford Airfield, Bedford, Massachusetts and Selfridge Field, Michigan, were also investigated. Bedford Airfield was selected for subsurface temperature measurements and the determination of frost penetration in a non-frost susceptible base and subgrade beneath both rigid and flexible pavements. Selfridge Field was selected for a comprehensive investigation on rigid pavements. The investigations included traffic tests with a 60,000 pound load on a B-29 dual wheel assembly.

During 1946-1947 field investigations were continued at five airfields as follows:

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(1) Dow Field, Bangor, Maine

(2) Bedford Airfield, Bedford, Massachusetts

(3) Selfridge Field, Michigan

(4) Sioux Falls Airfield, Sioux Falls, South Dakota

(5) Fargo Airfield, Fargo, North Dakota.

4. CONDITIONS AT AIRFIELDS INVESTIGATED.

a. Locations. The two airfields added to those previously studied are Bedford Airfield, Bedford, Massachusetts, New England Division, and Selfridge Field, Michigan, Great Lakes Division.

The following tabulation, in addition to the geographical location shown on Plate 1, summarizes the locations, elevations, and general physiography:

AIRFIELD	NORTH LAT.	WEST LONG.	ELEV. ABOVE M.S.L. (Ft)	PHYSIOGRAPHY
Bedford	42°	62°	130	Rolling terrain of low relief
Selfridge	43°	83°	580	Level lake plain

b. Weather. Bedford has a normal freezing index of 680 and a normal freezing period from 1 December to 10 March. Selfridge has a normal freezing index of 520 and a normal freezing period from 1 December to 10 March.

Precipitation during the three months prior to the freezing period has been considered to be influential regarding the position of the water table and degree of saturation of the subgrade at the start of freezing. The normal precipitation for this three-month period is 10.2 inches at Bedford and 7.7 inches at Selfridge.

A record of snowfall at each airfield is presented in Fig. 3, Plates 3 to 8 inclusive.

c. Traffic History. A brief traffic history is tabulated for each airfield as part of Table 1. The data was obtained from Pavement Evaluation Reports of 1944, with the addition of available subsequent data.

d. Type and Condition of Pavements. The thickness and type of pavement for each airfield is shown in Table 1. The condition of the pavement surfaces prior to the investigations is briefly summarized below. Pavement crack surveys were made during the normal period and after the frost melting periods at Presque Isle, Dow, Selfridge, Pierre, and Sioux Falls. The location of all test areas covered by this addendum, which were not shown on the original report or where the test area limits have been changed are shown on Plate 2.

		PAVEMENT		CONDITION	
AIRFIELD	TEST AREA	TYPE	THICKNESS (INCHES)	FALL OF 1945	FALL OF 1946
Dow	D and E	B.C.	3.5	Good -scattered longitudinal cracks along construction lanes	No change
	F	P.C.C.	7.0	Fair - about 20 percent of area cracked	Few additional cracks
Presque Isle	A	P.C.C.	7.0	Good - few small cracks	No data
	C & D	B.C. (overlying 2 to 3 in. penetrated crushed rock)	3.5	Good - few small cracks & depressions	No data
Bedford	A	P.C.C.	6.0	Good	No change
	B	B.C.	5.0	Good	

PAVEMENT (CONT'D.)

AIRFIELD	TEST AREA	TYPE	THICKNESS (INCHES)	CONDITION FALL OF 1945	CONDITION FALL OF 1946
Truax	A	B.C.	2.5	Good - minor cracking	No data
	B	P.C.C.	6.0	Good - minor cracking & depressions	
	D	B.C.	2.5	Good	
Selfridge	A	P.C.C.	10.0	Fair - about 25 percent of area cracked. Every other lane numerous joint failures and cracks (placed during severe winter conditions)	No change
Pierre	A	P.C.C.	7.0	Good - few cracks, minor ponding condition.	No data
	C and D	B.C.	5.5	Good - minor cracking and depressions, ponding	
Sioux Falls	A	B.C.	2.0	Fair - numerous cracks	No change
	B	P.C.C.	6.0	Good - no cracks	Minor cracking
Watertown	A	P.C.C.	8.0	Good	No change
	B	B.C.	5.0	Good	
Fargo	A	B.C.	1.5	Transverse cracking and minor deformations.	No data
Great Bend	A	P.C.C.	7.0	Good	No data

e. Bases. The base material at Selfridge ranges from 7 to 20 inches in thickness and consists of a GF material with from two to five percent by weight finer than 0.02 mm. The base at Test Area A at Bedford is 18 inches thick and consists of a GW material with three per cent by weight finer than 0.02 mm. The same material was found in Test Area B

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with a thickness of 13 to 19 inches. The classification and gradation of the materials in each test area are shown in Figure 4 on Plates 3 to 8, inclusive.

f. Subgrades. In addition to the subgrade soils described in the original report the material at Bedford in both test areas consisted of a well graded sand (SW-SF) with from zero to ten per cent by weight finer than 0.02 mm. and the subgrade at Selfridge consisted of sandy silt (ML) overlying a sand (SF) with 13 to 25 per cent by weight finer than 0.02 mm., underlain by lean clay (CL). All subgrade soils at Selfridge are frost susceptible. Figure 4, Plates 3 to 8, inclusive, shows the classification and gradations of the predominant subgrade soils.

g. Ground Water. Bedford and Selfridge have ground water tables ranging from two to approximately eight feet below the pavement surface.

5. TEST SECTION, DOW FIELD, BANGOR, MAINE. A test section constructed during August and September 1946 was observed to determine the rate of frost penetration in non-frost susceptible base materials with rigid and flexible pavements and to study the effect of density, degree of saturation, and water supply on frost action. The test section consisted of 14 portland cement concrete cylinders each eight feet high and five feet inside diameter, containing specimen material of either cinders, sand and gravel, crushed rock or silty clay. These cylinders are referred to hereinafter as elements. Four inches of bituminous concrete was placed over the various specimen materials in eleven of the elements and a six-inch cover of portland cement

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concrete was placed over the remaining three elements. The effect of shallow ground water was obtained in four of the elements by connections to a controlled water supply. The rate of freezing temperature penetration in each test element was determined by thermocouple installations. The degree of saturation, water content, and density at time of placing, and pavement heave and subsidence during freezing and frost melting periods was determined. The water content and density were determined after the frost melting period in four elements in which the subgrade was placed at a low density. A plan and typical section of the test section is shown on Plate 9.

6. RESULTS.

a. Tests for Soil Classification. Laboratory tests consisting of sieve analysis, hydrometer analysis, Atterberg limits and specific gravity were conducted on representative base and subgrade materials from Selfridge and Bedford during the 1945-1946 investigations. During 1945-1946 and 1946-1947, tests were conducted at airfields previously investigated for the purpose of checking and obtaining additional data. Grain size distribution curves and classification data for typical materials and typical logs for each test area are shown in Figure 4, Plates 3 to 8, inclusive. A summary tabulation of the results of tests, including Atterberg limits, soil classification and percentage of particles finer than 0.02 mm., by weight, is included in Table 1.

b. Tests for Availability of Water for Frost Action.

(1) Precipitation. Precipitation data for the various airfields were obtained from either the U. S. Weather Bureau Station

nearest the airfields or from the AAF Weather Office at the specific airfield. Cumulative rainfall for the months of September to December and snow-fall record are shown in Figures 2 and 3 on Plates 3 to 8, inclusive. Tabulation of the records of precipitation for the three months prior to the freezing period for all airfields is included in Table 1.

(2) Ground Water. Ground water elevations in both the subgrade and base were obtained periodically from October to June by means of observation wells. These measurements were augmented by excavation of test pits at periodic intervals. The fluctuations of the ground water table measured from the surface of the pavements are plotted in Figure 5 on Plates 3 to 8, inclusive. Tabulation of the average depth of the water table from the pavement surface of each test area for the normal, freezing, and frost melting periods is also included in Table 1.

(3) Water Content and Density. Water content and density determinations of the base and subgrade materials were obtained in test pits excavated during the normal, freezing, and the frost melting periods, and during the period when subsurface conditions had returned to normal, generally in May or June. The specific time for the excavation of the test pits was based on analysis of data obtained in previous investigations. The variations in density and water content for the subgrade and base materials during these periods are shown graphically for all test areas in Figure 9 on Plates 3 to 8, inclusive. Results are also summarized in Table 1.

(4) Degree of Saturation. The degree of saturation of the base and subgrade materials during the normal, freezing, and frost

melting periods was computed from the density (unit dry weight), water content, and specific gravity of the various materials. Variations in the degree of saturation during these periods are included in Figure 9 on Plates 3 to 8, inclusive. The average degrees of saturation of the base and subgrade materials for the various testing periods are summarized in Table 1.

c. Measurements of Temperature. Air Temperature measurements were made or obtained at all airfields investigated. Measurements of subsurface temperatures were made at 20 test areas in 1945-1946 and at ten test areas in 1946-1947.

(1) Air Temperatures. The air temperatures were obtained from either the nearest U. S. Weather Bureau Station or the A.A.F. Weather Officer at the airfield. At some fields, these were supplemented by Corps of Engineer thermographs located at the test areas. For each airfield air temperature data in the form of degree-day curves for the winters of 1945-1946 and 1946-1947, and the normal curve are shown in Figure 1 on Plates 3 to 8, inclusive. The normal freezing index, the freezing index for 1945-1946 and 1946-1947 and the percentage of normal for 1945-1946 and 1946-1947 are included in Table 1.

(2) Subsurface Temperatures. Subsurface temperatures were measured either by thermocouples or thermometers as described in the original report.

At some locations thermometer wells were installed adjacent to thermocouple installations for comparison of results. The following table lists the fields where thermometer and/or thermocouple measurements of subsurface temperature were made:

AIRFIELD	TEST AREA	
	BITUMINOUS CONCRETE	CEMENT CONCRETE
Dow Field*	Thermometer and Thermocouple	Thermometer and Thermocouple
Presque Isle*	Thermometer and Thermocouple	Thermometer and Thermocouple
Bedford	Thermometer	Thermometer and Thermocouple
Truax	Thermometer	- - - - - - - - - - - - - -
Sioux Falls	Thermometer and Thermocouple	Thermometer and Thermocouple
Pierre	Thermometer and Thermocouple	Thermometer and Thermocouple
Fargo	Thermometer	(No cement concrete areas)
Watertown	Thermometer and Thermocouple	Thermocouple
Selfridge	(No bituminous concrete areas)	Thermometer
Great Bend	(No bituminous concrete areas)	Thermometer

* Thermometers and thermocouples were also installed in turfed areas.

A study of typical readings at three fields during the period of investigation shows that the thermocouples generally gave higher temperature readings than the thermometers at comparative depths. Comparative subsurface temperatures are plotted on Plate 10. Differences between the two methods of measurement ranged, generally, from one to three degrees Fahrenheit, although some readings differed by six degrees. In Figure 8, Plates 3 to 8, inclusive, are shown plots of the 32°F subsurface temperature from December to April with respect to depth. Similarly plotted on these charts is the depth of frost penetration as measured in test pits.

d. Field Measurements of Frost Penetration. The depth of frost penetration and the rate the frost entered the ground was obtained by observations in test pits excavated at the start of freezing and extending to the end of the frost melting periods. At some of the airfields test pits were excavated to obtain the maximum depth of frost penetration only. The results of these observations are plotted in Figure 8 on Plates 3 to 8, inclusive. From these plots, it will be noted that there is a relatively close agreement between the depth of the 32°F curve obtained from results of subsurface temperature readings and the frost penetration obtained by observations in test pits.

e. Tests for Frost Action.

(1) Ice Lenses. The presence of ice lenses was investigated by means of test pits excavated during the freezing period. Location and thickness of ice lenses in each test area are shown in Figure 6 on Plates 3 to 8, inclusive. These data are summarized in Table 1. The ice lenses observed in the subgrades occurred in noncontinuous horizontal layers ranging from 3/4 of an inch to hairline in thickness and were generally irregularly spaced less than 1/2 inch apart with the lenses becoming thicker and more closely spaced near the bottom of the frost penetration. Ice lenses observed in excavations during the freezing period in subgrade soils were consistently of increasing thickness and extent with depth at all test areas at Dow and Truax and at Test Area A at Presque Isle. Small, thin, scattered ice lenses were observed during the freezing period at all test areas at Selfridge, Pierre and Sioux Falls. No ice lenses were found at Test Areas C and D and Turfed Area at Presque Isle and at

Bedford. No observations of ice lens formations were made at Watertown, Fargo, and Great Bend.

(2) Pavement Heave. During 1945-1946 the pavement heave was measured by means of level surveys during the normal, freezing, and frost melting periods at Dow, Presque Isle, Truax, Selfridge, Pierre, Sioux Falls, Watertown, and Fargo. The amount of heave is shown in Table 1 and in Figure 7 on Plates 3 to 8. The maximum pavement heave was 0.4 foot and occurred in Test Area D at Presque Isle. Test Area F at Dow showed the greatest average heave for the entire area (0.25 feet). The average pavement heave at all test areas except those at Dow, Presque Isle, Truax, Selfridge, and Sioux Falls was practically negligible, being less than 0.05 foot. The pavement heave was relatively uniform for all airfields except Dow, Presque Isle, and Watertown. In Test Area C at Pierre, and Test Area B at Watertown pavement heave observations indicate that the pavement at the crown did not heave but subsided a small amount while the pavement at the edges heaved.

During 1946-1947 pavement heave was measured by means of level surveys during the normal, freezing, and frost melting periods at Dow, Sioux Falls, and Selfridge. The heave was measured by wire line measurements at Fargo before freezing and at the time of maximum heave. The amount of heave is shown in Table 1 and in Figure 7 on Plates 3, 5 and 6. The maximum pavement heave of 0.26 foot and the greatest average heave of an entire test area (0.14 foot) occurred at Test Area F at Dow Field.

f. Tests for Flexible Pavement Supporting Capacity. The supporting capacity of flexible pavements was investigated by means of plate bearing tests conducted during the normal period and repeated during the frost melting period at Dow, Presque Isle, Truax, Pierre, and Sioux Falls during 1945-1946. Figure 10, Plates 3, 4, 6, 7 and 8, presents the average results of the plate bearing tests. The field test procedures for plate bearing tests during 1945-1946 were the same as used during 1944-1945 investigations as described in paragraph 6f, of the original report. The maximum ratio of loads required to produce a 0.1 inch deflection in the normal period to those required to produce the same deflection in the frost melting period are given below. Also tabulated below are the ratios of deflections produced during the frost melting period by loads on a 24-inch diameter steel plate after ten repetitions to the deflections produced by the same loading during the normal period. The values presented in each box of the following table are arranged, from top to bottom, to give the arithmetic average, the range of values, and the number of tests.

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Airfield	Dow	Presque Isle	Truax	Pierre	Sioux Falls
Thickness Frozen Subgrade (feet)	0.8 0.6-1.0 (5)	3.0 2.8-3.2 (6)	1.3 1.1-1.5 (15)	2.5 2.5-2.6 (7)	2.9 2.9 (2)
Static Load Tests Max. ratio of loads at 0.1" deflection for normal period vs. frost melting period	1.8 1.6-2.0 (2)	1.8 1.0-2.3 (3)	4.4 3.7-5.0 (2)	1.6 1.3-1.9 (2)	2.7 2.7 (1)
Repeating Load Tests Ratio of deflections after 10 repetitions of load for frost melting period vs. normal period	1.8* 1.6-2.0 (2)	2.9* 1.8-4.3 (3)	3.1* 1.9-4.2 (5)	1.7** 0.6-2.3 (5)	2.9** 1.9-2.8 (3)

Notes: * Total load on plate, 20,000 pounds (only 5 repetitions at Dow)
** Total load on plate, 25,000 pounds

A summary of all the plate bearing tests conducted is presented in Table 2 (Sheets 1 through 7).

During 1946-1947 the supporting capacity of flexible pavements was investigated at Dow by means of plate bearing tests conducted during both the normal period and the frost melting period. The field test procedure for these plate bearing tests was as follows:

An area 25 by 25 feet was laid out for plate bearing tests. The soil profile of the area was determined from an auger hole at each corner and the center. The loading tests were performed with as great a dispersion of location as possible to give average results. Twelve tests were conducted in the Fall (normal period). Tests were conducted in groups of three at weekly intervals for five weeks during the frost melting period. The tests were performed by loading a rigid

30-inch diameter steel plate to 20,000 pounds and maintaining the load until complete deflection had occurred or 15 minutes had elapsed (whichever occurred first). The maximum deflection was recorded and a curve was plotted showing the deflections (average of tests performed on the same day) to indicate the period of weakness during the frost melting period. The average deflections for Test Areas D and E are shown in Figure 10, Plate 3 and also on Sheet 3 of Table 2.

g. Tests for Rigid Pavement Supporting Capacity. The supporting capacity of rigid pavements was investigated by means of rupture tests and subgrade modulus tests conducted during the normal period and the frost melting period and a traffic test at Selfridge conducted during the frost melting period in 1946. The rupture and subgrade modulus test procedures were the same as those used during the 1944-1945 investigations.

Rupture tests and subgrade modulus tests were conducted at Dow, Presque Isle, Truax, Selfridge, Pierre, and Sioux Falls during the Fall and again during the frost melting period 1945-1946 and at Dow Field during 1946-1947 to obtain the difference in bearing capacity during these periods. The results of rupture and subgrade modulus tests at the above listed airfields are presented in Figure 10, Plates 3, 4, 6, 7 and 8. Results of the rupture tests are summarized in the following tabulation. Also included, for comparison, are subgrade modulus values for both the normal and frost melting periods. The ratios of loads at 0.1 inch deflection during the normal period to loads at the same deflection during the frost melting period are presented, for each airfield investigated, in Table 2, together with a complete summary of plate bearing tests.

1945-1946	Load Appli-cations	Slab Thick. (in.)	Load lbs.	Fail-ure	Max. Defl. (in.)	Normal Period	Frost Melting Period	Ratio
	Rupture Tests on Slab Corners During the Frost Melting Period					Av. Subgrade Modulus lbs./sq. in./in.		
Dow	6	7.2	60,000	No	0.28	200	140	1.4
Presque Isle	6	8.4	60,000	No	0.17	410	155	2.6
Truax	1	6.5	47,000	No	0.12	240	120	2.0
Selfridge	1	10.8	90,000	No	0.15	165	155	1.1
Pierre	1	7.0	58,000	Yes	0.23			
"	1	7.0	80,000	Yes	0.21			
"	1	7.0	80,000	No	0.22	160	125	1.3
"	2	7.0	70,000	Yes	0.22			
Sioux Falls	1	6.0	60,000	No	0.31	90	75	1.2
"	1	6.0	70,000	Yes	0.45			
"	2	6.0	80,000	No	0.40			
1946-1947								
Dow	2	8.4	60,000	Yes	0.43	200	135	1.5
"	6	8.4	60,000	No	0.28			

h. Traffic Tests at Selfridge Field. Traffic tests were conducted at Selfridge on a rigid pavement during the frost melting period (2-25 March 1946) to simulate daily operations on runways and taxiways, utilizing a 60,000-pound load on a B-29 dual wheel assembly. A photograph and pertinent data concerning the equipment are given on Plate 11. This load on the dual wheel assembly is assumed equivalent to a 47,500 pound load on a single wheel. Two areas of the portland cement concrete apron were chosen with similar pavement, base, and subgrade conditions and traffic applied to one area at the rate of 15 coverages per day (runway traffic) and to the other at the rate of 45 coverages per day (taxiway traffic). The traffic applied did not crack the pavement in either area with the exception of slight spalling along the longitudinal and transverse dummy joints with a final vertical deformation of 0.11 foot to 0.135 foot in the area with 15 coverages per day and 0.100 foot to 0.138 foot in the area with 45 coverages per day. Complete information on these tests is contained in "Report on Frost Investigations and Traffic Tests, Selfridge Field, Michigan", dated June 1946.

i. Studies of Soil Properties Influencing Freezing. In studying the effect of frost action on airfield pavements and the influence of the depth of frost penetration, the thermal properties of frozen soils must be considered. The principal soil properties influencing freezing are thermal conductivity, latent heat, volumetric heat, and freezing temperature of soil moisture. The investigation of these thermal properties involved review of previous investigations by others, laboratory studies, and mathematical studies of the rate and depth of frost penetration into soils. The four principal factors studied were the following:

(a) Laboratory studies of thermal conductivity and a review of previous investigations by others.

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(b) Study of previous investigations made by others regarding latent heat of soil moisture.

(c) Study of previous investigations made by others regarding volumetric heat capacity of soil.

(d) Study of previous investigations made by others of the temperature at which water in the soil freezes.

(1) Thermal Conductivity of Soil.

(a) Investigations by Others. The most recent investigation for determining the thermal conductivity of soils was made by the University of Minnesota for the St. Paul District, Corps of Engineers, U. S. Army, as part of the Permafrost Investigations. Some of the results from these studies are summarized in Table 3. A comparison of the results of thermal conductivity tests on Lowell Sand made independently by the University of Minnesota and by the New England Division is shown on Plate 12. These tests indicate fairly good agreement, although the test procedures were different.

A diagram of thermal conductivity values for clay and sand versus density, porosity, and degree of saturation, prepared by Dr. Terzaghi, is shown on Plate 13. This diagram is based on University of Minnesota test data. The diagram shows the limiting values of thermal conductivity for clays and sand both frozen and unfrozen. As the porosity, n, approaches 100 percent, the thermal conductivity of a saturated unfrozen porous soil approaches the thermal conductivity value for water, which is approximately 0.35 BTU/ft./hr/^{o}F.;

for frozen saturated soil, the thermal conductivity of ice, 1.30 BTU/ft./hr./^{o}F., is approached. For very porous soils whose voids are filled with air the thermal conductivity approaches that of good insulating materials such as dry asbestos or cotton with coefficients of thermal conductivity ranging from 0.029 to 0.053 BTU/ft./hr./^{o}F. As the porosity, n, approaches zero the thermal conductivity of the soil must approach the average thermal conductivity of its mineral constituents. The above relationships determine the positions of the horizontal tangents or asymptotes of the curves shown on Plate 13.

(b) Laboratory Studies. Controlled laboratory tests for determining thermal conductivity, similar to those performed on unfrozen base materials during the 1944-1945 frost investigation and described on page 32 of the original report were continued to include tests on the same materials in a frozen condition. The investigations were performed in the cold room at Harvard University Graduate School of Engineering, Cambridge, Mass. Tests were performed to determine the thermal conductivity of sand, sand and gravel, cinders, slag, and crushed rock, all in a frozen condition. These materials are non-frost susceptible and are commonly used for base course construction. The test specimens were prepared as described in paragraph 6e, (2)(b) of the original report. Each test consisted of subjecting all sides of the test cylinder to a constant freezing temperature of approximately minus 4 degrees F. inside the freezing cabinet until temperature equilibrium was established and them immersing it into a brine bath in the cold room at a constant temperature of approximately 27 degrees F. The bath consisted of circulating brine maintained at constant temperature by the addition of either hot water or dry ice as required. The resulting temperature change was measured at the midpoint of the specimen until temperature equilibrium was again established.

The results of tests made during 1945-1946 on the frozen soil specimens were compared with the results of similar tests made during the 1944-1945 investigations, where non-frozen specimens were tested. Curves for determining the thermal conductivity from the measurements obtained, together with an example, are shown on Plate 14. Table 4 contains a summary of test data showing the comparison between the unfrozen and frozen groups of thermal conductivity tests. Plate 15 contains a plot of the same test results to illustrate, in general, the greater thermal conductivity of both frozen and unfrozen material as the water content is increased.

(2) Latent Heat of Soil Moisture. The latent heat of soil moisture is directly determined from the quantity of water in the soil which freezes. Figure 1, Plate 16, shows the relationship between unit weight, water content and latent heat, assuming that all the water freezes. An investigation reported by the Bureau of Public Roads* is briefly summarized in the following paragraphs:

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*"Percentage of Water Freezable in Soils" Bureau of Public Roads, Public Roads February 1925.

(a) Bureau of Public Roads Tests. The Bureau of Public Roads tests were performed to determine the percentage of water in the soil which freezes, this percentage determining the latent heat. In performing the tests, the entire soil was subjected to below freezing temperature and water content of the soil was maintained constant during the test. The materials tested were clean quartz sand (standard Ottawa sand), and soils containing silt and clay.

These tests indicated that, for the conditions tested, all water in a clean quartz sand froze at or slightly below 0 degrees C. (32 degrees F.) and from 32 to 83 percent of the water in the soils containing silt and clay froze at a temperature of minus 1.5 degrees C. (29.3 degrees F.), the percentage of water freezing depending principally on the amount of fines.

(3) Volumetric Heat of Soil. Studies by various investigators, as summarized by H. E. Patten in "Heat Transference in Soils," demonstrated that the total volumetric heat of a given volume of soil is the sum of the volumetric heats of the individual components of the soil, i.e., dry soil and water or ice. Figure 2, Plate 16 shows the relationship between unit dry weight, water content and volumetric heat for average values of the specific heats of soil, water and ice.

There are tabulated below a number of values for specific heats for various soils, rocks, and minerals. These values were obtained from "Handbook of Chemistry and Physics" 1945 Edition, and "Mechanical Engineer's Handbook" by Marks, 1941. Most determinations were made at about room temperature.

MATERIAL	SPECIFIC HEAT BTU/(LB)(°F)	MATERIAL	SPECIFIC HEAT BTU/(LB)(°F)
Asbestos	0.195	Humus	0.44
Basalt	0.20	Kaolin	0.224
Calcspar	0.20	Marble	0.21
Cement	0.20	Mica	0.206
Chalk	0.214	Quartz	0.188
Clay, dry	0.22	Salt, rock	0.21
Cinders	0.18	Sand	0.195
Dolomite	0.222	Sandstone	0.22
Gneiss	0.18	Serpentine	0.25
Granite	0.192	Talc	0.209
Hornblende	0.195		

The specific heat based on the above tabulation as used in the calculations of frost penetration is 0.20 BTU/(LB)(°F).

(4) Freezing Temperature of Soil Moisture. The determination of the temperature at which soil freezes was made from field investigations, and from a study of investigations performed by others* which are summarized below.

*"Degree of Temperature to which Soils can be Cooled Without Freezing," by G. Bouyoucos - Journal of Agricultural Research, November 1920.

"Ice Pressure Determination in Clay Soils," Engineering News Record, 25 July 1935.

"A Progress Report on an Investigation of Frost Action in Soils," by Mackintosh - Proceedings of the International Conference on Soils Mechanics and Foundation Engineering, 1936.

"Studies of Frost Penetration," by H. U. Fuller - Journal N.E. Water Works Association, September 1940.

(a) Supercooling. Studies by Bouyoucos involved tests in cooling cohesionless and cohesive soils with and without agitation. The tests indicate that cohesionless soils can be supercooled without agitation to a temperature of 24.4 degrees F. and cohesive soils to 23 degrees F. before they freeze. Distilled water can be supercooled to 21.2 degrees F. before it freezes. With constant agitation, it can be cooled to about 30.2 degrees F. before it freezes.

(b) Bureau of Public Roads Tests. Tests performed by the Bureau of Public Roads on clean quartz sand indicated that the freezing temperature of soil moisture was at or slightly below 32° F. In soils containing silt and clay 35 to 80 percent of the soil moisture froze at 29.3° F.

(c) Harvard University Tests. Two sets of tests were performed independently at Harvard University, both on soft clay. In the first series of tests, the temperature at the bottom of the zone of ice lenses ranged from minus 1.0°C. to minus 2.0°C. (30.2°F. to 28.4°F.) and in the second series of tests, the boundary temperature between ice lenses and the unfrozen clay ranged from minus 0.5°C. to minus 0.7°C. (31.1°F. to 30.7°F.)

(d) Observations by H. U. Fuller. Observations were made by Fuller on a gravel soil and in a clay soil at Portland, Maine, by reading thermometers installed at 6-inch intervals of depth and observing the frost penetration. These observations indicated that the temperature at the bottom of the frozen layer was 32.5°F. for both types of soil.

(e) Field Observations. Temperatures ranging from 30.2°F. to 35.1°F. were observed at 49 subsurface temperature installations during 1944-1947 at the depth of frost penetration as determined from adjacent test pits. The average temperature at the boundary of frozen and unfrozen soil in these test pits which were located within 50 feet of a temperature measuring installation and having approximately the same thickness of pavement and base was 32.3°F. The temperatures at each of these installations and the frost penetration data are contained in Table 5.

j. Mathematical Studies of Thermal Properties of Soils. A comprehensive, mathematical study was made of the thermal conditions in a semi-infinite, homogeneous, isotropic soil mass due to variations in surface air temperature. The studies are presented in the form of 17 problems in Appendix A. The problems deal with the determination of the thermal diffusivity, depths of frost and melt penetration, effect of radiation and surface film, and the effect of an insulating layer. A series of formulae were developed to predict the depth of frost penetration and several of these were selected for calculating the depth of frost penetration at airfields where frost observations were made. These studies were principally performed by Dr. L. A. Pipes, Harvard University.

k. Tests for Insulating Qualities of Turf and Snow Cover. Investigations were conducted at two turfed areas, one at Presque Isle, during 1945-1946 and one at Dow Field during 1945-1947. The tests conducted and observations made included soil classification, availability of water for frost action, air and subsurface temperatures, ice lens formation, depth of frost penetration, and snow cover. The snow was not plowed at the turfed areas. Results of tests in turfed areas are summarized in Table 1 and included on Plates 3 to 8, inclusive. For comparison, depth of frost is also given for paved areas. The paved test areas were plowed and snow removed as close to the pavement as practicable, immediately after each snow fall. It was not possible to remove the snow completely to the bare pavement, with the result that a layer of packed snow or ice, from 0.5 to two inches in thickness, covered the paved areas. At the turfed areas, measurements of snow cover were made periodically. A comparison of the depths of frost attained in various areas at approximately the same time is contained in the following table in which the depth of frost is tabulated against the freezing index.

Airfield	Pavement or Cover	Frost Penetration (in feet) at time of Freezing Index (in degree-days)		
		705	1240	2200
Presque Isle 1945-1946	P.C. Concrete	4.0	4.3	6.5
	Bit. Concrete	3.5	4.2	5.7
	Turf without snow	1.5	3.0	4.2
	Turf with snow	---	2.7	---

		Freezing Index (in degree-days)						
		240	306	445	940	1070	1385	1415
Dow 1945-1946	P.C. Concrete	2.3	---	3.1	---	4.5	4.4	---
	Bit. Concrete	---	2.6	3.0	---	4.2	4.1	---
	Turf with snow	---	1.2	---	2.0	---	---	2.2

		Freezing Index (in degree-days)							
		593	597	721	753	833	869	932	965
Dow 1946-1947	P.C. Concrete	3.5	---	---	---	---	---	3.7	---
	Bit. Concrete	---	3.2	---	3.6	3.7	---	---	3.9
	Turf with snow	---	1.1	2.2	---	---	2.2 1.7	---	2.3

m. Airfield Pavement Failures. A study was made of all reports of airfield pavement failures to determine which failures were influenced by frost action. A summary of the 30 airfields at which frost action was a contributing factor to the pavement failure is contained in Table 6 together with pertinent information concerning the pavement, base, subgrade, water table, traffic, and nature of the failure.

n. Summary Tabulation of Airfield Pavements. From data available from the Airfield Pavement Evaluation Reports, the Pavement Failure Reports, and from the frost investigational program, a summary has been prepared presenting the pavement evaluation, traffic history, pavement condition and other pertinent data for all permanent Air Force installations constructed on frost susceptible subgrades. This summary tabulation is presented as a complete report in Appendix B of this addendum.

p. Studies of Base Course Treatment to Prevent Frost Action. The following studies were made of base course treatments with the purpose of developing a method of making frost-susceptible soils non-frost susceptible: (1) a review of previous investigations performed by others; (2) a performance of laboratory tests to determine the suitability of various admixtures and combinations of admixtures to prevent frost action; and (3) the performance of laboratory tests to determine whether leaching of salt admixtures could be retarded or prevented by the addition of bituminous materials.

The results of the laboratory tests using admixtures with selected soils are contained in Table 7. Plate 17 contains classification data on the soils tested and Plates 18, 19, and 20 show the

6p

amount of heave of the various samples versus the accumulated degree-hours below 32°F., together with temperature data.

A complete description of the tests and results is contained in two reports dated June 1946 and August 1947 both entitled "Report on Studies of Base Course Treatment to Prevent Frost Action."

7. ANALYSES.

a. Effect of Water Source on Frost Action. Observations of soil moisture, depth to ground water table, and precipitation data are summarized and presented in Table 8. From a study of the available data no revisions to the analyses presented in the original report are warranted.

b. Effect of Temperature on Frost Action. In order to determine the effect of temperature on frost action, the freezing index and amount of frost action would be required for a period of many years at the same test site. At one test area observations have been made for four years and at three test areas observations have been made for three years. Because of yearly variations in rate of freezing, fluctuating ground water conditions, and limited number of years of observations, a relationship between freezing index and amount of frost heaving is not discernible.

c. Effect of Soil on Frost Action. For the occurrence of frost action, three conditions must occur simultaneously as described in Paragraph 4 of the original report. The criterion that a given soil must have more than three percent by weight of sizes finer than 0.02 mm. in diameter to be frost susceptible is substantiated in general by the observations reported herein. However, with the exception of Bedford which has a non-frost susceptible base, the base materials at all fields investigated contain soil particles with more than three percent by weight finer than 0.02 mm. in diameter, yet only occasional ice crystals were reported. This may be explained either by the absence of a readily available water supply or by the degree of compaction of the base materials. There are no data from these investigations to show the reason for the lack of frost action but previous investigators have shown that there is a critical density above which ice segregation and heaving are greatly diminished, if not eliminated, in frost susceptible soils. These investigations do not indicate which soils are more susceptible to frost action since other factors such as water availability and freezing index were different at the various locations tested and mask the effect of the soil type on frost action.

d. Analysis of Frost Penetration Based on Field Observations. A study of the actual frost penetrations in non-frost susceptible soils at all sites investigated shows that the depth of frost penetration versus the freezing index plots as a straight line when plotted to a logarithmic scale as shown on Plate 21. On Plate 21 there are plotted the freezing index versus frost penetration in non-frost susceptible soils beneath airfield pavements, for the years 1944-1947, inclusive. Figure 1 shows data for portland cement concrete pavements, Figure 2 for bituminous concrete pavements, and Figure 3 contains data for both types of pavements. In each figure, the design curve presented in the original report is shown. On the basis of the additional data obtained during these investigations as plotted on Plate 21 no change in the original design curve is recommended. The design curve in Figure 3 may be used to predict the depth of frost penetration beneath paved areas, regardless of pavement type, which are maintained snow free and which have bases constructed on non-insulating and non-frost susceptible materials such as sand, gravel or crushed rock. The mean annual air temperature and the normal freezing index for any part of the Continental United States may be estimated from Figures 1 and 2, Plate 22. The duration of the normal freezing index in days may be estimated from Figure 3.

Correlation of the depth of frost penetration, as determined by test pit excavations and the 32°F. curves as determined by either thermometers or thermocouple measurements, is given in Figure 8, Plates 3 to 8 inclusive, and indicates that for all practical purposes, the maximum penetration of the 32°F. curves can be considered as the maximum depth of frost penetration.

A tabulation of the temperature at the depth of frozen soil as shown in Table 5 indicates that the soil moisture freezes at approximately 32°F.

e. Analysis of Frost Penetration Based on Mathematical Studies.

(1) Discussion of Thermal Properties Influencing Freezing. The principal thermal properties of soils which influence freezing are the thermal conductivity, the latent heat of fusion (of water in the soil), and the volumetric heat (of water and soil).

(a) Thermal Conductivity. Analyses of investigations made by others and of the controlled laboratory tests indicate that the thermal conductivity of frozen cohesionless soils is greater than that of unfrozen soils at high water contents and that the thermal conductivity of most types of soils increases with increasing water content and increasing unit dry weight.

Thermal conductivity studies made for the Corps of Engineers by the University of Minnesota indicate that values of thermal conductivity for cohesionless materials as found in base course construction range from 1.0 to 1.8 BTU/ft./hr./°F. This range does not include the organic soils such as peat, soils of volcanic origin, or cohesive soils which may be expected to differ in thermal properties. An assumed thermal conductivity value of 1.3 BTU/ft./hr./°F. has been used in computing the depth of frost penetration as contained in Table 9 as part of the analysis of the mathematical method.

(b) <u>Latent Heat of Fusion.</u> The latent heat of soil moisture is a direct function of the percentage of soil water that freezes. For all practical purposes, all the water in clean cohesionless soils of the GW, GP, SW, and SP classifications will freeze at or slightly below 32°F. In silt soils of the ML classification, most of the water may be expected to freeze at approximately 32°F. In the remaining soils of the GC, GM, SC, SM, CL, OL, MH, CH, and OH classifications, the percentage of water which will freeze will be less than the total water content. Figure 1, Plate 16 shows the relationship between density in pounds per cubic foot and latent heat of fusion in BTU per cubic foot for various water contents assuming that all the water freezes. This figure is a nomographic presentation of the graph shown in Figure 3, Plate 22 of the original report. The average latent heat, where there are several soil layers at different water contents, may be determined using the following equation:

$$L = \frac{L_1d_1 + L_2d_2 + L_3d_3 + \dots + L_nd_n}{d_1 + d_2 + d_3 + \dots + d_n}$$

where:

L is average latent heat of soil moisture in BTU per cubic foot.

L_1, L_2, L_3, are latent heats of soil moisture in BTU per cubic foot in layers 1, 2, 3, etc.

d_1, d_2, d_3, are the thicknesses of layers 1, 2, 3, in feet etc. (note that $d_1 + d_2 + d_3 + \dots + d_n$ equals the depth of freezing).

(c) Volumetric Heat. Based on the specific heats of the various soils, rocks and minerals, an average value of 0.2 BTU/(lb)(°F.) has been used for the specific heat of soil and values of 1.0 and 0.5 BTU/(lb)(°F.) for water and ice, in all calculations involving the prediction of the depth of frost penetration. Figure 2 Plate 16 shows the relationship between density in pounds per cubic foot and volumetric heat in BTU per cubic foot per degree F. for various water contents for both frozen and nonfrozen states. This figure is a nomographic presentation of the graph shown on Figures 4 and 4A, Plate 22 of the original report. Where the soil is fully saturated, the volumetric heat of the non-frozen soil is nearly constant, varying from 40 to 45 BTU/(cu.ft.)(°F.) within reasonable limits of unit dry weight and for frozen soil it may be considered constant at approximately 32 BTU/(cu.ft.)(°F.). Where there are several layers at different unit dry weights and water contents, the following equation may be used to determine an average value for volumetric heat:

$$C = \frac{C_1d_1 + C_2d_2 + C_3d_3 + \ldots + C_n d_n}{d_1 + d_2 + d_3 + \ldots + d_n}$$

where:

C is the average volumetric heat in BTU/(cu.ft.)(^{o}F.).

C_1, C_2, C_3, etc. are volumetric heats in frozen or unfrozen states for layers 1, 2, 3, in BTU/(cu.ft.)(^{o}F.) etc.

d_1, d_2, d_3, etc. are thickness of layer 1, 2, 3 in feet, etc.

(2) Analysis of Theoretical Problems. The accuracy of determination of the values of thermal diffusivity "a", in the manner outlined in Problems 1 to 5, inclusive, Appendix A, is dependent on the accuracy of temperature measurements at various depths, at the same or different times. With the exception of Problem 3, the results involve the determination of the slope of the temperature curve at any given point which may also introduce some error.

The remaining problems, with the exception of Problem 15, are concerned with the depth of freezing "x". Problem 15 deals with the effect of ground film and radiation. The computed depths of frost penetration, neglecting ground film and radiation, are somewhat greater than observed depths, however, the difference decreases with increase in frost penetration. Problems 6 and 7 neglect the latent heat of fusion; both problems assuming that the air temperature is periodic over a sufficiently long period so that the interior soil temperature is also periodic. Problem 7 is further complicated by assuming that the soil is composed of two layers, the solution being obtained only by cut-and-try method. Problems 8 and 9 consider latent heat but neglect volumetric heat. Problems 10 through 14 consider both latent heat and volumetric heat. Problem 16 assumes that the temperature of the soil varies uniformly with the depth. Problem 17 considers the effect on the depth of freezing of an insulation layer placed over the soil.

(3) Discussion of Equations. Equations 83, 93, 154, and 158 from Problems 9, 10, 16 and 17, respectively, were selected for study and comparison with observed depths of frost penetration. The results of computations for these four formulae for all airfields are contained in Table 9 together with all pertinent data necessary for the computations. Equation 83 ($x = \sqrt{48kF/L}$) gives values which are consistently too large. Equation 93 $\left(x = \sqrt{\dfrac{48\ k\ F}{L + C\ (v_o - 32 + F/2t)}}\right)$ gives values of "x" which, though less than those of equation 83, are still consistently too high. Equation 154 $\left(x = \sqrt{\dfrac{24\ k\ F}{L + C\ (v_o - 32 + F/2t)}}\right)$ gives value of "x" which bracket the observed values. Assuming that the temperature at the surface of the pavement is essentially the same as the temperature at the bottom of the pavement, a column is contained in Table 9 in which the thickness of pavement is added to the predicted depth as determined by equation 154. Equation 158 $\left(x_R = -\dfrac{d}{2} + \sqrt{\left(\dfrac{d}{2}\right)^2 + \dfrac{24\ k\ F}{L + C\ (v_o - 32 + F/2t)}}\right)$ has been used for areas having a turf cover. The results of these calculations bracket the observed depths, but in general the dispersion is great, with the average very high. Also contained in Table 9 are predicted depths using the design curve (Figure 2, E.M. Part XII, Chapter 4,

July 1946). The values of "x" thus obtained bracket the observed depths with the greatest percentage being within 6 inches of the observed depths. Comparison of the relative merits of each formula is given below:

Equation	Ratios of Predicted to Observed Depths Avg.	Max.	Min.	Percent of Observations Within 6 Inches
83	1.60	3.39	1.09	6
93	1.32	2.69	.83	29
154	.94	1.89	.58	42
154 + pave.	1.10	2.31	.67	54
Empirical	1.08	1.93	.67	63
158 (Turf)	1.95	5.67	.92	50

In all calculations, the average value of 1.3 BTU/(ft.)(^{o}F.)(hr.) was used as the coefficient of thermal conductivity and the full value of the latent heat was used as derived from the nomograph in Figure 1, Plate 16. Because of the inability to determine for each separate layer of soil, the exact quantity of water which froze, it was assumed that all the water to the maximum depth of freezing was frozen, which is contrary to the data presented and analyzed in paragraph 6i(2)(a).

f. <u>Effect of Frost Action on Flexible Pavement Supporting Capacity</u>. The pavement bearing tests performed at Dow, Presque Isle, Truax, Pierre, Watertown, and Sioux Falls during 1943-1946 indicate that a reduction in flexible pavement supporting capacity occurs during the frost melting period as a result of frost action in the subgrades. The ratio of the maximum load causing 0.1-inch deflection during the normal period to the minimum load causing the same deflection during the frost melting period, is plotted against the maximum thickness of frozen subgrade in Figure 1, Plate 23, to indicate the relationship between the depth of frost penetration and the reduction in strength. These data indicate that there is little variation in the loss of strength with the maximum depth of frozen subgrade.

The pavement bearing tests performed at Dow Field during 1946-1947 were performed using a new procedure as described in Paragraph 6f. The purpose of this new procedure was to measure the length of the period of weakness in the flexible pavement test areas. The results of the tests for the first normal to normal period cycle are not conclusive due to a break in performance of the tests with no tests made during the month of May 1947 as the equipment was needed at another site. In Test Area D the frost began leaving the ground on approximately 15 March 1947 and the first test was performed on 24 March 1947. The tests indicate that the supporting capacity of the area returned to normal between 8 and 15 April 1947. There was a subsequent drop in supporting capacity but it is believed that this was caused by the heavy rain that fell between 10-17 April (approximately 2 inches). This indicated that the period of weakness due to frost melting was from three to four weeks in Test Area D. In Test Area E (after the initial decrease) there was an increase in supporting capacity shortly after the start of the frost melting period to a maximum about 28 March, then a decrease until about 11 April when the supporting capacity of the runway began to return toward normal about 15 April. Tests performed in Test Area E during June indicated considerable variation in the deflection obtained from week to week. Also there was considerable range of deflections in the ten tests performed on 28 October 1946.

Discounting two values in Test Area E which were 0.04 inch greater than the highest of the other ten deflections, there was very little difference in the load supporting capacity of the two test areas during the normal period in October. With the exception of two test periods in April and one in June there was very little difference in the deflections obtained in the two test areas during the frost melting period.

g. Effect of Frost Action on Rigid Pavement Supporting Capacity. Rupture tests performed on the top of the rigid pavement indicate that the load required to produce a 0.1-inch deflection during and immediately after the frost melting period was between 48 and 84 percent of the load required to produce the same deflection during the normal period. Correlation between the reduction in strength as indicated by the rupture tests and the maximum thickness of the frozen subgrade, is indicated in Figure 3, Plate 23. The ratios of loads at 0.1 inch deflection of the subgrade modulus tests are plotted on Plate 23, Figure 2, against the maximum thickness of frozen subgrade, and indicate that for the limited number of observations, the loss in strength during the frost melting period is not greatly influenced by the maximum depth of frost penetration into the subgrade.

The traffic tests at Selfridge did not cause any failure of the pavement with either the 15 or the 45 coverages per day of the B-29 dual wheel assembly loaded to 60,000 pounds. The deformation at the end of the tests was approximately the same for both coverages. The theoretical evaluation of the test area as a runway during the frost melting period was for a 49,000-pound wheel load and as a taxiway during the same period was for a 40,000-pound wheel load in accordance with Chapter 4, Part XII of the Engineering Manual dated July 1946. Assuming that the 60,000-pound dual wheel load is equivalent to 47,500 pounds on a single wheel, the pavement was satisfactory for runway traffic but was overloaded by the taxiway traffic. It is possible that the traffic pattern of 45 daily coverages is not sufficiently severe or that the equivalent load of 47,500 pounds may be high accounting for the fact that the pavement withstood the apparent overloading during the frost melting period.

h. Insulation Qualities of Turf and Snow Cover. Inspection of the table on frost penetration as presented in paragraph 6k, indicated that the turf acts as an insulating blanket which appreciably retards frost penetration. The one measurement made for turf with snow cover as against turf without snow cover, indicates that the blanket of snow has provided additional frost penetration protection. However, the data are very meager and no quantitative statements can be made. Owing to the fact that a layer of snow or ice usually covered the paved surfaces, the depth of frost under the paved area is influenced by the thickness of the snow or ice layer above it.

i. Airfield Pavement Failures. A study of the pavement failure reports, indicates that the failures at 30 airfields were influenced by frost action. A summary of the data for these airfields is contained in Table 6. Examination of the data indicates that 24 failures occured on flexible pavements and 16 on rigid pavements. In 17 failures, the base was either frost susceptible or a borderline material. In all of the failure areas the subgrade was frost susceptible. The ground water elevation was reported at a shallow depth in ten failed areas and more than 18 feet below the pavement surface in 13 failed areas. The ground water elevation was not reported in 17 failed areas. The freezing temperature conditions varied from periods of alternate freezing and thawing with relatively low cumulative degree-days to a freezing index of more than 2500 degree-days.

The field evaluations presented in Table 6, for the normal and frost melting periods, are based upon Chapter 2, dated May 1947, and Chapters 3 and 4, dated July 1946, Part XII of the Engineering Manual. The evaluation for frost conditions of the failed areas compared with the traffic using the areas indicated that the pavement was overloaded, or loaded to the evaluation load in approximately 70% of the failed areas.

j. Summary Tabulation of Airfield Pavements. An analysis of the pavements at permanent Air Force installations on frost susceptible subgrades as presented in Appendix B of this report, indicated that eight airfields on which complete pavement data are available had failures or signs of distress. The traffic history shows that seven of the eight had been subjected to wheel loadings in excess of the frost condition evaluation. Complete data are presented in Appendix B.

k. Analysis of Base Course Treatment Investigation. A study of the data obtained from numerous laboratory investigations of soils with admixtures of calcium oxide, water repellents (Stabinol, 321, and ferrous sulphate plus 321)*, salts (sodium and calcium chloride), portland cement, vinsol resin, and bituminous materials (asphalt emulsions, asphalt cutbacks, tars, and oils) indicated that only two groups of admixtures, the salts and the bituminous materials were effective in preventing frost action in the soils tested. Additional laboratory tests were performed to supplement the data already available and to obtain information on admixtures which had not been previously tested. These admixtures consisted of Bunker "C" oil, tar (RT-2), calcium chloride, Darex AEA (an air entraining agent), calcium chloride and Bunker "C" oil in combination, and calcium chloride and RT-2 in combination. These tests substantiated the conclusions drawn from the study of previous investigations, that salts and bituminous materials could be used effectively in laboratory tests to prevent frost action. Darex AEA was unsatisfactory as a preventative of frost action in the soil with which it was used.

From a study of all tests performed using sodium chloride and calcium chloride as admixtures an approximate method of determining the quantity of salt that should be used to prevent frost action was developed using the air temperatures at which frost action started

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* Stabinol consists of three parts of portland cement and one part of a complex salt consisting of unneutralized abietic acid, sodium resinate and calcium resinate.
321 is a finely powdered, white resinous substance formed by reacting sodium hydroxide with rosin in such proportions that one-fourth of the abietic acid in the rosin in neutralized, thus resulting in a complex salt of three parts abietic acid and one part sodium abietate.

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(indicated by heaving), the theoretical freezing temperature of the brine formed by the salt and water in the sample at the start of the test, and the void ratio of the sample. This method is described in the report referred to in paragraph 6p. The use of salts for frost action preventatives affords only temporary protection due to their tendency to migrate or leach out of the soil; therefore they are regarded as unsatisfactory for use under pavements where permanent protection is essential.

The waterproofing property of bituminous materials and the percentage of the soil finer than 0.02 mm. by weight are two factors from which a quantitative method of design for bituminous admixtures may be developed. If the waterproofing is regarded as being effected by filling the voids in the soil with bituminous material up to a point where the entrance of water is prevented, then the void ratio with admixture of the soil gives a measure of this waterproofing. Void ratio with admixture is defined as the ratio of the volume of the voids to the total volume of solids (including the admixture). For any soil, therefore, there could be a critical void ratio with admixture at which frost action would be eliminated. Such a critical void ratio with admixture was well defined in the tests performed using Bunker "C" oil and RT-2 and appeared evident for tests performed during previous investigations. The void ratio with admixture at which no frost action occurred has been plotted against the percentage by weight of soil particles finer than 0.02 mm. in diameter and the results are shown on Plate 24. Additional tests using a wider variety of soils having different gradations are necessary before any definite conclusions can be reached. It appears that all bituminous materials are not equally effective as frost action preventatives. Those admixtures which prevent frost action at the highest void ratio with admixture (that is, filling the least volume of void space) can be considered the most effective. From Plate 24 it is, therefore, apparent that asphalt emulsion, "AES-1" gives the best results, followed by tar and asphalt cutbacks and lastly by Bunker "C" oil.

Tests were performed using calcium chloride alone and calcium chloride with Bunker "C" oil on a sandy silt soil in order to find some method of preventing or retarding the leaching of calcium chloride. The results of these tests indicated no appreciable retarding of the leaching of the calcium chloride.

8. CONCLUSIONS. Based upon the analyses of the data presented herein no change to the conclusions presented in the original report are warranted.

9. RECOMMENDATIONS. The following revisions to Chapter 4, Part XII of the Engineering Manual as presented in the original report and the following continued studies are recommended:

a. Revisions to Chapter 4, Engineering Manual. It is recommended that revisions to Chapter 4, Part XII of the Engineering Manual be made:

(1) to clarify paragraphs under 4-01a "Conditions Affecting Frost Action". The criterion on frost susceptible soils stating that a soil containing more than 3 percent by weight of grains

smaller than 0.02 mm. is frost susceptible should be modified to include very uniform fine-grained cohesionless soils which may contain up to ten percent by weight of grains smaller than 0.02 mm. before becoming susceptible to frost action.

(2) to include more specific criteria for ground water conditions necessary for frost susceptibility.

(3) to clarify paragraph 4-03 "Protection of Subgrade for Concrete Pavements" by simplifying the procedure for determining the minimum required thickness of base course material on subgrade susceptible to frost action.

b. Continued Studies.

(1) The period during which there is a decrease in supporting capacity of pavements during and after the frost melting period.

(2) The rate of frost penetration in non-frost susceptible materials and the effect of water content, density, degree of saturation, and ground water on frost action in frost susceptible soils.

(3) Admixtures which would make frost susceptible materials non-frost susceptible.

(4) The influence of various quantities of coarse materials in fine grained soils on frost action.

(5) The influence of snow cover on frost penetration.

(6) The effect of grain size distribution on frost action.

GLOSSARY

The following words and terms in addition to those presented in Paragraph 2d of the original report are defined with respect to their specialized use in this report.

Admixture	An admixture is a material which is added to a soil to prevent frost action.
Degree-day	Each degree in any one day that the mean daily temperature varies from 32°F. is called a degree-day. The difference between the daily mean temperature and 32°F. equals the degree-days for that day. The degree-days are plus when the daily mean temperature is below 32°F. and minus when above. A cumulative degree-days-time curve is obtained by plotting cumulative degree-days against time.
Degree-hour	A degree-hour is the cumulative total of degrees per hour below 32°F.
Freezing Period	The freezing period is the time during which the frost is in the ground and there is no reduction in strength of foundation materials due to frost action.
Frost Melting Period	The frost melting period is the time of the year during which the frost in the foundation materials is returning to a liquid state.
Normal Period	The normal period is the time of the year, Summer and Fall, when there is no reduction in strength of foundation materials due to frost action.
Porosity	The degree of porosity of a soil is defined as the ratio of the volume of voids to the total volume (including soil and voids).

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FOREWORD

This bibliography contains additional references procured since the publication of the "Report on Frost Investigation 1944-1945" and it supplements the bibliography contained therein.

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FROST INVESTIGATION
1945-1947
SUMMARY OF FACTORS INFLUENCING FROST ACTION
OTHER AIRFIELD DATA

Surface and underlying material

SITE	TEST AREA	SURFACE: TYPE	SURFACE: THICKNESS INCHES (a)	UNDERLYING MATERIAL: CLASSIFICATION	UNDERLYING MATERIAL: THICKNESS (INCHES)	PERCENT FINER THAN 0.02 MM
DOW	D E F TURF	Bit. Conc. Bit. Conc. P.C. Conc. Topsoil	3.5 3.5 7,10 2-6	Base GW Subgrade CL Base GW Subgrade CL Base GW Subgrade CL Subgrade CL	36-49 - 32-41 - 19-23 - -	2-6 40-97 2-6 40-97 2-6 40-97 40-97
PRESQUE ISLE	A C D TURF	P.C. Conc. Bit. Conc. Bit. Pen. C.R. Bit. Conc. Bit. Pen. C.R. Topsoil	7,10 3.5 2-4 3.5 2-4 3-5	Base GW Subgrade GC Base GW Subgrade GC Base GW Subgrade GC Subgrade GC	24-37 - 22-38 - 25 - -	0-7 10-35 0-7 10-35 0-7 10-35 10-35
BEDFORD	A B	P.C. Conc. Bit. Conc.	6,9 5	Base GW Subgrade SW Base GW Subgrade SW	18 - 13-19 -	3 0-10 3 0-10
TRUAX	A C D	Bit. Conc. P.C. Conc. Bit. Conc.	2.5 7,9 2.5	Base (Cr. Rk.) Subbase GF Subgrade CL Subgrade SF Base GF Subgrade CL Subgrade SF Base (Cr. Rk.) Subbase GF Subgrade CL	8 18 26,>7.5' 36 26-36 32 - 20 24-33 -	0 8-21 60-80 7 8-21 60-80 7 0 8-21 60-80
SELFRIDGE	A	P.C. Conc.	10,12	Base GP Subgrade ML Subgrade SP Subgrade CL	7-20 6-34 17-41 -	2-5 25-40 13-23 68
PIERRE	A C&D	P.C. Conc. Bit. Conc.	7,10 6	Base GP Subbase CL Subgrade CL Subgrade CH Base GP Subbase CL Subgrade CL	5-11 5-12 16-38 - 5-11 6-12 -	8-15 28-53 34-57 38-79 7-10 37-50 40-54
SIOUX FALLS	A B	Bit. Conc. P.C. Conc.	2 6,9	Base GC Subbase CL Subg CL or CH Subg SP-CL Subgrade CH Subgrade CL Subgrade SC	10 12 48 Varies (h) 90 10-12 -	7-12 37-41 55-69 1-26 60-77 56 14
WATERTOWN	A B	P.C. Conc. Bit. Conc.	9,12 5	Subgrade SF-OL,SF-CL Subg OL-CL OL & SP-CL Subg GP&SP Base GP Subgrade SF-OL,OL-CL Subg SP or GP	22-25 18-28 - 10-12 16-44 -	18-25 31-38 2-4 8-12 21-42 3
FARGO	A	Bit. Conc.	1.5	Soil Cement Subb CL-SP Subg OH-CH Subgrade CH	6-7 10-12 10-12 -	- 11-16 45-56 75-92
GREAT BEND	A	P.C. Conc.	7, 10.5	Base SP or SW, SP Subg CL-SF or SF-CL Subgrade CL Subg. SP, SW & SF	5-8 Varies (h) - -	2-17 23-33 32-60 1-17

Water content (percent dry weight)

SITE	1945-1946 NORMAL PERIOD	1945-1946 FREEZING PERIOD (b)	1945-1946 FROST MELTING PERIOD (b)	1946-1947 NORMAL PERIOD	1946-1947 FREEZING PERIOD (b)	1946-1947 FROST MELTING PERIOD (b)
DOW	13.5 17.7 10.1 22.4 8.1 22.5 -	- - - - (7.9) (25.0)17.5 (43.0)19.6	(5.8)6.8 (22.8)21.7 (7.5)9.4 (23.6)22.3 10.7 33.9 -	8.3 24.5 6.6 23.6 10.0 22.8 -	(15.1) 29.0 (10.9) (25.0)23.5 (9.5) (22.6)24.4 (31.6)28.5	8.4 22.4 (14.3)9.1 (28.1)24.5 (12.3)11.3 (19.8)21.3 -
PRESQUE ISLE	10.4 17.0 6.3 13.6 9.1 16.0 -	(8.0) (16.8) (10.3) (13.6)11.0 - - (18.3)	(8.1)9.4 (17.6)18.4 11.2 15.6 (9.8)10.5 (16.8)18.4 -	-	-	-
BEDFORD	4.8 5.3 - -	(10.6) (8.0)4.5 (5.9) (6.0)4.6	-	-	-	-
TRUAX	- 6.0 27.5 19.8 10.1 35.5 20.4 - 5.6 25.9	(6.5) (8.0) (31.2)28.4 18.8 (13.1) (23.6)36.0 22.5 (8.1) (6.3) (24.5)34.5	5.2 6.1 27.7 - 11.2 34.6 - 7.4 6.8 27.2	-	-	-
SELFRIDGE	7.4 28.5 20.1 34.9	(11.5) (18.0) 16.0 -	8.3 18.5 19.7 38.5	-	(13.1) (35.9)18.4 25.6 35.1	-
PIERRE	7.4 15.9 21.6 - 6.7 15.6 12.7	(8.5) (13.1) (15.3)24.3 - (5.5) (10.6) (12.2)14.1	7.5 12.9 (17.2)15.2 21.7 6.4 12.6 14.1	-	-	-
SIOUX FALLS	7.1 21.4 29.0 15.9 33.0	(8.9) (18.3)21.0 (26.0)29.4 - (33.0)33.0	8.2 18.0 (31.0)26.1 27.3 (34.0)33.0 27.5	-	(8.7) (18.8) (27.3)29.4 15.9 (33.9)34.7 25.4	-
WATERTOWN	-	-	-	-	-	-
FARGO	-	-	-	-	-	-
GREAT BEND	-	-	-	-	-	-

Density (dry weight - lbs./cu. ft.)

SITE	1945-1946 NORMAL PERIOD	1945-1946 FREEZING PERIOD (b)	1945-1946 FROST MELTING PERIOD	1946-1947 NORMAL PERIOD	1946-1947 FREEZING PERIOD	1946-1947 FROST MELTING PERIOD
DOW	128 115 136 101 138 110 -	-	139 107 139 109 137 95 -	120 100 145 101 144 109 -	-	132 104 145 102 - - -
PRESQUE ISLE	133 117 132 115 124 129 -	-	140 114 138 114 142 120 -	-	-	-
BEDFORD	119 103 - -	-	-	-	-	-
TRUAX	- 140 95 118 129 87 113 - 139 99	-	- 138 96 - 125 88 - - 138 95	-	-	-
SELFRIDGE	112 84 103 -	(99) (112) - -	121 106 104 -	-	-	-
PIERRE	142 110 97 - 126 115 92	-	141 117 (105)102 97 137 118 95	-	-	-
SIOUX FALLS	137 103 89 97 85	-	133 110 95 90 84 87	-	-	-
WATERTOWN	-	-	-	-	-	-
FARGO	-	-	-	-	-	-
GREAT BEND	-	-	-	-	-	-

Degree of saturation

SITE	1945-1946 NORMAL PERIOD	1945-1946 FREEZING PERIOD (b)	1945-1946 FROST MELTING PERIOD (b)	1946-1947 NORMAL PERIOD	1946-1947 FREEZING PERIOD (b)	1946-1947 FROST MELTING PERIOD
DOW	100 100 100 93 100 100 -	-	92 100 100 100 100 100 -	95 100 100 100 100 100 -	-	82 100 100 100 - - -
PRESQUE ISLE	100 100 64 84 71 100 -	-	100 100 100 94 100 100 -	-	-	-
BEDFORD	33 23 - -	-	-	-	-	-
TRUAX	- 85 100 100 93 100 100 - 70 100	-	- 78 100 - 93 100 - - 83 97	-	-	-
SELFRIDGE	41 78 84 -	(45) (100) - -	59 87 86 -	-	-	-
PIERRE	100 82 80 - 56 79 41	-	100 80 (73) 63 78 76 81 49	-	-	-
SIOUX FALLS	80 93 86 59 92	-	79 90 93 85 90 83	-	-	-
WATERTOWN	-	-	-	-	-	-
FARGO	-	-	-	-	-	-
GREAT BEND	-	-	-	-	-	-

Atterberg limits, precipitation and general drainage conditions

SITE	LIQUID LIMIT	PLASTICITY INDEX	PRECIPITATION NORMAL (INCHES)	1945-1946 INCHES	1945-1946 PERCENT OF NORMAL	1946-1947 INCHES	1946-1947 PERCENT OF NORMAL	GENERAL DRAINAGE CONDITIONS
DOW	Nonplastic 29-36 Nonplastic 29-36 Nonplastic 29-36 29-36	Nonplastic 11-17 Nonplastic 11-17 Nonplastic 11-17 11-17	11	11	100	9.3	83	Paved gutters, ditches, culverts, pipe drains and catch basins. Surface water from landing strips collected by longitudinal open ditches parallel to outer edges.
PRESQUE ISLE	Nonplastic 29 Nonplastic 30 Nonplastic 30 29	Nonplastic 8 Nonplastic 10 Nonplastic 10 8	10	11	110	-	-	Surface water drained by ditches at outer edges of safety strips. Runways have under drains installed to control springs and wet areas. All open and closed joint pipe 5' below surface.
BEDFORD	Nonplastic Nonplastic Nonplastic Nonplastic	Nonplastic Nonplastic Nonplastic Nonplastic	10.2	10.1	99	3.3	33	Ditches, pipes and catch basins. Surface water from paved areas collected by catch basins. Subsurface drains at edges of original 150' runways.
TRUAX	- 19-30 (e) 43 Nonplastic 19-30 (e) 38 - - 19-30 (e) 44	- 2-9 (e) 20 Nonplastic 2-9 (e) 18 - - 2-9 (e) 20	7	7.8	111	-	-	French drains along edges of runways and apron draining into lateral sewers. Surface runoff is collected by inlets at the edges of the graded strips. Open perimeter ditches discharge into drainage ditch at southwest corner of field.
SELFRIDGE	Nonplastic 28 23 46	Nonplastic 8 5 24	7.1	8.8	124	5.7	80	Paved gutters, ditches, catch basins, field tile 2.5' below apron surface. Perforated drain tile at edge of apron. Surface water collected by catch basins. Average elevation of test area is 3.5' above that of Lake St. Clair.
PIERRE	26-33 34-42 39-48 52-86 23-29 40-43 38-41	8-16 16-26 20-26 23-48 7-12 18-23 19-23	2.4	2.1	87	-	-	Surface drainage supplemented by storm sewer system discharging into open ditches outside the landing strips. Area naturally well drained.
SIOUX FALLS	23 36-44 51 16-26 50-68 44 17	8 15-21 30 0-11 27-41 25 4	5.9	3.2	54	10.8	183	Drained by surface runoff. Temporary ponding relieved by seepage into permeable strata. Drainage poor during flood stage and intensive rainfall periods.
WATERTOWN	32-41 36-50 Nonplastic 19-24 30-43 Nonplastic	12-14 12-18 Nonplastic 5-9 12-16 	4.4	3.2	73	-	-	Surface drainage supplemented by storm sewers discharging into open ditches outside the landing area. Ponding surface water relieved by seepage.
FARGO	- 30-31 62-64 73-80	- 12 29-31 40-56	4.8	3.9	81	6.5	135	Surface drainage supplemented by complete underground drainage and storm sewer systems.
GREAT BEND	16-22 18-28 25-43 17-20	0-8 3-14 9-24 0-5	5.3	4.6	87	-	-	Ditches and drainage into ponds and sumps. Surface conditions poor during periods of high precipitation.

Depth of water table (ft.), freezing index and max. depth of frost

SITE	WATER TABLE 1945-1946 NORMAL PERIOD	1945-1946 FREEZING PERIOD	1945-1946 FROST MELTING PERIOD	1946-1947 NORMAL PERIOD	1946-1947 FREEZING PERIOD	1946-1947 FROST MELTING PERIOD	FREEZING INDEX NORMAL (DEGREE DAYS)	1945-1946 DEGREE DAYS	1945-1946 PERCENT OF NORMAL	1946-1947 DEGREE DAYS	1946-1947 PERCENT OF NORMAL	MAX. DEPTH OF FROST (FEET) 1945-1946	MAX. DEPTH OF FROST (FEET) 1946-1947
DOW	3.4 3.4 - -	7.0 7.0 7.5 5.8	3.0 3.3 1.3 0.2	3.4 3.9 3.6 3.7 1.6 2.4 1.5	3.7 3.7 3.5 4.4 1.5 3.6 2.7	2.9 2.9 2.9 3.7 1.0 3.6 1.5	1275	1421	111	965	76	4.2 4.0 4.5 2.2	4.05 3.9 3.7 2.3
PRESQUE ISLE	1.2 3.5 - 4.9 - 2.5 8.5	- 5.6-7.1 - 6.4-8.5 - 4.5-6.8 8.5	0.7 4.4-6.0 1.4 3.5-6.5 0.8 0.0-6.2 5.0	-	-	-	2061	2304	112	-	-	6.5 5.7 5.75 4.2	-
BEDFORD	(d)4.5 (d)4.5	3.5-5.5 3.5-5.5	3.5-4.8 3.5-4.8	-	-	-	680	825	121	422	62	3.3 2.2	2.3 (i) 1.9 (i)
TRUAX	4.5 6.3 7.5	1.6-5.3 5.7-6.7 5.8-7.6	1.3 5.0 6.0	-	-	-	1220	1060	87	-	-	3.8 4.0 4.9	-
SELFRIDGE	4.6	5.8	3.6	1.9-2.3 4.3-5.1	1.4-2.3 3.9-5.5	1.4-2.1 4.0-4.4	521	647	124	600	115	2.9	2.8
PIERRE	- (f) - (f)	-	- >11.0	-	-	-	1288	1026	80	-	-	4.0 3.7	-
SIOUX FALLS	8.0 4.2	8.5 15.2	4.0 11.6	5.9-7.1 12.2-13.2	6.0-7.1 13.5	5.7-7.1 13.0	1216	1311	108	1314	108	3.9 3.5	3.5 3.3
WATERTOWN	- 0.6	- 11.2	- 9.5	-	-	-	1781	2017	113	-	-	6.25 (i) 6.6 (i)	-
FARGO	5.3	6.4	3.0	-	-	-	2646	2463	93	2179	82	6.0 (i)	4.8 (i)
GREAT BEND	10.3	12.2	12.0	-	-	-	50	207	414	-	-	2.0 (i)	-

Ice segregation

SITE	1945-1946 CRYSTALS	1945-1946 LENSES THICKNESS (INCHES)	1945-1946 LENSES DESCRIPTION	1946-1947 CRYSTALS	1946-1947 LENSES THICKNESS (INCHES)	1946-1947 LENSES DESCRIPTION
DOW	Found Found Found Found Found Found 0.1-1.7	- 0-1/16 - 0-1/16 - 0-1/8 1/4-3/4	None Isolated None Isolated None Isolated 1.7-2.2'	Found Found Found None Found Found Found	- 0-1/16 - 0-1/4 - Hairline 0-1/2	None Numerous None Numerous None Numerous Numerous
PRESQUE ISLE	Found Found Found Found Found Found Found	-	None Hairline None None None None None	-	-	-
BEDFORD	None None None None	-	None None None None	-	-	-
TRUAX	Found None None Found None Found Found None	- - 0-1/10 0-0.05 0.01-0.02 - 0-0.02 0-0.02	None Hairline Numerous Numerous - None Few Numerous	-	-	-
SELFRIDGE	Found Found - -	- 0-1/8 - -	None 0.06' (Total) -	Found None - -	- 0-1/16 - -	- Few - -
PIERRE	Found Found 0.6-3.7 None None None	-	None (g) None None None None None	-	-	-
SIOUX FALLS	None None 3.6-3.9 None	- 0-1/8 0-1/8	None Hor. & Vert. (1.0-3.6) Hor. & Vert. (1/4-3" apart)	None None 3.2-3.5 None	- 1/8 1/32	None 2.4-3.2 Hor. & Vert.
WATERTOWN	-	-	-	-	-	-
FARGO	-	-	-	-	-	-
GREAT BEND	-	-	-	-	-	-

Pavement heave (feet) and traffic history

SITE	1945-1946 MIN	1945-1946 MAX	1945-1946 AVG	1946-1947 MIN	1946-1947 MAX	1946-1947 AVG	TRAFFIC PERIOD	GROSS PLANE WEIGHT (LBS)	CYCLES PER DAY
DOW	0.05 0.10 0.20 -	0.10 0.20 0.30 -	0.08 0.12 0.25 -	0.02 0.00 0.04 -	0.11 0.17 0.26 -	0.06 0.08 0.14 -	5-10/42 1-12/43 6/44 1945 1946 1947	All wts. to 60,000 max. No data No data No data	14 10 17
PRESQUE ISLE	0.10 0.05 0.15 -	0.25 0.10 0.40 -	0.18 0.06 0.22 -	-	-	-	1943 1944 1945 1945-1947	27-38,000 65,000 5-15,000 29-65,000 48-65,000 <10-30,000 No data	5 25 22 20 21 16
BEDFORD	-	-	-	-	-	-	1943-1944 1944-1945 1946-1947	10-35,000 35-60,000 50-100,000 10-30,000 No data	7 3 7 20
TRUAX	0.10 0.06 0.02	0.18 0.18 0.05	0.13 0.12 0.04	-	-	-	1942-1944 1945-1947	All wts. to 60,000 max. No data	10-100
SELFRIDGE	0.01	0.10	0.06	0.02	0.10	0.06	5-8/43 8-12/45 1945-1946 1947	60,000 4.5-15,000 15,000 120,000 No data	75 137 59 <1
PIERRE	0.00 -0.02	0.03 0.04	0.01 -0.01	-	-	-	12/42-9/43 9/43-6/44 9/44-6/46 1947	29-60,000 10-15,000 5-10,000 No data	5-200 50 4
SIOUX FALLS	0.05 0.02	0.16 0.10	0.08 0.08	0.06 0.01	0.17 0.11	0.11 0.06	6/42-11/45 1946-1947	35-65,000 No data	50 80
WATERTOWN	0.00 -0.02	0.09 0.07	0.05 0.02	-	-	-	1/42-1/43 3-12/44 1945-1946 1947	60,000 16-60,000 Commercial No data	100 100 4
FARGO	0.02	0.09	0.05	0.03	0.06	0.04	1941-1946 1941-1946 1947	60,000 5-65,000 No data	2 28
GREAT BEND	-	-	-	-	-	-	3-8/43 8/43-7/45 7/44-1/45 1-4/45 1946-1947	Lt. Planes 47-120,000 " " No data	<20 130 115 53

NOTES:

(a) P.C.C. thickened edge thicknesses shown by second figure.
(b) Figures in brackets are values for frozen soil.
(c) Principal source of water influencing frost action is from water tables at Dow through Selfridge and Fargo airfields; from water tables and infiltration through pavement at Sioux Falls, Watertown and Great Bend airfields; from infiltration through pavement at Pierre airfield.
(d) Water table depths for all periods from subsurface drainage report for 1945-1946.
(e) Atterberg limits for GF soil on portion passing No. 200 sieve.
(f) Borings in airfield area indicate absence of water table at any depth liable to influence frost action. (Evaluation report indicates depth to water table in excess of 25 feet)
(g) Thin ice layer between base and subbase.
(h) Test pits indicate extremely variable subgrade soil strata.
(i) Depth of frost determined only by thermometer or thermocouple observations.
\- Dashes in columns indicate that no observations have been made to determine the specific information.

SUMMARY OF
FACTORS INFLUENCING FROST ACTION
OTHER AIRFIELD DATA

TABLE I

FROST INVESTIGATION
PRESQUE ISLE AIRFIELD, PRESQUE ISLE, ME.
SUMMARY OF PLATE BEARING TESTS
1945-1946

TEST AREA	TEST NO.	DATE	TYPE OF TEST	STATION LOCATION	OFFSET (feet)	NEAREST EXPLORATION	MATERIAL UNDERLYING TEST PLATE (thickness in inches): PAVEMENT (A)	BASE (B)	BASE (C)	SUBGRADE	DIAMETER OF TEST PLATE (inches)	TOTAL LOAD IN POUNDS @ 0.05 inch Deflection	@ 0.10 inch Deflection	@ 0.20 inch Deflection	MAX. RATIO OF NORMAL TO FROST MELTING PERIOD LOAD FOR 0.10" DEFLECTION	AVG. THICKNESS OF PAVEMENT PLUS BASE (feet)	MAX. DEPTH OF FROST PENETRATION (feet)	THICKNESS OF FROZEN SUBGRADE (feet)
A	PBT 87	8 May 1946	Rupture	49+49	62 E of W edge	T376p	8.4 P.C.C.		32.4		24	22,000	45,000	(D)		3.4	6.5	3.1
A	PBT 98	16 June 1946	"	49+49	102 E "	T380p	8.4 "		31.2		24	41,000	(D)	(D)				
A	PBT 77	19 Oct 1945	"	52+49	74 E "	T352p	7.2 "		31.2	Compact clayey silt, sand and gravel (Till) GC classification	24	41,000	60,000	(D)				
A	PBT 88	9 May 1946	"	52+49	86 E "	T377p	8.4 "		32.4		24	32,000	48,000	(D)	1.3	3.4	6.5	3.1
A	PBT 97	16 June 1946	"	52+49	98 E "	T379p	9.6 "		31.2		24	19,500	47,000	(D)				
A	PBT 78	24 Oct 1945	Foundation Modulus	49+46	54 E "	T376p	8.4 "		32.4		30	10,000	22,000	43,000				
A	PBT 95	23 May 1946		49+48	74 E "	T376p	8.4 "		32.4		30	9,000	20,000	36,000	3.1	3.4	6.5	3.1
A	PBT 106	22 June 1946		49+48	86 E "	T380p	8.4 "		31.2		30	1,500	7,000	25,000				
A	PBT 79	25 Oct 1945		52+44	72 E "	T352p	7.2 "		31.2		30	19,000	31,000	52,000				
A	PBT 96	23 May 1946		52+48	98 E "	T379p	9.6 "		31.2		30	2,000	5,000	18,000	6.2	3.4	6.5	3.1
A	PBT 105	22 June 1946		52+47	104 E "	T379p	9.6 "		31.2		30	8,000	18,000	31,000				
C	PBT 81	29 Oct 1945	Pavement Bearing Static Load	7+20	15 W of ℄	T349p	3.6	2.5	24.0		30	50,000	(D)	(D)				
C	PBT 86	2 Nov 1945		7+30	10 W "	T349p	3.6	2.5	24.0		30	18,000	32,000	(D)				
C	PBT 89	10 May 1946		7+20	18 W "	T374p	3.6	3.6	27.0		30	16,000	32,000	(D)	1.0	2.7	5.7	3.0
C	PBT 99	19 June 1946		7+25	20 E "	T378pa	3.6	3.6	18.0		30	40,000	(D)	(D)				
D	PBT 82	30 Oct 1945		18+50	25 E "	T350pa	3.6	3.6	25.1		30	26,000	45,000	(D)				
D	PBT 90	10 May 1946		18+70	22 E "	T350pa	3.6	3.6	25.1		30	15,000	23,000	38,000	2.0	2.7	5.7	3.0
D	PBT 101	19 June 1946		18+50	30 E "	T350pa	3.6	3.6	25.1		30	15,500	28,000	49,000				
D	PBT 83	31 Oct 1945		18+65	25 W "	T375p	3.6	3.6	24.0		30	27,000	45,000	(D)				
D	PBT 91	13 May 1946		18+70	16 W "	T375p	3.6	3.6	24.0		30	13,000	20,000	36,000	2.3	2.6	5.7	3.1
D	PBT 103	20 June 1946		18+49	15 W "	T375p	3.6	3.6	24.0		30	14,000	25,000	44,000				

TEST AREA	TEST NO.	DATE	TYPE OF TEST	STATION LOCATION	OFFSET (feet)	NEAREST EXPLORATION	PAVEMENT (A)	BASE (B)	BASE (C)	SUBGRADE	DIAMETER OF TEST PLATE (inches)	Deflection in inches @ 20,000 pounds: 1st Load	10th Load	MAX. RATIO	AVG. THICKNESS OF PAVEMENT PLUS BASE (feet)	MAX. DEPTH OF FROST PENETRATION (feet)	THICKNESS OF FROZEN SUBGRADE (feet)
C	PBT 80	26 Oct 1945	Pavement Bearing Repeating Load	7+30	10 W "	T349p	3.6	2.5	24.0	Compact clayey silt, sand and gravel (Till) GC classification	24	.037	.053				
C	PBT 94	23 May 1946		7+20	10 E "	T349p	3.6	2.5	24.0		24	.074	.130		2.1	5.7	3.6
C	PBT 100	19 June 1946		7+30	30 E "	T378pa	3.6	3.6	18.0		24	.077	.096				
D	PBT 84	1 Nov 1945		18+80	15 W "	T351p	3.6	3.6	25.1		24	.056	.099				
D	PBT 92	14 May 1946		16+78	12 W "	T375p	3.6	3.6	24.0		24	.297	.421		2.3	5.7	3.4
D	PBT 104	21 June 1946		18+35	15 W "	T375p	3.6	3.6	24.0		24	.116	.156				
D	PBT 85	1 Nov 1945		18+60	25 E "	T350pa	3.6	3.6	25.1		24	.063	.079				
D	PBT 93	14 May 1946		18+80	20 E "	T357p	3.6	3.6	25.2		24	.105	.142		2.4	5.7	3.3
D	PBT 102	20 June 1946		18+20	30 E "	T350pa	3.6	3.6	25.1		24	.088	.144				

NOTES:

(A) Pavements are bituminous concrete unless otherwise noted.

(B) Bituminous penetrated crushed rock.

(C) Sand and gravel, GW classification.

(D) Deflection not reached with available maximum load.

PRESQUE ISLE AIRFIELD
SUMMARY OF PLATE BEARING TESTS
1945-1946

FROST INVESTIGATION
DOW FIELD, BANGOR, MAINE
SUMMARY OF PLATE BEARING TESTS
1945-1946

TEST AREA	TEST NO.	DATE	TYPE OF TEST	STATION LOCATION	OFFSET (in Feet) (A)	NEAREST EXPLORATION	MATERIAL UNDERLYING TEST PLATE Thickness in inches: PAVEMENT	BASE	SUBGRADE	DIAM. OF TEST PLATE (inches)	TOTAL LOAD IN POUNDS: ● 0.05 inch Deflection	● 0.10 inch Deflection	● 0.20 inch Deflection	MAX. RATIO OF NORMAL TO FROST MELTING PERIOD LOAD FOR 0.1" DEFLECTION	AVG. THICKNESS OF PAVEMENT PLUS BASE (Feet)	MAX DEPTH OF FROST PENETRATION (Feet)	THICKNESS OF FROZEN SUBGRADE (Feet)
D	PBT 91	14 Nov. 1945	Static Load	8+85	18' N	T888 pa	3.6 Bit. Conc.	49	Silty Clay (CL)	30	17,000	36,000*	(D)				
D	PBT 95	16 Apr. 1946	" "	8+75	33' N	T941 pa	3.6 " "	39		30	12,500	21,000*	47,000	1.7	4.0	4.2	0.2
D	PBT 98	17 Apr. 1946	" "	9+00	30' N	T941 pa	3.6 " "	39		30	13,000	24,000	46,000				
D	PBT 102	7 Jun. 1946	" "	8+90	10' N	T945 pa	3.6 " "	39		30	18,000	34,000	57,000				
E	PBT 92	15 Nov. 1945	" "	3+10	65' N	T886 pa	3.6 " "	32		30	21,000	34,000*	(D)	2.0	3.0	4.0	1.0
E	PBT 101	19 Apr. 1946	" "	3+17	48' N	T940 pa	3.6 " "	32		30	9,000	17,000*	32,000				
E	PBT 103	7 Jun. 1946	" "	3+15	40' N	T946 pa	3.6 " "	41		30	16,000	31,000	59,000				
F	PBT 93	16 Nov. 1945	Rupture	1+69	41' N	T887 pa	7.2 P. C. C.	22		24	24,000	40,000	(D)				
F	PBT 99	18 Apr. 1946	"	1+89	21' N	T939 pa	7.2 " " "	23		24	16,000	27,000*	47,000				
F	PBT 104	10 Jun. 1946	"	2+09	2' N	T947 pa	9.6 " " "	22		24	23,000	43,000*	(D)	1.6	2.5	4.5	2.0
F	PBT 94	19 Nov. 1945	Foundation Modulus	1+64	43' N	T887 pa	-	22		30	7,000	12,000*	20,000				
F	PBT 100	18 Apr. 1946	" "	1+85	22' N	T939 pa	-	23		30	5,000	11,000*	21,000	1.1	2.5	4.5	2.0
F	PBT 107	12 Jun. 1946	" "	2+05	3' N	T947 pa	-	22		30	6,000	11,000	17,000				
											Deflection in inches @ 20,000 lbs. 1st. Load		5th. Repetition				
E	PBT 90	9 Nov. 1945	Repeating Load	3+05	35' N	T886 pa	3.6 Bit. Conc.	32		24	.063		.083		3.0	4.0	1.0
E	PBT 97	12 Apr. 1946	" "	3+15	35' N	T940 pa	3.6 " "	32		24	.135		.168				
E	PBT 105	11 Jun. 1946	" "	3+20	35' N	T946 pa	3.6 " "	41		24	.080		.108				
D	PBT 89	8 Nov. 1945	" "	8+75	5' N	T888 pa	3.6 " "	49		24	.073		.085		3.9	4.2	0.3
D	PBT 96	8 Apr. 1946	" "	8+85	5' N	T941 pa	3.6 " "	39		24	.114		.136				
D	PBT 106	11 Jun. 1946	" "	8+70	15' N	T945 pa	3.6 " "	39		24	.080		.116				

(Base: Sand & Gravel (GW); Subgrade: Silty Clay (CL))

TEST AREA F
1946-1947

TEST AREA	TEST NO.	DATE	TYPE OF TEST	STATION LOCATION	OFFSET (in Feet) (A)	NEAREST EXPLORATION	PAVEMENT	BASE	SUBGRADE	DIAM. OF TEST PLATE (inches)	● 0.05 inch Deflection	● 0.10 inch Deflection	● 0.20 inch Deflection	MAX. RATIO	AVG. THICKNESS OF PAVEMENT PLUS BASE (Feet)	MAX DEPTH OF FROST PENETRATION (Feet)	THICKNESS OF FROZEN SUBGRADE (Feet)
F	PBT 108	23 Oct. 1946	Rupture	2+11	29' N	T969 pa	8.4 P. C. C.	22	Silty Clay (CL)	24	16,500	28,000	45,000				
F	PBT 152	9 Apr. 1947	"	2+11	21' S	T1003 pa	8.4 " " "	21		24	17,500	25,000*	37,000				
F	PBT 153	10 Apr. 1947	"	2+09	51' N	T1002 pa	8.4 " " "	18		24	17,500	32,000	53,000	2.1	2.4	3.7	1.3
F	PBT 171	4 Jun. 1947	"	2+11	9' S	T1003 pa	8.4 " " "	21		24	32,000	53,000*	(D)				
F	PBT 172	5 Jun. 1947	"	2+11	39' S	T1006 pa	8.4 " " "	16		24	14,000	28,500	48,000				
F	PBT 193	24 Jun. 1947	"	2+09	59' S	T1006 pa	8.4 " " "	16		24	31,000	47,500	(D)				
F	PBT 109	25 Oct. 1946	Foundation Modulus	2+14	28' N	T969 pa	-	22		30	7,000	11,500*	19,500				
F	PBT 154	11 Apr. 1947	" "	2+11	19' S	T1003 pa	-	21		30	5,500	9,500	16,500				
F	PBT 158	14 Apr. 1947	" "	2+09	49' N	T1002 pa	-	18		30	4,000	7,500*	14,000	1.5	2.2	3.7	1.8
F	PBT 173	5 Jun. 1947	" "	2+09	41' S	T1006 pa	-	16		30	4,000	8,000	14,500				
F	PBT 180	10 Jun. 1947	" "	2+09	12' S	T1003 pa	-	21		30	5,000	9,500	16,500				
F	PBT 194	26 Jun. 1947	" "	2+12	62' S	T1006 pa	-	16		30	6,500	10,500	18,000				

(Base: Sand & Gravel (GW); Subgrade: Silty Clay (CL))

Notes:

(A) Offsets of tests performed in Areas D & E are measured from ¢ of E-W runway. Offsets of tests performed in Test Area F are measured from ¢ of taxiway A.

(D) Deflection not reached with maximum available load.

● Values used to determine maximum ratios.

DOW FIELD
SUMMARY OF PLATE BEARING TESTS
1945-1946
TEST AREA F
1946-1947

FROST INVESTIGATION
DOW FIELD, BANGOR, MAINE

SUMMARY OF PLATE BEARING TESTS

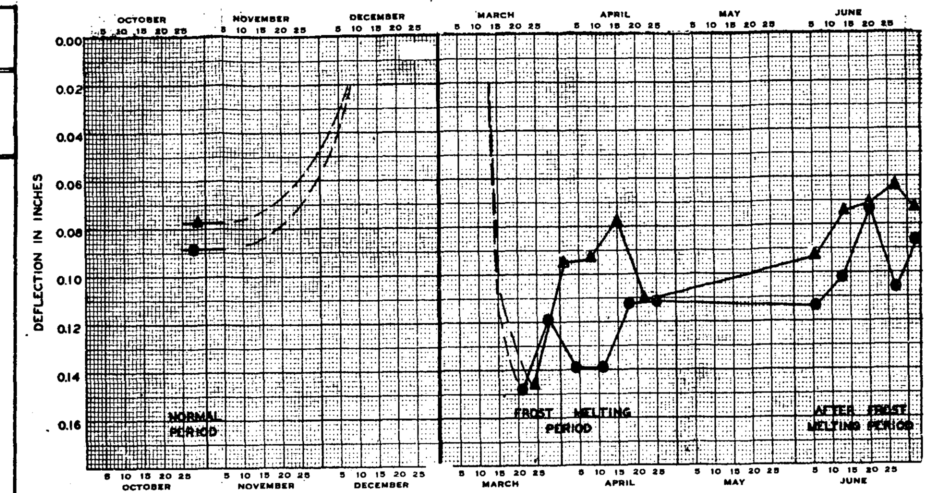
1946-1947

TEST AREA D

TEST NO.	DATE	LOAD (pounds)	DEFLECTION (inches)	AVG. DEFLECTION (inches)
PBT 122	29 Oct 1946	20,000	0.0695	
123	"	"	0.0735	
124	"	"	0.0650	
125	"	"	0.0890	
126	"	"	0.0795	
127	"	"	0.0850	0.0773
128	"	"	0.0750	
129	"	"	0.0965	
130	"	"	0.0610	
131	"	"	0.0595	
132	"	"	0.0880	
133	"	"	0.0865	
137	24 Mar 1947	20,000	0.1395	
138	"	"	0.1405	0.1463
139	"	"	0.1590	
143	1 Apr 1947	20,000	0.0895	
144	"	"	0.0835	0.0950
145	"	"	0.1120	
149	8 Apr 1947	20,000	0.0655	
150	"	"	0.1040	0.0937
151	"	"	0.1115	
159	15 Apr 1947	20,000	0.0815	
160	"	"	0.0800	0.0768
161	"	"	0.0690	
165	22 Apr 1947	20,000	0.1235	
166	"	"	0.1470	0.1108
167	"	"	0.0620	
174	6 June 1947	20,000	0.0775	
175	"	"	0.1010	0.0928
176	"	"	0.1000	
181	13 June 1947	20,000	0.0705	
182	"	"	0.0905	0.0747
183	"	"	0.0630	
190	20 June 1947	20,000	0.0690	
191	"	"	0.0805	0.0708
192	"	"	0.0630*	
198	27 June 1947	20,000	0.0870	
199	"	"	0.0570	0.0633
200	"	"	0.0550	
204	2 July 1947	20,000	0.0815	
205	"	"	0.0555*	0.0736
206	"	"	0.0855	
207	"	"	0.0720	

TEST AREA E

TEST NO.	DATE	LOAD (pounds)	DEFLECTION (inches)	AVG. DEFLECTION (inches)
PBT 110	28 Oct 1946	18,000	0.0675	
111	"	20,000	0.0680	
112	"	"	0.0855	
113	"	"	0.0915	
114	"	"	0.1345	
115	"	"	0.0730	0.0888
116	"	"	0.0685	
117	"	"	0.0775	
118	"	"	0.0780	
119	"	"	0.0740	
120	29 Oct 1946	"	0.0950	
121	"	"	0.1315	
134	21 Mar 1947	21,200	0.1445	
135	"	"	0.1485	0.1483
136	"	"	0.1520	
140	28 Mar 1947	20,000	0.1350	
141	"	"	0.1310	0.1190
142	"	"	0.0910	
146	4 Apr 1947	20,000	0.1395	
147	"	"	0.1715	0.1390
148	"	"	0.1060	
155	11 Apr 1947	20,000	0.1065	
156	"	"	0.1775	0.1397
157	"	"	0.1350	
162	18 Apr 1947	20,000	0.1005	
163	"	"	0.1560	0.1128
164	"	"	0.0820	
168	25 Apr 1947	20,000	0.0870	
169	"	"	0.1275	0.1115
170	"	"	0.1200	
177	6 June 1947	20,000	0.0920	
178	"	"	0.0975	0.1140
179	"	"	0.1525	
184	13 June 1947	20,000	0.1110	
185	"	"	0.1150	0.1018
186	"	"	0.0795	
187	20 June 1947	20,000	0.0915	
188	"	"	0.0770	0.0750
189	"	"	0.0565	
195	27 June 1947	20,000	0.1165	
196	"	"	0.0995	0.1063
197	"	"	0.1030	
201	2 July 1947	20,000	0.0915	
202	"	"	0.0855	0.0862
203	"	"	0.0815	



DEFLECTIONS - 20,000 POUND LOAD

LEGEND
▲ TEST AREA D
● TEST AREA E

NOTE
TESTS PERFORMED BY APPLYING A 20,000 POUND LOAD TO A 30" DIAMETER PLATE ON THE PAVEMENT SURFACE.

NOTES:

* Questionable reading.

All tests conducted with a 30" diameter test plate.

All tests in each test area were made within 25' square sections.
For location of individual tests, see Plate 3.

Materials underlying test plate are as follows:
Area D 0.4' Bituminous Concrete pavement
4.0' Sand and gravel base
- Silty clay subgrade
Area E 0.4' Bituminous Concrete pavement
3.2' Sand and gravel base
- Silty clay subgrade
These depths represent the average logs of 5 auger holes excavated within each 25' square.

DOW FIELD
SUMMARY OF PLATE BEARING TESTS
TEST AREAS D AND E
1946-1947

Sheet 3 of 7 TABLE 2

FROST INVESTIGATION
TRUAX FIELD, MADISON, WISCONSIN
SUMMARY OF PLATE BEARING TESTS
1945-1946

TEST AREA	TEST NO.	DATE	TYPE OF TEST	STATION LOCATION	OFFSET (in Feet)	NEAREST EXPLORATION	MATERIAL UNDERLYING TEST PLATE Thickness in inches: PAVEMENT	BASE	SUBGRADE	DIAM. OF TEST PLATE (inches)	TOTAL LOAD IN POUNDS: @ 0.05 inch Deflection	@ 0.10 inch Deflection	@ 0.20 inch Deflection	MAX. RATIO NORMAL TO FROST MELTING PERIOD AT 0.1" DEFLECTION	AVG. THICKNESS OF PAVEMENT PLUS BASE (Feet)	MAX. DEPTH OF FROST PENETRATION (Feet)	THICKNESS OF FROZEN SUBGRADE (Feet)
A	PBT-E4	29 Oct. 1945	Static Load	2+71	30N	TP-2	2.5 BC	8.2 CR; 16.3 GF	SILTY CLAY (CL)	30	26,000	40,000*	-	5.0	2.3	3.8	1.5
A	PBT-E5	22 Mar. 1946	" "	2+57	30N	TP-2	2.5 BC	8.2 CR; 16.3 GF	SILTY CLAY (CL)	30	5,000	8,000*	15,000				
A	PBT-E6	28 Mar. 1946	" "	2+63	27N	TP-2	2.5 BC	8.2 CR; 16.3 GF	SILTY CLAY (CL)	30	8,500	13,000	20,500				
A	PBT-E7	3 Apr. 1946	" "	2+65	34N	TP-2	2.5 BC	8.2 CR; 16.3 GF	SILTY CLAY (CL)	30	10,000	17,000	29,000				
A	PBT-E8	8 Apr. 1946	" "	2+58	23N	TP-2	2.5 BC	8.2 CR; 16.3 GF	SILTY CLAY (CL)	30	9,000	14,500	23,000				
C	PBT-M5	2 Nov. 1945	Foundation Modulus	3+62	25N	TP-16	6.5 PCC	26.9 GF	SILTY CLAY (CL)	30	7,000	11,000*	17,500	1.8	2.9	4.0	1.1
C	PBT-M8	27 Mar. 1946	" "	3+52	25N	TP-19	6.7 PCC	28.3 GF	SILTY CLAY (CL)	30	4,000	6,000*	10,000				
C	PBT-M9	9 Apr. 1946	" "	3+78	25N	TP-20	6.5 PCC	28.5 GF	SILTY CLAY (CL)	30	5,000	6,500	10,000				
C	PBT-M6	6 Nov. 1945	" "	1+37	25N	TP-1	6.7 PCC	39.3 GF	SILTY CLAY (CL)	30	10,000	14,000*	21,500	2.3	3.8	4.0	0.2
C	PBT-M7	20 Mar. 1946	" "	1+40	45N	TP-1	6.7 PCC	39.3 GF	SILTY CLAY (CL)	30	4,000	6,000*	10,000				
C	PBT-C6	20 Nov. 1945	Rupture	2+01	21N	TP-1	6.7 PCC	39.3 GF	SILTY CLAY (CL)	24	45,000*	(D)	(D)	1.6 @ 0.05" Defl.	3.8	4.0	0.2
C	PBT-C8	18 Mar. 1946	"	2+01	21N	TP-1	6.7 PCC	39.3 GF	SILTY CLAY (CL)	24	31,500	46,500	(D)				
C	PBT-C10	21 Mar. 1946	"	2+01	21N	TP-1	6.7 PCC	39.3 GF	SILTY CLAY (CL)	24	28,000*	50,000	(D)				
C	PBT-C13	26 Mar. 1946	"	2+01	21N	TP-1	6.7 PCC	39.3 GF	SILTY CLAY (CL)	24	34,000	(D)	(D)				
C	PBT-C15	29 Mar. 1946	"	2+01	21N	TP-1	6.7 PCC	39.3 GF	SILTY CLAY (CL)	24	42,500	(D)	(D)				
C	PBT-C17	2 Apr. 1946	"	2+01	21N	TP-1	6.7 PCC	39.3 GF	SILTY CLAY (CL)	24	42,000	(D)	(D)				
C	PBT-C20	5 Apr. 1946	"	2+01	21N	TP-1	6.7 PCC	39.3 GF	SILTY CLAY (CL)	24	38,000	(D)	(D)				
C	PBT-C24	10 Apr. 1946	"	2+01	21N	TP-1	6.7 PCC	39.3 GF	SILTY CLAY (CL)	24	40,500	(D)	(D)				
C	PBT-C7	21 Nov. 1945	"	2+98	141N	TP-13	6.0 PCC	52.5 GF	SILTY CLAY (CL)	24	38,000*	(D)	(D)	1.7 @ 0.05" Defl.	4.9	4.0	0.0
C	PBT-C9	19 Mar. 1946	"	2+98	141N	TP-13	6.0 PCC	52.5 GF	SILTY CLAY (CL)	24	28,000	44,000	(D)				
C	PBT-C12	26 Mar. 1946	"	2+98	141N	TP-13	6.0 PCC	52.5 GF	SILTY CLAY (CL)	24	22,500*	42,000	(D)				
C	PBT-C19	3 Apr. 1946	"	2+98	141N	TP-13	6.0 PCC	52.5 GF	SILTY CLAY (CL)	24	25,000	52,000	(D)				
C	PBT-C22	10 Apr. 1946	"	2+98	141N	TP-13	6.0 PCC	52.5 GF	SILTY CLAY (CL)	24	26,000	54,000	(D)				
C	PBT-C11	21 Mar. 1946	"	3+98	21N	TP-20	6.5 PCC	28.5 GF	SILTY CLAY (CL)	24	23,000	41,500	(D)		2.9	4.0	1.1
C	PBT-C14	29 Mar. 1946	"	3+98	21N	TP-20	6.5 PCC	28.5 GF	SILTY CLAY (CL)	24	22,000	41,000	(D)				
C	PBT-C21	5 Apr. 1946	"	3+98	21N	TP-20	6.5 PCC	28.5 GF	SILTY CLAY (CL)	24	24,000	48,000	(D)				
C	PBT-C25	11 Apr. 1946	"	3+98	21N	TP-20	6.5 PCC	28.5 GF	SILTY CLAY (CL)	24	19,000	40,000	(D)				
C	PBT-C16	1 Apr. 1946	"	2+98	101N	TP-3	6.5 PCC	51.5 GF	SILTY CLAY (CL)	24	20,500	39,000	(D)		4.8	4.0	0.0
C	PBT-C18	2 Apr. 1946	"	2+98	101N	TP-3	6.5 PCC	51.5 GF	SILTY CLAY (CL)	24	29,000	(D)	(D)				
C	PBT-C23	10 Apr. 1946	"	2+98	101N	TP-3	6.5 PCC	51.5 GF	SILTY CLAY (CL)	24	26,000	(D)	(D)				
D	PBT-E1	31 Oct. 1945	Static Load	12+05	23W	TP-5	2.5 BC	18.5 CR; 24.0 GF	SILTY CLAY (CL)	30	30,000	50,000*	(D)	3.7	3.8	4.9	1.1
D	PBT-E2	19 Mar. 1946	" "	12+09	15W	TP-5	2.5 BC	18.5 CR; 24.0 GF	SILTY CLAY (CL)	30	7,500	13,500*	28,000				
D	PBT-E3	25 Mar. 1946	" "	12+18	23W	TP-5	2.5 BC	18.5 CR; 24.0 GF	SILTY CLAY (CL)	30	13,000	23,000	46,000				
D	PBT-E4	27 Mar. 1946	" "	11+99	23W	TP-5	2.5 BC	18.5 CR; 24.0 GF	SILTY CLAY (CL)	30	13,000	22,000	37,500				
D	PBT-E5	1 Apr. 1946	" "	12+33	23W	TP-5	2.5 BC	18.5 CR; 24.0 GF	SILTY CLAY (CL)	30	15,500	26,000	46,000				
D	PBT-E6	4 Apr. 1946	" "	12+29	15W	TP-5	2.5 BC	18.5 CR; 24.0 GF	SILTY CLAY (CL)	30	15,500	25,000	40,500				
D	PBT-E7	9 Apr. 1946	" "	12+21	15W	TP-5	2.5 BC	18.5 CR; 24.0 GF	SILTY CLAY (CL)	30	16,000	28,000	48,000				
											Deflection in inches @ 20,000 lbs.						
											1st. Load		10th Repetition				
A	PBT-R4	30 Oct. 1945	Repeating Load	2+78	30N	TP-2	2.5 BC	8.2 CR; 16.3 GF	SILTY CLAY (CL)	24	.054		.073		2.3	3.8	1.5
A	PBT-R5	28 Mar. 1946	" "	2+70	27N	TP-2	2.5 BC	8.2 CR; 16.3 GF	SILTY CLAY (CL)	24	.189		.305				
A	PBT-R6	8 Apr. 1946	" "	2+65	23N	TP-2	2.5 BC	8.2 CR; 16.3 GF	SILTY CLAY (CL)	24	.190		.287				
D	PBT-R1	31 Oct. 1945	" "	11+98	23W	TP-5	2.5 BC	18.5 CR; 24.0 GF	SILTY CLAY (CL)	24	.048		.061		3.8	4.9	1.1
D	PBT-R2	20 Mar. 1946	" "	12+02	15W	TP-5	2.5 BC	18.5 CR; 24.0 GF	SILTY CLAY (CL)	24	.142		.196				
D	PBT-R3	25 Mar. 1946	" "	12+26	23W	TP-5	2.5 BC	18.5 CR; 24.0 GF	SILTY CLAY (CL)	24	.108		.140				
D	PBT-R4	4 Apr. 1946	" "	12+36	15W	TP-5	2.5 BC	18.5 CR; 24.0 GF	SILTY CLAY (CL)	24	.075		.113				

Offsets in Test Areas A&B are measured from the ℄ of the E-W Taxiway and the N-S Runway, respectively
Offsets in Test Area D are measured from SE edge of Apron.

PCC - Portland Cement Concrete
BC - Bituminous Concrete
CR - Crushed Rock
GF) CL) Casagrande Soil Classification

* Values used to determine maximum ratio.
(D) Deflection not reached with maximum available load.

TRUAX FIELD
SUMMARY OF PLATE BEARING TESTS
1945-1946

FROST INVESTIGATION
SELFRIDGE FIELD, MICHIGAN
SUMMARY OF PLATE BEARING TESTS
1945-1946

TEST NO.	DATE	TYPE OF TEST	STATION AND LOCATION (1)	NEAREST EXPLORATION	MATERIAL UNDERLYING TEST PLATE Thickness in Feet: Portland Cement Concrete Pavement	Base GF	Subgrade	DIAMETER OF TEST PLATE	TOTAL LOAD IN POUNDS: @ 0.05 inch deflection	@ 0.10 inch deflection	@ 0.20 inch deflection	MAX. RATIO OF NORMAL TO FROST MELTING PERIOD LOAD FOR 0.1" DEFLECTION	AVERAGE THICKNESS OF PAVEMENT PLUS BASE (in feet)	MAX. DEPTH OF FROST PENETRATION (in feet)	THICKNESS OF FROZEN SUBGRADE (in feet)
PBT-1	13 Nov. 1945	Foundation Mod.	4+57.5W, 0+32N	TP-2	0.85	0.85	ML-SF	30"	6600	9650 *	14500	1.6	1.7	2.9	1.2
PBT-2	4 Dec. 1945	" "	1+37W, 1+09.5N	TP-1	0.90	1.00	" "	"	5000	7600	12000				
PBT-3	15 Mar. 1946	" "	4+77W, 0+36N	TP-9	0.85	0.94	" "	"	4300	6200 *	10500				
PBT-4	17 Mar. 1946	" "	1+82W, 1+35N	TP-10	0.90	1.40	" "	"	6800	10700	16200				
PBT-5	5 Apr. 1946	" "	5+20W, 0+92N	TP-11C	0.90 (2)	1.14	" "	"	8050	13750	22700				
PBT-6	6 Apr. 1946	" "	2+20W, 0+92N	TP-12C	0.76	1.65	" "	"	10000	17300	----				
PBT-7	14 May 1946	" "	1+82.5W, 1+14.5N	TP-14	0.96	1.45	" "	"	4400	6300	9100				
PBT-8	16 May 1946	" "	4+82.5W, 0+64.5N	TP-15	0.90	0.80	" "	"	4800	7000	----				
PBT-9	8 Mar. 1946	Rupture	1+00W, 0+40N	TP-13W	0.90	(AVG.) 0.65	" "	24"	52000	----	----				
PBT-10	12 Mar. 1946	"	" "	"	"	" "	" "	"	51500	----	----				
PBT-11	14 Mar. 1946	"	" "	"	"	" "	" "	"	43750	----	----				
PBT-12	15 Mar. 1946	"	" "	"	"	" "	" "	"	37500	----	----				
PBT-13	19 Mar. 1946	"	" "	"	"	" "	" "	"	41000	----	----		1.5	2.9	1.4
PBT-14	22 Mar. 1946	"	" "	"	"	" "	" "	"	40750	79300	----				
PBT-15	25 Mar. 1946	"	" "	"	"	" "	" "	"	32000	72750	----				
PBT-16	27 Mar. 1946	"	" "	"	"	" "	" "	"	30000	61500	----				
PBT-17	29 Mar. 1946	"	" "	"	"	" "	" "	"	20500	62250	----				
PBT-18	1 Apr. 1946	"	" "	"	"	" "	" "	"	22500	61000	----				

(1) Offsets measured from the south edge of apron.

(2) Pavement removed before performing test.

* Tests used to determine maximum ratio.

SELFRIDGE FIELD
SUMMARY OF PLATE BEARING TESTS
1945-1946

FROST INVESTIGATION
PIERRE AIRFIELD, PIERRE, SOUTH DAKOTA
SUMMARY OF PLATE BEARING TESTS
1945-1946

TEST AREA	TEST NO.	DATE	TYPE OF TEST	STATION LOCATION	OFFSET (in Feet) (1)	NEAREST EXPLORATION	MATERIAL UNDERLYING TEST PLATE (Thickness in inches)			DIAM. OF TEST PLATE (in inches)	TOTAL LOAD IN POUNDS			MAX. RATIO OF NORMAL TO FROST MELTING PERIOD LOAD FOR 0.1" DEFLECTION	AVG. THICKNESS OF PAVEMENT PLUS BASE (Feet)	MAX. DEPTH OF FROST PENETRATION (Feet)	THICKNESS OF FROZEN SUBGRADE (Feet)
							PAVEMENT	BASE	SUBGRADE		@ 0.05 inch Deflection	@ 0.10 inch Deflection	@ 0.20 inch Deflection				
A	FMT 5	16 Nov. 1945	Foundation Modulus	35+43	62 Rt	TP-12	-	7 GF		30	7,000	10,920*	17,500	2.0	1.2	4.0	2.8
"	FMT 6	16 Nov. 1945		35+42	32 Rt	TP-11	-	5.5 "			4,200	8,840	16,140				
"	FMT 10	5 Mar. 1946		35+60	36 Rt	TP-15	-	5 "			6,140	10,180	16,530				
"	FMT 15	7 Mar. 1946		35+76	51 Rt	TP-14	-	8.5 "			3,830	7,570	13,070				
"	FMT 19	19 Mar. 1946		35+97	49 Rt	TP-16	-	7 "			3,500	5,900	9,670				
"	FMT 20	19 Mar. 1946		36+03	49 Rt	TP-16	-	7 "			3,680	5,480*	8,950				
"	FMT 23	25 Mar. 1946		36+03	36 Rt	TP-17	-	7 "			3,910	6,480	10,760				
"	FMT 24	25 Mar. 1946		35+97	36 Rt	TP-17	-	7 "			4,360	7,340	12,010				
"	FMT 28	31 Mar. 1946		36+03	26 Rt	TP-18	-	6 "			4,160	6,900	11,270				
"	FMT 29	31 Mar. 1946		35+97	26 Rt	TP-18	-	6 "			5,250	8,980	13,800				
"	FMT 34	22 Apr. 1946		36+02	60 Rt	TP-19	-	7 "			3,730	6,600	16,540				
"	FMT 35	22 Apr. 1946		35+98	60 Rt	TP-19	-	7 "			4,460	7,230	11,780				
"	PBT 7	16 Nov. 1945	Pavement Rupture	35+32	49 Rt	TP-11	7 PCC	5 GF	Gray and tan lean clay Quite plastic, contains some very fine sand (CL)	24	27,500	44,940	(A)				
"	PBT 13	6 Mar. 1946		35+60	49 Rt	TP-13	" "	9 "			21,450	44,800	62,240				
"	PBT 17	15 Mar. 1946		35+88	49 Rt	TP-16	" "	7 "			17,250	36,400*	56,850				
"	PBT 26	27 Mar. 1946		36+19	49 Rt	TP-14	" "	8.5 "			24,500	37,650	55,400	1.4	1.2	4.0	2.8
"	PBT 27	31 Mar. 1946		36+15	26 Rt	TP-18	" "	6 "			30,000	53,750	77,730				
"	PBT 37	24 Apr. 1946		36+20	76 Rt	TP-19	" "	7 "			31,580	50,880*	58,250				
"	PBT 8	16 Nov. 1945		35+47	26 Rt	TP-11	7 PCC	5 GF		24	20,400	42,500	(A)				
"	PBT 14	6 Mar. 1946		35+75	61 Rt	TP-14	" "	8.5 "			21,500	44,150*	70,000 (B)				
"	PBT 18	15 Mar. 1946		35+88	36 Rt	TP-17	" "	7 "			23,500	46,100	67,700	1.0	1.2	4.0	2.8
"	PBT 25	27 Mar. 1946		36+51	36 Rt	TP-17	" "	7 "			26,100	48,500	76,300				
"	PBT 36	24 Apr. 1946		36+20	63 Rt	TP-19	" "	7 "			22,000	44,340*	65,260				
C	PBT 2	15 Nov. 1945	Static Load	34+05	45 Rt	TP-11	1.5 AC	12 GF		30	23,700	41,950*	62,800	1.3	1.1	3.7	2.6
"	PBT 12	6 Mar. 1946		34+20	45 Rt	TP-12	"	12 "			20,680	32,040*	52,140				
"	PBT 32	19 Apr. 1946		34+39	45 Rt	TP-16	"	12 "			24,650	38,150	62,320				
"	PBT 4	15 Nov. 1945		34+15	5 Lt	TP-13	6 AC	9 GF			50,720	69,600*	(C)	1.9	1.2	3.7	2.5
"	PBT 9	5 Mar. 1946		34+20	5 Lt	TP-16	"	8.5 "			34,550	54,150	86,000				
"	PBT 21	20 Mar. 1946		34+30	5 Lt	TP-16	"	8.5 "			26,800	45,700	73,400				
"	PBT 33	19 Apr. 1946		34+45	4 Lt	TP-15	"	8.5 "			22,660	36,500*	56,850				
											Deflection in inches @ 25,000 lbs. 1st Loading	10th Repetition					
"	PBT 1	15 Nov. 1945	Repeated Loading	34+10	5 Rt	TP-12	6 AC	8 GF	Brown clay loam Some sand, plastic (CL)	24	.055	.067			1.2	3.7	2.5
"	PBT 11	6 Mar. 1946		34+17	4 Rt	TP-11	"	8 "			.094	.136					
"	PBT 22	20 Mar. 1946		34+35	5 Rt	TP-14	"	8 "			.085	.128					
"	PBT 30	17 Apr. 1946		34+40	5 Rt	TP-14	"	8 "			.108	.154					
"	PBT 3	15 Nov. 1945		34+05	45 Lt	TP-13	1.5 AC	12 GF			.121	.169			1.2	3.7	2.5
"	PBT 16	8 Mar. 1946		33+98	42 Lt	TP-13	"	12 "			.062	.098					
"	PBT 31	18 Apr. 1946		34+30	42 Lt	TP-16	"	12 "			.085	.124					

(1) Offsets in test areas A & C are measured from the SW edge of the apron and from the ℄ of Taxiway No. 4 respectively.

(A) Pavement ruptured before deflection reached
(B) Second application of 70,000-pound loading
(C) Deflection not reached with available maximum load.
* Tests used to determine maximum ratio

PIERRE AIRFIELD
SUMMARY OF PLATE BEARING TESTS
1945-1946

FROST INVESTIGATION

SIOUX FALLS AIRFIELD, SIOUX FALLS, SOUTH DAKOTA

SUMMARY OF PLATE BEARING TESTS

1945-1946

TEST AREA	TEST NO.	DATE	TYPE OF TEST	STATION	OFFSET (in Feet) (1)	NEAREST EXPLORATION	MATERIAL UNDERLYING TEST PLATE (Thickness in inches) PAVEMENT	BASE	SUBGRADE	DIAM. OF TEST PLATE (in inches)	0.05 inch Deflection	0.10 inch Deflection	0.20 inch Deflection	MAX. RATIO OF NORMAL TO FROST MELTING PERIOD LOAD FOR 0.1" DEFLECTION	AVG. THICKNESS OF PAVEMENT PLUS BASE (Feet)	MAX. DEPTH OF FROST PENETRATION (Feet)	THICKNESS OF FROZEN SUBGRADE (Feet)
B	FMT 4	10 Nov. 1945	Foundation Modulus	4+90	9 Lt	TP 1	-	-	Black silty clay, very plastic (CH)	30	2,960	4,920	7,880	1.3	0.5	3.5	3.0
"	FMT 5	11 Nov. 1945		4+92	25 Lt	TP 2	-	-			3,180	5,290*	8,560				
"	FMT 10	17 Mar. 1946		5+20	4 Lt	TP 6	-	-			2,300	4,100	6,620				
"	FMT 11	17 Mar. 1946		5+20	8 Lt	TP 6	-	-			2,690	4,650	7,750				
"	FMT 17	28 Mar. 1946		5+32	8 Lt	TP 8	-	-			2,920	4,260	6,150				
"	FMT 18	28 Mar. 1946		5+32	2 Lt	TP 8	-	-			2,430	3,990	5,730				
"	FMT 23	7 May 1946		5+32	22 Lt	TP 9	-	-			2,360	4,320	7,345				
"	FMT 24	7 May 1946		5+32	27 Lt	TP 9	-	-			2,100	3,980*	7,000				
B	PBT 3	10 Nov. 1945	Pavement Rupture	4+75	9 Lt	TP 2	6 PCC	-		24	19,120	40,250*	63,170	1.5	0.5	3.5	3.0
"	PBT 6	11 Nov. 1945		5+02	29 Lt	TP 2	"	-			12,730	31,200	59,460				
"	PBT 9	16 Mar. 1946		5+17	9 Lt	TP 6	"	-			14,380	27,200*	48,050				
"	PBT 12	18 Mar. 1946		5+20	18 Lt	TP 5	"	-			18,190	29,600	55,680				
"	PBT 14	25 Mar. 1946		5+32	19 Lt	TP 9	"	-			18,950	34,550	56,080				
"	PBT 19	29 Mar. 1946		5+19	49 Lt	TP 4	"	-			19,300	33,050	50,750				
"	PBT 20	29 Mar. 1946		5+19	9 Rt	TP 6	"	-			13,570	27,810	43,440				
"	PBT 25	8 May 1946		5+34	9 Rt	TP 8	"	-			17,400	35,300	70,370				
"	PBT 26	8 May 1946		5+34	49 Lt	TP 7	"	-			21,100	37,650	59,000				
A	PBT 2	10 Nov. 1945	Static Load	3+75	on ℄	TP 11	2 AC	10 GC	Dark brown clay loam and silty loam, plastic (CL)	30	12,050	23,400*	38,750	2.7	1.0	3.9	2.9
"	PBT 7	14 Mar. 1946		3+78	on ℄	TP 11	"	10 "			10,600	16,550	28,550				
"	PBT 13	20 Mar. 1946		4+47	2 Lt	TP 10	"	10 "			4,350	8,700*	16,000				
"	PBT 15	26 Mar. 1946		3+73	8 Lt	TP 12	"	10 "			6,500	12,300	21,550				
"	PBT 21	30 Apr. 1946		3+73	8 Rt	TP 11	"	10 "			5,840	16,100	25,350				
											Deflection in inches @ 25,000 lbs. 1st Loading	10th Repetition					
A	PBT 1	10 Nov. 1945	Repeated Load	4+25	on ℄	TP 10	"	10 "		24	.189	.248			1.0	3.9	2.9
"	PBT 8	14 Mar. 1946		4+18	on ℄	TP 10	"	10 "			.294	.473					
"	PBT 16	26 Mar. 1946		3+80	8 Lt	TP 12	"	10 "			.405	.694					
"	PBT 22	2 May 1946		3+63	7 Rt	TP 11	"	10 "			.302	.480					

(1) Offsets in test areas A & B are measured from the ℄ of Taxiway 2 and the Apron respectively.

* Values used to determine maximum ratio.

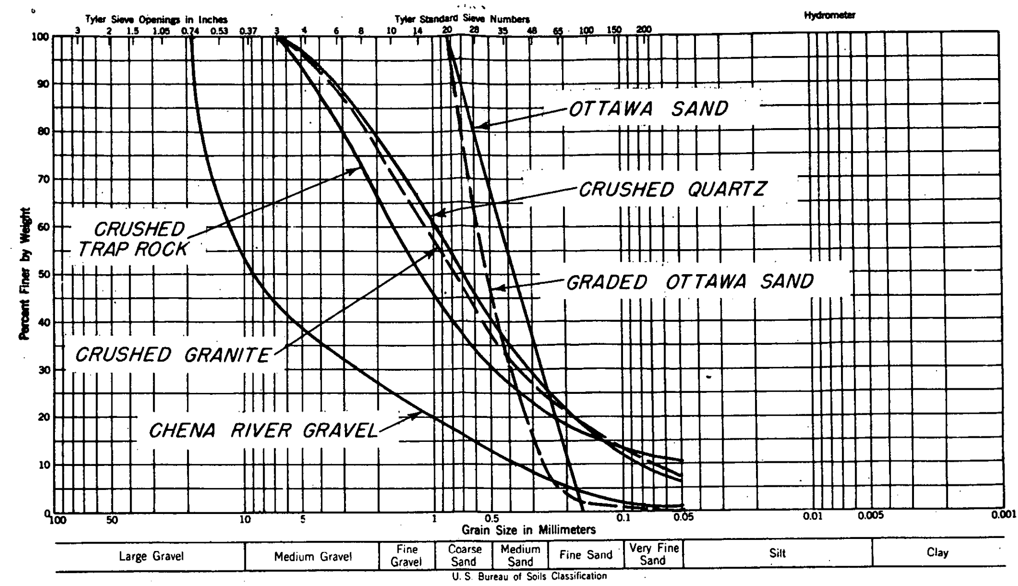
SIOUX FALLS AIRFIELD
SUMMARY OF PLATE BEARING TESTS
1945-1946

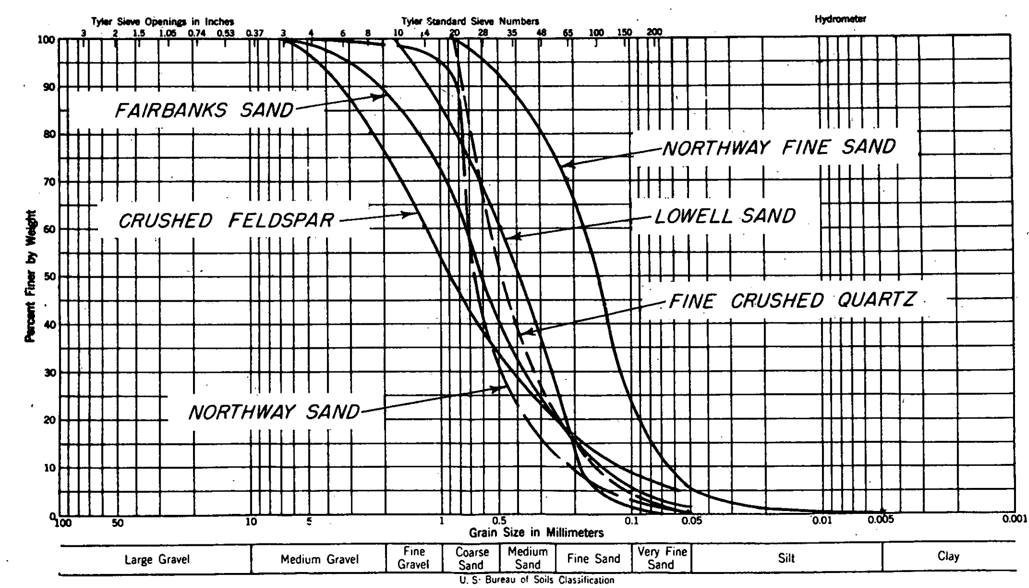
THERMAL CONDUCTIVITY OF COHESIONLESS SOILS

Tests conducted for the Corps of Engineers
U. S. Army by University of Minnesota

SOIL TESTED	SPECIFIC GRAVITY	WATER CONTENT (% dry weight)	DEGREE OF SATURATION %	THERMAL CONDUCTIVITY BTU/(FT)(°F)(HR) (1) UNFROZEN	FROZEN	UNIT DRY WEIGHT (Lbs./cu.ft.)
CHENA RIVER GRAVEL	2.70	0.2 1.6 3.9 5.2	2 15 35 24	0.500 1.208 1.362 0.728	0.502 0.841 1.178 0.483	133.3 130.2 129.3 105.3
CRUSHED QUARTZ	2.65	0.6 3.7 4.3(4.2)	4 26 19(18)	0.803 1.763 1.073	0.755 1.623 0.787	120.0 120.2 102.7
CRUSHED TRAP ROCK	2.97	0.2 1.1(1.0) 3.7	1 6(5) 22	0.272 0.374 0.573	0.272 0.350 0.548	120.0 119.8 120.3
CRUSHED FELDSPAR	2.56	0.9 1.8 4.1	7 14 32	0.501 0.628 0.786	0.468 0.608 0.781	119.7 120.2 119.9
CRUSHED GRANITE	2.67	1.7(1.6) 3.9	12(11) 27	0.559 0.798	0.481 0.757	120.4 120.1
STANDARD OTTAWA SAND (20-30 mesh)	2.65	1.0 1.7	5 9	0.547 1.065	0.326 0.381	107.6 108.7
GRADED OTTAWA SAND	2.65	0.7 5.3(4.9)	4 27(25)	0.373 1.227	0.342 0.701	107.9 108.3
FINE CRUSHED QUARTZ	2.65	0.7(0.6) 4.3	4(3) 22	0.494 1.269	0.470 ---	108.3 107.7
FAIRBANKS SAND	2.72	0.2 6.1(6.0) 10.5(10.4)	1 40(39) 70	0.301 1.267 1.469	0.300 1.132 1.850	120.4 119.7 120.4
LOWELL SAND	2.67	0.2 4.4 11.8 10.7(10.6)	1 21 54 70(71)	0.189 0.844 1.007 1.429	0.189 0.683 --- 1.788	105.5 105.9 104.8 118.5
NORTHWAY SAND	2.74	0.8 4.3 16.5(16.0)	4 19 74(72)	0.167 0.452 0.677	0.167 0.393 0.931	105.7 105.6 105.8
NORTHWAY FINE SAND	2.76	0.5 5.2 10.9	2 22 45	0.135 0.501 0.628	0.138 0.493 0.730	102.7 102.7 102.7

GRADATION OF MATERIALS TESTED





NOTES:

(1) The thermal conductivity of unfrozen specimens was determined at a temperature of approximately 40°F; the frozen specimens at approximately 25°F.

( ) The figures in parantheses, in the water content and degree of saturation columns, give the water content and degree of saturation, respectively, of the frozen specimens whenever a difference exists.

FROST INVESTIGATION
1948-1949

THERMAL CONDUCTIVITY TESTS
BY UNIVERSITY OF MINNESOTA

FROST EFFECTS LABORATORY, BOSTON, MASS.

TABLE 3

SERIES NO.	MATERIAL	SPECIFIC GRAVITY g	SPECIFIC HEAT (1) DRY SOIL BTU./(LB)(DEG.F) c	NONFROZEN							FROZEN						
				LABORATORY SAMPLE NO.	UNIT DRY WEIGHT LBS./CU.FT. γ	VOID RATIO e	WATER CONTENT PER CENT DRY WEIGHT w	PER CENT SATURATION G	VOLUMETRIC HEAT CAPACITY TOTAL SAMPLE BTU/(FT^3)(DEG.F) C_u	THERMAL CONDUCTIVITY BTU/(FT.)(DEG.F)(HR) k	LABORATORY SAMPLE NO.	UNIT DRY WEIGHT LBS/CU.FT. γ	VOID RATIO e	WATER CONTENT PER CENT DRY WEIGHT w	PER CENT SATURATION G	VOLUMETRIC HEAT CAPACITY TOTAL SAMPLE BTU/(FT^3)(DEG.F) C_f	THERMAL CONDUCTIVITY BTU/(FT)(DEG.F)(HR) k
3A	LOWELL SAND	2.66	0.20	3A-4	105.0	0.581	0.2	0.9	21.2	0.188	3A-18	106.2	0.563	0.16	0.7	21.3	0.185
	(Well graded	2.66	0.20	3A-4a	105.0	0.581	0.2	0.9	21.2	0.188	3A-19	102.9	0.612	0.16	0.7	20.7	0.164
	medium to coarse	2.66	0.20	3A-5(3)	101.0	0.645	0.2	0.8	20.4	0.169	3A-20	102.5	0.620	5.4	23.2	23.3	0.885
	sand (2)	2.66	0.20	3A-6c	106.5	0.560	16.4	78.4	38.8	1.025	3A-21	106.2	0.563	16.5	77.7	30.0	1.755
		2.66	0.20	3A-7	101.0	0.642	20.9	87.1	41.3	1.000	3A-22	102.6	0.618	18.5	79.6	30.0	1.540
		2.66	0.20	3A-8	103.0	0.611	4.5	19.7	25.3	0.718	3A-23	102.5	0.620	20.5	88.2	31.0	1.610
		2.66	0.20	3A-9	83.5	0.985	4.9	13.3	20.8	0.469	3A-24	105.0	0.581	2.2	10.1	22.2	0.460
		2.66	0.20	3A-10(3)	84.5	0.961	2.3	6.4	18.8	0.335	3A-25	106.0	0.565	4.2	19.8	23.4	0.912
		2.66	0.20	3A-11(3)	91.1	0.821	1.9	6.2	19.9	0.352	3A-26(4)	111.8	0.485	0.66	3.7	22.4	0.265
		2.66	0.20	3A-12	109.0	0.523	2.2	11.3	24.3	0.582	3A-27(4)	111.1	0.494	0.98	5.3	22.8	0.314
		2.66	0.20	3A-13	103.0	0.611	2.0	8.8	22.7	0.476							
		2.66	0.20	3A-15	89.3	0.859	2.1	6.5	19.7	0.463							
		2.66	0.20	3A-16	105.0	0.581	5.1	23.5	26.4	0.777							
		2.66	0.20	3A-17	90.8	0.826	2.1	6.8	20.1	0.437							
3B	BANGOR SAND &	2.70	0.20	3B-1	127.0	0.326	3.4	28.3	29.8	0.890	3B-4(4)	130.8	0.289	2.1	19.6	27.5	0.725
	GRAVEL (Well	2.70	0.20	3B-2	131.5	0.281	1.1	10.6	27.7	0.673	3B-5	127.1	0.326	3.6	30.2	27.7	1.038
	graded - 1½"	2.70	0.20	3B-3	127.0	0.328	9.3	77.5	36.3	1.125	3B-6	130.8	0.289	9.9	90.0	32.8	1.528
	maximum)	2.70	0.20	3B-11	133.3	0.265	0.3	3.3	27.1	0.472	3B-7	127.1	0.326	10.6	87.8	32.2	1.489
		2.70	0.20								3B-8	130.2	0.295	1.8	16.5	27.2	0.665
		2.70	0.20								3B-9	130.2	0.295	10.3	96.2	32.8	1.475
		2.70	0.20								3B-10	132.9	0.267	0.2	2.3	26.7	0.465
3C	SOMERVILLE CINDERS	2.27	0.18	3C-1	60.9	1.326	20.7(5)	35.4	23.6	0.353	3C-5	60.8	1.330	11.7	20.0	14.5	0.372
	(Well graded - 1"	2.27	0.18	3C-2	60.0	1.360	36.6	61.1	32.8	0.462	3C-6	60.8	1.330	35.5	60.7	21.7	0.700
	maximum)	2.27	0.18	3C-3	60.8	1.330	21.2(6)	36.2	23.9	0.354	3C-7	63.4	1.233	0.09	0.1	11.4	0.152
		2.27	0.18	3C-4	61.7	1.295	11.3	19.8	18.1	0.297							
		2.27	0.18	3C-8	61.9	1.288	1.1	1.9	11.9	0.173							
3D	MYSTIC SLAG	2.45	0.17	3D-1	79.1	0.935	9.1	23.9	17.5	0.188	3D-3	87.2	0.753	5.5	17.8	17.2	0.245
	(1½" maximum)	2.45	0.17	3D-2(7)	81.2	0.884	33.5	92.8	40.9	0.553	3D-4	87.2	0.753	27.7	89.2	26.9	0.673
		2.45	0.17	3D-6	92.3	0.659	0.6	2.2	16.3	0.146	3D-5	89.3	0.710	0.2	0.7	15.3	0.122
3E	WINCHESTER CRUSHED	2.91	0.20	3E-1	99.2	0.830	1.9	6.7	21.7	0.350	3E-9	102.8	0.767	1.5	5.7	21.3	0.328
	TRAP ROCK (3/4"	2.91	0.20	3E-2	100.0	0.816	2.1	7.5	22.1	0.371	3E-10(8)	102.8	0.767	25.8	97.9	33.8	1.189
	maximum)	2.91	0.20	3E-3	98.5	0.843	4.4	15.2	23.6	0.403	3E-11	106.5	0.705	2.2	9.1	22.5	0.417
		2.91	0.20	3E-4	98.5	0.843	27.2	93.8	46.5	0.849	3E-12	103.6	0.753	1.2	4.6	21.3	0.334
		2.91	0.20	3E-5(7)	99.3	0.828	28.4	99.6	48.0	2.320	3E-13(9)	106.5	0.705	22.1	92.0	33.1	0.989
		2.91	0.20	3E-6a(7)	100.0	0.816	27.7	98.9	47.7	1.850	3E-14(8)	103.5	0.754	25.0	96.5	33.6	1.060
		2.91	0.20	3E-7	102.0	0.780	2.5	9.3	23.0	0.371	3E-15	104.7	0.734	2.0	7.9	22.0	0.375
		2.91	0.20	3E-8	102.0	0.780	26.7	99.6	47.7	1.479	3E-17	102.5	0.772	0.2	0.7	20.6	0.157
		2.91	0.20	3E-21	112.4	0.616	0.2	0.1	22.7	0.196	3E-18	111.3	0.631	0.1	0.5	22.3	0.196
3F	ASPHALTIC BITUMINOUS	2.60	0.20	3F-1(11)	150.0(10)	0.082	0.0	0.0	30.3	0.690							
	CONCRETE	2.60	0.20	3F-2(12)	150.0(10)	0.082	0.0	0.0	30.3	0.686							
3G	BLENDED BITUMINOUS CONCRETE AGGREGATE	2.81	0.20	3G-1(3)	133.5	0.312	0.0	0.0	26.7	0.313							

NOTES

(1) Assumed
(2) Minimum dry density 92.9 lbs/cu.ft.
Maximum dry density 110.9 lbs/cu.ft.
(3) Sample not properly sealed; some water leaked into sample during test.
(4) Slight leaking into cylinder during test.
(5) Average - w = 14.2% - top of sample
w = 27.3% - bottom of sample
(6) Non-uniform water content.
(7) Test results are not consistent with results of other tests.
(8) Cover lifted off cylinder due to heaving. Results slightly affected by leaking of brine into specimen during test.
(9) Average heave 0.08". Slight leaking.
(10) Per cent Bitumen 4.5%. Specific Heat of Bitumen = 0.22 BTU/(Lb.)(Deg.F)
(11) Diameter of Cylinder = 4.70".
Length = 11.94"
(12) Diameter of Cylinder = 4.72"
Length = 11.92"

RANGE OF STONE SIZES - SERIES 3E

3E-1 & 3E-9	(1/2" - 3/4")
3E-2 & 3E-10	(1/2" - 3/4")
3E-3 & 3E-11	(1/8" - 3/8")
3E-4 & 3E-12	(3/8" - 1/2")
3E-5 & 3E-13	(1/8" - 3/8")
3E-6a & 3E-14	(3/8" - 1/2")
3E-7 & 3D-15	50%(1/2" - 3/4")
	25%(3/8" - 1/2")
	25%(1/8" - 3/8")
3E-8 & 3E-17	(1/2" - 3/4")
3E-21 & 3E-18	(1/8" - 3/8")

FROST INVESTIGATION
1945-1946

THERMAL PROPERTIES OF SOILS
SUMMARY OF TEST DATA

FROST EFFECTS LABORATORY
BOSTON, MASS. JUNE, 1946.

TABLE 4

OBSERVED TEMPERATURES AT DEPTHS OF FROST PENETRATION

AIRFIELD	YEAR	TEST AREA	TYPE OF TEMPERATURE MEASURING INSTALLATION	THICKNESS OF PAVEMENT AND BASE (INCHES)		CLASS OF FROZEN SOIL	MEASURED DEPTH OF FROST PENETRATION (INCHES)	TEMPERATURE AT DEPTH OF FROST PENETRATION (°F)	DISTANCE BETWEEN TEMPERATURE INSTALLATION AND TEST PIT (FEET)
				AT TEMPERATURE INSTALLATION	AT TEST PIT				
Presque Isle	1944-45	B	Thermocouple	30	30	GC	68	32.7	40
				30	31	GC	71	32.7	37
	1945-46	A	Thermocouple	31	31	GC	32	32.7	47
					31	GC	68	33.2	47
		C	Thermocouple	30	31	GC	42	32.7	12
					30	GC	68	31.7	35
					29	GC	65	31.9	48
		Turf	Thermocouple	-	5*	GC	18	32.1	25
					2*	GC	36	30.7	10
					4*	GC	32	30.3	45
Dow	1944-45	A	Thermocouple	20	19	CL	47	35.1	39
					20	CL	45	34.9	45
		Turf	Thermocouple	-	7*	CL	24	34.0	14
	1945-46	D	Thermometer	42	41	CL	50	33.1	28
		E	Thermocouple	38	37	GW	31	32.4	38
					36	GW	36	33.5	28
					37	CL	19	31.4	35
					37	CL	48	32.0	35
		Turf	Thermocouple	-	2*	CL	24	33.3	10
					4*	CL	24	32.9	15
					1*	CL	26	33.7	20
	1946-47	E	Thermometer	38	38	-	38	31.4	37
					40	CL	44	31.0	28
					38	CL	47	31.8	29
					36	CL	45	32.1	37
					38	-	25	32.0	49
					38	CL	41	32.3	49
		Turf	Thermometer	-	4*	CL	26	31.5	22
					2*	CL	26	31.9	41
					4*	CL	26	31.9	40
Sioux Falls	1945-46	A	Thermocouple	12	12	CL, CH	31	33.8	36
					12	CL, CH	41	32.4	36
	1946-47	A	Thermometer	12	10	CL	42	33.0	30
		B	Thermometer	6	6	CH	40	32.2	25
Pierre	1945-46	A	Thermocouple	14	12	CL-SF	48	33.1	25
					12	CL-SF	22	31.7	25
Fargo	1944-45	A	Thermometer	8	7	SF,OH-CH,CH	46	31.3	15
Watertown	1944-45	Turf	Thermocouple	-	*	SF-OL,OL,GF	42	34.5	18
Truax	1945-46	C	Thermometer	42	43	GF	41	31.5	16
					42	CL	48	32.0	20
		D	Thermometer	54	54	GF	48	31.9	20
					54	CL	59	32.1	30
Bedford	1945-46	A	Thermocouple	22	24	SW	26	32.1	21
					24	GW	24	30.2	17
					24	SW	36	32.6	33
					25	SW	40	32.9	33
		B	Thermometer	18	18	SW	26	31.8	8
					18	SW	20	30.6	16
					18	SW	25	32.1	24

NOTE: * Topsoil.

OBSERVED TEMPERATURES
AT DEPTHS OF FROST PENETRATION

SUMMARY OF AIRFIELD PAVEMENT FAILURES WHERE FROST ACTION WAS CONTRIBUTING CAUSE

AIRFIELD	LOCATION OF DISTRESSED AREA	PAVEMENT: TYPE	PAVEMENT: THICKNESS INCHES	PAVEMENT: FLEXURAL STRENGTH OF CONCRETE LBS./SQ.IN.	BASE: TYPE	BASE: THICKNESS INCHES	BASE: SATURATED	BASE: FROST SUSCEPTIBLE	BASE: CBR OR SUBGRADE MODULUS (k)	SUBGRADE: AIRFIELD CLASSIFICATION	SUBGRADE: SATURATED	SUBGRADE: FROST SUSCEPTIBLE	SUBGRADE: ATTERBERG LIMITS P.L.	SUBGRADE: ATTERBERG LIMITS L.L.	SUBGRADE: CBR OR SUBGRADE MODULUS (k) IN PLACE UNLESS OTHERWISE NOTED	GROUND WATER DEPTH (FEET)	SUB SURFACE DRAINAGE	DISTRESS OR FAILURE: DESCRIPTION	DISTRESS OR FAILURE: DATE FIRST NOTED	DISTRESS OR FAILURE: REPORTED CAUSE	FREEZING INDEX FOR WINTER PRECEDING DISTRESS	DEPTH OF FROST PENETRATION	TRAFFIC: PERIOD OF USE PRIOR TO LAST DATED REPORT OF DISTRESS	TRAFFIC: PREDOMINATE GROSS PLANE WT. USING FIELD IMMEDIATELY PRECEDING DISTRESS (LBS.)	PRESENT EVALUATION (4) LBS. GROSS PLANE WT.: NORMAL PERIOD	PRESENT EVALUATION (4) LBS. GROSS PLANE WT.: FROST MELTING PERIOD	REMARKS
DOW FIELD, BANGOR, MAINE	Apron widening, turnaround and warm-up apron 10,000 sq. yds.	Non-reinforced concrete	7	600	Bank run sand and gravel	17	100%(2)	Borderline	k = 315 (1)	CL	100%	Yes	19	30	CBR = 4 (1)	Approx. 2 to 4	Around pavement periphery	Concrete developed random cracks and some corner cracks (9% of slabs cracked by spring '43 and 30% by fall '46.)	Winter 1942-43	Settlement of subgrade, low strength of concrete and frost action.	1550	55"(3)	Fall 1942 to 1945	60,000	< 30,000	< 30,000	
PRESQUE ISLE AIRFIELD PRESQUE ISLE, MAINE	Portion of N-S Runway 500 sq.yds.	Asphaltic concrete	3.7 Avg.		Bank run sand and gravel	4 to 44 12.3 Avg.	30% to 60% (1)	Borderline	CBR = 80 (1)	GF	70% to 80%	Yes	20	30	CBR = 10 (1)	Approx. 2 to 6	At edges of runway	Pavement developed weaving in the spring of 1943 as frost came out of the ground.	Spring 1943	Severe frost action in subgrade resulting in its softening during spring thaw.	2280	65"(3)	Not given	60,000	60,000	13,000	
BRIDGETON - MILLVILLE AIRFIELD MILLVILLE, N. J.	Portions of NE-SW and NW-SE Runways from 50 to 1,000 sq. ft.	Asphaltic concrete	2		None					GF	48% to 94%	Yes	19	28	CBR = 16 (1)	Not given	At edges of runways	Localized cracking and rutting (1" deep) developed in March and April 1943 and pavement pulled out under traffic in some areas.	Spring 1943	Subgrade not compacted to maximum density. Inadequate maintenance of drainage and pavement. Failures started when frost was coming out of the ground.	Dec.'42 72 Jan.'43 31 Feb.'43 69 Alternate freezing and thawing	19"(3)	Jan. 1943 to Aug. 1943	13,000	< 10,000	< 10,000	
MORRIS FIELD CHARLOTTE, N. C.	15,000 sq. yds. scattered areas principally in center of 3 runways and particularly bad at intersections	Sand asphalt	2		Crusher run stone	3 to 8	100%	No	Not reported	Micaceous clays CH	85%	Yes	11 to 61	41 to 77	CBR = 8 (1)	Not given	Not adequate where failed.	Heaving of subgrade and overloading caused long longitudinal cracks which later branched out. Percolation of surface water hastened deterioration. Stone base impregnated with wet clay and frost action caused heaving which resulted in reduced bearing power.	Mid 1942	Foundation too weak to support imposed load. Micaceous clays have high swell factor and not suitable for foundations. Stone base course poorly graded.	Dec.'42 16 Feb.'43 24 Mar.'43 7 Alternate freezing and thawing	10"(3)	June 1941 to Aug. 1943	1942-118 cycles per day-18,000 1943-151 cycles per day-20,000	< 10,000	< 10,000	
GLASGOW AIRFIELD GLASGOW, MONTANA	Scattered small to one large area on SE end of NW-SE runway	Asphaltic concrete	5		Processed bank run sand and gravel with 15% oversize crushed.	8	Not reported.	No	CBR = >80 (1)	CL	Not reported	Yes	20	35	CBR = 5 to 30(1)	Indefinite but deep	Not reported	Area showed no signs of distress until frost left the ground when depressions began to appear which in some instances increased to a depth of 6" with accompanying cracking.	Probably Spring 1943	Excessive moisture in subgrade when pavement laid and at some points saturation due to ponding at edges of pavement through lack of drainage and insufficient base as a contributing factor.	Winter 1942-1943 2554	70"(3)	May thru July 1943	50,000	15,000	< 15,000	
HARVARD AIRFIELD HARVARD, NEBRASKA	Taxiway 2 and small areas of south and north ends of N-S Runway Edge of Apron	Portland cement concrete	11-8-11 14-10-14	Taxiway 2 490 Runway 420 610	None None None					CL, ML CH, OL	90% to 100%	Yes	22	44	k = 145(2) k = 200(1)	20	Limited (reported adequate)	Localized areas of bad checking, cracking, settlement, spalled expansion and contraction joints, water seepage from contraction joints and cracks.	Not reported	Insufficient thickness of taxiway and apron pavement for unfavorable subgrade conditions existing during thawing.	Winter 1943-1944 283	25"(3)	Aug. 1943 to June 1944	60,000	< 30,000 40,000	< 30,000 32,000	
CUT BANK SATALLITE AIRFIELD CUT BANK, MONTANA	Portions of taxiway 1, 2 and 3, west end of E-W Runway and NW end of NW-SE Runway	Asphalt concrete	5-6½		Pit run gravel	5½ to 8	26% to 96%	Yes	CBR = 25 to >80 CBR of 25 under taxiway 1 and 3.	ML	32% to 63%	Yes	12 to 20	19 to 55	CBR = 3 to 12 (1)	>15	Poor at edge of Runways	Areas showed signs of distress when frost left ground in spring months, as these areas were used, they started to rut and failed completely.	When frost left ground (probably spring 1943)	Improper compaction of fill under runways, poor drainage, weak subgrade materials, placing of asphalt concrete pavement on frozen subgrade and placing during cold and wet weather. Insufficient base.	Winter 1942-1943 1804	3-5 ft.	Spring '43 to August 31, 1943	50,000	< 10,000	< 10,000	
BUCKLEY FIELD, DENVER, COLORADO	E-W and NW-SE Runway, taxiways A, B, C, D, E, F, G, W and X	Portland cement concrete	8-6-8	350 to 590	None					CH, CL, SF SF-CL CL-SF	Average 74%	Yes	21	43	k = 38 (1) k = 27 (2)	Not reported	Not reported	All airfield pavements in poor condition due to existence of cracking, scaling and heaving.	Not reported	Not reported	Winter 1943-1944 Dec. = 81 Jan. = 49 Feb. = 111 Mar. = 40 (alternate freezing and thawing)	24"(3)	Jan. 1942 to 1 Aug. 1944	20,000	< 30,000	< 30,000	
CAMP WILLIAMS AIRFIELD, CAMP DOUGLAS, WISCONSIN	Lanes in Apron	Portland cement concrete	8	735	None					SP, SF	100% (Est.)	Yes	Non-plastic		k = 117 (1)	3 to 5	Tile drains around edge of pavement	Heaving and cracking of concrete apron along lanes cleared of snow. Additional cracks in other sections of apron.	April 1943	Frost action caused cracking of apron. Head of water under apron causing bleeding at cracks and joints.	1942-1943 1898	40-55 inches maximum penetration below paved areas	1942-1943	35,000	30,000	< 30,000	
OTIS FIELD, CAMP EDWARDS, MASS.	Main service apron, extension to service apron, Runways (original)	Portland cement concrete Bituminous concrete	7 4½-6½	470	Bank run Sand and Gravel Compacted gravelly sand subgrade.	6 8 to 12	14% to 89% Not reported	No 1942 construction contains some areas that are frost susceptible	k = 415 (1) CBR = 65 (1)	SW, GW SF, GP SW, GW SF, GP	60% to 100%	Isolated Pockets	18	21	CBR = 35 (1)	20 to 40	At edge of runways, and taxiways	Apron cracked and heaved as much as 1" at joints between slabs. Runway heaves of 4-6" found in 15% of pavement. Surface stones in unsealed portion of runways loosened and were picked out by traffic.	Feb. 1944 March 1943	Poor compaction and inorganic matter in base. Poor drainage and lack of seal coat, pockets of poor material found in 1942 constructed areas. Frost action caused cracking.	1942-1943 420 1943-1944 328	2 ft.	Jan. 1942 to Jan. 1944 May 1944 to Nov. 1944	32,000 12,000 to 15,000	< 30,000 80,000	< 30,000 < 10,000	No detrimental frost action has occurred since the installation of an open joint subsurface drainage system and the application of a bit. seal coat on the runway pavement during the summer of 1945
BILLY MITCHELL FIELD CUDAHY, WISCONSIN	800 ft. at West end of E-W runway, 1200 ft. at SW end of NE-SW runway, entire 2400 ft of apron taxiway	Bituminous concrete	4		Pit run gravel. Crushed stone.	7	Not reported	No	CBR = 80 (1)	CL	88% to 91%	Yes	14 to 21	24 to 43	CBR = 3 to 6(1)	>6	Rock filled trenches 25 ft. c. to c. in herring bone arrangement. Also at edge of runways.	E-W runway and taxiway showed some cracking and rutting in summer of 1942. During spring of 1943 additional cracks and ruts 2" and 3" deep appeared in both runways. Rutting especially bad where taxiway joins runway.	Summer 1942 Spring 1943	Insufficient base for traffic imposed, inferior pavement and base materials a contributing factor.	1942-1943 1296	50"(3)	June to Sep. 1942 April to June 1943	28,000 to 60,000 60,000	12,000	< 12,000	

NOTES

(1) Normal period
(2) Frost melting period
(3) Frost penetration predicted from Figure 3 of Plate 19.
(4) Based on Engineering Manual, Part XII, Chap. 2 dated May 1947, and Chap. 3 and 4 dated July 1946.

SUMMARY OF AIRFIELD PAVEMENT FAILURES WHERE FROST ACTION WAS CONTRIBUTING CAUSE

AIRFIELD	LOCATION OF DISTRESSED AREA	PAVEMENT			BASE					SUBGRADE						GROUND WATER DEPTH (FEET)	SUB SURFACE DRAINAGE	DISTRESS OR FAILURE			FREEZING INDEX FOR WINTER PRECEDING DISTRESS	DEPTH OF FROST PENETRATION	TRAFFIC		PRESENT EVALUATION (4) LBS. GROSS PLANE WT.		REMARKS
		TYPE	THICKNESS INCHES	FLEXURAL STRENGTH OF CONCRETE LBS./SQ.IN.	TYPE	THICKNESS INCHES	SATURATED	FROST SUSCEPTIBLE	CBR OR SUBGRADE MODULUS (k)	AIRFIELD CLASSIFICATION	SATURATED	FROST SUSCEPTIBLE	ATTERBERG LIMITS P.L.	ATTERBERG LIMITS L.L.	CBR OR SUBGRADE MODULUS (k) IN PLACE UNLESS OTHERWISE NOTED			DESCRIPTION	DATE FIRST NOTED	REPORTED CAUSE			PERIOD OF USE PRIOR TO LAST DATED REPORT OF DISTRESS	PREDOMINATE GROSS PLANE WT. USING FIELD IMMEDIATELY PRECEDING DISTRESS (LBS.)	NORMAL PERIOD	FROST MELTING PERIOD	
KEARNEY AIRBASE KEARNEY, NEBRASKA	Approximately 150 ft. of taxiway 1a and approximately 100 ft. into the apron. Also taxiway 2, 3, 1b and east edge of apron	Portland cement concrete non-reinforced.	12½-8½-11	390 to 500	Sand-Soil base Sand	8	Not reported	No	Not reported	CL,CH ML,SF	86%	Yes	21	37	k = 143 (1) k = 101 (2)	18 - 30	Good (no details)	Excessive cracking of slab, particularly at the joints.	March 1943	Pavement constructed on localized area of adverse subgrade. 60% of traffic passes over this area and planes are also warmed up.	1942-1943 656	35"(3)	Feb. 1943 to Aug. 1943	74,000	<30,000	<30,000	
STROTHER AIRFIELD, WINFIELD, KANSAS	Extensive areas of NE-SW runway, NW-SE runway and NS Runway No. 1. Center portion of taxiway 2. Limited areas of NW-SE, NE-SW and N-S No. 1 and taxiways No. 1 and 2.	Asphalt concrete	1½ to 2		Cement treated gravel on clay gravel subbase. Clay gravel under taxiway Nos. 2 and 2a.	6 4 7½	Base = 47% Average subbase = 91% 91%	Base Yes Subbase Yes	CBR = 80 /(1) 20 (1) 20 (1)	CL, CH	61%	Yes	16 to 24	30 to 54	CBR = 7 to 11(1)	High water table not prevalent	No subsurface drainage.	Excessive rutting and shoving of surface course developed on SW end of NE-SW runway. NW end of NW-SE runway and in west quarter of taxiway No. T-2. North third of N-S runway failures consisted of rutting, cracking, and pot holes.	April 1944 Spring 1945	Moisture content of base above optimum at time of cement stabilization thus preventing proper cementation of the base course material, which has a high P. I. Low CBR, and becomes unstable when saturated. Excess water was probably trapped in base and subgrade, cycles of freezing and thawing during 1943 and 1944 deteriorated base.	1944-1945 Maximum freezing index = 35	9"(3)	16 Dec. 1942 to 1 June 1944	5,000 to 15,000	20,000 to 30,000 10,000	<10,000 <10,000	
COFFEYVILLE AIRFIELD COFFEYVILLE, KANSAS	Extensive areas of N-S No. 1, NE-SW, and NW-SE runways and taxiways No. 1 and 2.	Asphalt concrete (before reconstruction)	1½		Gravel. Water bound chat subbase.	6	Highly Saturated	Yes	Not reported	CL, CH ML	75%	Yes	11	28	CBR = 7 (1)	High water table not prevalent	No subsurface drainage system	Taxiway 2 completely failed. Other areas showed signs of distress by rutting. Ruts 2" deep were formed when testing by power grader.	May 1943	Unstable base course, high P.I. low CBR and an abnormal moisture content due principally to heavy rainfall and adverse weather conditions during construction.	Jan. 1943 92 Mar. 1943 66 (Alternate freezing and thawing)	19"(3)	Nov. 1942 to Dec. 1943	8,000	< 10,000	<10,000	
COFFEYVILLE AUXILIARY FIELD NO. 3 COFFEYVILLE, KANSAS	Areas on NE-SW and NW-SE runways.	Portland cement concrete	6	575 to 685	None					CL-ML CL,CH	96%	Yes	19 to 29	30 to 65	k = 39(1) k = 24(2)	Not reported	Not reported	Pavements cracked severely under traffic, pavements generally in poor condition. Seepage of water from cracks and joints noted in many areas.	Not reported	Cracked areas are concentrated in areas having thin pavement sections varying from 3½ to 5½". Pavement constructed under adverse weather during winter of 14 Jan. 1943 to 24 Feb. 1943.	1943-1944 Dec. = 82 Feb. = 32 (Alternate freezing and thawing)	15"(3)	Feb. 1943 to Feb. 1944	4,500	< 30,000	< 30,000	
WEAVER AIRBASE RAPID CITY, SOUTH DAKOTA	E-W Runway. Runway shoulders.	Asphalt concrete	3½ 1½		Gravel	8 6	Reported high	Yes	CBR = 60 (Est.)	CH, CL	92%	Yes	21 (Average)	48	CBR = 4	Reported as very deep	No subsurface drainage system	Rutting under traffic in joint sections on runway. Displacement by plane wheels of 1½" A.C. pavement, 6" base course and several inches of saturated subgrade on the runway shoulders.	Mar. 1943	Moisture penetration into base course, and inability to support load under existing moisture content. Leakage of water into base course and subgrade through longitudinal joints accelerated failure.	1942-1943 1097	45"(3)	Oct. 1942 to June 1943	48,000	<10,000	< 10,000	Original 3½" A.C. pavement rebuilt July 1943 with 7" concrete slab.
GODMAN FIELD AIRPORT, FORT KNOX, KENTUCKY	100 ft. of taxiway strip. N-S runway E-W runway Turnaround at NE end of NE-SW runway	Asphalt concrete	1 to 3½		Penetration and water bound macadam	3 to 5	Not reported	No	Not reported	CL	Not reported	Yes	24	38	CBR = 6 to 12(1)	Undetermined (Not a factor)	Rock drains under runway	Areas showed signs of distress and began map cracking. Failure was progressive with break-up, ravelling and complete deterioration with ruts approximately 6" deep. Greatest distress occurred at the south end of the N-S Runway where the majority of heavy aircraft made first contact.	Mar. 1943	Inadequate base. Surface water percolating through wearing surface contributed to final failure.	Dec. 1942 101 Jan. 1943 28 Feb. 1943 53 Mar. 1943 57	23"(3)	Oct-Feb '42 Feb-Apr '42 Apr-Aug '42 Aug 1942 - Mar. 1943 Mar-Aug '43	8,000 22,000 12,000 27,000 33,000	<10,000	< 10,000	
BUFFALO MUNICIPAL AIRPORT, BUFFALO, NEW YORK	Portions of E-W runway NE-SW runway, NW-SE runway and east taxiway	Bit. conc. Penetration surface course	2 2		Stone Stone	7 7	Not reported	No	CBR = 78 (1)	ML	59% (fill) 100% (cut)	Yes	14 to 18	22 to 25	CBR = 9 to 34(1)	Not reported	At edges of runways. Poor working order and badly clogged.	Soft spongy surface which is badly cracked and in a generally sunken condition. Bird baths and seepage into base and subgrade.	Not reported	Insufficient thickness of pavement for heavy traffic. Penetration macadam has insufficient amount of bitumens. Low density of fill areas.	1943-1944 629	3 ft.	1944 Principally P-40, C-47, C-46 51,795 landings and take-offs.	45,000	15,000 10,000	< 10,000 < 10,000	
WATERTOWN AIRPORT, WATERTOWN, N. Y.	Taxiways Nos. 1 and 3.	Asphalt concrete	2		Bank run gravel.	20	100%	Yes	CBR = 8(1)	GC-ML	100%	Yes	30 to 35	41 to 48	CBR = 7	Not reported	None	Soft spongy surface consistently under water during wet weather. Asphaltic concrete surfacing was easily peeled off by wheels of a two ton truck and free water spouted from saturated base course under load of truck.	Not reported	Poor surface and subsurface drainage. Excess water ponds over asphalt pavement and seeps into base course weakening the subgrade. Insufficient thickness of pavement. Poor base course.	1943-1944 1042	45"(3)	1943 (light use)	1,200 to 2,100	<30,000	<10,000	
SCHENECTADY AIRPORT, SCHENECTADY, N. Y.	Sections of E-W, N-S, NW-SE runway and NE-SW taxiway and N-S taxiway	Asphalt concrete	2 to 3		Stabilized bank run sand and gravel.	7 to 12	63%	Yes	CBR = 30(1	SF-GF	77%	Yes	Non-plastic		CBR = field 25(1) to 28 Lab. 40 to 27	Not reported	Edge of pavement	Badly failed areas characterized by a rutty, soft, spongy surface with numerous cracks.	Not reported	Low bearing values of base course brought about by low density and excess moisture filtering through open joints, cracks and porous areas.	1943-1944 1072	2' to 3'	15 May 1945 to 15 June 1945	1,100 to 3,300	<30,000	<10,000	
LEWISTON AIRFIELD, LEWISTON, MONTANA	SW end of NE-SW runway NW end of NW-SE runway perimeter taxiways "D-D" taxiway, "A" taxiway east end of E-W runway	Asphalt concrete	6		Gravel	6 to 12	76%	Yes	CBR = 80/ (1)	CL	71%	Yes	14 to 25	31 to 52	CBR = 7 (1)	100 / below surface	Not reported (Poor)	Pavement cracked and depressions 2" to 6" deep were found. Ruts and break through by wheels when frost left ground.	March 1943	Saturation of base course, weak subgrade, poor drainage, poorly compacted base course, "Chinook" weather causing excessive freezing and thawing.	1942-1943 1221 (Great Falls weather data used as base)	3' to 5'	Jan. to Apr. 1943	48,000	20,000 to 10,000	< 10,000	160,000 sq. yds. of pavement failed during 5 months of use by Very Heavy Bombers

NOTES

(1) Normal period
(2) Frost melting period
(3) Frost penetration predicted from Figure 3 of Plate 19.
(4) Based on Engineering Manual, Part XII, Chap. 2 dated May 1947, and Chap. 3 and 4 dated July 1946.

SUMMARY OF AIRFIELD PAVEMENT FAILURES WHERE FROST ACTION WAS CONTRIBUTING CAUSE

AIRFIELD	LOCATION OF DISTRESSED AREA	PAVEMENT: TYPE	PAVEMENT: THICKNESS INCHES	PAVEMENT: FLEXURAL STRENGTH OF CONCRETE LBS/SQ.IN.	BASE: TYPE	BASE: THICKNESS INCHES	BASE: SATURATED	BASE: FROST SUSCEPTIBLE	BASE: CBR OR SUBGRADE MODULUS (k)	SUBGRADE: AIRFIELD CLASSIFICATION	SUBGRADE: SATURATED	SUBGRADE: FROST SUSCEPTIBLE	SUBGRADE: ATTERBERG LIMITS P.L.	SUBGRADE: ATTERBERG LIMITS L.L.	SUBGRADE: CBR OR SUBGRADE MODULUS (k) IN PLACE UNLESS OTHERWISE NOTED	GROUND WATER DEPTH (FEET)	SUB SURFACE DRAINAGE	DISTRESS OR FAILURE: DESCRIPTION	DISTRESS OR FAILURE: DATE FIRST NOTED	DISTRESS OR FAILURE: REPORTED CAUSE	FREEZING INDEX FOR WINTER PRECEDING DISTRESS	DEPTH OF FROST PENETRATION	TRAFFIC: PERIOD OF USE PRIOR TO LAST DATED REPORT OF DISTRESS	TRAFFIC: PREDOMINATE GROSS PLANE WT. USING FIELD IMMEDIATELY PRECEDING DISTRESS (LBS.)	PRESENT EVALUATION (4) LBS. GROSS PLANE WT.: NORMAL PERIOD	PRESENT EVALUATION (4) LBS. GROSS PLANE WT.: FROST MELTING PERIOD	REMARKS
GREAT FALLS AIRBASE GREAT FALLS, MONTANA	Bituminous paved taxiways and runways	Asphalt concrete	6		Pit run gravel	9 to 11	27%	Yes	CBR = 58(1)	Predominately CL, SF and SC	62%	Yes	16 to 28	32 to 54	CBR = 2 to 28(1) 13 Avg.	200 ∠ ft. below surface	Reported as poor	Failures became apparent at the joint between the runway proper and the shoulder. Shoulder constructed of 2" A.C. pulls away from 6" runway A.C. pavement, allowing water to enter longitudinal cracks. Depressions became evident from aircraft wheels which pass over this joint.	Not reported	Inadequate drainage. Water flows across runways, saturation of areas adjacent to runways by heavy snowfall and plowing. Frost action contributes to deterioration.	1942-1943 1221	5' Average 30"	January to Sept. 1943 Dec. 1943 to Jan. '44	48,000 8,500 to 38,000	55,000	< 10,000	
GORE FIELD GREAT FALLS, MONTANA	Parts of runway No. 1 and edges of runway No. 3 Parts of taxiways A, B, D, F, G, L, and M	Asphalt concrete	5 and 6		Crushed gravel GW, GF, GC.	7	68%	Yes	CBR = 10 to 75(1) 50∠ Avg.	SF, GF, GC ML, and CL	80%	Yes	3 to 21	20 to 34	CBR = 15 to 30(1) 20∠ Avg.	Not reported	Poor	Pavement becoming wavy, weakness along edges of the pavement, complete failure of taxiways "A" and "J", gradual longitudinal cracks appeared along the tire tracks followed by general cracking and breaking of the pavement.	Not reported	Poor surface drainage, instability of the gravel base, overloading of pavements. Frost action may be a contributing factor.	1942-1943 1221	5'	Jul. 1942 to Oct. '43	8,500 to 50,000 (50% very heavy bombers)	30,000	< 10,000	90,561 cycles since occupancy. Very heavy bombers.
GEIGER FIELD WASHINGTON STATE	10,000 sq. ft. of taxiway No. 2	Asphalt concrete	3		Gravel sand and silt	8 to 12	100% (Ponded water seeped under pavement)	Yes	CBR = 17(1)	GF to GP	100%	Yes	19	29	CBR = 35(1)	12 to 15 below surface	None	Cracking and rutting developed near outside of strip spreading towards the center of strip and longitudinally under effects of traffic.	Apr. 1943	Insufficient base and inadequate drainage. Snow windrows in thaw period caused saturation of subgrade.	1942-1943 336	25"(3)	May 1943 to July 1943	60,000	< 30,000	< 10,000	
PUEBLO AIRFIELD PUEBLO, COLORADO	Apron N-S, NW-SE, E-W Runways. Taxiways T-1, T-2, T-3 and T-6	Portland cement concrete Asphalt concrete	8-6-8 2 to 4	510	Sand Stabilized gravel	6 8 to 12	100%	Not reported Yes	CBR = 4 to 38(1)	CL CH	100%	Yes	20	40	k = 49(2) CBR = 3 to 6	Artesian springs encountered.	Some gravel back-filled drains. New subsurface drains installed after failures appeared.	Concrete apron badly cracked, slab displacement along taxiway lanes. Settlement of bituminous surface 3" to 5". Bituminous failures consisted of rutting, cracking and disintegration of surface and base. Wavy surface and softening of shoulders.	Fall of '42 to Spring of '43 Other failure dates not reported.	Overloaded pavements. Softening of subgrade by water entering from surface or shale fissures. Failure at junction of bituminous pavement and concrete due to differential settlement.	1942-1943 Jan. 1943 120 Mar. 1943 105 (Alternate freezing and thawing)	20"(3)	Oct. 1942 to Aug. 1943	60,000	< 30,000 < 10,000	< 30,000 < 10,000	
CHANUTE FIELD RANTOUL, ILLINOIS	NE-SW, E-W, NW-SE runways	Portland cement concrete	8-6-8	700 to 815	Pit run sand and gravel	0 to 6	Not reported	Yes	k = 63(1)	CL to OL	90%	Yes	15 to 20	19 to 48	k = 57(1)	Below influence depth (not reported)	Poor at pavement edges	Sheared tongue and groove joints, corner cracks, transverse cracks, spalling and fracturing of concrete for a width of several inches	Jun. 1944	Insufficient bearing capacity of subgrade, softening of subgrade during thawing and freezing, overloading slabs with heavy wheel loads.	1943-1944 308	12" to 18" Average max. equals 30"	1943 to 1944	60,000	30,000	< 30,000	
SCOTT FIELD BELLEVILLE, ILLINOIS	N-S, E-W, NE-SW, NW-SE runways and apron	Portland cement concrete	8-6-8	590	None					OL and CL	100%	Yes	20 to 26	26 to 43	k = 66(1)	Depth not reported (believed below influence depth)	Longitudinal combination open tile drains 15' from edges of runway.	Extensive failure in apron section adjoining concrete box storm drains. Cracking at tongue and groove joints and at corners. Long cracks along central portion of E-W runway. Cracks also at transverse drains.	Fall of '43	Lack of subsurface drainage and instability of back-fill at drain. Over stressing of pavements during heavy traffic, fall and spring 1943, caused cracking.	1943-1944 142	12 to 16" Average 24 to 36" Maximum	Mar. 1942 to Aug. 1943 Aug. 1943 to Jul. 1944	6,000 60,000	< 30,000	< 30,000	
GREAT BEND AIRFIELD GREAT BEND, KANSAS	West edge of apron. Original taxiway #1. Taxiways at ends of N-S runway.	Portland cement concrete	10½-7-10½	540	Sand	3 to 12	No data	No	No data	ML, CL, CH, and SF in thin stratas	86%	Yes	15	22	k = 86(1) k = 59(2)	2 to 5	None	Extensive cracking, pavement broken up at local areas into small patterns.	1944 24 May 1945	Pavement used extensively for taxiing and warm up. Pavement apparently has insufficient load carrying capacity.	1944-1945 64	3'	1944 to May 1945	47,000	< 30,000	< 30,000	No heaving noticed after one winter cycle.
CASPER AIRBASE CASPER, WYOMING	Scattered areas on taxiways 1, 2, 5, 9, 12, and 13 Runways and runway shoulders. Apron	Asphalt concrete Bituminous material P. C. C.	6 3 9-7-9	675	Sand SF, ML, SP, SC, SW, CL. None	6 to 8 SUBBASE 9 to 14	46% BASE P.I.= 14 L.L.= 19 46%	Yes Yes	CBR = 40 CBR= 10 (Av.)	SP, SC, SF, ML, CL, SW. SW, CL, SC.	37%	Yes	15	23	CBR= 5 k = 279(1) k = 200(2)	> 90	None	Cracking and rutting then complete breakup of pavement and base course. Small depressed, cracked, and check areas. Cracking and slab displacement.	Mar. 1944	Local poor S.C., water ponding, poor base. Slight frost action in subgrade. Different settlement under traffic, ponding in depressions. Overstressing taxiing lanes.	5 Year av. equals 532 1944 = 870	24"	Nov. 1942 to Mar. '45	50,000	12,000 30,000	< 10,000 < 30,000	
MILES CITY AIRFIELD MILES CITY, MONTANA	Areas on various runways and taxiways	Asphalt concrete	2½		Pit run gravel	6	No data	Borderline	No data	Sandy loam (SF)	No data	Yes	No data		No data	No data	No data	Cracks across entire taxiways. Rutting, cracking, spalling full width of runway ends.	Apr. 1943 to May 1943	Frost action in subgrade. Turning, standing, too much stress for pavement design.	1942-1943 1462	50"(3)	No data	25,000	< 10,000	< 10,000	

NOTES

(1) Normal period
(2) Frost melting period
(3) Frost penetration predicted from Figure 3 of Plate 19.
(4) Based on Engineering Manual, Part XII, Chap. 2 dated May 1947, and Chap. 3 and 4 dated July 1946.

BASE COURSE TREATMENT TO PREVENT FROST ACTION
1945 - 1947
SUMMARY OF FROST ACTION TEST DATA

SERIES AND SAMPLE NO.	SOIL TYPE	PER CENT AND TYPE OF ADMIXTURE				DENSITY		LENGTH OF TEST IN DAYS (A)	WATER CONTENT			SATURATION		VOID RATIO AT START OF TEST		WATER CONTENT BOTTOM INCH		DEGREE HOURS IN TEST	DEGREE HOURS TO START OF HEAVE (APPROX.)	HEAVE IN PERCENT	FROST ACTION	FROZEN ZONE
		BUNKER "C"	RT-2	$CaCl_2$	DAREX AEA	WET BEFORE TEST LBS/CF	DRY BEFORE TEST LBS/CF		END OF TEST %	START OF TEST %	GAIN DURING TEST %	START OF TEST %	END OF TEST %	WITH ADMIXTURE	WITHOUT ADMIXTURE	BEFORE TEST %	AFTER TEST %					
A-1	East Boston Till	-	-	-	-	139.1	127	26	46.4	9.7	36.7	77	100/	-	.35	10	110	7155	793	63.8	Severe	Entire
A-2		2	-	-	-	138.4	124		20.6	9.2	11.4	69	100/	.30	.37	9	79		1205	20.6	Severe	Entire
A-3		4	-	-	-	133.8	120		12.9	7.1	5.8	48	87	.27	.42	7	41		3931	6.7	Moderate	Bottom 1.3"
A-4		6	-	-	-	133.8	119		8.7	6.2	2.5	41	58	.23	.44	6	13		-	0.0	None	Bottom 1"
A-5		-	-	1	-	140.0	127		13.7	9.4	4.3	75	100/	-	.35	9	13		3931	0.3	Slight	None
A-6		2	-	1	-	140.9	126		10.6	9.0	1.6	70	83	-	.36	9	12		-	0.0	None	None
A-7		4	-	1	-	135.0	130		9.5	6.9	2.6	47	65	-	.42	7	11		-	0.0	None	None
A-8		6	-	1	-	132.2	117		6.1	5.6	0.5	36	39	-	.46	6	9		-	0.0	None	None
A-9		-	-	2	-	138.8	125		13.1	8.9	4.2	68	100	-	.37	9	12		-	0.0	None	None
A-10		2	-	2	-	137.8	122		11.3	8.8	2.5	63	80	-	.40	9	14		-	0.0	None	None
A-11		4	-	2	-	132.8	118		9.4	6.5	2.9	42	60	-	.45	6	11		-	0.0	None	None
A-12		6	-	2	-	133.4	117		7.5	5.8	1.7	37	48	-	.46	6	9		-	0.0	None	None
A-13		-	-	-	-	136.6	125		46.8	9.6	37.2	71	100/	-	.37	10	21		639	69.9	Severe	Bottom 0.5" Not Frozen
A-14		-	2	-	-	133.4	121		21.6	8.0	13.6	54	100/	.35	.41	8	24		2912	16.3	Severe	Bottom 4.75" Not Frozen
A-15		-	4	-	-	133.4	119		11.7	7.7	4.0	51	78	.31	.43	8	15		5871	3.5	Slight	Bottom 1" Not Frozen
A-16		-	6	-	-	133.1	117		9.3	7.5	1.8	47	58	.28	.47	7	11		-	0.0	None	None
B-1		-	-	1	-	137.4	125	24	14.0	8.6	5.4	65	100/	-	.37	9	15	5854	-	0.0	None	Top 3"
B-2		-	1	1	-	139.0	125		12.4	9.0	3.4	68	100/	-	.37	9	14		-	0.0	None	None
B-3		-	2	1	-	138.2	124		10.8	8.5	2.3	62	79	-	.38	8	15		-	0.0	None	None
B-4		-	4	1	-	140.0	122		10.0	9.4	0.6	67	72	-	.40	9	11		-	0.0	None	None
B-5		-	-	0.5	-	138.5	126		17.7	9.2	8.5	71	100/	-	.36	9	18		1735	9.2	Moderate	Bottom 0.5" Not Frozen
B-6		-	1	0.5	-	138.4	123		13.6	9.0	4.6	68	100/	-	.37	9	16		3893	1.4	Slight	Frozen 1"-3.5" From Bottom
B-7		-	2	0.5	-	136.7	122		12.4	8.4	4.0	60	89	-	.39	8	14		-	0.0	None	None
B-8		-	4	0.5	-	137.2	127		9.1	7.7	1.4	55	64	-	.41	8	12		-	0.0	None	None
B-9		-	-	0.5	-	139.8	127		16.4	9.2	7.2	72	100/	-	.35	9	19		2455	5.4	Moderate	Bottom 0.5" Not Frozen
B-10		1	-	0.5	-	138.7	126		12.1	8.6	3.5	66	93	-	.36	9	13		-	0.0	None	None
B-11		2	-	0.5	-	138.0	124		11.4	8.1	3.3	61	86	-	.38	8	13		-	0.0	None	None
B-12		4	-	0.5	-	134.4	121		8.1	6.6	1.5	45	55	-	.42	7	14		-	0.0	None	None
B-13	New Hampshire Silt	-	-	-	-	114.6	101		102.5	13.4	89.1	55	100/	-	.66	13	29		620	161.5	Severe	Bottom 2.8" Not Frozen
B-14		2	-	-	-	117.8	101		82.5	13.9	68.6	53	100/	.57	.66	14	26		620	118.5	Severe	Bottom 1.9" Not Frozen
B-15		4	-	-	-	122.3	103		82.7	14.9	67.8	65	100/	.47	.64	15	21		620	128.0	Severe	Bottom 1.8" Not Frozen
B-16		6	-	-	-	121.0	101		63.1	13.0	50.1	56	100/	.42	.66	13	20		620	91.0	Severe	Bottom 1.8" Not Frozen
C-20		-	-	3	-	107.6	87	25	26.2	20.3	5.9	60	78	-	.93	20	31	6393	-	0.0	None	None
C-19		-	-	6	-	107.2	85		23.2	19.4	3.8	56	67	-	.98	19	27		-	0.0	None	None
C-21		-	-	8	-	108.1	85		23.8	18.1	5.7	54	71	-	.98	18	32		-	0.0	None	None
C-22		-	-	10	-	108.9	84		22.8	18.1	4.7	53	67	-	1.00	18	26		-	0.0	None	None
C-8	Frost Heaving Gravel	-	-	-	-	139.4	132		11.2	5.7	5.5	57	100/	-	.27	6	11		966	16.3	Severe	Entire
C-17		-	-	1	-	140.6	131		10.0	6.0	4.0	59	99	-	.27	6	10		-	0.0	None	None
C-6		-	-	2	-	142.9	132		9.1	6.4	3.7	65	92	-	.27	6	9		-	0.0	None	None
C-7		-	-	3	-	142.6	130		8.1	6.7	1.4	64	77	-	.29	7	8		-	0.0	None	None
C-9		-	-	2	-	128.8	117		9.7	8.3	1.4	52	61	-	.44	8	12		-	0.0	None	None
C-10		-	-	3.5	-	128.2	114		9.0	8.6	0.4	51	54	-	.47	9	10		-	0.0	None	None
C-11		-	-	4.5	-	128.6	114		8.9	8.0	0.9	48	53	-	.47	8	10		-	0.0	None	None
C-12		-	-	5.5	-	130.8	115		8.5	7.9	0.6	49	53	-	.46	8	10		-	0.0	None	None
C-13		1	1	2	-	143.7	131		8.0	6.4	1.6	64	80	-	.28	6	8		-	0.0	None	None
C-14		2	-	2	-	143.3	129		7.6	6.5	1.1	62	73	-	.29	7	9		-	0.0	None	None
C-15		3	-	2	-	143.3	128		7.4	6.4	1.0	59	69	-	.30	6	9		-	0.0	None	None
C-16		4	-	2	-	143.0	127		7.1	6.6	0.5	58	63	-	.32	7	10		-	0.0	None	None
D-1	Mix 1*	-	-	-	-	132.5	123	27	14.8	7.8	7.0	57	100/	-	.37	8	14	5870	300	7.4	Moderate	Entire
D-2		2	-	-	-	131.1	121		12.6	6.0	6.6	43	90	.31	.38	6	22		1250	4.8	Slight	Entire
D-3		4	-	-	-	131.6	121		8.0	4.6	3.4	33	57	.25	.39	5	12		1250	1.4	Slight	Entire
D-4		5	-	-	-	130.3	119		5.6	4.0	1.6	28	39	.23	.41	4	6		1250	1.5	Slight	-
D-5		6	-	-	-	131.0	121		2.5	2.3	0.2	17	18	.19	.39	2	3	6190	2200	0.4	Slight	None
D-6	Mix 2*	-	-	-	-	139.0	131		10.4	6.1	4.3	58	99	-	.28	6	11		400	4.0	Slight	Entire
D-7		2	-	-	-	134.2	127		7.2	3.9	3.3	33	60	.25	.33	4	8		400	1.1	Slight	Entire
D-8		4	-	-	-	136.2	128		2.4	2.7	-0.3	24	21	.18	.32	3	3		400	0.9	Slight	Entire
D-9		5	-	-	-	135.3	127	26	1.2	1.8	-0.6	16	10	.16	.33	2	1	6360	-	0.0	None	-
D-10		6	-	-	-	142.4	133		0.8	0.8	0.0	9	9	.08	.26	1	1		-	0.0	None	-
D-11	Mix 3*	-	-	-	-	144.6	135		12.0	7.3	4.7	77	100/	-	.26	7	11		175	13.2	Severe	Entire
D-12		2	-	-	-	134.1	126		10.0	4.0	6.0	32	81	.27	.34	4	13		400	5.4	Moderate	Entire
D-13		4	-	-	-	137.2	128		2.8	3.0	-0.2	26	24	.19	.32	3	4	5710	560	0.7	Slight	Top 2"
D-14		5	-	-	-	138.7	130		1.8	2.0	-0.2	18	16	.14	.31	2	2		560	0.8	Slight	None
D-15		6	-	-	-	143.3	134		1.3	1.3	0.0	14	14	.08	.27	1	2		-	0.0	None	None
										AS MOLDED / START TEST												
E-1	New Hampshire Silt	-	-	-	.05	121.1	104	22	73.4	16.1(B) / 16.1	57.3	71	100/	-	.61	16	- (C)	4412	150	62.4	Severe	Entire
E-2		-	-	-	.10	114.6	100		48.0	14.6 / 14.6	33.4	57	100/	-	.69	15	134		350	30.5	Severe	Entire
E-3		-	-	-	.10	112.4	98		47.6	14.5 / 14.5	33.1	55	100/	-	.71	15	35		150	31.7	Severe	Entire
E-4		-	-	-	.10	116.7	102		31.8	14.5 / 6.2	25.6	26	100/	-	.65	6	69		1790	16.0	Severe	Entire
E-5		-	-	-	.10	118.3	103	23	57.2	14.7 / 3.0	54.2	13	100/	-	.63	3	86	5068	280	74.1	Severe	Entire
E-6		-	-	-	.10	118.0	103		42.0	14.5 / 1.6	40.4	7	100/	-	.63	2	65		280	30.5	Severe	Entire
E-7		-	-	-	.10	113.9	99		30.1	14.6 / 0.5	29.6	2	100/	-	.69	1	45		120	17.6	Severe	Entire
E-8		-	-	-	.60	118.0	103		48.3	14.6 / 14.6	33.7	62	100/	-	.63	15	62		280	29.8	Severe	Entire
E-9		-	-	-	.90	114.6	101		52.9	12.9 / 12.9	40.0	52	100/	-	.66	13	42	5177	350	43.4	Severe	Entire
E-10		-	-	-	.90	115.5	102		37.0	12.7 / 12.7	24.3	53	100/	-	.64	13	41		1380	20.3	Severe	Entire
E-11		-	-	-	.90	114.9	101		38.5	13.2 / 6.1	32.4	25	100/	-	.66	6	30		350	22.3	Severe	Entire
E-12		-	-	-	.90	115.5	101		45.8	13.5 / 2.4	43.4	10	100/	-	.65	2	37		350	46.2	Severe	Entire
E-13		-	-	-	.90	114.9	101		27.7	12.4 / 1.1	26.6	4	100/	-	.65	1	26	4644	1370	10.5	Severe	Entire
E-14		-	-	-	.90	111.8	98		31.1	13.2 / 0.5	30.6	2	100/	-	.70	1	28		180	12.0	Severe	Entire
E-15		-	-	-	1.20	114.2	101		38.6	11.6 / 11.6	27.0	48	100/	-	.65	12	26		180	28.0	Severe	Entire
E-16		-	-	-	2.00	113.6	100		31.9	11.1 / 11.1	20.8	45	100/	-	.65	11	27		420	15.9	Severe	Entire

NOTE:

(A) Length of test computed from time sample was placed in drawer until it was removed.

(B) Samples E-4 and 11 were air dried one day, E-5 and 12 two days, E-6 and 13 three days, E-7 and 14 four days.

(C) No correction applied for evaporation of Darex AEA.

Bureau of Soils Classification

* Mix 1 - approx. 17% silt, 58% sand, 25% gravel
Mix 2 - approx. 17% silt, 33% sand, 50% gravel
Mix 3 - approx. 17% silt, 15% sand, 68% gravel

SUMMARY OF FROST ACTION TEST DATA

TABLE 7

DATA SHOWING INFLUENCE OF WATER ON FROST ACTION 1945 – 1947

AIRFIELD	TEST AREA	ICE FORMATIONS OBSERVED – IN BASE 1946	ICE FORMATIONS OBSERVED – IN BASE 1947	ICE FORMATIONS OBSERVED – IN SUBGRADE 1946	ICE FORMATIONS OBSERVED – IN SUBGRADE 1947	PAVEMENT HEAVE (FEET) AVERAGE 1946	PAVEMENT HEAVE (FEET) AVERAGE 1947	PAVEMENT HEAVE (FEET) RANGE 1946	PAVEMENT HEAVE (FEET) RANGE 1947	DEPTH TO GROUND WATER IN WINTER (FEET) 1946	DEPTH TO GROUND WATER IN WINTER (FEET) 1947	WATER CONTENT OF FROST SUSCEPTIBLE SUBGRADE FALL 1945	WATER CONTENT WINTER 1946	WATER CONTENT FALL 1946	WATER CONTENT WINTER 1947	ATTERBERG LIMITS LIQUID	ATTERBERG LIMITS PLASTIC	DEGREE OF SATURATION OF FROST SUSCEPTIBLE SOIL PRIOR TO FREEZING 1945	DEGREE OF SATURATION 1946	PRECIPITATION DURING 3 MONTHS PRIOR TO START OF FREEZING (INCHES) NORMAL	PRECIPITATION 1945	PRECIPITATION 1946	SOURCE OF WATER FOR FROST ACTION
DOW	D	Crystals	Crystals	Widely isolated lenses from hairline to 1/16" in thickness and few crystals.	Lenses from hairline to 1/16" thickness and crystals.	0.08	0.06	0.05 to 0.10	0.02 to 0.11	7.0	3.1-4.6 (Base) 3.0-4.4 (Subgrade)	CL 17.7	-	CL 24.5	CL 29.0	GW Nonplastic CL 29-36	CL 11-17	GW 100 CL 100	GW 55 CL 100	11	11	9.3	Water table
	E	Crystals	Crystals	Isolated lenses from hairline to 1/16" in thickness and crystals	Lenses from hairline to 1/4" in thickness spaced 1/4" apart at frost line	0.12	0.08	0.10 to 0.20	0.00 to 0.17	7.0	3.5 (Base) 3.4-6.7 (Subgrade)	CL 22.4	-	CL 23.6	CL (25.0) 23.5	GW Nonplastic CL 29-36	CL 11-17	GW 100 CL 93	GW 100 CL 100	11	11	9.3	Water table
	F	Crystals	Crystals	Isolated lenses from hairline to 1/8" in thickness and crystals	Crystals throughout. Hairline lenses from 2.2' to 3.0'.	0.25	0.14	0.20 to 0.30	0.04 to 0.26	7.5	0.4-2.0 (Base) 1.5-6.3 (Subgrade)	CL 22.5	CL (25.0) CL 17.5	CL 22.8	CL (22.6) 24.4	GW Nonplastic CL 29-36	CL 11-17	GW 100 CL 100	GW 100 CL 100	11	11	9.3	Water table
	TURF	No Base		Crystals from 0.1' to 1.7'. Lenses from 1.7' to 2.2' from 1/4" to 3/4" in thickness.	Crystals throughout. Lenses from hairline to 1/2" in thickness from 2.0' to 2.25'.	-	-	-	-	5.8	0.1-4.6	-	CL (43.0) CL 19.6	-	CL (31.6) CL 28.5	CL 29-36	CL 11-17	-	-	11	11	9.3	Water table
PRESQUE ISLE	A	Crystals	-	Crystals and hairline lenses	-	0.18	-	0.10 to 0.25	-	5.6-7.1	-	GC 17.0	GC (16.8)	-	-	GW Nonplastic GC 29	GC 8	GW 100 GC 100	-	10	11	-	Water table
	C	Crystals	-	Crystals	-	0.06	-	0.05 to 0.10	-	6.4-8.5	-	GC 13.6	GC (13.6) GC 11.0	-	-	GW Nonplastic GC 29	GC 8	GW 64 GC 84	-	10	11	-	Water table
	D	Crystals	-	Crystals	-	0.22	-	0.15 to 0.40	-	4.5-6.8	-	GC 16.0	-	-	-	GW Nonplastic GC 29	GC 8	GW 71 GC 100	-	10	11	-	Water table
	TURF	No Base		Crystals	-	-	-	-	-	8.5	-	-	GC (18.3)	-	-	GW Nonplastic GC 29	GC 8	-	-	10	11	-	Water table
TRUAX	A	Crystals	-	Few hairline lenses in subbase, and hairline to 1/10" in thickness in subgrade.	-	0.13	-	0.10 to 0.18	-	1.6-5.3	-	CL 27.5 SF 19.8	CL (31.2) CL 28.4 SF 16.8	-	-	GF 19-30* CL 43 SF Nonplastic	GF 2-9* CL 20	CL 100 SF 100	-	7	7.8	-	Water table
	C	Numerous lenses from hairline to .05". Few crystals.	-	Lenses from .01" to .02" in thickness.	-	0.12	-	0.06 to 0.18	-	5.7-6.7	-	CL 35.5 SF 20.4	CL (23.6) CL 36.0 SF 22.5	-	-	GF 19-30* CL 38	GF 2-9* CL 18	CL 100 SF 100	-	7	7.8	-	Water table
	D	Crystals	-	Few crystals and hairline lenses in subbase. Lenses from hairline to .02" 1/2" apart in subgrade.	-	0.04	-	0.02 to 0.05	-	5.8-7.6	-	CL 25.9	CL (24.5) CL 34.5	-	-	GF 19-30* CL 44	GF 2-9* CL 20	CL 100	-	7	7.8	-	Water table
SELFRIDGE	A	Crystals	Scattered crystals.	Crystals. Lenses from hairline to 1/8" in thickness.	Scattered crystals. Lenses from hairline to 1/16" in thickness.	0.06	0.06	0.01 to 0.10	0.02 to 0.10	5.3	1.4-2.3 (Base) 3.9-5.5 (Subgrade)	ML 28.5 SF 20.1 CL 34.9	ML 18.0 SF 16.0	-	ML (35.9) ML 18.4 SF 25.6 CL 35.1	ML 30 SF Nonplastic CL 46	ML 10 CL 24	ML 78 SF 84	-	7.1	8.8	5.7	Water table
PIERRE	A	Crystals	-	Crystals in subbase and subgrade from 2.5' to 3.7'.	-	0.01	-	0.00 to 0.03	-	-	-	CL 21.6	CL (15.3) CL 24.3	-	-	GF 26-33 CL 34-42 CL 39-48 CH 52-86	GF 8-16 CL 16-26 CL 20-26 CH 23-48	CL 82 CL 80	-	2.4	2.1	-	Infiltration through cracks in pavement and through pavement edges.
	C&D	Homogeneously frozen	-	Homogeneously frozen	-	-0.01	-	-0.02 to +0.04	-	-	-	CL 12.7	CL (12.2) CL 10.4	-	-	GF 23-29 CL 40-43 CL 38-41	GF 7-12 CL 18-23 CL 19-23	CL 79 CL 41	-	2.4	2.1	-	Infiltration through cracks in pavement and through pavement edges.
SIOUX FALLS	A	None	None	Horizontal and vertical lenses from hairline to 1/8" in thickness from 1.0' to 3.6'.	Lenses from hairline to 1/8" in thickness. Not in well defined horizontal layers.	0.08	0.11	0.05 to 0.16	0.06 to 0.17	8.5	6.0-7.1	CL or CH 29.0 SF-CL 15.9	CL or CH (26.0)	-	CL (27.3)	GC 23 CL 36-44 CL or CH 51 SF-CL 16-26	GC 8 CL 15-21 CL or CH 30 SF-CL 0-11	CL 93 CL or CH 86 SF-CL 59	-	5.9	3.2	10.8	Water table and infiltration.
	B	No Base		Horizontal and vertical lenses from hairline to 1/8" in thickness and 1/2" to 3" apart.	Lenses from hairline to 1/8" in thickness. Not in well defined horizontal layers.	0.08	0.06	0.02 to 0.10	0.01 to 0.11	15.2	12.5-13.5	CH 33.0	CH (34.0) CH 33.0	-	CH (33.9) CH 34.7 SC 25.4	CH 50-68 CL 44 SC 17	CH 27-41 CL 25 SC 4	CH 92	-	5.9	3.2	10.8	Water table and infiltration.
WATERTOWN	A	-	-	-	-	0.05	-	0.00 to 0.09	-	-	-	-	-	-	-	SF-OL 32-41 SF-CL 32-41 OL-CL 36-50	SF-OL 12-14 SF-CL 12-14 OL-CL 12-16	-	-	4.4	3.2	-	Water table and infiltration.
	B	-	-	-	-	0.02	-	-0.02 to +0.07	-	11.2	-	-	-	-	-	GF 19-25 SF-OL 30-43 OL-CL 30-43	GF 5-9 SF-OL 12-18 OL-CL 12-18	-	-	4.4	3.2	-	Water table and infiltration.
FARGO	A	-	-	-	-	0.05	0.04	0.02 to 0.09	0.03 to 0.06	6.4	-	-	-	-	-	SF-CL 30-41 OH-CH 62-64 CH 73-80	SF-CL 12 OH-CH 29-31 CH 40-56	-	-	4.8	3.9	6.5	Water table.

NOTES

*Atterberg Limits for GF soil on portion passing No. 200 sieve.
()Numbers in parantheses indicate frozen soil.

DATA SHOWING INFLUENCE OF WATER ON FROST ACTION

TABLE 8

SITE	TEST AREA	YEAR	MEAN ANNUAL AIR TEMP. °F (v_o)	FREEZING INDEX °F DAYS (F)	FREEZING INDEX DURATION DAYS (t)	PAVEMENT (I) TYPE	PAVEMENT THICK. IN INCHES	BASE (II) (III) CLASS.	BASE THICK. IN INCHES	BASE WATER CONTENT % (W)	BASE DENSITY LBS./FT.³ (γ)	SUBGRADE (II) (III) CLASS.	SUBGRADE THICK. IN INCHES	SUBGRADE WATER CONTENT % (W)	SUBGRADE DENSITY LBS./FT.³ (γ)	AVG. VOL. HEAT B.T.U./(FT.³)(°F) (C)	AVG. LATENT HEAT B.T.U./FT.³ (L)	(IV) OBSERVED DEPTH OF FREEZING IN INCHES	PREDICTED DEPTH OF FREEZING IN INCHES-(12 X) EQ. 83	EQ. 93	EQ. 154	EQ. 154 PLUS PAVE.	EQ. 158	DESIGN CURVE
DOW	I AND III	1943-1944	42.5	1515	108	B.C.	4.0	GW	17	9.9	135	CL	-	30.5	81	39.6	2920	48	66	62	44◀	▶48◀		54◀
	II			1690	123	B.C.	3.5	GW	36	4.2 *	135 *	CL	-	19.3 *	107 *	39.5	1300	50	108	87	62	65		▶57
	IV TO VII			1745	130	P.C.C.	7.0	GW	15	9.2	133	CL GC	38 -	28.4 28.4 (+)	92 92 (+)	42.8	3900	48	63	58	41	▶48◀		58
	A	1944-1945		1445	104	P.C.C.	7.0	GW	15	11.1	119	CL GC	42 -	25.7 25.4 NF	98 103 NF	44.1	3035	54	65	58◀	41	48◀		▶53◀
	B			1445	104	B.C.	3.5	GW	31	6.9	131	CL	-	31.1 24.2 NF	93 92 NF	39.2	2310	52	75	66	47◀	50◀		▶53◀
	C			1345	88	B.C.	3.5	GW	42	9.2	121	CL	-	19.3	109	40.0	1960	60	79	▶67	47	50		51
	C			1445	104	B.C.	3.5	GW	42	9.2	121	CL	-	19.3	109	40.0	1995	62	61	▶69	49	52		53
	TURF			1445	104	T.S.	6.0	-	-	-	-	CL	-	23.4 15.2 NF	99 112 NF	39.0	3300	24					37	
	D	1945-1946		1420	99	B.C.	3.5	GW	40	13.5 *	128 *	CL	-	17.7 *	115 *	42.1	2530	50	71	62	44◀	▶47◀		▶53◀
	E			1420	99	B.C.	3.5	GW	36	10.1 *	136 *	CL	-	22.4 *	101 *	41.5	2205	48	76	66	▶47◀	50◀		53◀
	E			1090	75	B.C.	3.5	GW	36	10.1 *	136 *	CL	-	22.4 *	101 *	41.6	2110	44	68	59	42◀	▶45◀		47◀
	F			1080	74	P.C.C.	7.0	GW	20	8.1 *	138 *	CL	-	22.5 *	110 *	44.6	2700	54	59◀	▶52◀	37	44		46
	TURF			1420	99	T.S.	6.0	-	-	-	-	CL	-	22.4 (+)	101 (+)	42.0	3210	26					37	
PRESQUE ISLE	A	1944-1945	38.0	2060	115	P.C.C.	7.0	GW	33	6.3	134	GC	-	17.9 16.2 NF	108 113 NF	38.7	1945	70	98	85	60	▶67◀		63
	B			2060	115	B.C.	4.0	C.R. GW	4 30	- 6.5	- 134	GC	-	14.8 14.2 NF	114 114 NF	37.4	1870	71	99	87	62	▶70◀		63
	TURF			140	25	T.S.	5.0	-	-	-	-	GC	-	18.6 15.9 NF	105 110 NF	39.1	2790	13					12◀	
	A	1945-1946		2240	126	P.C.C.	7.0	GW	32	10.4 *	133 *	GC	-	17.0 *	117 *	41.1	2450	78	91	▶80◀	57	64		65
	C			2230	120	B.C.	3.5	C.R. GW	3.5 26	- 6.3 *	- * 132	GC	-	13.6 *	115 *	37.0	1785	68	106	92	▶65◀	72◀		▶65◀
	D			2230	124	B.C.	3.5	C.R. GW	3.5 25	- 10.5 **	- ** 142	GC	-	16.4 **	120 **	44.0	2740	69	85	76	64	61		▶65◀
	TURF			2240	128	T.S.	5.0	-	-	-	-	GC	-	13.6 (+)	115 (+)	37.5	2230	60					▶56◀	
BEDFORD	A	1945-1946	46.5	825	99	P.C.C.	6.0	GW	18	4.8 *	119 *	SW	-	5.3 *	103 *	26.0	800	40	96	76	54	60		▶41◀
	B			695	87	B.C.	5.0	GW	14	4.8 (+)	119 (+)	SW	-	5.3 (+)	103 (+)	26.0	805	26	86	70	49	54		▶38
	B			345	41	B.C.	5.0	GW	14	4.8 (+)	119 (+)	SW	-	5.3 (+)	103 (+)	26.0	805	26	62	49	35	40		▶27◀
OTIS	A	1944-1945	48.7	300	60	B.C.	6.0	-	-	-	-	SF OR ML SP GP	30 24 -	9.5 ** 23.5 ** 1.2 0.8	** 124 ** 87 119 126	27.4	2285	26	34	31◀	22◀	28◀		▶26◀
HOULTON	A	1944-1945	40.5	1605	107	B.C.	1.5	S.CEM.	6	16.3	113	GF GC	30 -	14.7 8.3 10.1 NF	110 134 NF 118	34.8	2160	49	81	72	▶51◀	52◀		56
TRUAX	A	1944-1945	46.0	1210	88	B.C.	2.5	C.R. GF	8 15	- 5.3 *	- * 141	CL SF CL	23 36 -	21.1 * 6.1 * 21.1 *	108 * 118 * 108 *	39.9	2385	48	68	58	41	51◀		▶48◀
	B			1245	95	B.C.	2.5	C.R. GF	18 25	- 7.7	- 122	CL	-	27.0	99	43.9	1605	56	78	64	45	65		▶50◀
	C			1245	97	P.C.C.	6.0	GF	48	12.7	112	CL	-	30.0	82	38.8	2070	55	74	62	44	▶50◀		▶50◀
	A	1945-1946		1020	93	B.C.	2.5	C.R. GF	8 18	- 6.0 *	- * 140	CL SF CL	26 36 -	27.5 * 19.8 * 27.5 *	95 * 118 * 95 *	43.7	2430	46	62	53	37	▶47◀		▶45◀
	C			1060	100	P.C.C.	7.0	GF	30	10.1 *	* 129	CL SF	32 -	35.5 * 20.4 *	87 * 113 *	43.9	2550	48	61	53◀	37	44◀		▶46◀
	D			1055	99	B.C.	2.5	C.R. GF	20 30	- 5.6 *	- * 139	CL	-	25.9 *	99 *	43.2	1560	59	78	▶63◀	44	66		46
SELFRIDGE	B	1945-1946	47.6	645	81	P.C.C.	10.0	GF	12	11.5	99	ML SF CL	13 30 -	16.0 22.3 * 36.2 *	112 100 * 85 (+)	44.6	2280	35	90	43	30◀	40◀		▶36◀
PIERRE	A	1944-1945	47.5	960	104	P.C.C.	7.0	GF	7	8.7 *	135 *	CL CH	32 -	15.1 * 23.5 *	105 * 90 *	37.9	2150	42	63	54	39◀	46◀		▶44◀
	B			695	71	B.C.	5.5	GF	9	6.4 *	140 *	CL	-	14.1 *	97 *	32.9	1640	25	62	52	▶37	42		38
	TURF			660	69	T.S.	4.0 (I)	-	-	-	-	CL CH	60 -	12.1 * 18.7 *	98 * 90 *	33.6	1680	6					34	
	A	1945-1946		1025	99	P.C.C.	7.0	GF CL	7 8	7.4 * 15.9 *	* 142 * 110	CL CH	27 -	21.6 * 21.7 **	97 * 97 **	39.1	2625	48	89	52◀	37	44◀		▶45◀
	C			1025	99	B.C.	6.0	GF CL	8 7	6.7 * 13.6 *	* 128 * 115	CL	-	12.7 *	92 *	30.0	1670	44	74	63	▶45◀	51		▶45◀
SIOUX FALLS	A	1944-1945	46.2	915	78	B.C.	2.0	GC CL	10 12	7.0 * 16.7 *	* 132 * 112	CL OR CH	-	23.8 * 30.9 *	95 * 84 *	40.6	2640	40	56	49	35◀	▶37◀		▶43◀
	A	1945-1946		1220	82	B.C.	2.0	GC CL	10 12	7.1 * 21.4 *	* 137 * 103	CL OR CH SF-CL	48 -	29.0 * 15.9 *	89 * 97 *	36.5	3020	47	60	53◀	38	40		▶49◀
	B			1310	100	P.C.C.	6.0	-	-	-	-	CH CL SC	90 11 -	33.0 * 27.5 ** 15.9 (+)	85 * 87 ** 97 (+)	38.9	3960	42	54	50	35	▶41◀		51
WATERTOWN	A	1944-1945	42.5	860	62	P.C.C.	8.0	-	-	-	-	SF-OL OL-CL GP	32 20 -	14.6 * 23.8 * 3.8 *	112 * 87 * 120 (+)	30.7	2325	38	58	52	▶37◀	45		42◀
	B			840	59	B.C.	5.0	GF	8	4.9 *	139 *	SF-OL OL-CL GP	22 11 -	14.1 * 22.1 * 4.4 *	103 * 88 * 120 (+)	29.9	1970	42	62	55	39◀	44◀		▶41◀
	TURF			880	64	T.S.	6.0	-	-	-	-	SF-OL GP	52 -	6.4 * 4.4 *	136 * 120 (+)	30.6	1240	42					43◀	
	A	1945-1946		1715	98	P.C.C.	8.0	-	-	-	-	SF-OL OL-CL GP	24 22 -	14.6 (+) 23.8 (+) 3.8 (+)	112 (+) 87 (+) 120 (+)	29.7	2010	75 TH	88	▶77◀	55	64		58
	B			1715	98	B.C.	5.0	GF	12	4.9 (+)	139 (+)	SF-OL GP	30 -	14.1 (+) 4.4 (+)	103 (+) 120 (+)	28.6	1330	79 TH	108	90	64	▶69		58
FARGO	A	1944-1945	39.2	1395	79	B.C.	1.5	S.CEM. CL-SF	6.5 14	11.1 * 10.6 *	* 122 * 126	OH-CH CH	8 -	28.7 * 31.1 *	99 * 89 *	43.2	2985	46	65	59	42◀	▶43◀		52◀
	A	1945-1946		2465	125	B.C.	1.5	S.CEM. CL-SF	6.5 11	11.1 (+) 10.6 (+)	122 (+) 126 (+)	OH-CH CH	12 -	28.7 (+) 31.1 (+)	99 (+) 89 (+)	42.3	3395	72 TH	81	▶73◀	52	53		69◀
GREAT BEND	A	1944-1945	55.0	50	5	P.C.C.	7.0	SW OR SF	6	2.0 *	120 *	SF-CL OR CL-SF CL	35 -	15.1 * 13.1 * 17.0 *	109 * 102 * 100 *	36.4	325	13	37	18◀	▶13◀	20		11◀
	A	1945-1946		130	11	P.C.C.	7.0	SF	5	2.0 (+)	120 (+)	SF-CL OR CL-SF CL	35 -	15.1 (+) 13.1 (+) 17.0 (+)	109 (+) 102 (+) 100 (+)	36.2	1600	24 TH	27◀	21◀	15	▶22◀		17
BISMARCK	A	1944-1945	39.0	1260	86	B.C.	4.5	SC	6	4.7 *	130 *	CL-ML SP	49 -	16.6 * 8.1 *	87 * 99 *	28.7	1905	46	76	70	▶50◀	54		▶50◀
CASPER	A	1944-1945	47.4	355	59	P.C.C.	7.0	-	-	-	-	SF-CL SF SP	29 12 -	11.4 * 6.6 * 5.3 *	114 * 120 * 111 *	29.2	1650	30	42	36◀	26◀	▶33◀		▶27◀
	B			355	59	B.C.	5.0	GW	7	3.6 *	131 *	SF-CL SP SF-CL	12 32 -	6.2 * 3.5 * 6.2 *	117 * 109 * 117 *	29.7	870	18	61	47	34	39		▶27
FAIRMONT	A	1944-1945	52.0	380	70	P.C.C.	8.0	-	-	-	-	CL CH	25 -	28.0 * 23.0 *	89 * 88 *	38.1	3550	15	31	28	▶20◀	28		28
GARDEN CITY	A	1944-1945	55.0	25	7	B.C.	1.5	SC	10	5.0 *	128 *	CL CH OR CH-CL	38 -	15.9 * 19.1 * 16.3 *	107 * 95 * 97 *	36.2	990	12	13◀	▶11◀	8◀	9◀		8◀

EQUATIONS:

83 $x = \sqrt{\dfrac{48\,kF}{L}}$

93 $x = \sqrt{\dfrac{48\,kF}{L + C\left(v_o - 32 + \dfrac{F}{2t}\right)}}$

154 $x = \sqrt{\dfrac{24\,kF}{L + C\left(v_o - 32 + \dfrac{F}{2t}\right)}}$

158 $x = -\dfrac{d}{2} + \sqrt{\left(\dfrac{d}{2}\right)^2 + \dfrac{24\,kF}{L + C\left(v_o - 32 + \dfrac{F}{2t}\right)}}$

DESIGN CURVE – FIG. 2, E.M. PART XII, CHAPT. 4, MARCH 1946

x = DEPTH OF FROST PENETRATION IN FEET.
k = THERMAL CONDUCTIVITY IN B.T.U./(FT.)(°F)(HR.)
F = FREEZING INDEX IN DEGREE-DAYS
L = AVERAGE LATENT HEAT IN B.T.U./FT.³
C = AVERAGE VOLUMETRIC HEAT IN B.T.U./(FT.³)(°F)
v_o = MEAN ANNUAL AIR TEMPERATURE IN °F
t = DURATION OF FREEZING INDEX IN DAYS
d = THICKNESS OF INSULATION LAYER IN FEET

AN AVERAGE VALUE FOR THERMAL CONDUCTIVITY (k) = 1.3 B.T.U./(FT.)(°F)(HR.), IS USED THROUGHOUT THESE CALCULATIONS.

VALUE FOR "d" USED IN EQUATION 158 IS THICKNESS OF TOPSOIL IN FEET.

NOTES:

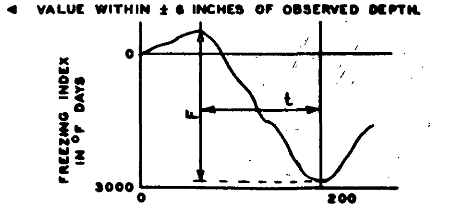
(I) PAVEMENT TYPES ARE AS FOLLOWS:
B.C. – BITUMINOUS CONCRETE.
P.C.C. – PORTLAND CEMENT CONCRETE.
T.S. – TOPSOIL (TURFED AREAS ONLY).

(II) VALUES USED FOR WATER CONTENT AND DENSITY ARE FOR FREEZING PERIOD WHEN AVAILABLE. EXCEPTIONS ARE NOTED AS FOLLOWS:
* – VALUES FOR NORMAL PERIOD.
** – VALUES FOR FROST MELTING PERIOD.
(+) – ASSUMED VALUES.
NF – VALUES FOR NON-FROZEN SUBGRADE SOIL (FREEZING PERIOD).

(III) SOIL CLASSIFICATION FOR AIRFIELDS EXCEPT AS FOLLOWS:
C.R. – CRUSHED ROCK.
S.CEM. – SOIL CEMENT.

(IV) DEPTHS OF FREEZING OBTAINED FROM TEST PIT OBSERVATIONS EXCEPT AS FOLLOWS:
TH – DEPTHS OF FREEZING OBTAINED FROM THERMOMETER AND THERMOCOUPLE OBSERVATIONS.

▶ CLOSEST VALUE TO OBSERVED DEPTH.
◀ VALUE WITHIN ± 6 INCHES OF OBSERVED DEPTH.



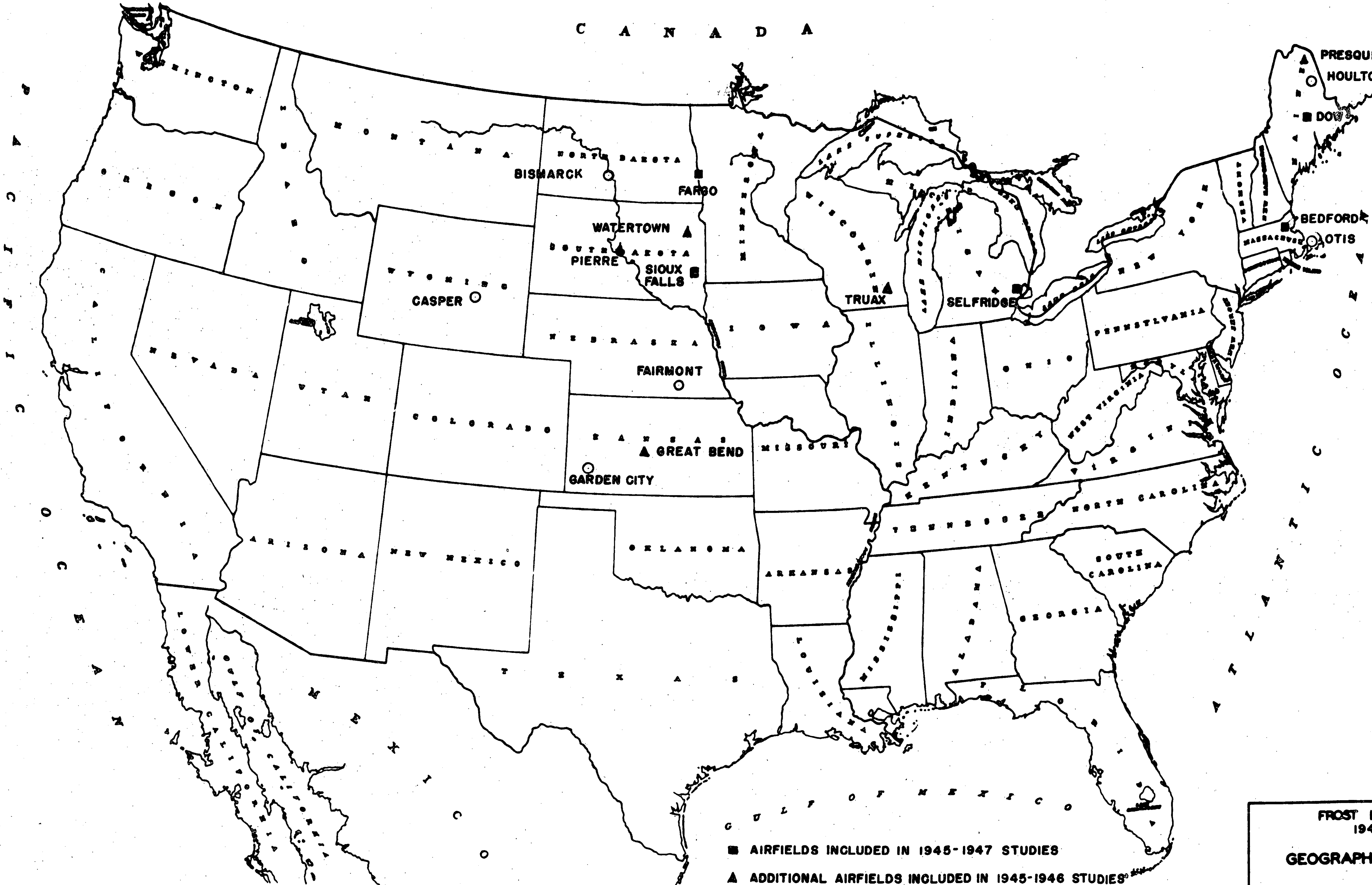
RELATIONSHIP BETWEEN F & t

FROST INVESTIGATION 1945-1946

PREDICTION OF FROST PENETRATION

FROST EFFECTS LABORATORY, BOSTON, MASS. JUNE 1946

TABLE 9



■ AIRFIELDS INCLUDED IN 1945-1947 STUDIES

▲ ADDITIONAL AIRFIELDS INCLUDED IN 1945-1946 STUDIES

○ OTHER AIRFIELDS FROM WHICH DATA, COLLECTED IN PREVIOUS YEARS, ARE USED FOR MATHEMATICAL STUDIES OF FROST PENETRATION.

FROST INVESTIGATION
1945-1947

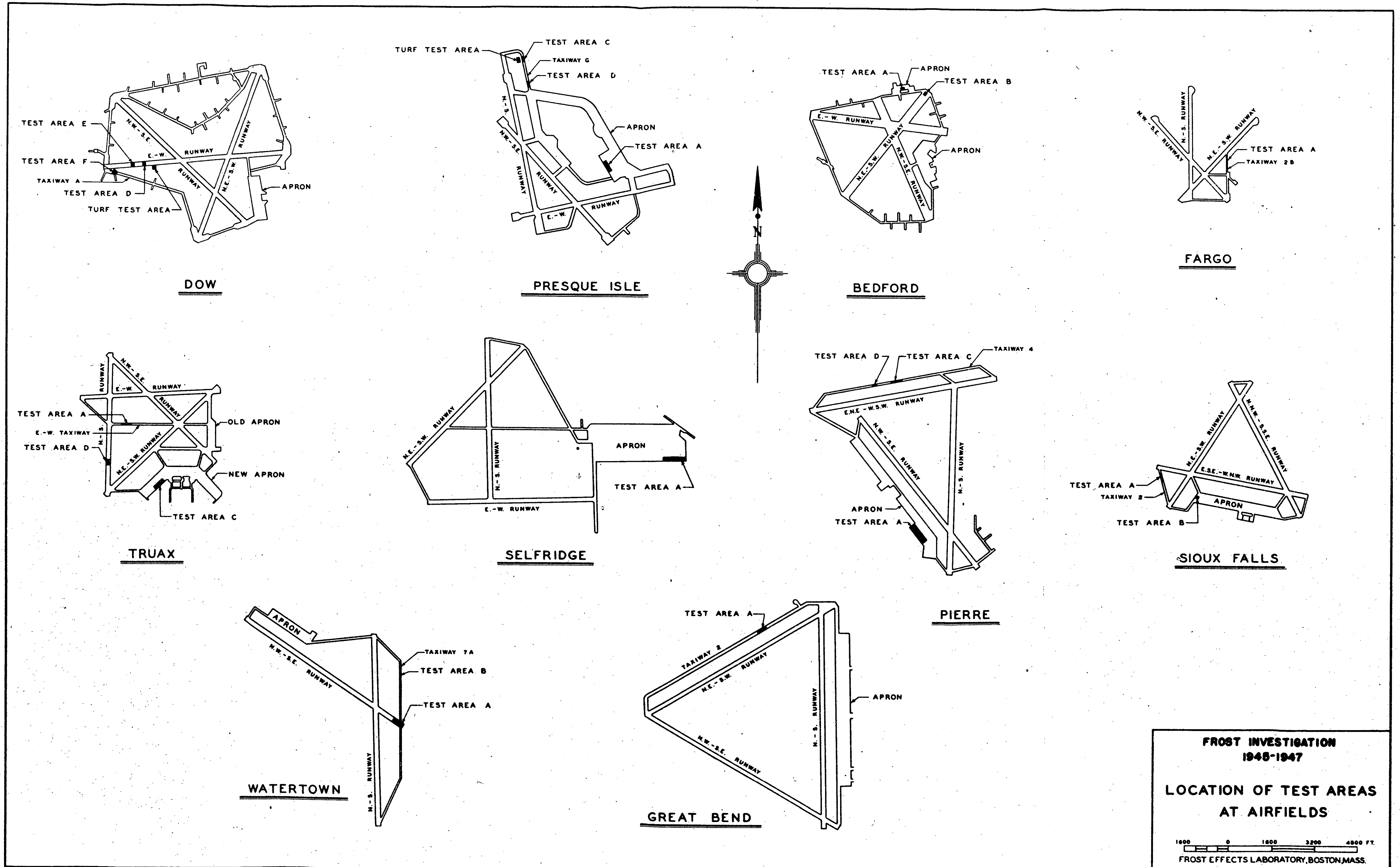
GEOGRAPHICAL LOCATION MAP

SCALE IN MILES

APRIL 1948

FROST EFFECTS LAB. BOSTON, MASS.

PLATE 1



FROST INVESTIGATION
1945-1947

LOCATION OF TEST AREAS AT AIRFIELDS

FROST EFFECTS LABORATORY, BOSTON, MASS.

PLATE 2

DOW FIELD - BANGOR, MAINE

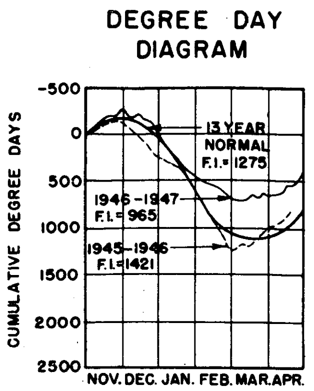


FIG. 1

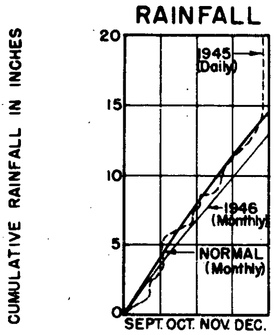


FIG. 2

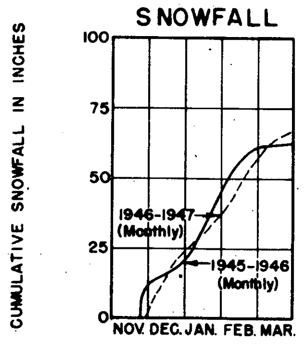


FIG. 3

GRADATION OF MATERIALS

CLASS	ATTERBERG LIMITS LL	PI
GW	NON PLASTIC	
CL	29 TO 36	11 TO 17

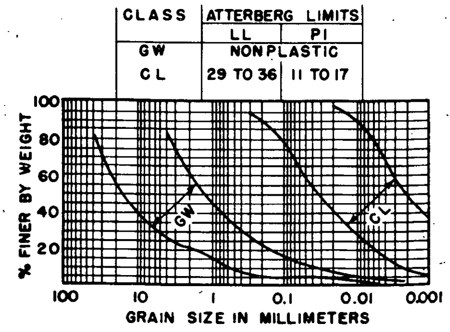


FIG. 4

GROUND WATER TABLE

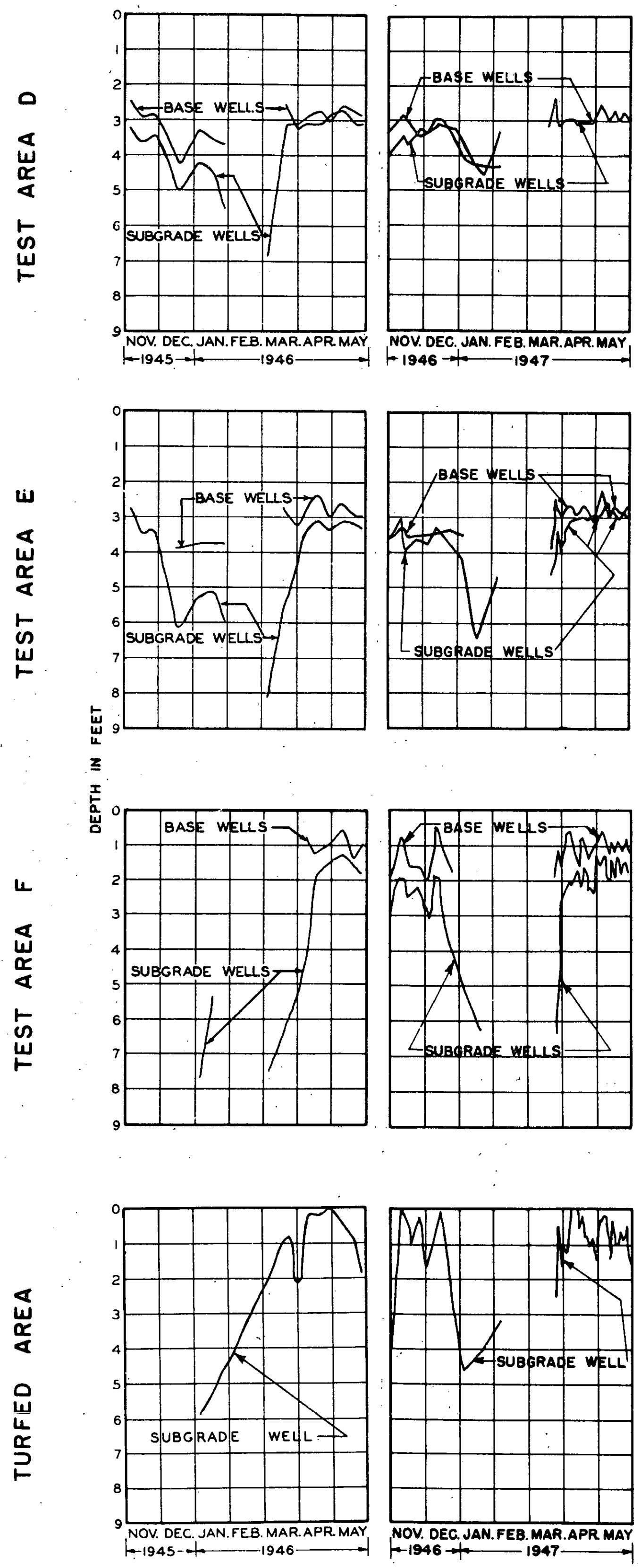


FIG. 5

TYPICAL LOG

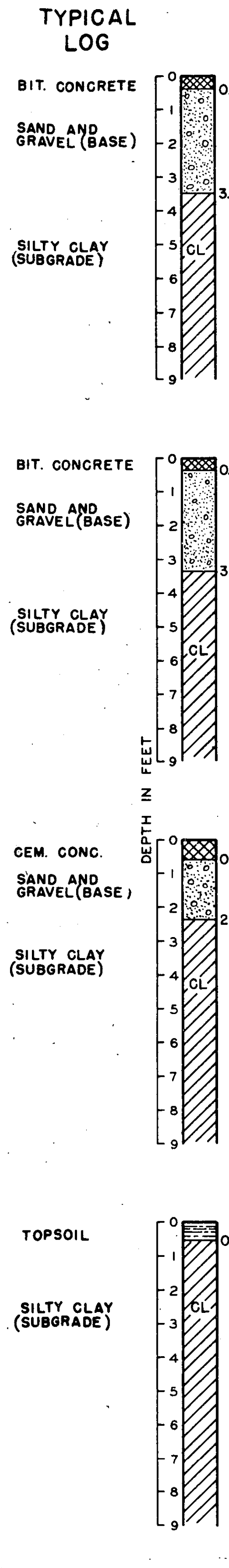


FIG. 6

ICE SEGREGATION

Test Area D

1945-1946

CRYSTALS IN BASE. FEW CRYSTALS AND WIDELY ISOLATED LENSES FROM HAIRLINE TO ONE SIXTEENTH INCH IN THICKNESS IN SUBGRADE. FROST PENETRATION 4.2 FT. ON 12 MARCH 1946.

1946-1947

CRYSTALS THROUGHOUT BASE AND FROZEN SUBGRADE. LENSES IN SUBGRADE FROM HAIRLINE TO ONE SIXTEENTH INCH IN THICKNESS. THICKEST AT FROST LINE. FROST PENETRATION 4.05 FT. ON 10 MARCH 1947.

Test Area E

1945-1946

CRYSTALS IN BASE AND FROZEN SUBGRADE ISOLATED LENSES IN SUBGRADE FROM HAIRLINE TO ONE SIXTEENTH INCH IN THICKNESS. FROST PENETRATION 4.0 FT. ON 11 MARCH 1946.

1946-1947

CRYSTALS THROUGHOUT BASE. LENSES FROM HAIRLINE TO ONE QUARTER INCH IN THICKNESS SPACED ONE INCH APART AT FROST LINE. FROST PENETRATION 3.9 FT. ON 5 MARCH 1947.

Test Area F

1945-1946

CRYSTALS IN BASE AND FROZEN SUBGRADE. ISOLATED LENSES IN SUBGRADE FROM HAIRLINE TO ONE EIGHTH INCH IN THICKNESS. FROST PENETRATION 4.5 FT. ON 5 FEBRUARY 1946.

1946-1947

CRYSTALS THROUGHOUT BASE AND FROZEN SUBGRADE. HAIRLINE LENSES FROM 2.2 FT. TO 3.0 FT. FROST PENETRATION 3.7 FT. ON 25 FEBRUARY 1947.

Turfed Area

1945-1946

CRYSTALS FROM 0.1 FT. TO 1.7 FT. LENSES FROM 1.7 FT. TO 2.2 FT. RANGING FROM ONE QUARTER TO THREE QUARTERS INCH IN THICKNESS. FROST PENETRATION 2.2 FT. ON 3 MARCH 1946.

1946-1947

CRYSTALS THROUGHOUT. LENSES FROM HAIRLINE TO ONE HALF INCH IN THICKNESS FROM 2.0 FT. TO 2.25 FT. FROST PENETRATION 2.3 FT. ON 6 MARCH 1947.

PAVEMENT HEAVE

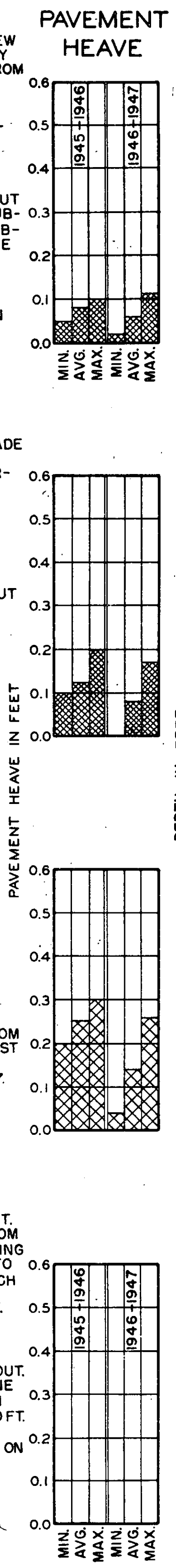


FIG. 7

SUBSURFACE TEMPERATURES

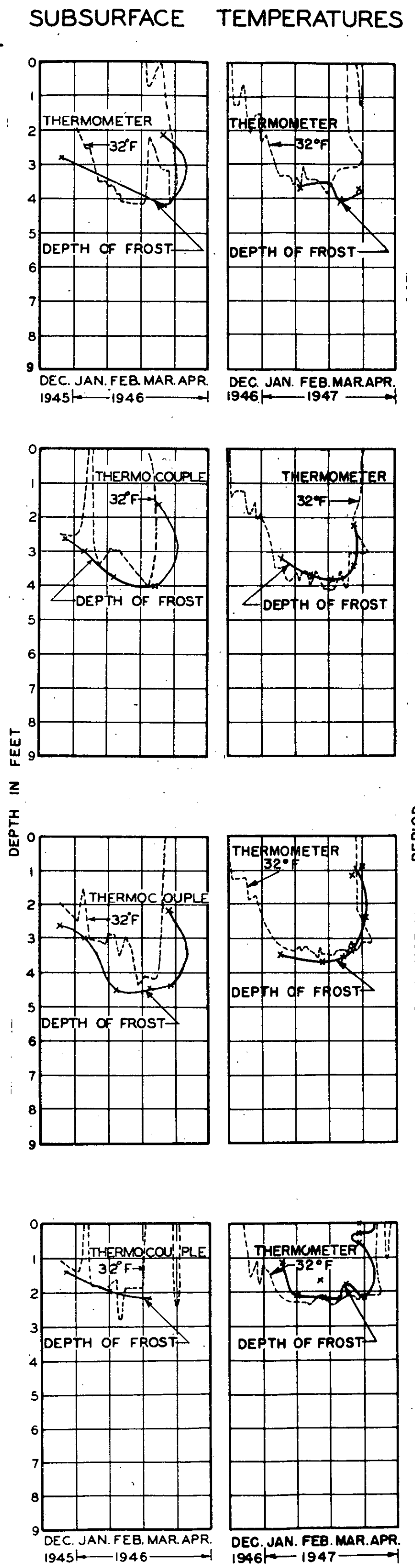


FIG. 8

DENSITY / WATER CONTENT

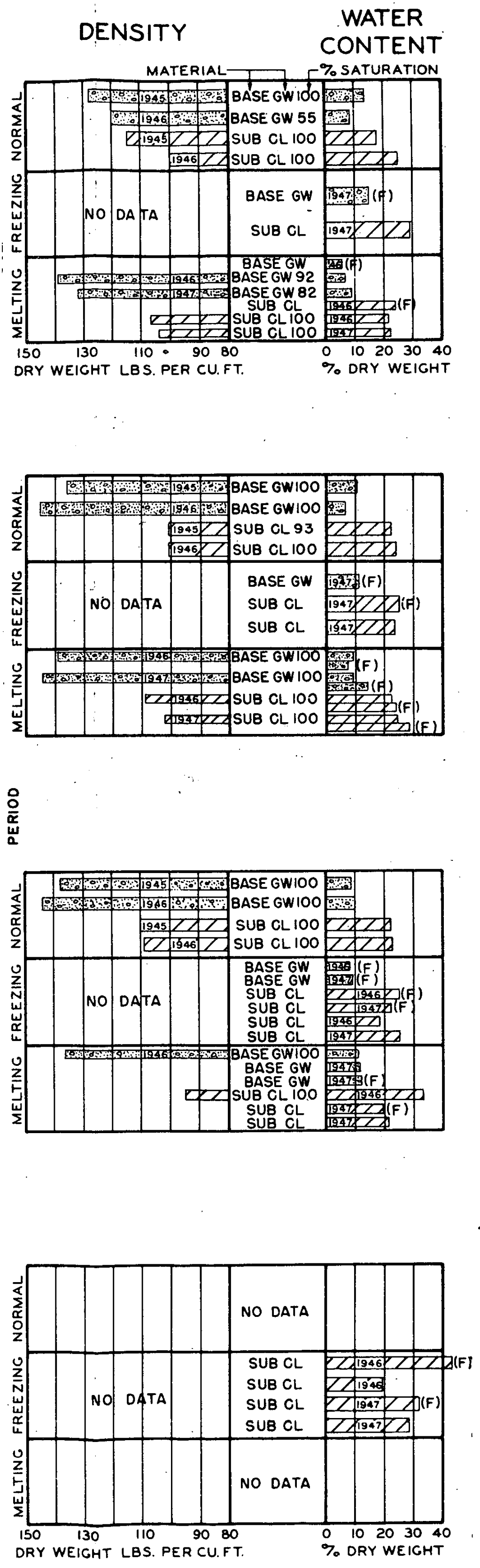


FIG. 9

PLATE BEARING TESTS

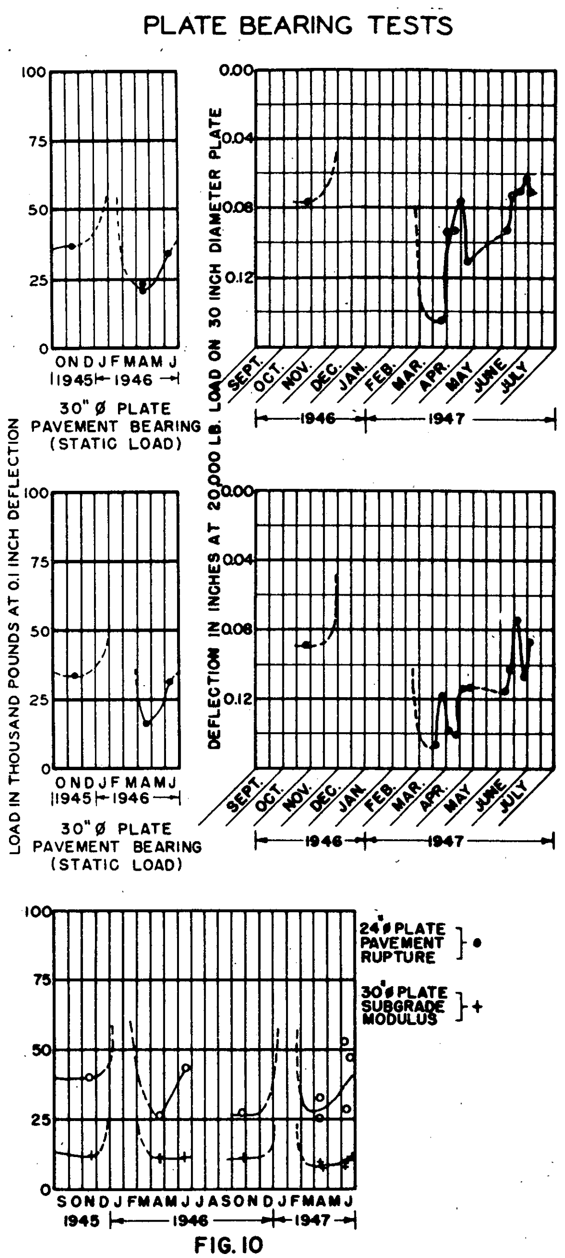


FIG. 10

(F) INDICATES FROZEN SOIL

FROST INVESTIGATION
1945 - 1947

SUMMARY OF DATA
DOW FIELD

FROST EFFECTS LABORATORY, BOSTON, MASS. JUNE 1946

PLATE 3

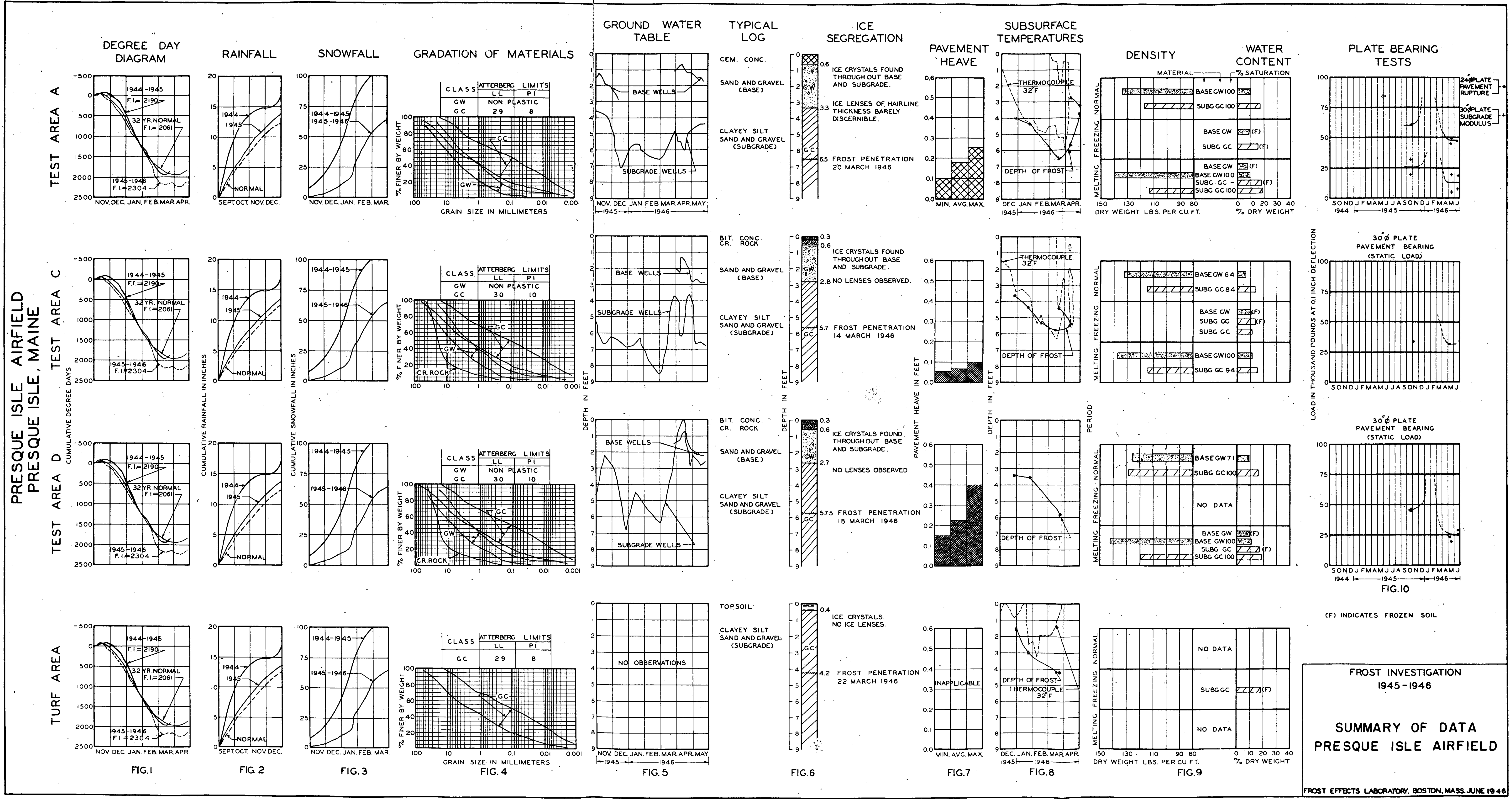

PRESQUE ISLE AIRFIELD
PRESQUE ISLE, MAINE
TEST AREA A
TEST AREA C
TEST AREA D
TURF AREA
DEGREE DAY DIAGRAM
RAINFALL
SNOWFALL
GRADATION OF MATERIALS
GROUND WATER TABLE
TYPICAL LOG
ICE SEGREGATION
PAVEMENT HEAVE
SUBSURFACE TEMPERATURES
DENSITY
WATER CONTENT
PLATE BEARING TESTS
CUMULATIVE DEGREE DAYS
CUMULATIVE RAINFALL IN INCHES
CUMULATIVE SNOWFALL IN INCHES
% FINER BY WEIGHT
GRAIN SIZE IN MILLIMETERS
DEPTH IN FEET
PAVEMENT HEAVE IN FEET
PERIOD
DRY WEIGHT LBS. PER CU. FT.
% DRY WEIGHT
LOAD IN THOUSAND POUNDS AT 0.1 INCH DEFLECTION
1944-1945
F.I.=2190
32 YR. NORMAL
F.I.=2061
1945-1946
F.I.=2304
NORMAL
CLASS
ATTERBERG LIMITS
LL
PI
GW
GC
NON PLASTIC
CR. ROCK
BASE WELLS
SUBGRADE WELLS
NO OBSERVATIONS
CEM. CONC.
BIT. CONC.
CR. ROCK
SAND AND GRAVEL (BASE)
CLAYEY SILT SAND AND GRAVEL (SUBGRADE)
TOPSOIL
ICE CRYSTALS FOUND THROUGH OUT BASE AND SUBGRADE.
ICE LENSES OF HAIRLINE THICKNESS BARELY DISCERNIBLE.
FROST PENETRATION 20 MARCH 1946
NO LENSES OBSERVED.
FROST PENETRATION 14 MARCH 1946
FROST PENETRATION 18 MARCH 1946
ICE CRYSTALS. NO ICE LENSES.
FROST PENETRATION 22 MARCH 1946
MIN. AVG. MAX.
INAPPLICABLE
THERMOCOUPLE 32°F
DEPTH OF FROST
NORMAL
FREEZING
MELTING
MATERIAL
% SATURATION
NO DATA
24"Ø PLATE PAVEMENT RUPTURE
30"Ø PLATE SUBGRADE MODULUS
30"Ø PLATE PAVEMENT BEARING (STATIC LOAD)
(F) INDICATES FROZEN SOIL
FIG.1
FIG. 2
FIG.3
FIG. 4
FIG. 5
FIG.6
FIG.7
FIG.8
FIG.9
FIG.10
FROST INVESTIGATION
1945-1946
SUMMARY OF DATA
PRESQUE ISLE AIRFIELD
FROST EFFECTS LABORATORY, BOSTON, MASS. JUNE 1946

PLATE 4

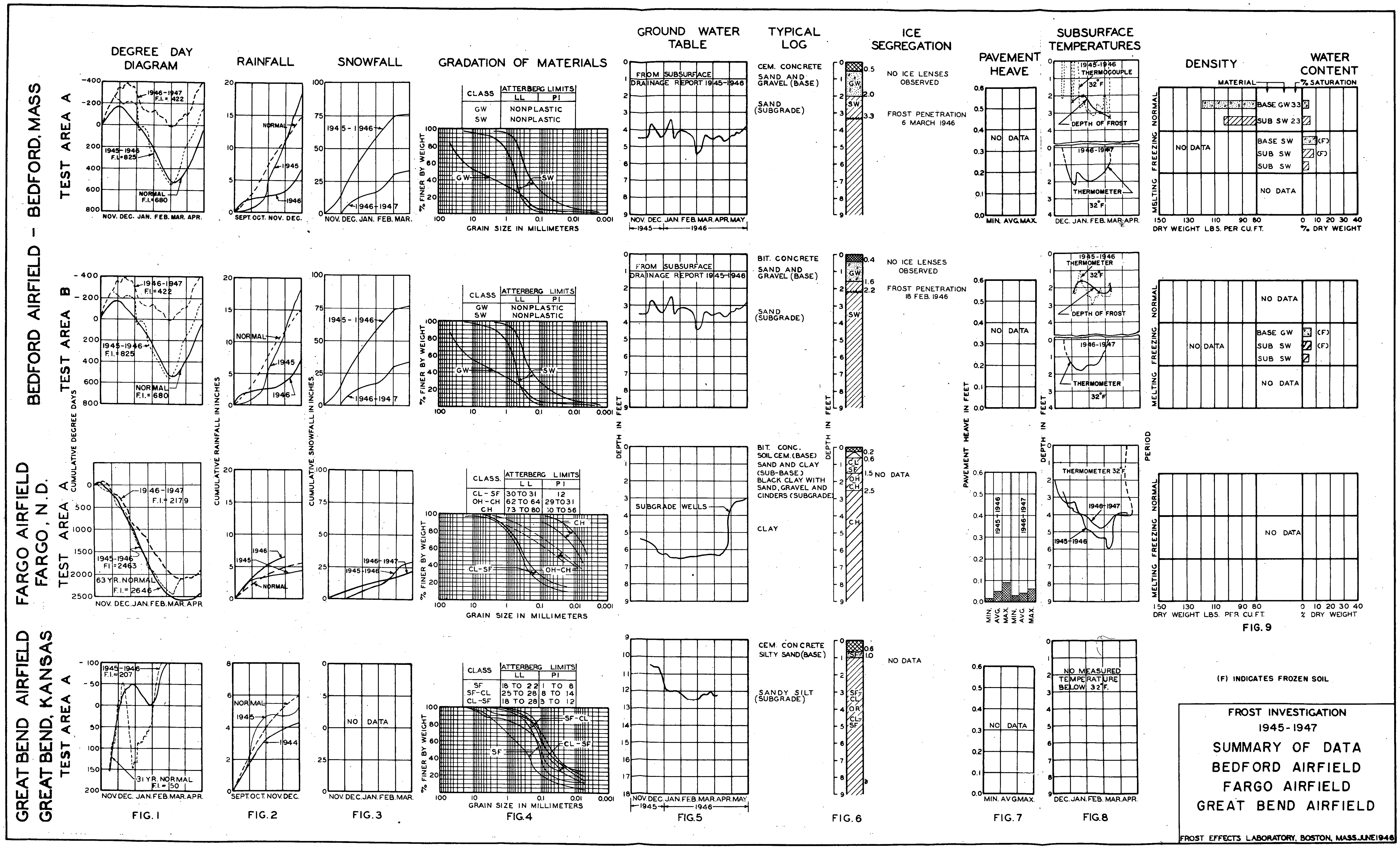
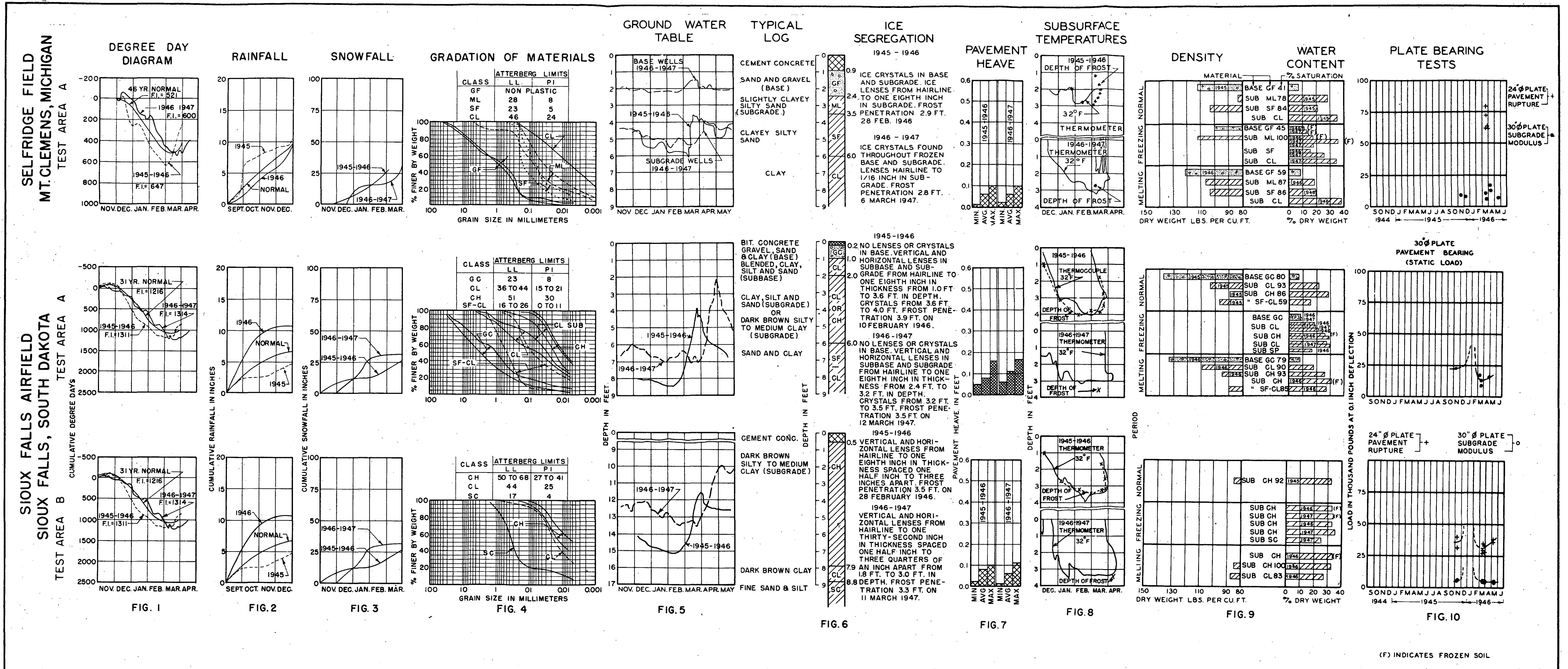

DEGREE DAY DIAGRAM
RAINFALL
SNOWFALL
GRADATION OF MATERIALS
GROUND WATER TABLE
TYPICAL LOG
ICE SEGREGATION
PAVEMENT HEAVE
SUBSURFACE TEMPERATURES
DENSITY
WATER CONTENT
BEDFORD AIRFIELD - BEDFORD, MASS
TEST AREA A
TEST AREA B
FARGO AIRFIELD FARGO, N. D.
TEST AREA A
GREAT BEND AIRFIELD GREAT BEND, KANSAS
TEST AREA A
CUMULATIVE DEGREE DAYS
CUMULATIVE RAINFALL IN INCHES
CUMULATIVE SNOWFALL IN INCHES
% FINER BY WEIGHT
GRAIN SIZE IN MILLIMETERS
DEPTH IN FEET
PAVEMENT HEAVE IN FEET
PERIOD
MELTING FREEZING NORMAL
DRY WEIGHT LBS. PER CU. FT.
% DRY WEIGHT
CEM. CONCRETE
SAND AND GRAVEL (BASE)
SAND (SUBGRADE)
BIT. CONCRETE
BIT. CONC.
SOIL CEM. (BASE)
SAND AND CLAY (SUB-BASE)
BLACK CLAY WITH SAND, GRAVEL AND CINDERS (SUBGRADE)
CLAY
SILTY SAND (BASE)
SANDY SILT (SUBGRADE)
NO ICE LENSES OBSERVED
FROST PENETRATION 6 MARCH 1946
FROST PENETRATION 18 FEB. 1946
NO DATA
FROM SUBSURFACE DRAINAGE REPORT 1945-1946
SUBGRADE WELLS
DEPTH OF FROST
THERMOCOUPLE
THERMOMETER
NO MEASURED TEMPERATURE BELOW 32°F.
FIG. 1
FIG. 2
FIG. 3
FIG. 4
FIG. 5
FIG. 6
FIG. 7
FIG. 8
FIG. 9
(F) INDICATES FROZEN SOIL
FROST INVESTIGATION
1945-1947
SUMMARY OF DATA
BEDFORD AIRFIELD
FARGO AIRFIELD
GREAT BEND AIRFIELD
FROST EFFECTS LABORATORY, BOSTON, MASS. JUNE 1946

PLATE 5



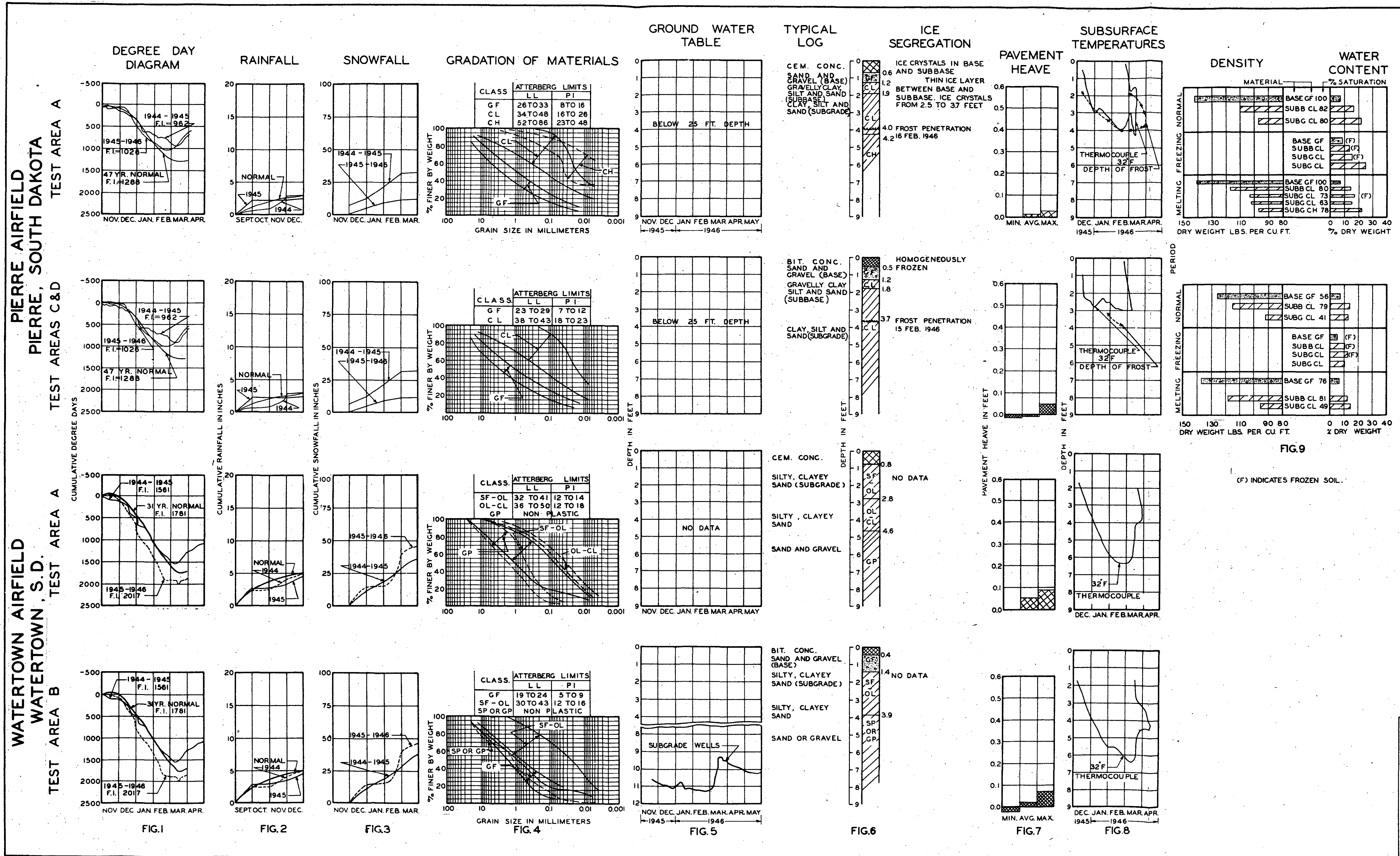
FROST INVESTIGATION
1945-1947

SUMMARY OF DATA

SELFRIDGE FIELD
SIOUX FALLS AIRFIELD

FROST EFFECTS LABORATORY, BOSTON, MASS. JUNE 1948

PLATE 6

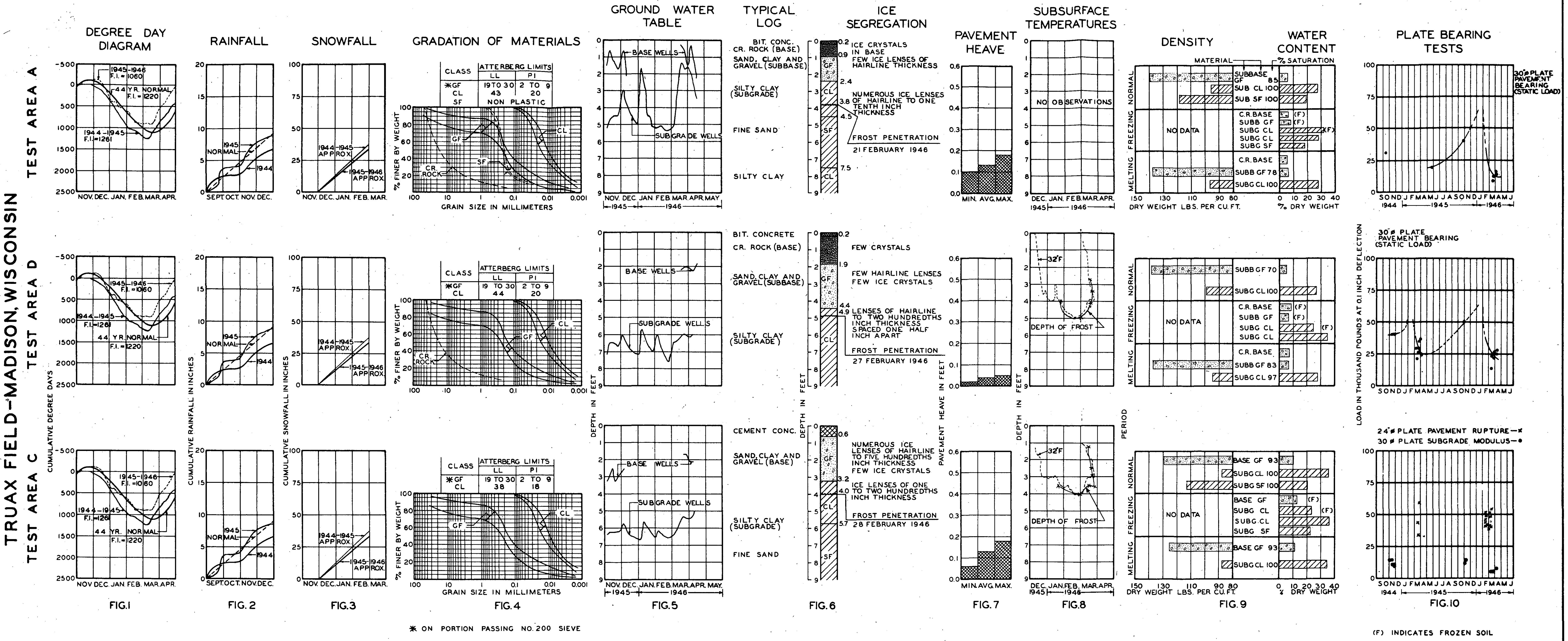


FROST INVESTIGATION
1945-1946

SUMMARY OF DATA
PIERRE AIRFIELD
WATERTOWN AIRFIELD

FROST EFFECTS LABORATORY, BOSTON, MASS. JUNE 1946

PLATE 7



FROST INVESTIGATION
1945-1946

SUMMARY OF DATA
TRUAX FIELD

FROST EFFECTS LABORATORY, BOSTON, MASS. JUNE 1946

PLATE 8

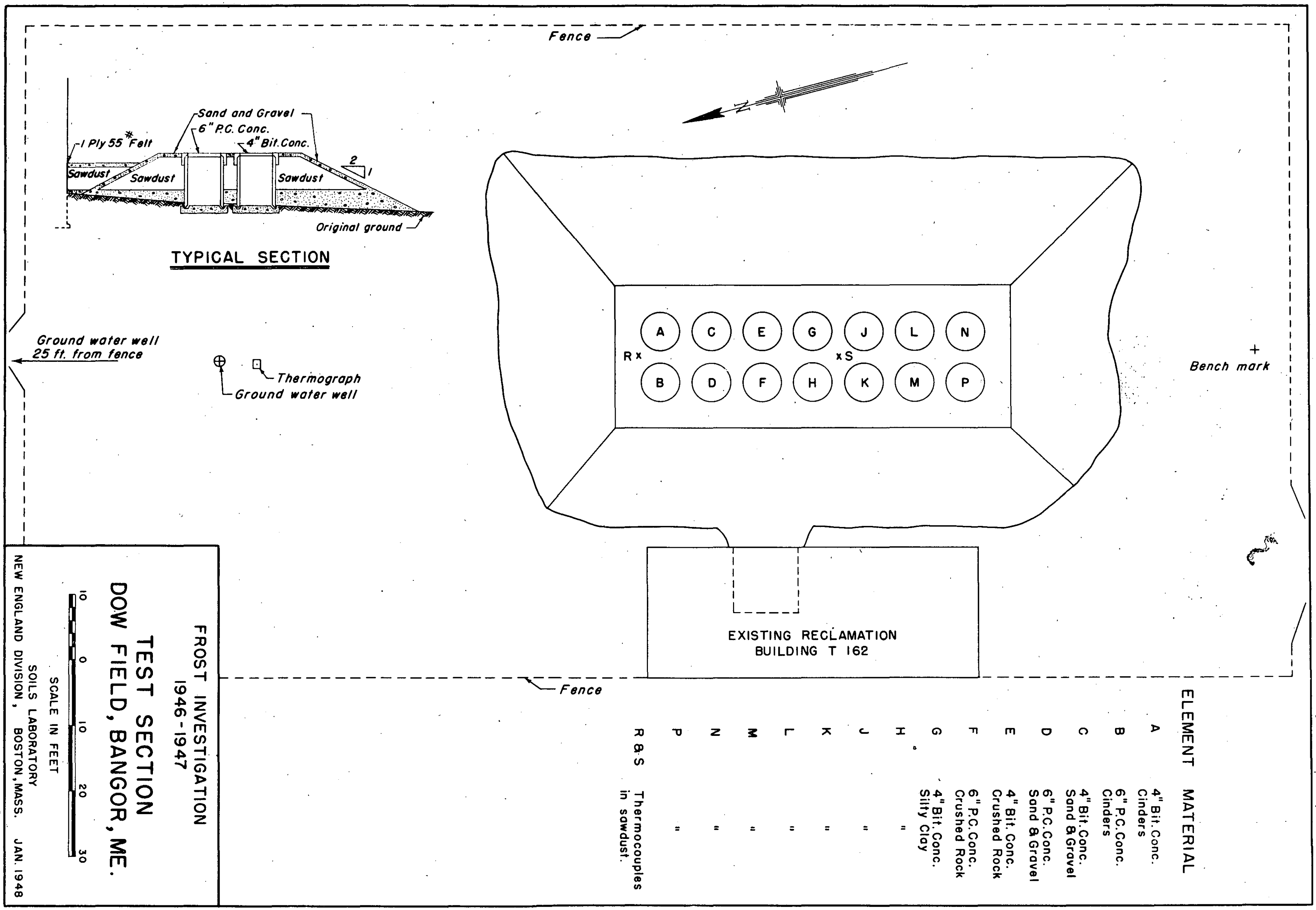
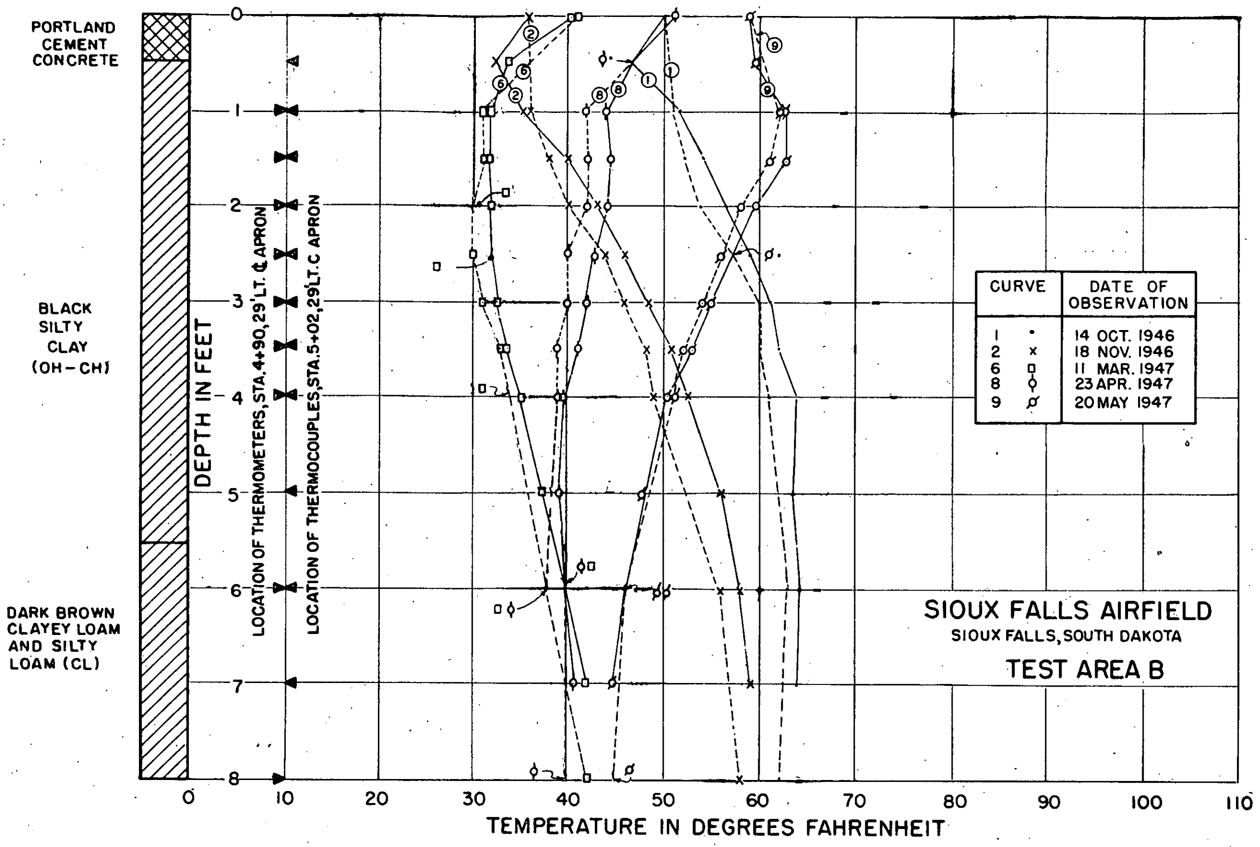
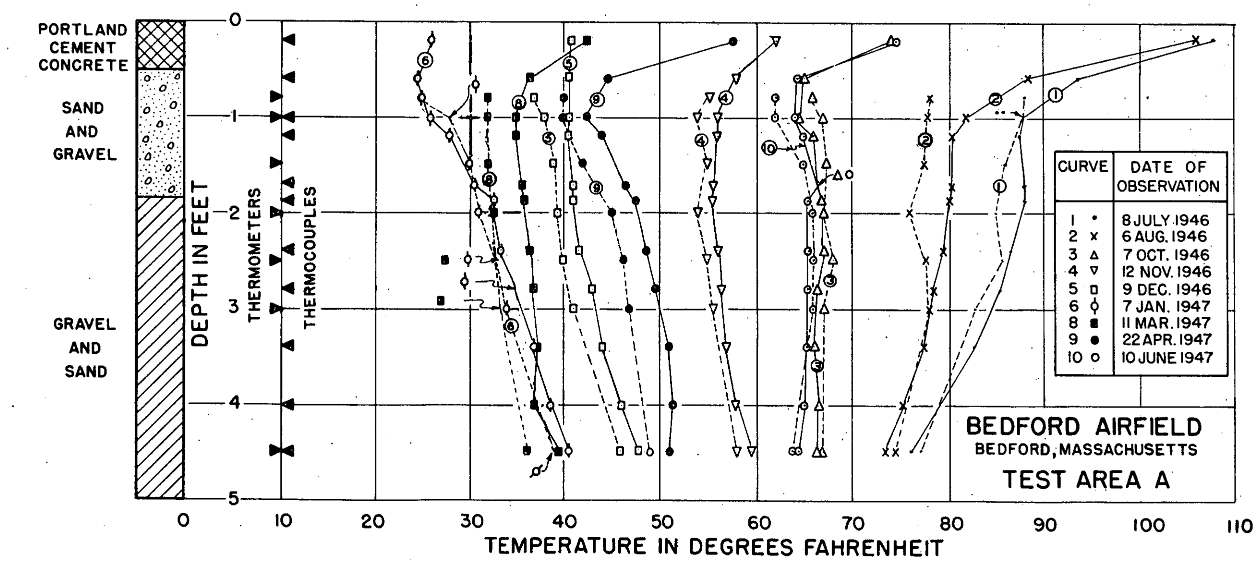
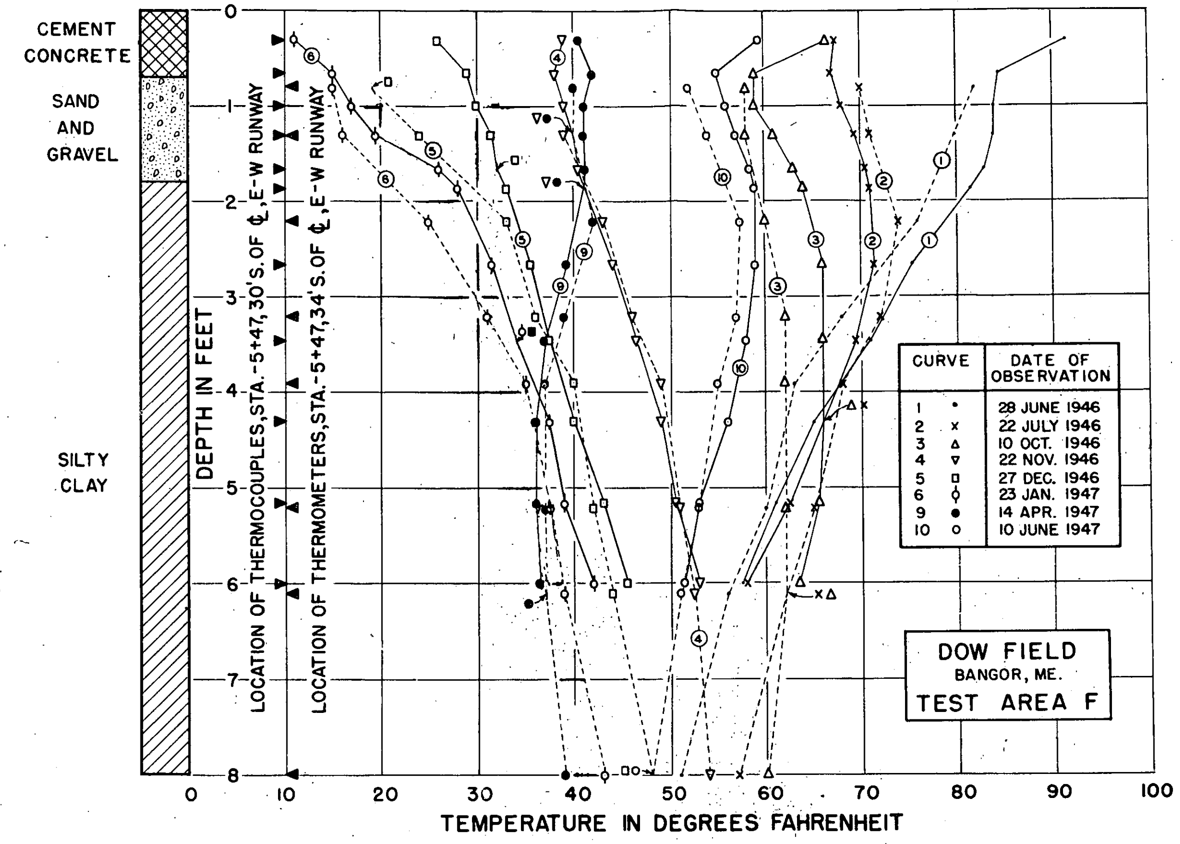

Fence
N
Sand and Gravel
6" P.C. Conc.
4" Bit. Conc.
1 Ply 55 * Felt
Sawdust
Sawdust
Sawdust
2
1
Original ground
TYPICAL SECTION
Ground water well
25 ft. from fence
Thermograph
Ground water well
A
C
E
G
J
L
N
R x
x S
B
D
F
H
K
M
P
Bench mark
EXISTING RECLAMATION
BUILDING T 162
Fence
ELEMENT MATERIAL
A 4" Bit. Conc. Cinders
B 6" P.C. Conc. Cinders
C 4" Bit. Conc. Sand & Gravel
D 6" P.C. Conc. Sand & Gravel
E 4" Bit. Conc. Crushed Rock
F 6" P.C. Conc. Crushed Rock
G 4" Bit. Conc. Silty Clay
H "
J "
K "
L "
M "
N "
P "
R & S Thermocouples in sawdust.
FROST INVESTIGATION
1946 - 1947
TEST SECTION
DOW FIELD, BANGOR, ME.
SCALE IN FEET
10 0 10 20 30
SOILS LABORATORY
NEW ENGLAND DIVISION, BOSTON, MASS. JAN. 1948

PLATE 9







NOTE:

——— THERMOCOUPLE OBSERVATIONS

------- THERMOMETER OBSERVATIONS

FROST INVESTIGATION
1946-1947

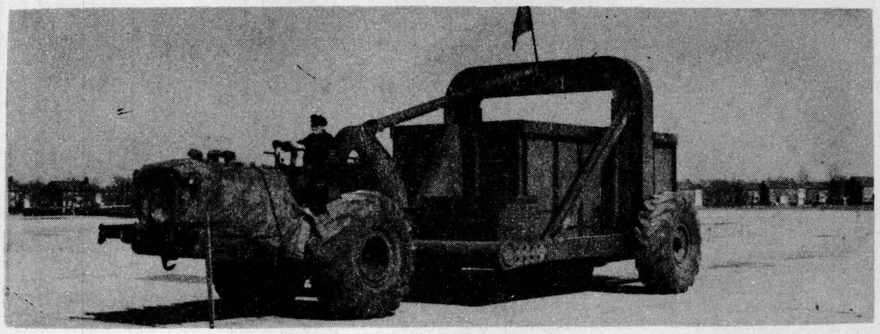
COMPARISON OF TYPICAL THERMOMETER AND THERMOCOUPLE OBSERVATIONS

SOILS LABORATORY JAN. 1948
NEW ENGLAND DIVISION BOSTON, MASS.

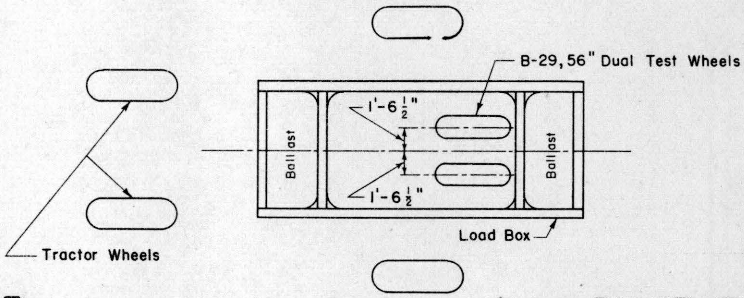
FROST INVESTIGATION
SELFRIDGE FIELD, MICHIGAN

TRAFFIC TEST LOAD EQUIPMENT
60,000 POUNDS TOTAL LOAD

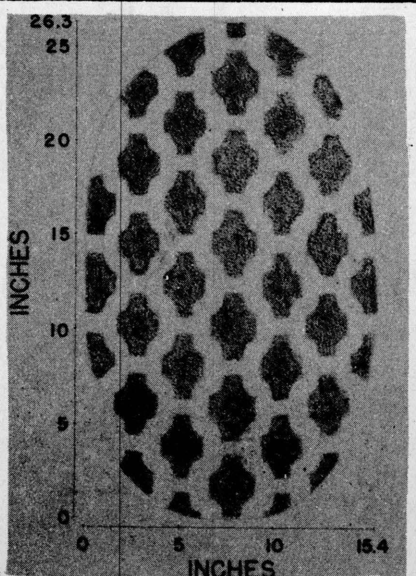
SUPER C TOURNAPULL WITH LOAD RIG



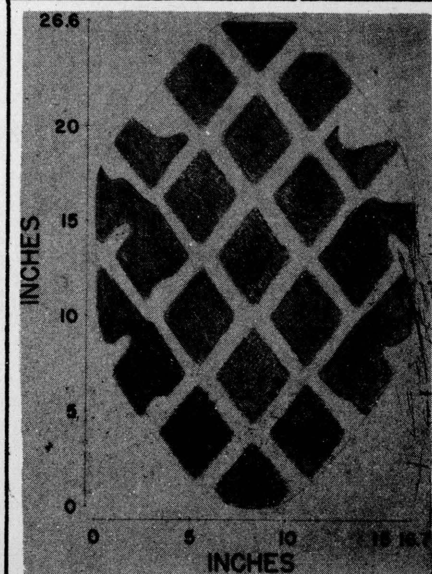
TOTAL MILAGE	TEST TIRE	TIRE TYPE	TIRE AIR PRESSURE LB. SQ. IN.	CONTACT PRESSURE LB. SQ. IN.	CONTACT AREA SQ. IN.
394.1	RIGHT	B-29, 56" DIA.	90	91.1	329.3
165.2	LEFT	B-29, 56" DIA.	90	89.0	337.2



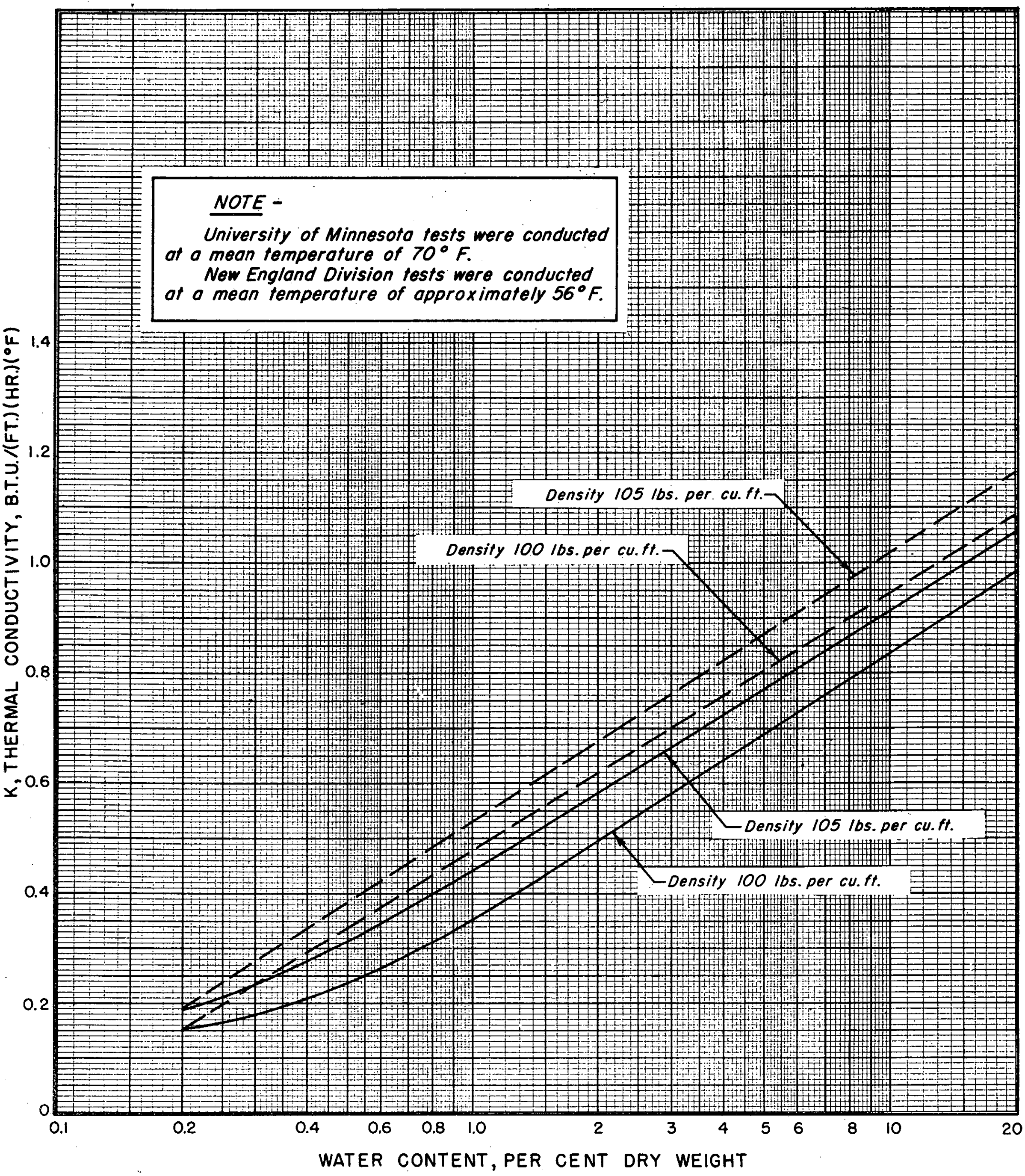
LEFT TIRE
56"–16 Ply Nylon
Smooth Contour



RIGHT TIRE
56"–16 Ply Nylon
Smooth Contour



TYPICAL PRINTS OF TEST TIRES



LEGEND

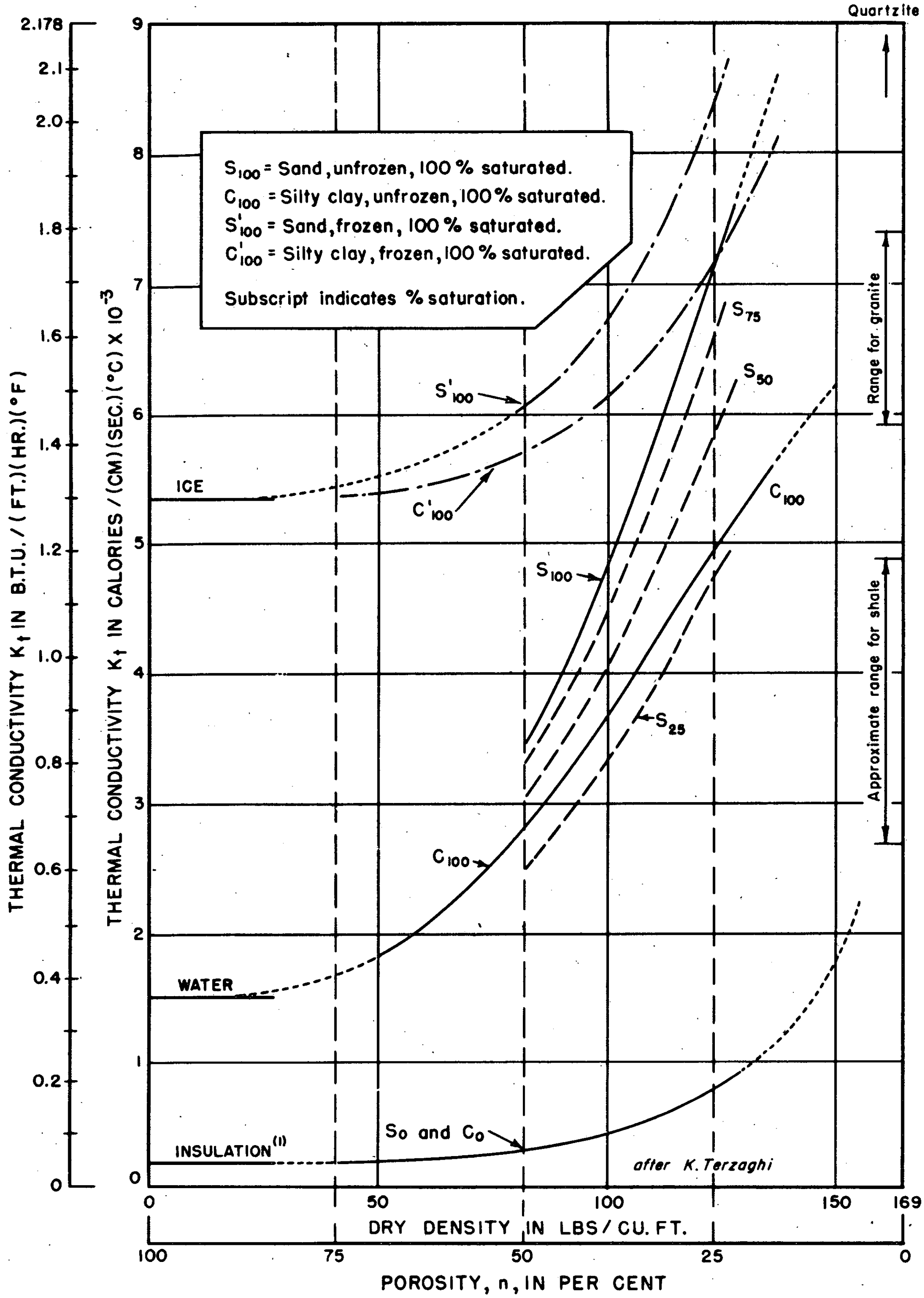
– – *University of Minnesota*

—— *New England Division*

FROST INVESTIGATION
1945 - 1947

COMPARISON OF
THERMAL CONDUCTIVITY TESTS
ON LOWELL SAND

FROST EFFECTS LABORATORY, BOSTON, MASS.

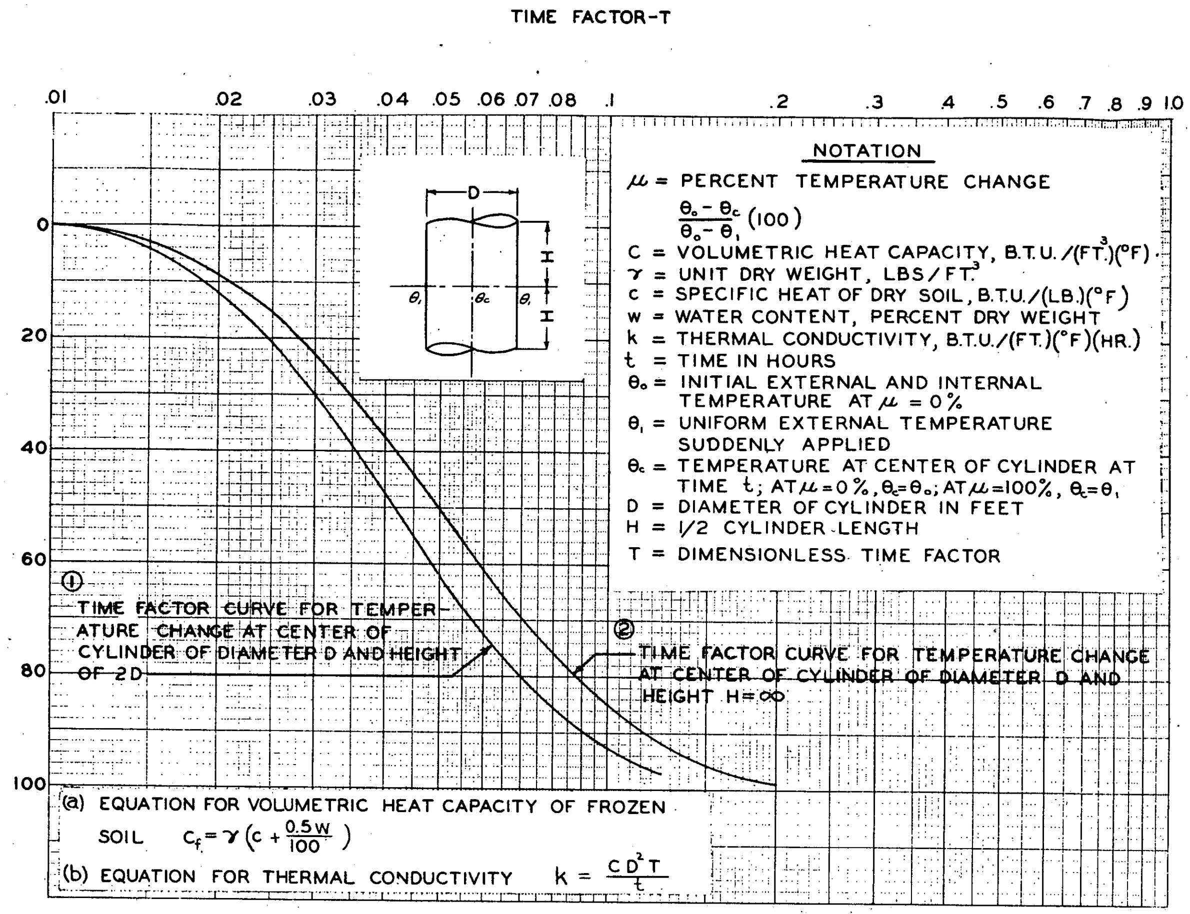


(1) *Such as dry asbestos or cotton.*

FROST INVESTIGATION
1948 - 1949

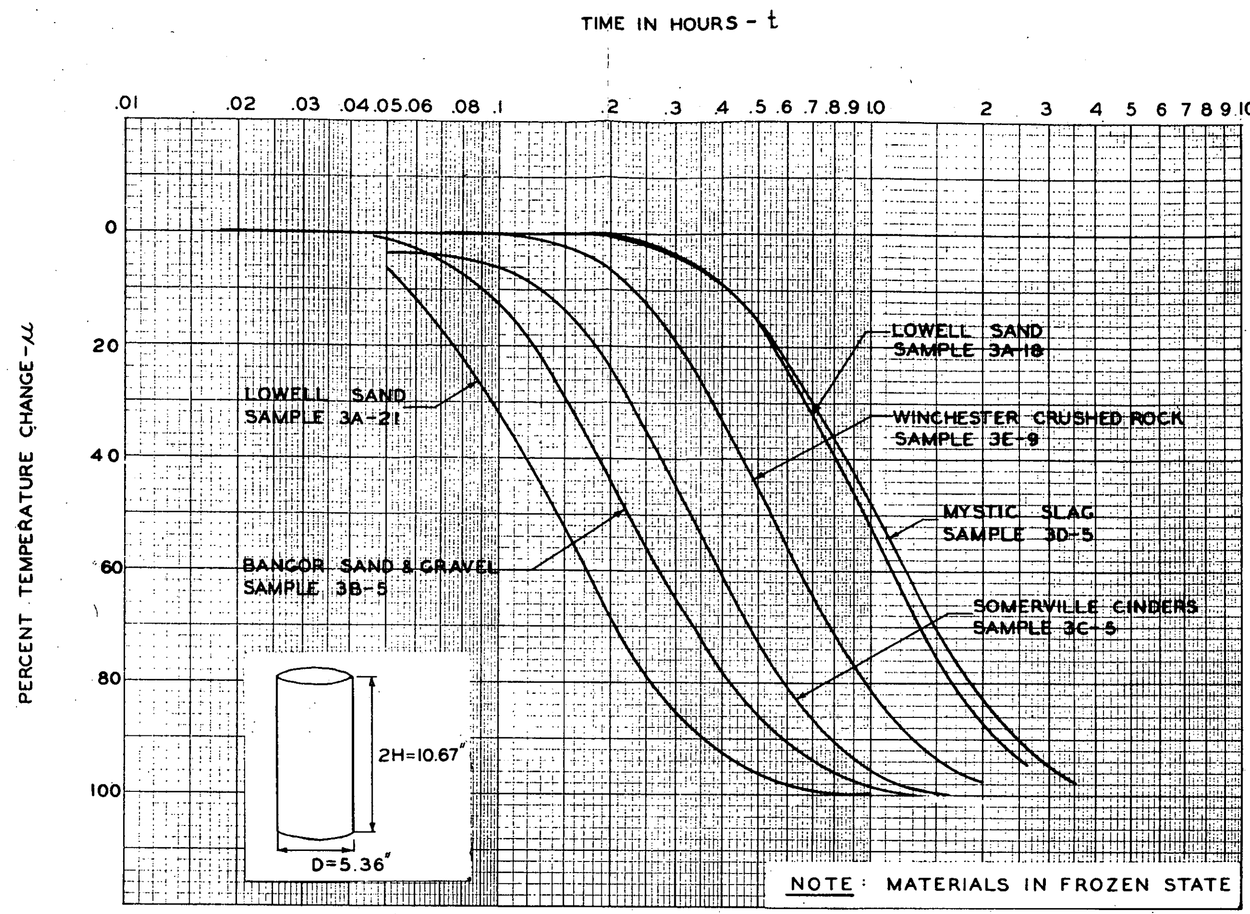
THERMAL CONDUCTIVITY VERSUS DENSITY, POROSITY AND SATURATION OF FROZEN AND UNFROZEN SOILS

FROST EFFECTS LABORATORY, BOSTON, MASS.



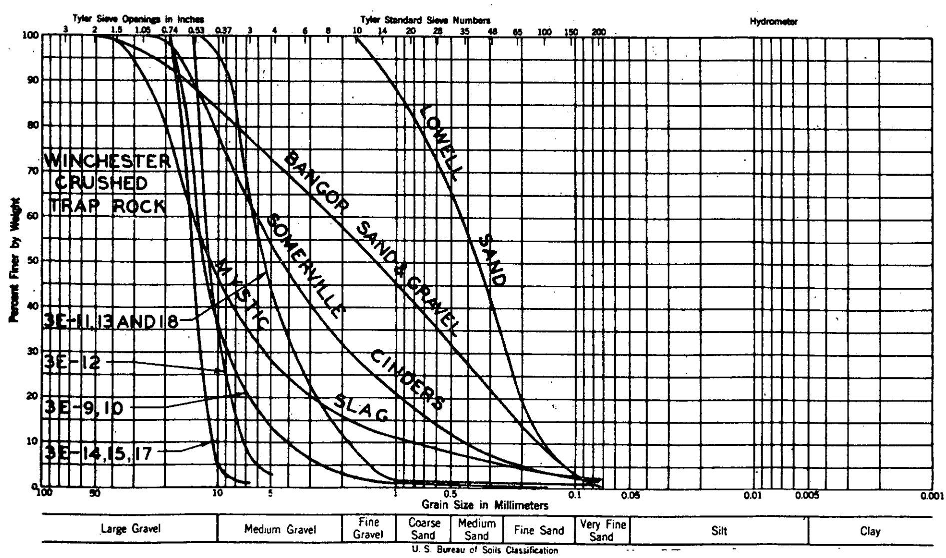
TIME FACTOR CURVES FOR TEMPERATURE CHANGE AT CENTER OF CYLINDER

FIG. 1



TYPICAL TIME CURVES
THERMAL CONDUCTIVITY DETERMINATIONS

FIG. 2



GRADATION OF BASE MATERIALS

FIG. 3

EXAMPLE FOR DETERMINATION OF THERMAL CONDUCTIVITY

GIVEN: $\mu = 50\%$

TEST DATA FOR SAMPLE NO. 3B-5, TABLE 4 AS FOLLOWS:

$c = 0.20$ B.T.U./(LB.)(°F)

$\gamma = 127.1$ LBS./FT.^{3}

$w = 3.6\%$

EQUATIONS:

(a) $C_f = \gamma\left(c + \frac{0.5w}{100}\right)$

(b) $k = \frac{C_f D^2 T}{t}$

SUBSTITUTING IN (a):

$C_f = 127.1\left(0.20 + \frac{(0.5)(3.6)}{100}\right) = 27.7$ B.T.U./(FT.^{3})(°F)

FROM FIG. 2:

$D = 5.36$ IN. $= 0.447$ FT., $D^2 = 0.1995$ FT.^{2}

$t = 0.224$ HR.

FROM FIG. 1, CURVE 1:

$T = 0.042$

SUBSTITUTING IN (b):

$k = \frac{(27.7)(0.1995)(0.042)}{0.224} = 1.038$ B.T.U./(FT.)(°F)(HR.)

FROST INVESTIGATION
1945-1946

THERMAL CONDUCTIVITY DETERMINATIONS
FROZEN BASE MATERIALS

FROST EFFECTS LABORATORY, BOSTON, MASS. JUNE 1946

PLATE 14

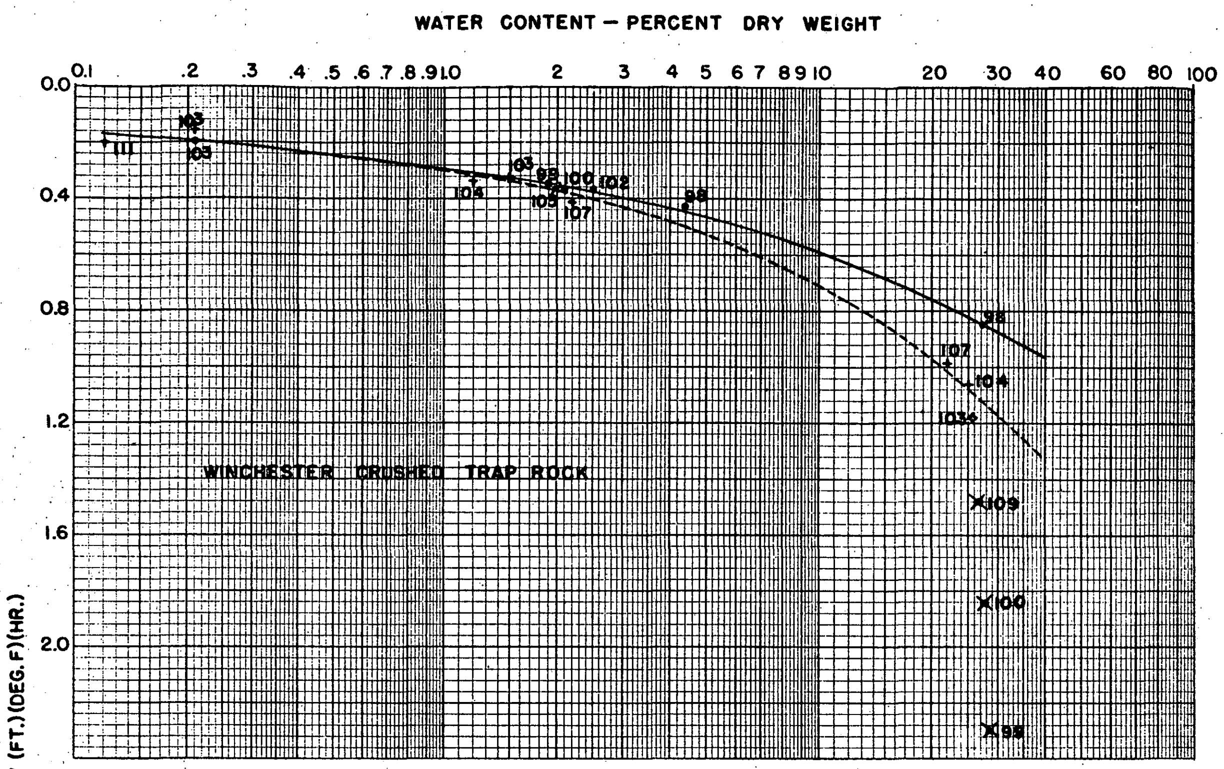


FIG. 1

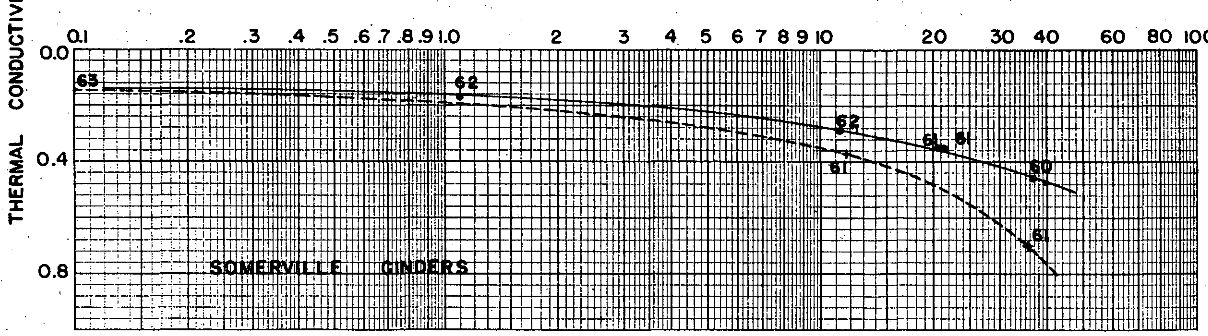


FIG. 2

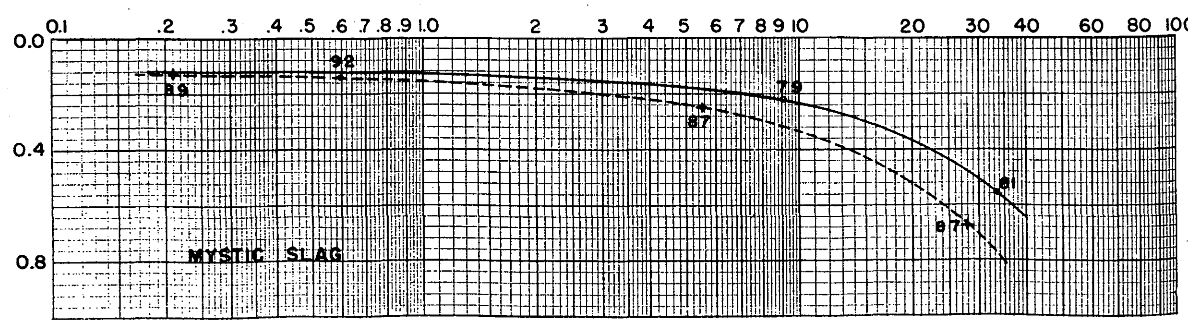


FIG. 3

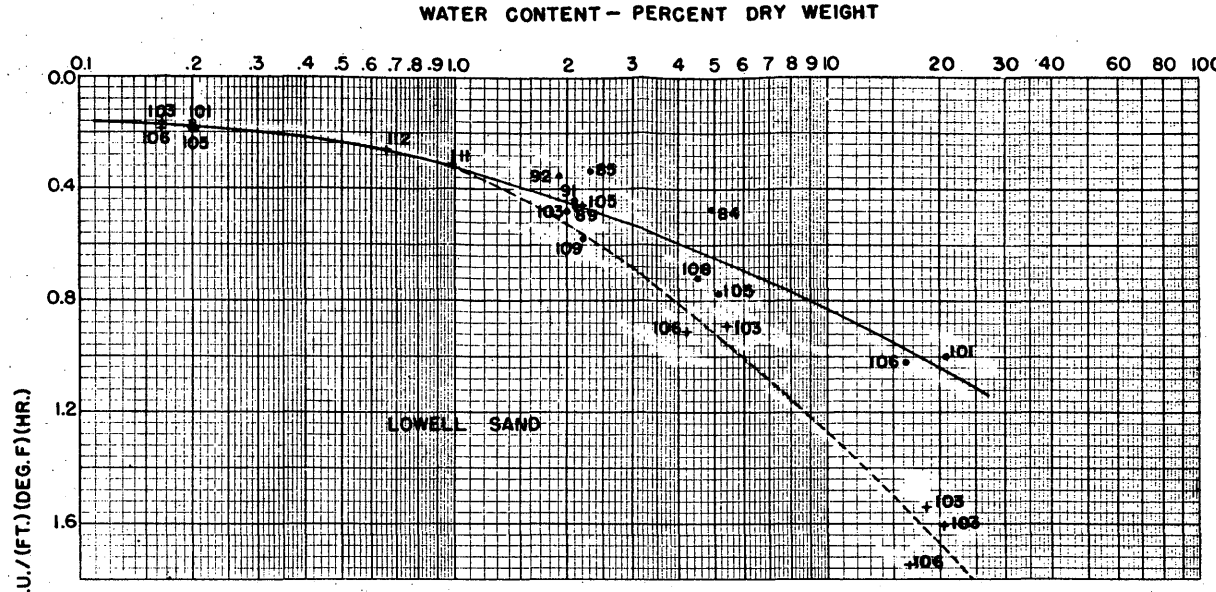


FIG. 4

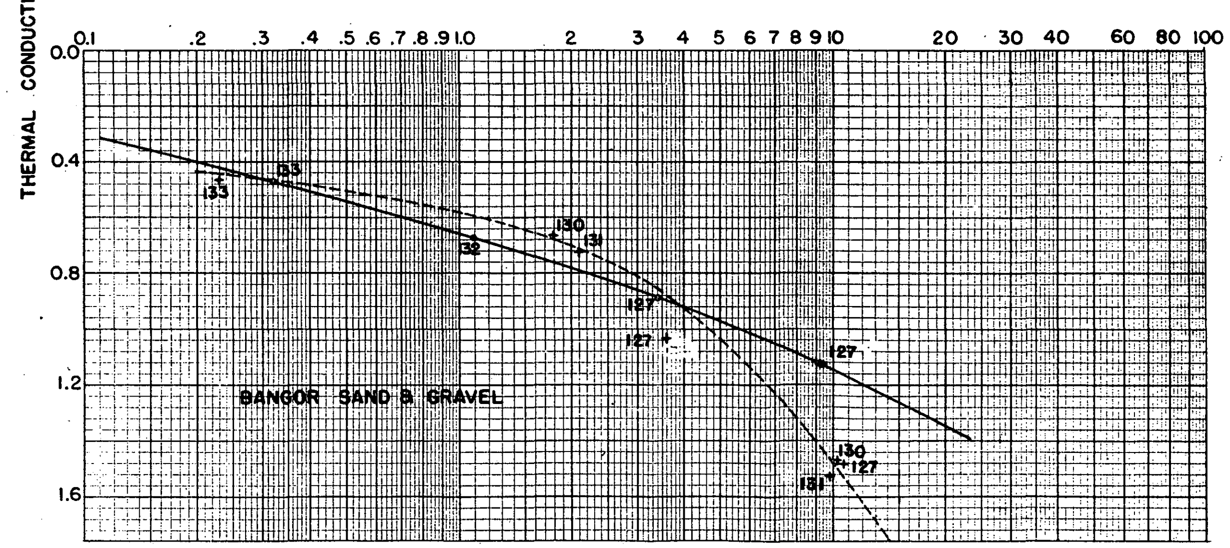


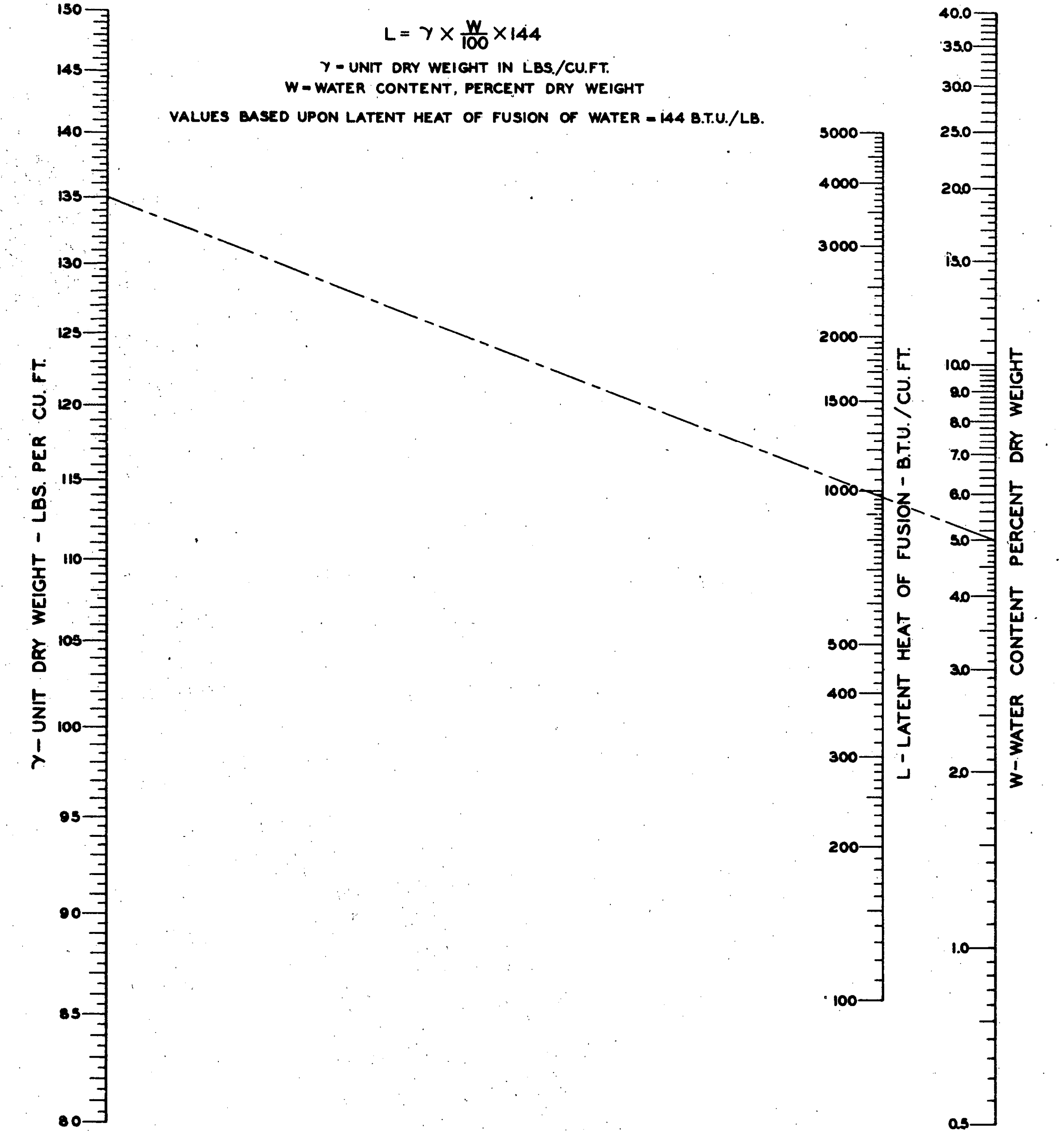
FIG. 5

NOTES:
NUMBERS BESIDE PLOTTED POINTS INDICATE UNIT DRY WEIGHT OF SAMPLE IN POUNDS PER CUBIC FOOT.
—●— UNFROZEN MATERIAL
--+-- FROZEN MATERIAL
✕ OBSERVATION IN ERROR

FROST INVESTIGATION
1945-1946

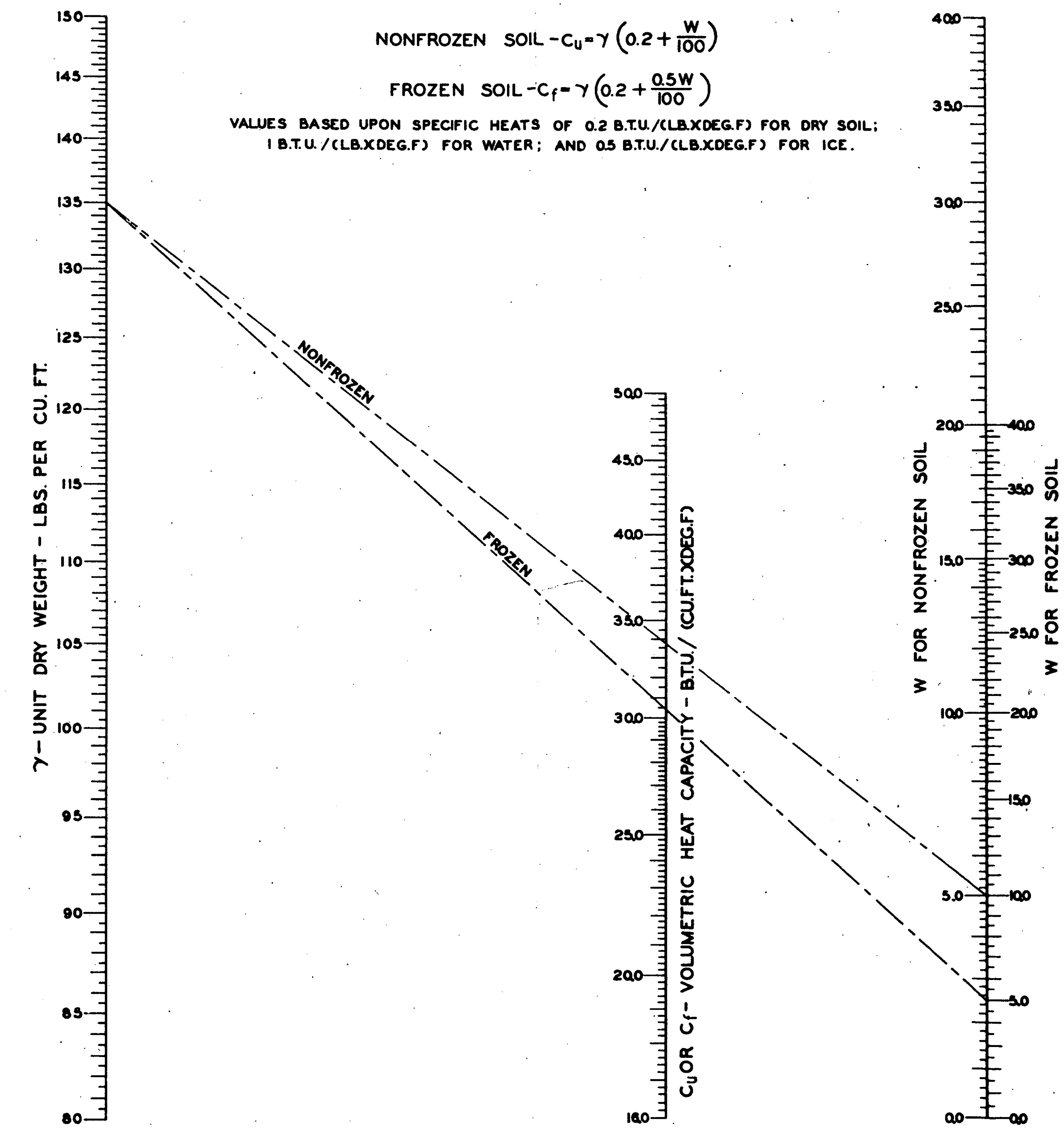
THERMAL CONDUCTIVITY VS. WATER CONTENT OF BASE MATERIALS

FROST EFFECTS LABORATORY, BOSTON, MASS. JUNE 1946



LATENT HEAT DETERMINATION

FIG. 1



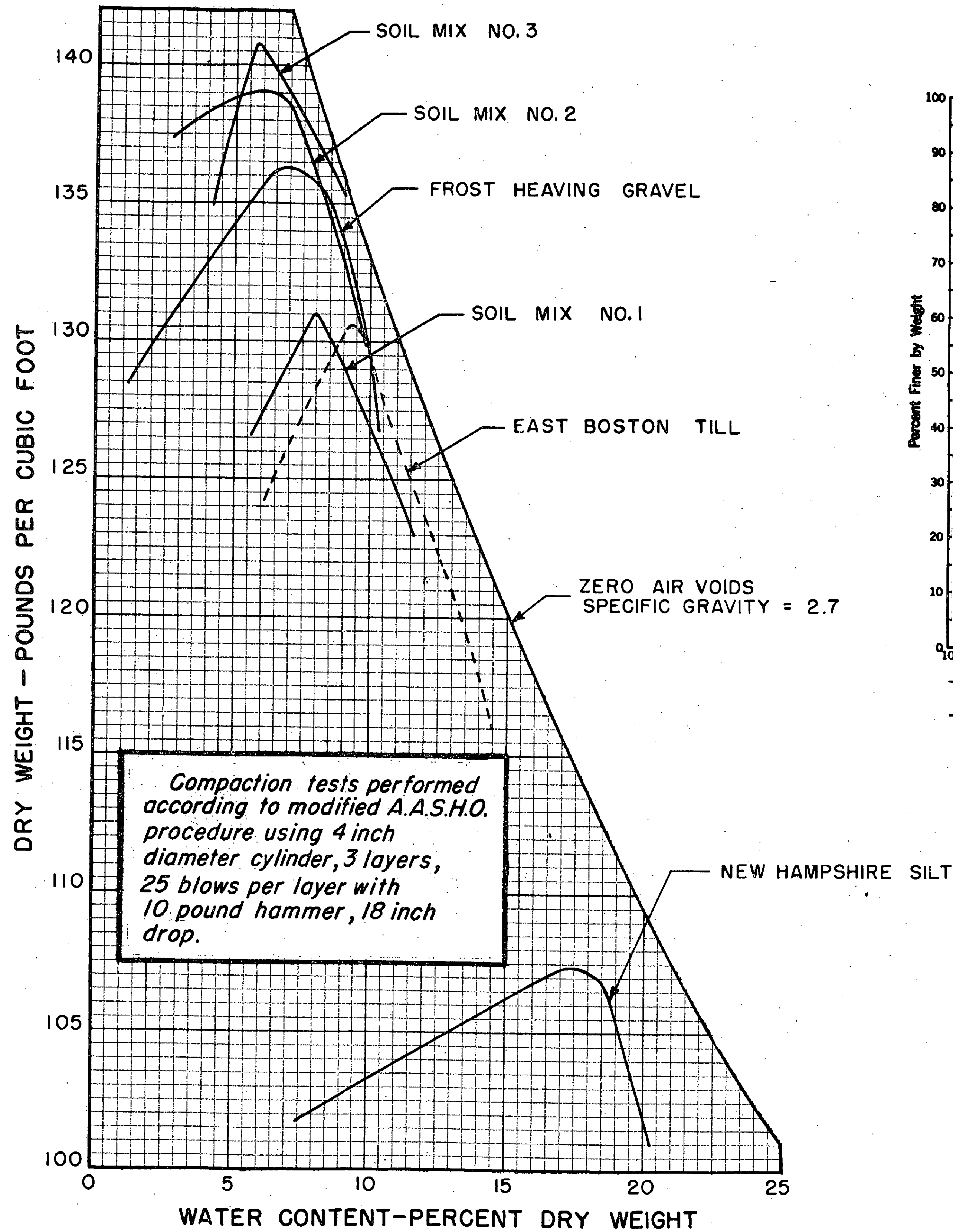
VOLUMETRIC HEAT CAPACITY DETERMINATION

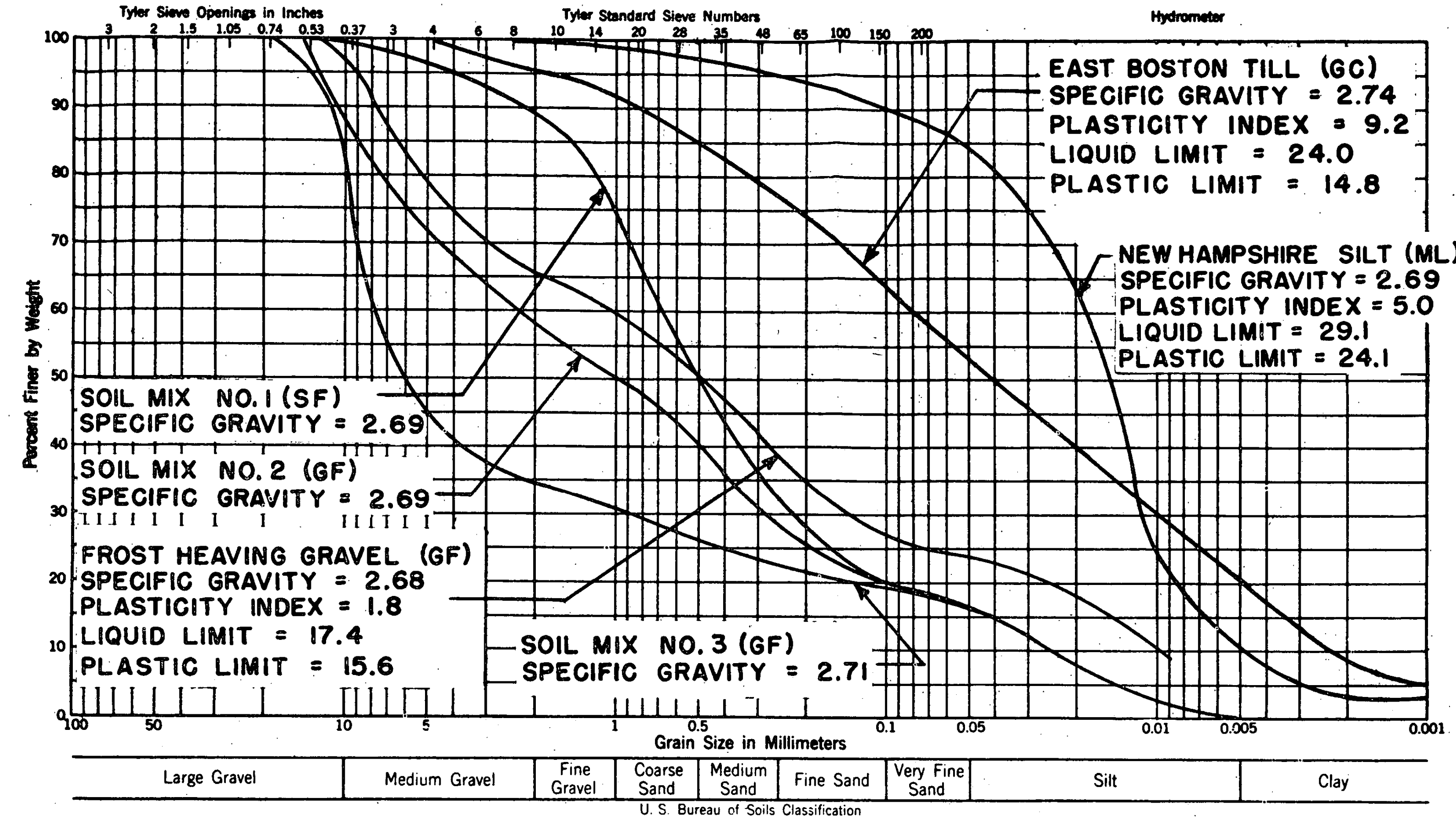
FIG. 2

FROST INVESTIGATION
1945-1946

DETERMINATION OF LATENT HEAT OF FUSION AND VOLUMETRIC HEAT CAPACITY

FROST EFFECTS LABORATORY, BOSTON, MASS. JUNE 1946





FROST INVESTIGATION
1945-1947

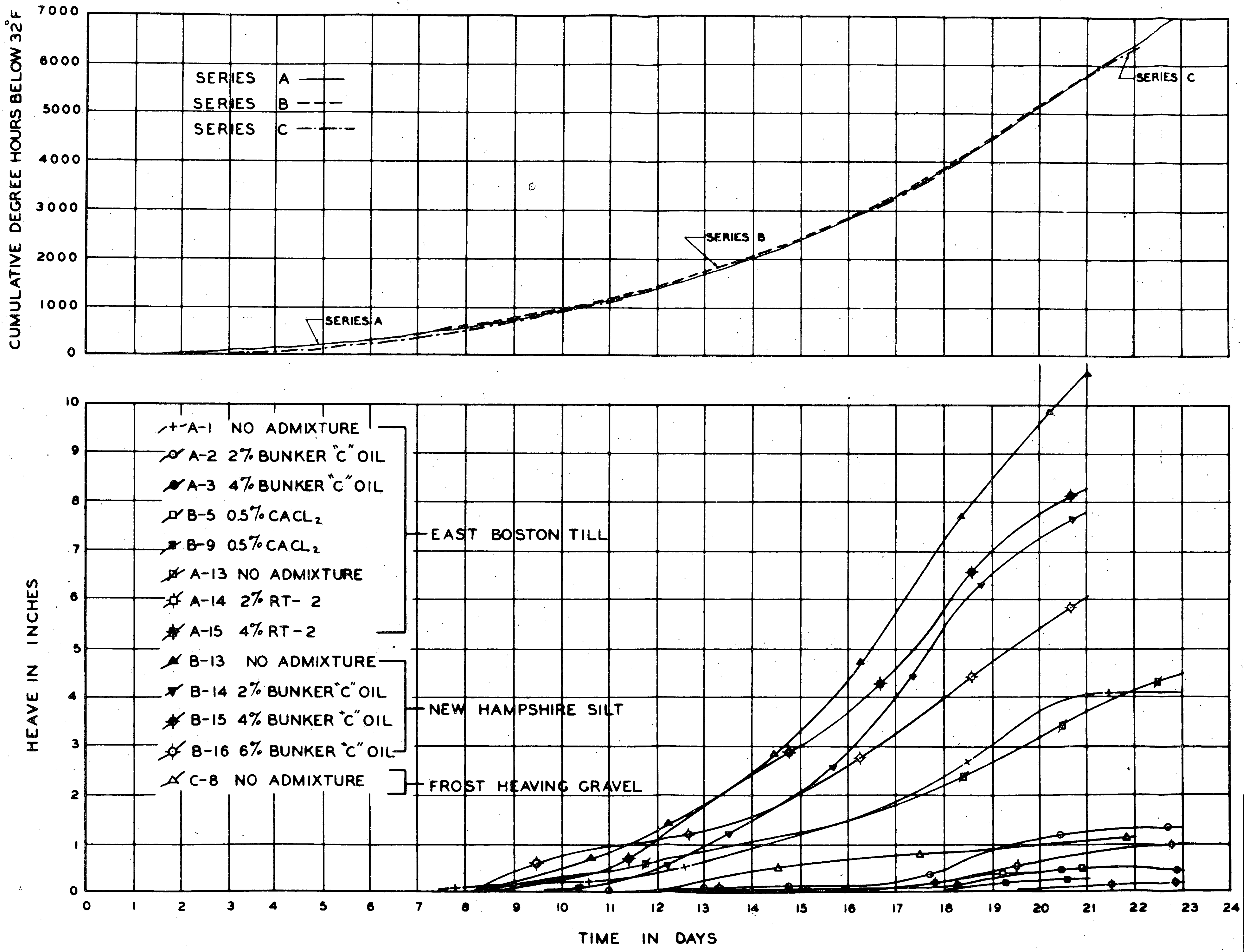
BASE COURSE TREATMENT TO PREVENT FROST ACTION

SUMMARY OF SOIL TEST DATA

SOILS LABORATORY
NEW ENGLAND DIVISION

JUNE, 1948
BOSTON, MASS.

PLATE 17



APPLIED TEMPERATURES

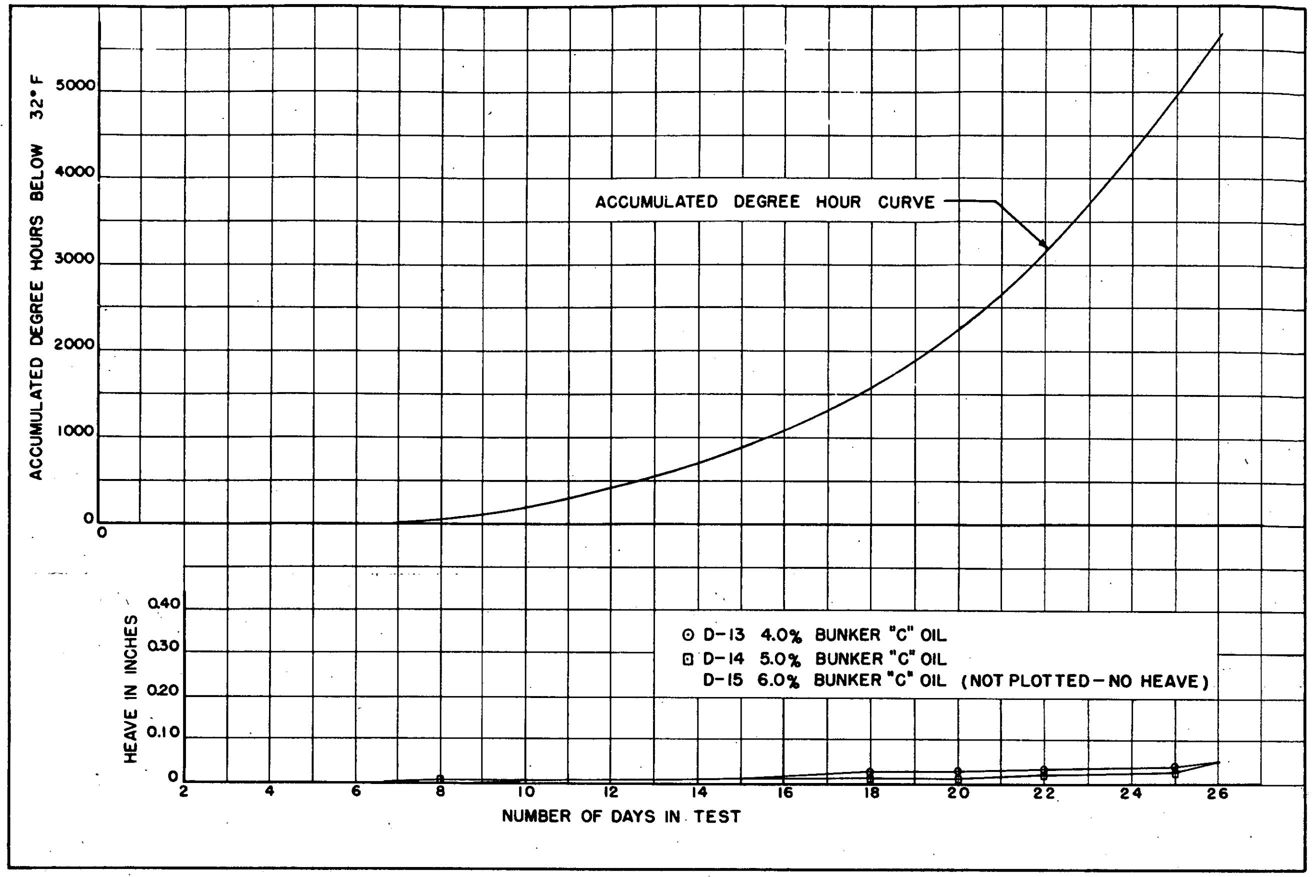
ELAPSED TIME (DAYS)	TEST SERIES A (°F)	TEST SERIES B (°F)	TEST SERIES C (°F)
-2	34	34	40
-1	35	34	35
0	32	32	32
1	32	31	31
2	31	31	31
3	30	30	55
4	29	29	30
5	29	29	27
6	28	28	27
7	27	27	26
8	26	26	26
9	25	25	25
10	24	24	24
11	23	23	23
12	22	22	22
13	20	20	20
14	18	18	18
15	16	16	14
16	14	14	14
17	12	12	13
18	10	10	11
19	5	5	5
20	5	5	5
21	5	5 *	5
22	5	-	5 *
23	5 *	-	-

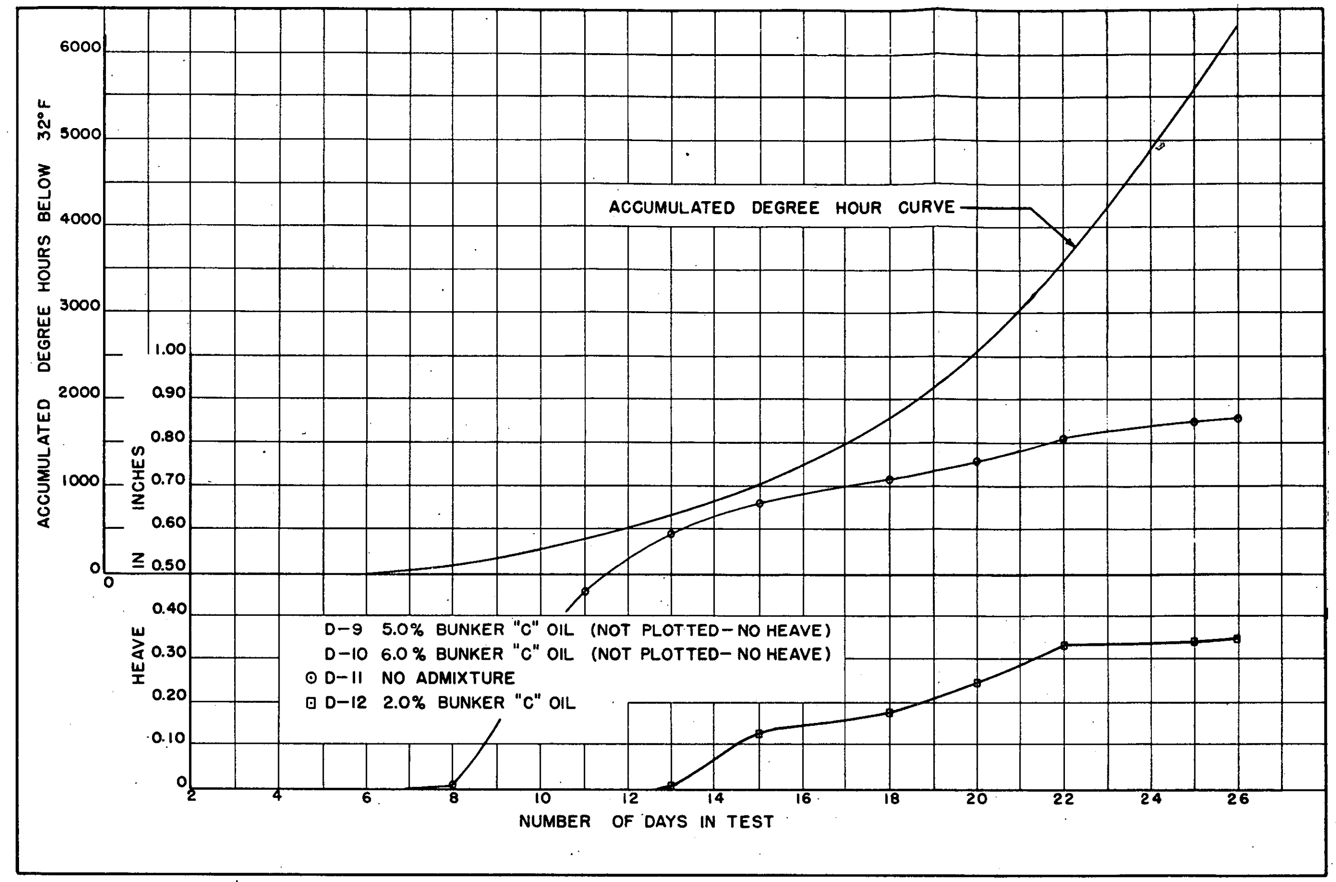
* FINAL DAY OF TEST

FROST INVESTIGATION
BASE COURSE TREATMENT
TO PREVENT FROST ACTION
1945 - 1946

HEAVE AND TEMPERATURE DATA

JUNE 1946
FROST EFFECTS LABORATORY, BOSTON, MASS.

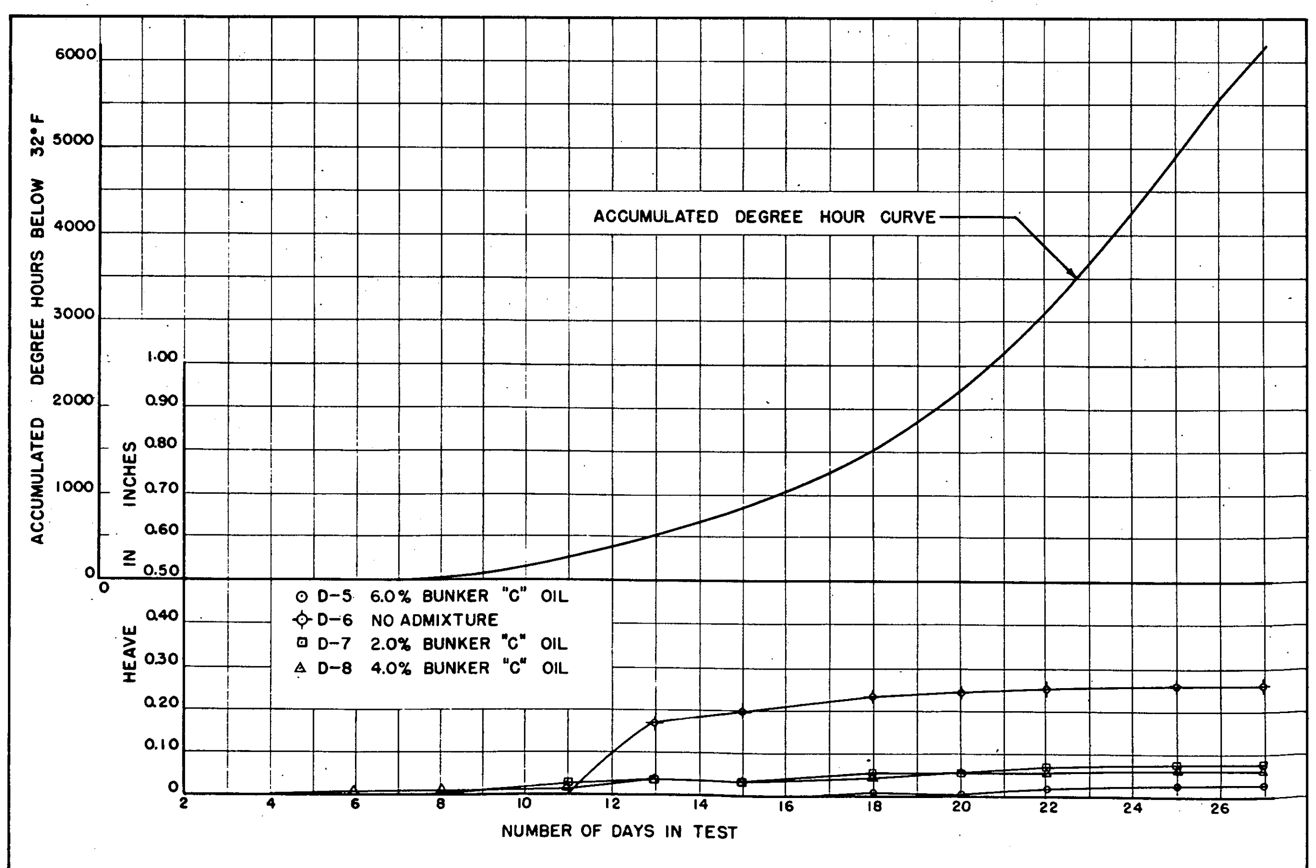


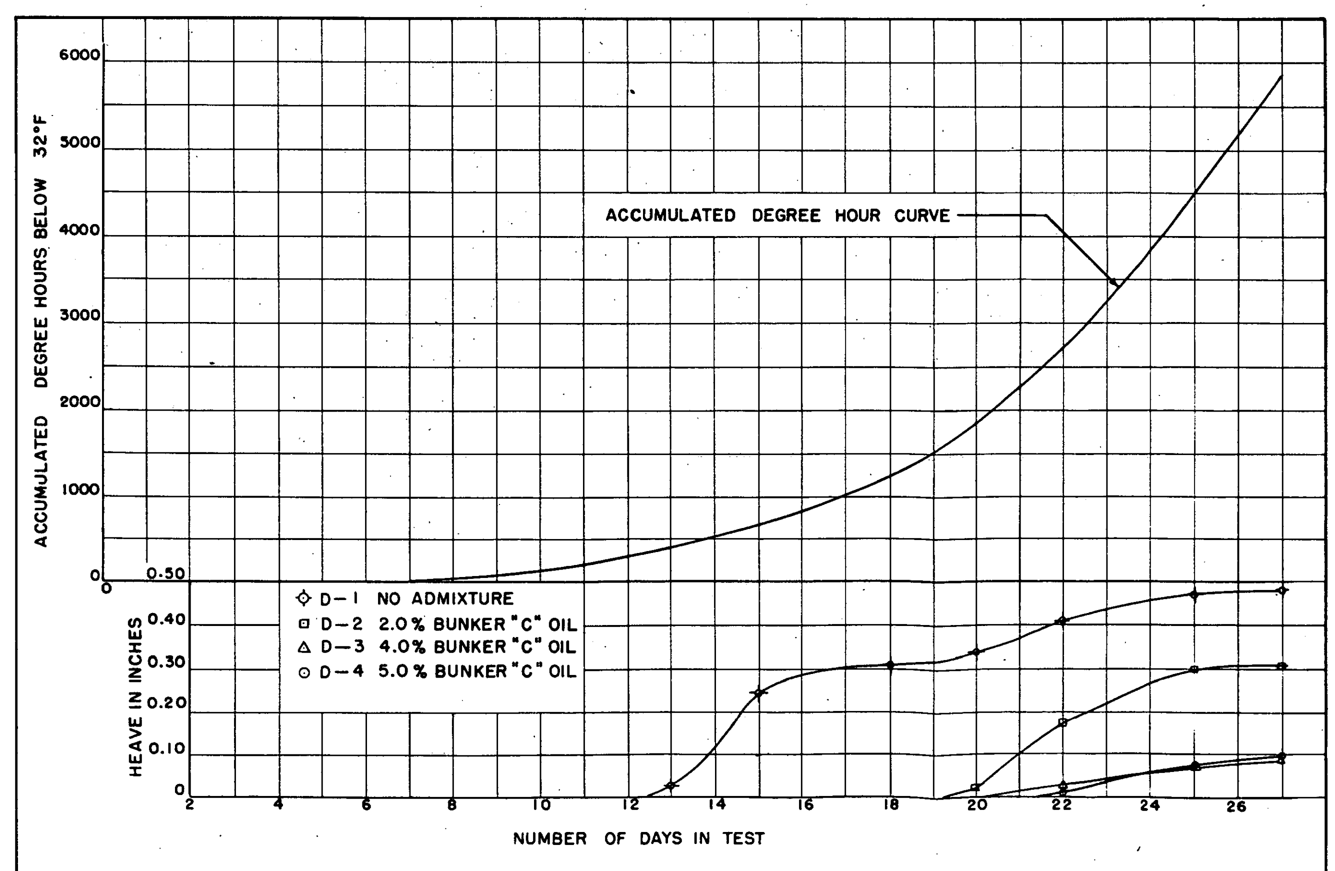


APPLIED TEMPERATURES

ELAPSED TIME (DAYS)	TEST SAMPLES D1 TO D4	D5 TO D8	D9 TO D12	D13 TO D16
1	38	37	37	37
2	38	37	37	37
3	38	37	37	37
4	38	37	37	37
5	33	33	32	32
6	34	33	31	33
7	32	33	31	32
8	31	30	29	30
9	31	30	29	30
10	29	29	28	28
11	29	28	27	28
12	28	28	27	28
13	27	26	26	26
14	27	26	25	25
15	26	25	23	25
16	25	24	23	24
17	25	23	22	23
18	23	22	21	21
19	20	19	17	19
20	18	16	14	16
21	15	14	12	14
22	13	12	9	12
23	10	10	7	10
24	7	6	3	6
25	5	4	1	5
26	5	5	1	4
27	4	4	-	-

Specimens D-1 through D-5 prepared with Soil Mix No. 1.
Specimens D-6 through D-10 prepared with Soil Mix No. 2.
Specimens D-11 through D-15 prepared with Soil Mix No. 3.





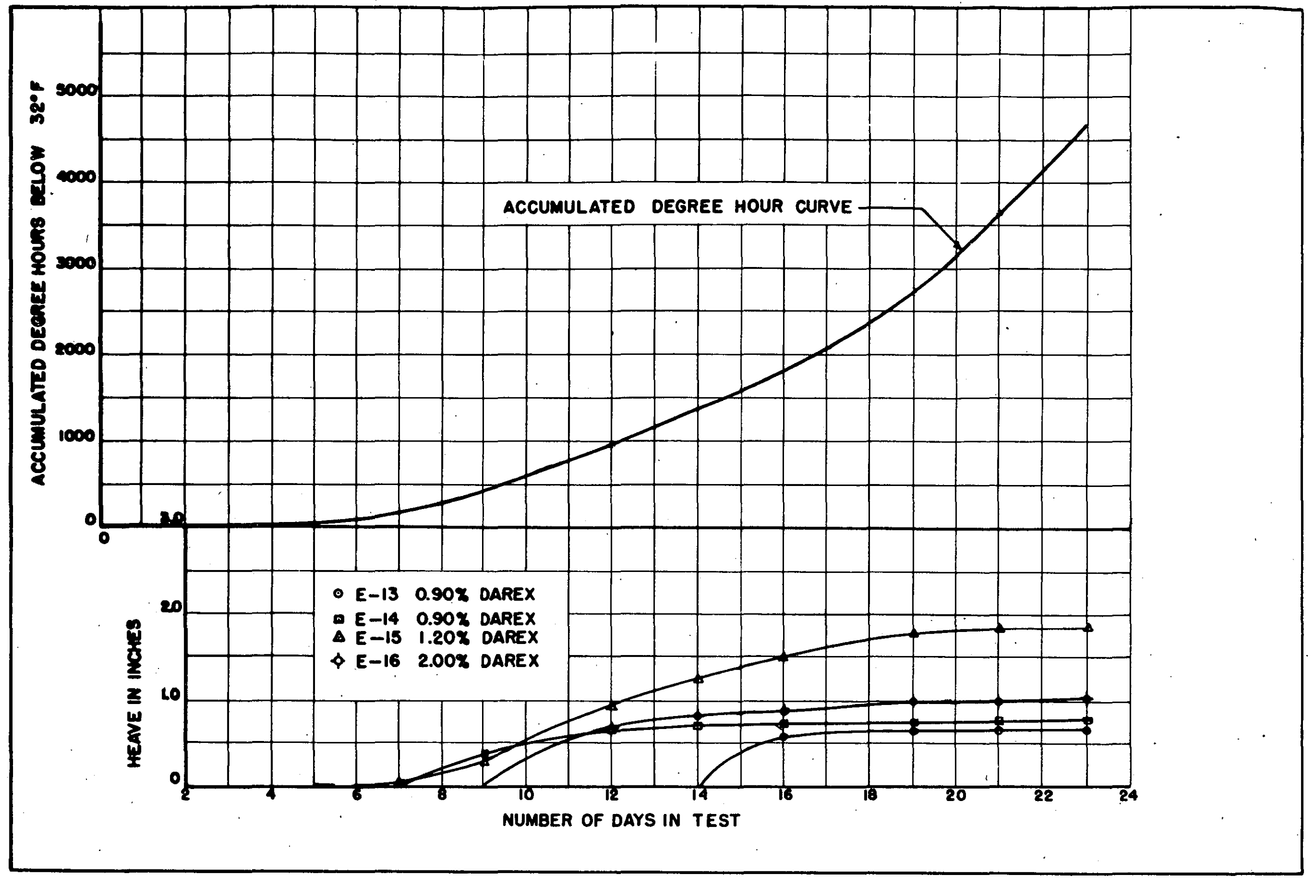
FROST INVESTIGATION
1946-1947

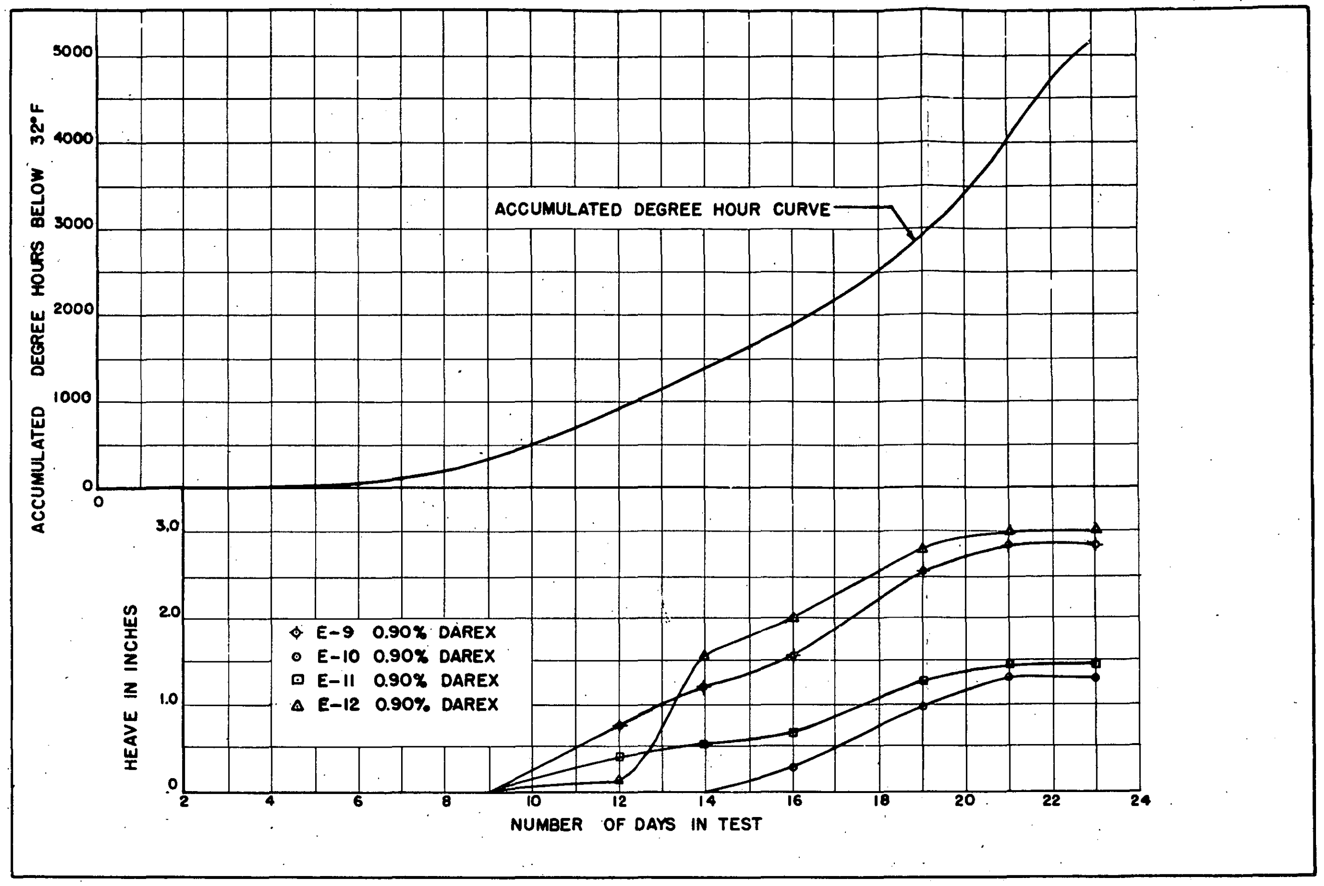
BASE COURSE TREATMENT
TO PREVENT FROST ACTION

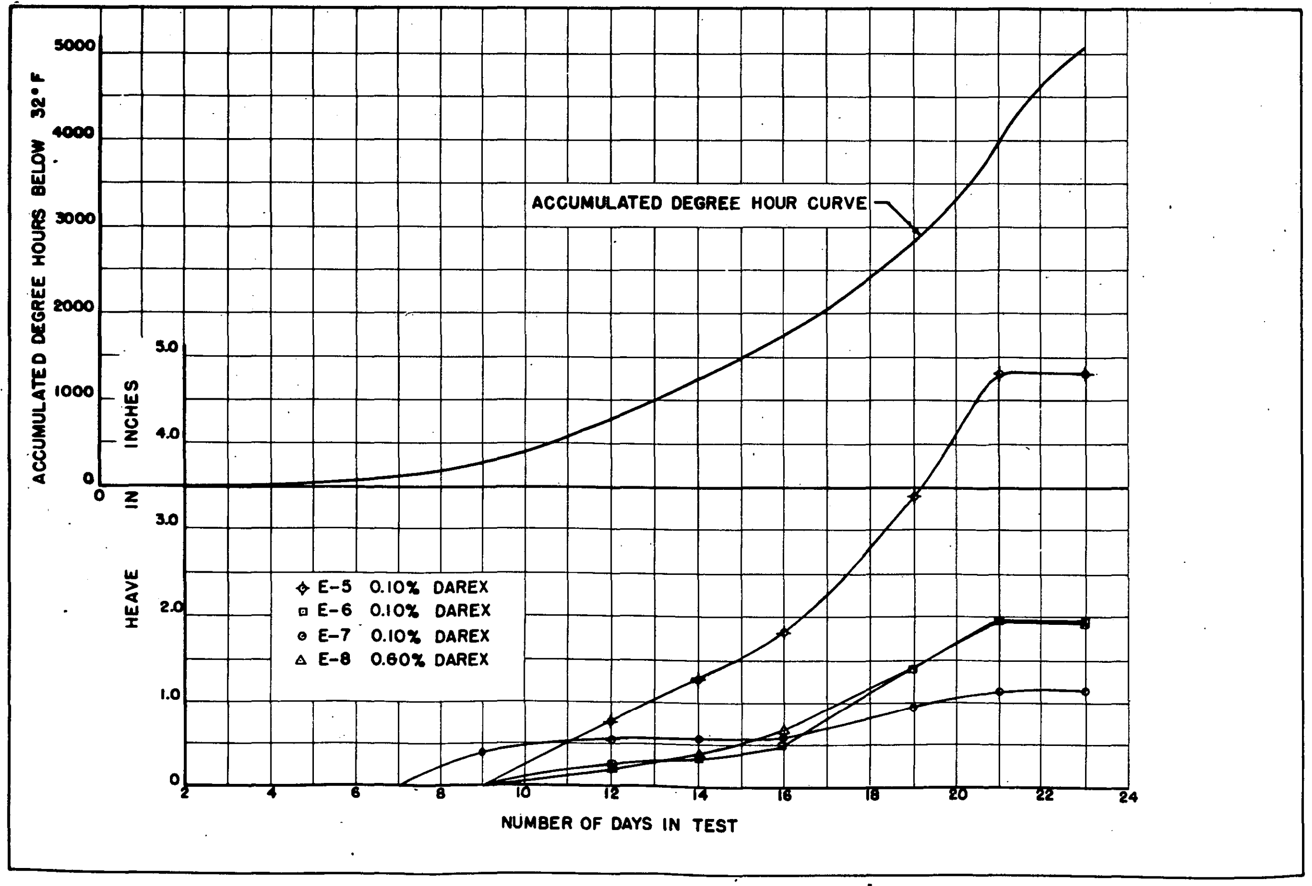
RATE OF HEAVE AND CUMULATIVE TEMPERATURE DIAGRAM SERIES D

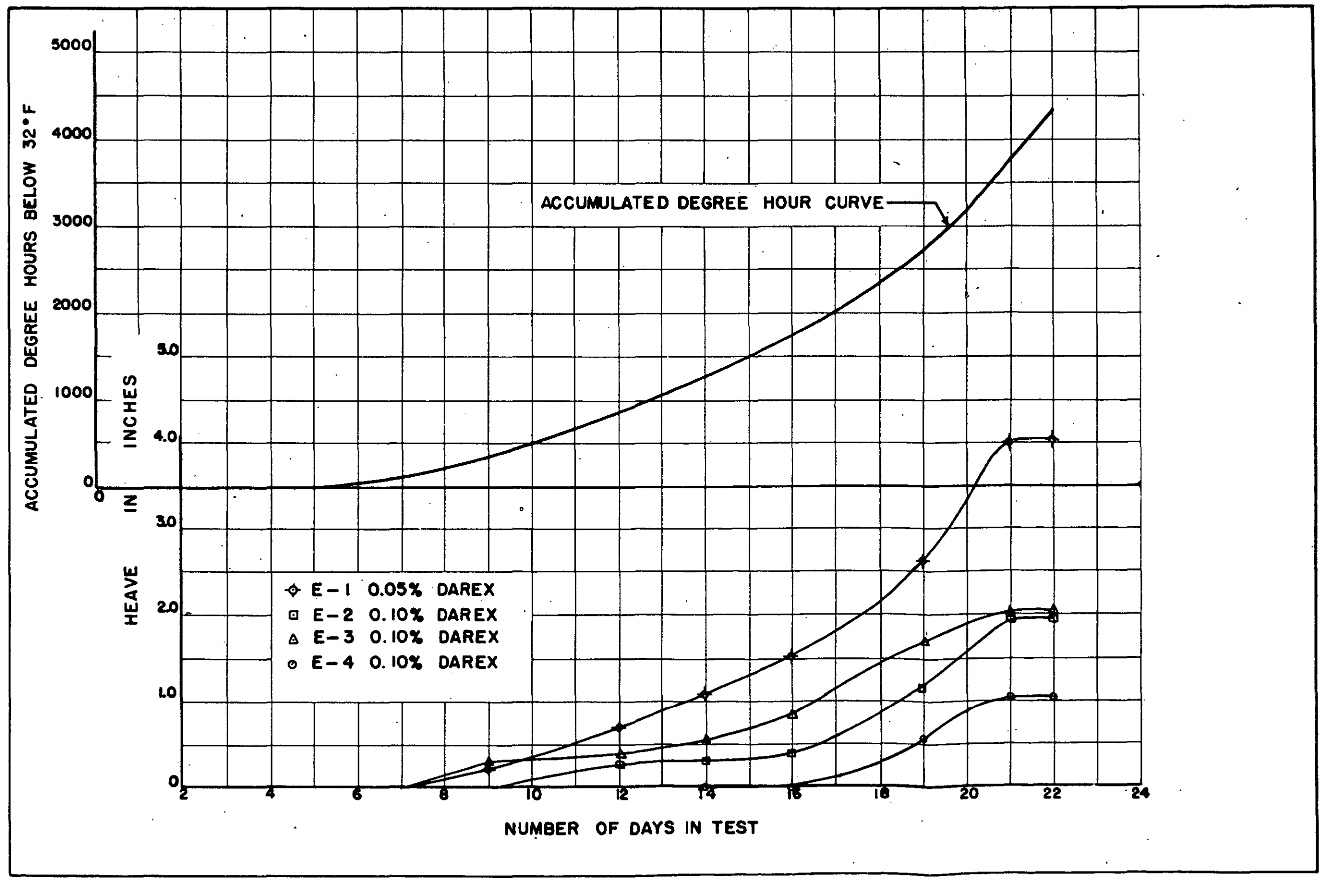
SOILS LABORATORY
NEW ENGLAND DIVISION

JUNE 1947
BOSTON, MASS.









APPLIED TEMPERATURES

ELAPSED TIME (DAYS)	TEST SAMPLES			
	E1 TO E4	E5 TO E8	E9 TO E12	E13 TO E16
1	39	39	38	39
2	34	34	34	34
3	34	33	34	34
4	33	32	33	33
5	31	31	31	31
6	30	31	30	30
7	28	30	29	28
8	28	29	28	28
9	27	28	27	26
10	25	26	25	24
11	25	24	24	25
12	24	24	24	25
13	23	23	22	23
14	23	23	23	23
15	23	22	22	23
16	22	22	22	23
17	21	20	21	22
18	18	17	17	19
19	16	14	15	18
20	12	11	11	15
21	8	6	6	11
22	6	5	5	10
23	—	10	7	6

All specimens were prepared with New Hampshire Silt.

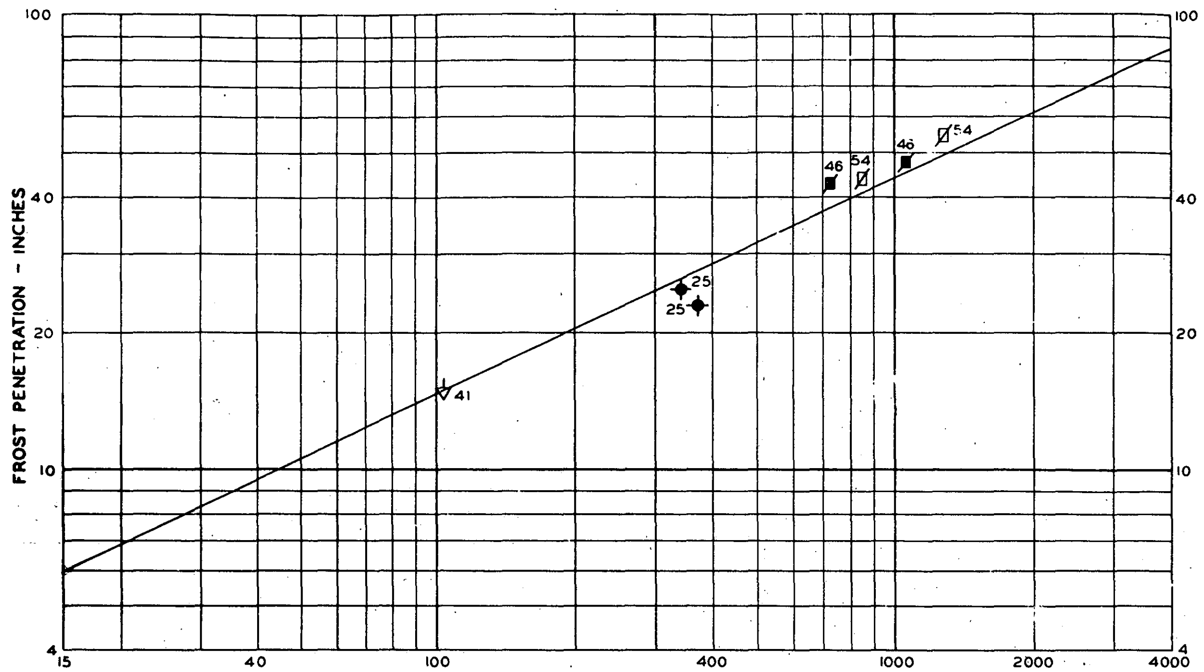
FROST INVESTIGATION
1946-1947

BASE COURSE TREATMENT
TO PREVENT FROST ACTION

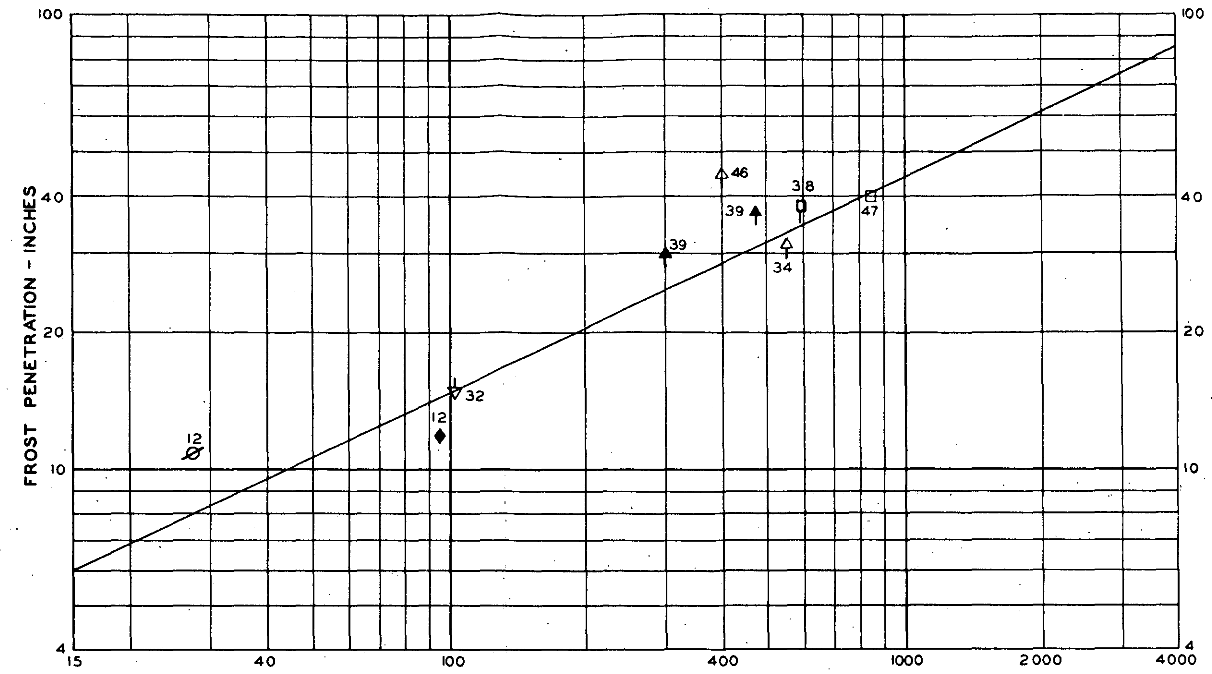
RATE OF HEAVE AND CUMULATIVE TEMPERATURE DIAGRAM SERIES E

SOILS LABORATORY
NEW ENGLAND DIVISION

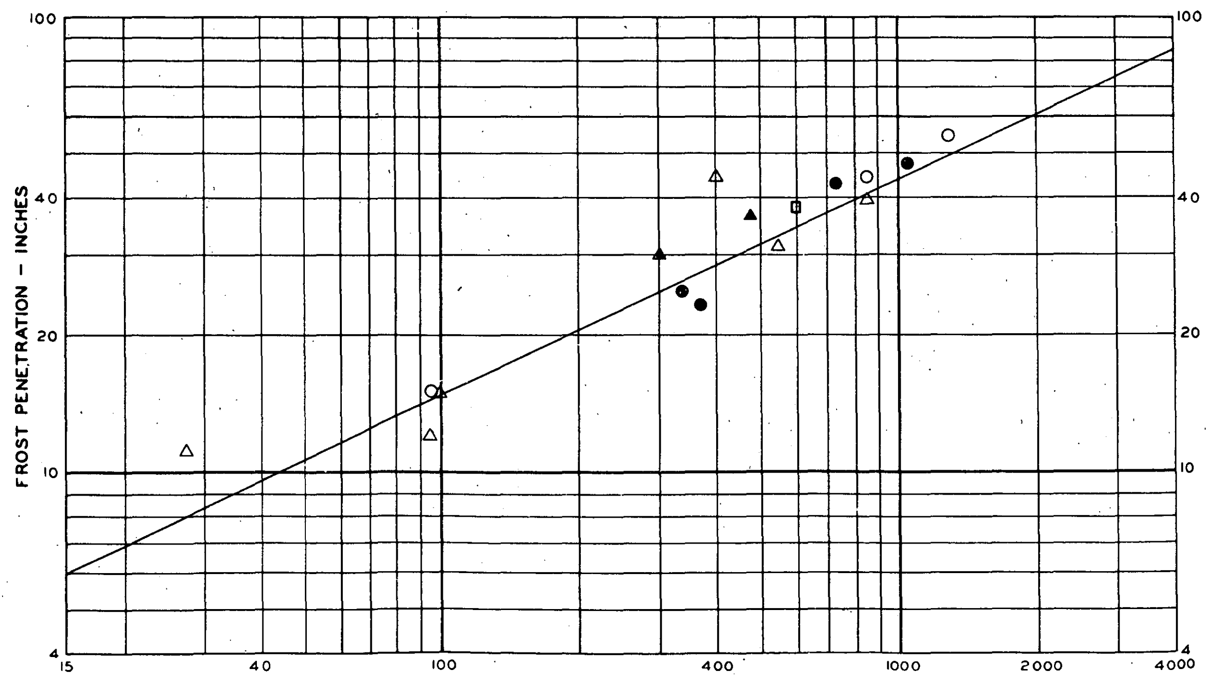
JUNE 1947
BOSTON, MASS.



CEMENT CONCRETE
FIG. 1

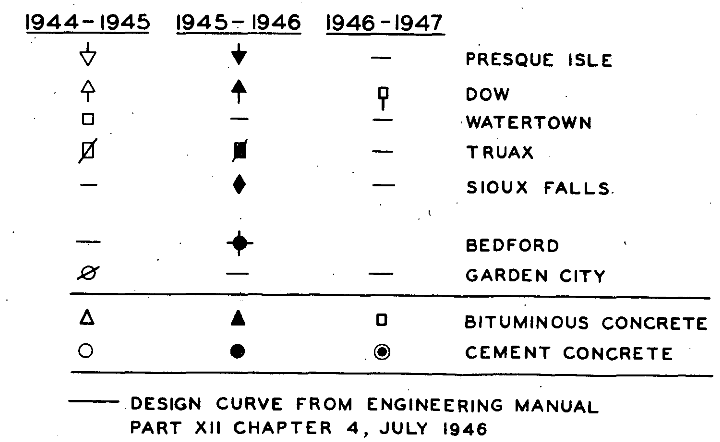


BITUMINOUS CONCRETE
FIG. 2



BITUMINOUS CONCRETE AND CEMENT CONCRETE
FIG. 3

LEGEND



NOTES -

NUMBERS NEXT TO PLOTTED VALUES SHOW COMBINED THICKNESS OF PAVEMENT PLUS BASE.

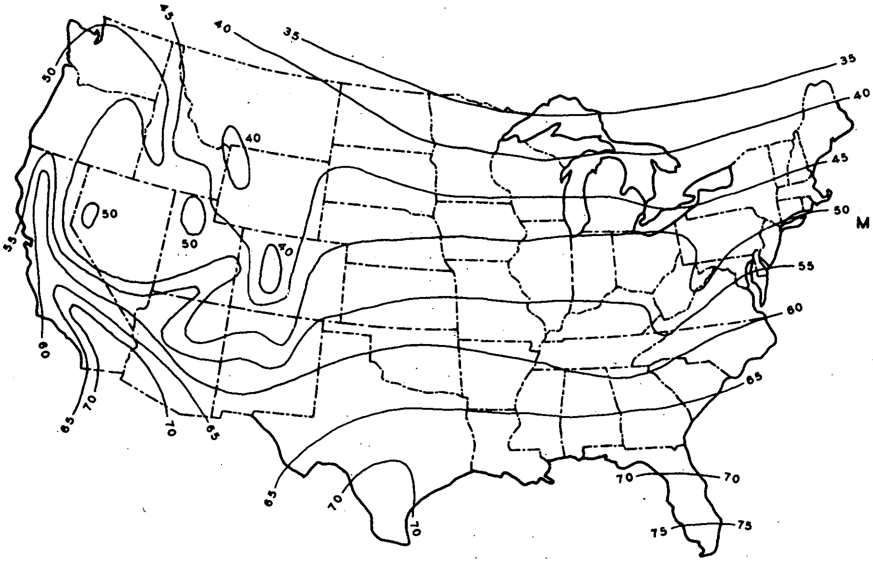
FROST PENETRATION IS IN NON-FROST SUSCEPTIBLE MATERIALS ONLY.

FROST INVESTIGATION
1946-1947

CORRELATION BETWEEN FROST PENETRATION AND FREEZING INDEX

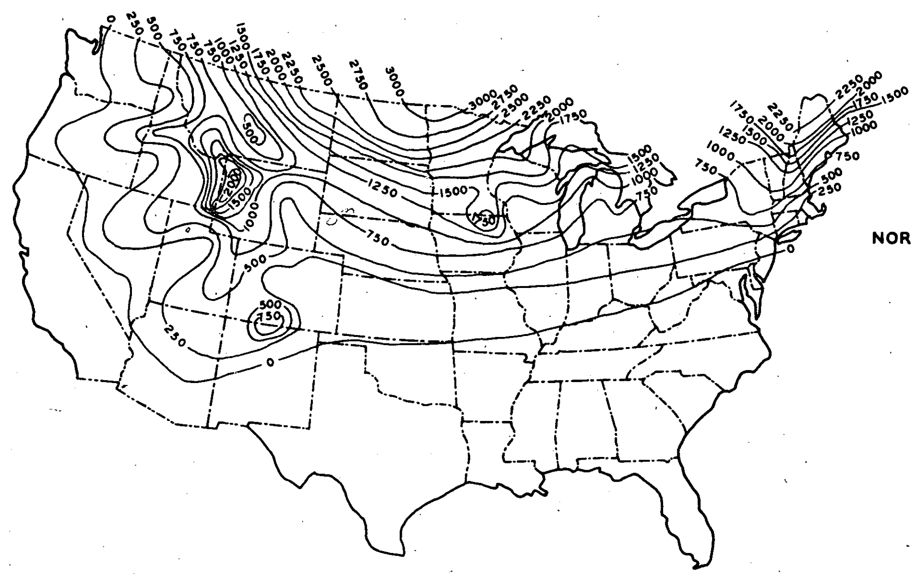
FROST EFFECTS LABORATORY, BOSTON, MASS. JAN. 1948

PLATE 21



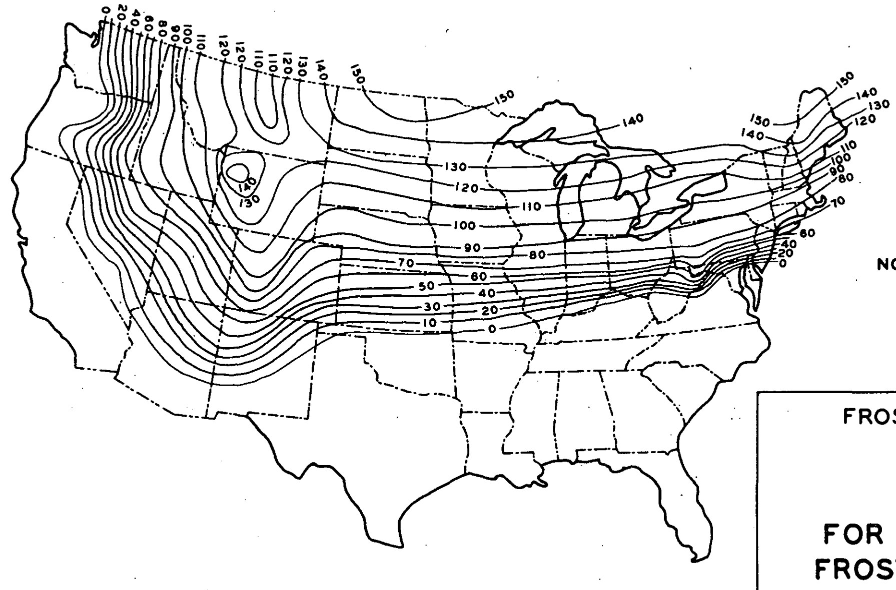
MEAN ANNUAL AIR TEMPERATURE
(DEGREES FAHRENHEIT)

FIG. 1



NORMAL FREEZING INDEX
(DEGREE DAYS)

FIG. 2



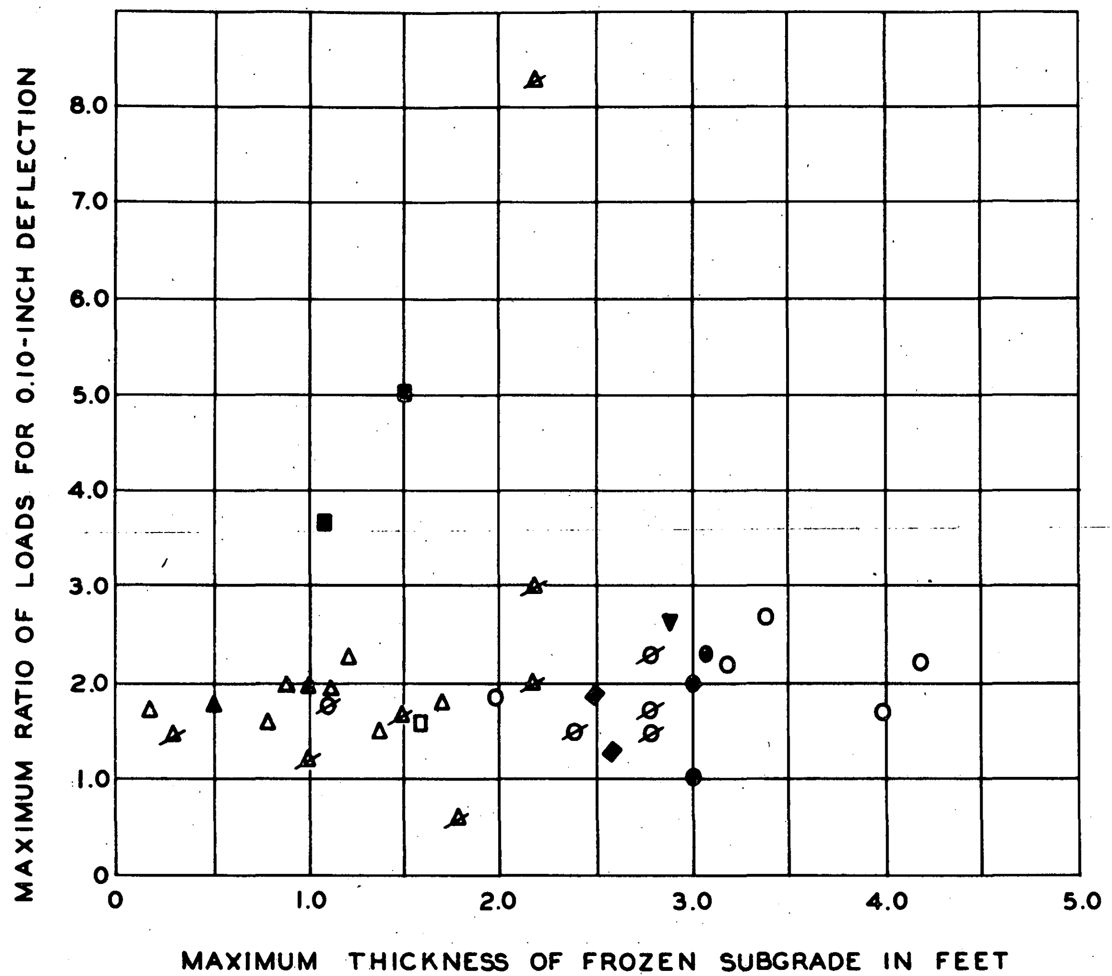
DURATION
OF
NORMAL FREEZING INDEX
(DAYS)

FIG. 3

FROST INVESTIGATION
1945 - 1946

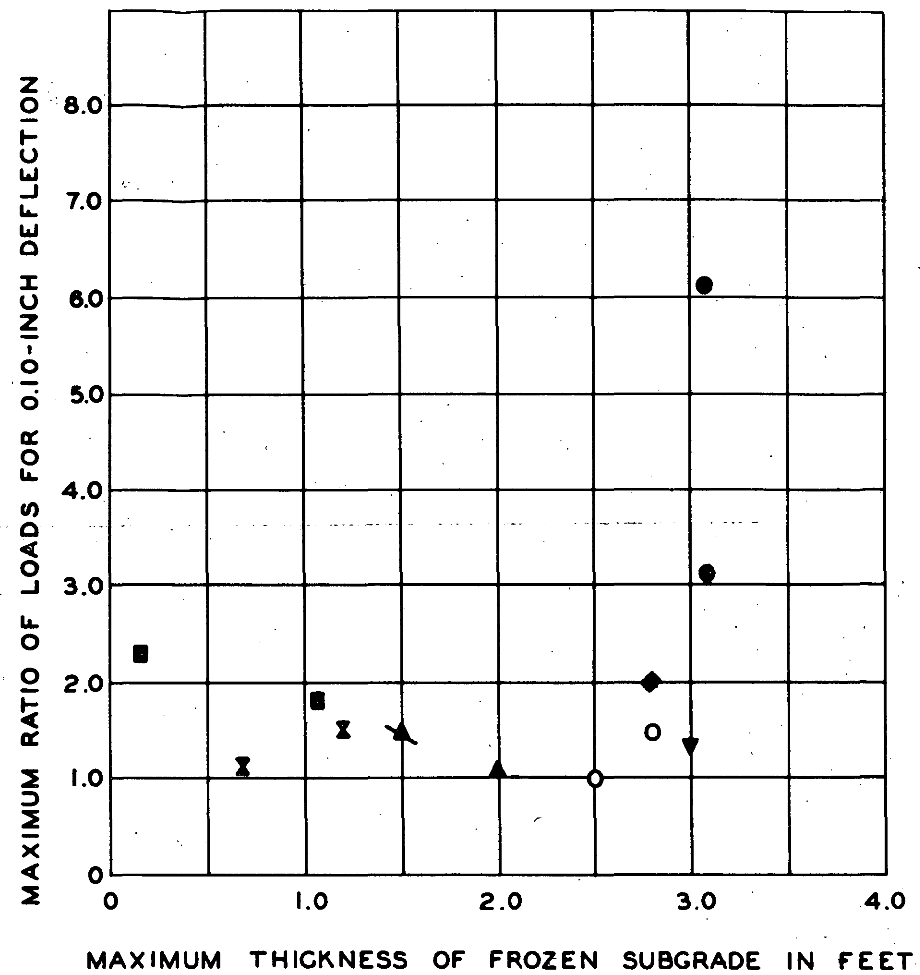
ISOGRAMS FOR PREDICTION OF FROST PENETRATION

JUNE 1946
FROST EFFECTS LABORATORY, BOSTON, MASS.



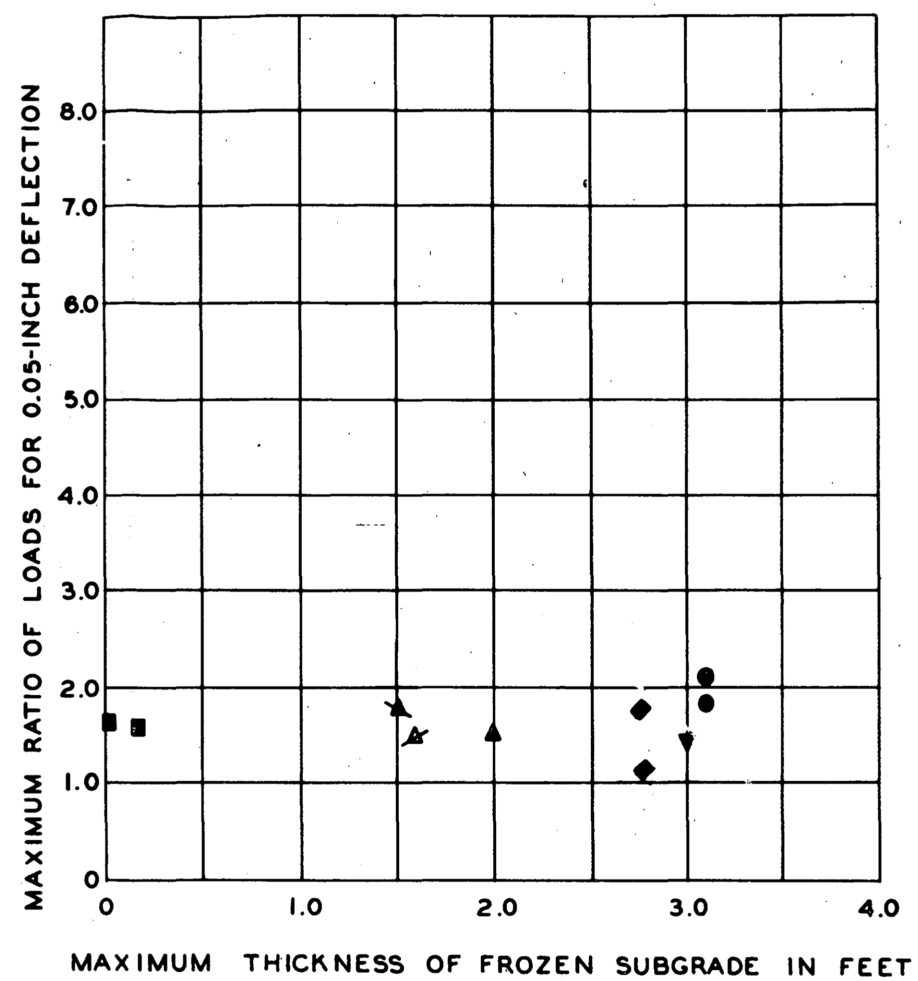
30-INCH PLATE BEARING TESTS (STATIC LOAD) ON BITUMINOUS CONCRETE PAVEMENTS.

FIG. 1



30-INCH PLATE BEARING TESTS (SUBGRADE MODULUS) ON SOIL UNDER PORTLAND CEMENT PAVEMENTS.

FIG. 2



24-INCH PLATE BEARING TESTS (RUPTURE) ON PORTLAND CEMENT PAVEMENTS.

FIG. 3

AIRFIELD	YEAR				CLASS OF SUBGRADE SOILS
	43-44	44-45	45-46	46-47	
DOW	△ (slashed)	△	▲	◣	CL
PRESQUE ISLE	○ (slashed)	○	●		GC
TRUAX		□	■		CL & SF
SELFRIDGE			⧗		ML & SF
PIERRE			◆		CL
SIOUX FALLS			▼		CL & CH

NOTE:

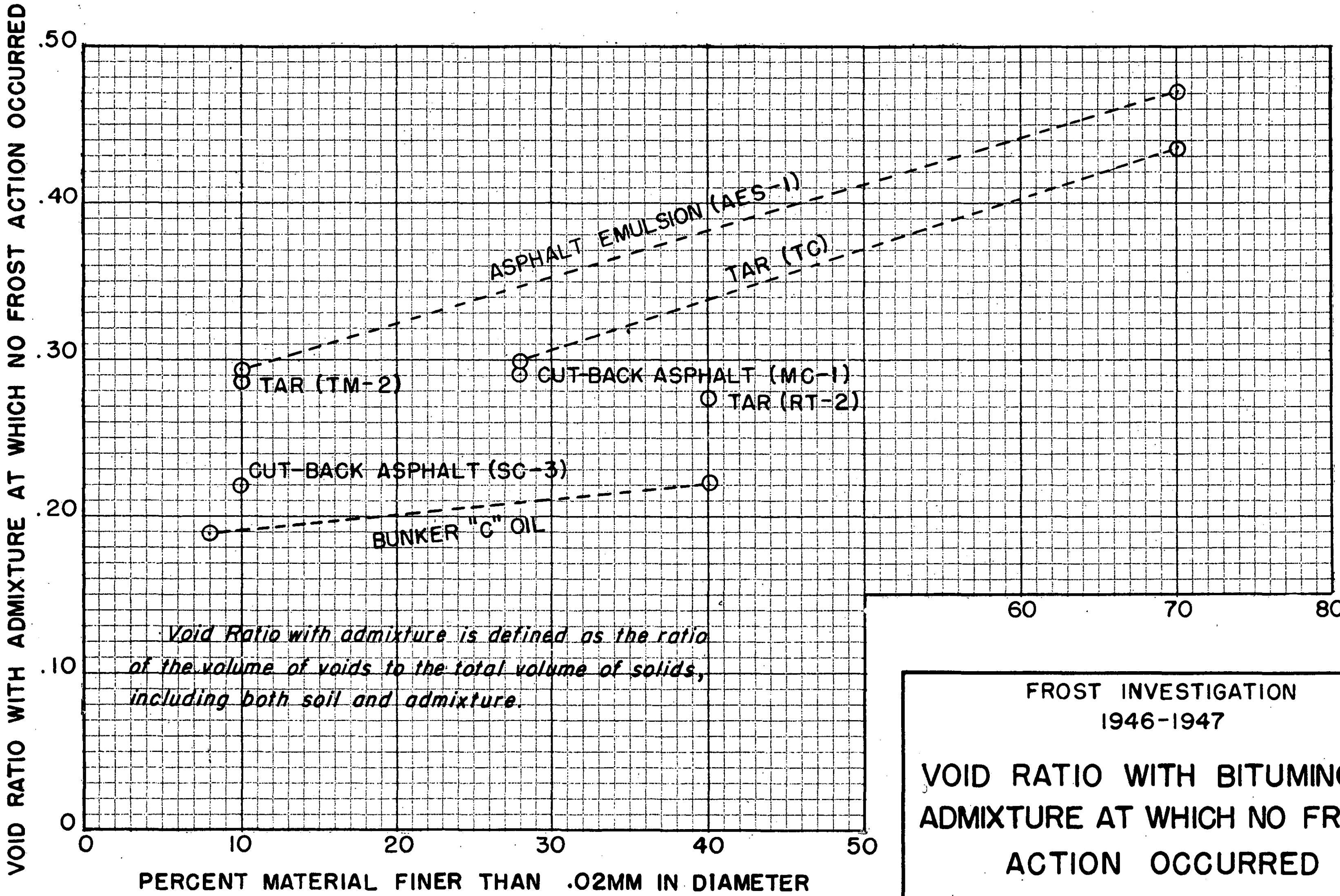
$$\text{Maximum Ratio Of Loads} = \frac{\text{Maximum Load During Normal Period}}{\text{Minimum Load During Frost Melting Period}}$$

FROST INVESTIGATION
1945-1947

EFFECT OF THICKNESS OF FROZEN SUBGRADE ON PAVEMENT STRENGTH

FROST EFFECTS LABORATORY
BOSTON, MASS. JUNE 1948

PLATE 24



FROST INVESTIGATION
1946-1947

VOID RATIO WITH BITUMINOUS ADMIXTURE AT WHICH NO FROST ACTION OCCURRED

SOILS LABORATORY — JUNE, 1948
NEW ENGLAND DIVISION — BOSTON, MASS.

NEW ENGLAND DIVISION
CORPS OF ENGINEERS, U. S. ARMY
BOSTON, MASS.

APPENDIX A

MATHEMATICAL STUDIES OF THERMAL PROPERTIES OF SOILS

SOILS AND FROST EFFECTS LABORATORY
OCTOBER 1949

APPENDIX A

MATHEMATICAL STUDIES OF THERMAL PROPERTIES OF SOILS

Symbols and Definitions

The following symbols are used in the mathematical studies:

Symbol	Definition	Unit
A	Temperature difference between annual mean air temperature (v_o) and freezing temperature (32°)	°F
a	Thermal Diffusivity = k/C	$ft^2/hr.$
B	Amplitude of air temperature change for yearly cycle = 1/2 range	°F
C	Volumetric heat	$BTU/(ft^3)(^oF)$
C_1, C_2, C_n	Volumetric heat of layers 1,2,..n respectively	$BTU/(ft^3)(^oF)$
C_f	Volumetric heat in frozen state	$BTU/(ft^3)(^oF)$
C_u	Volumetric heat in non-frozen state	$BTU/(ft^3)(^oF)$
c	Specific heat	BTU/(lb)(°F)
d_1, d_2, d_n	Thickness of insulation layers 1, 2,...n, respectively	ft.
E	Surface coefficient = $k\psi$	
e	Base of natural (Napierian) logarithms = 2.718 +	
F	Freezing index	°F days
H	Total heat given up by soil = Qt	BTU/ft^2
h	Depth below ground surface	ft.
i	Thermal gradient	°F/ft
$\overline{K}$	Constant of integration	
k	Thermal conductivity	BTU /(ft)(°F)(hr)

Symbol	Definition	Unit
k_1, k_2, k_n	Thermal conductivity of layers 1,2,...n respectively	BTU/(ft)(^oF)(hr)
k_f	Thermal conductivity in frozen state	BTU/(ft)(^oF)(hr)
k_u	Thermal conductivity in non-frozen state	BTU/(ft)(^oF)(hr)
L	Latent heat of fusion of water in soil	BTU/ft^3
Q	Rate of heat flow from ground surface = ki	BTU/(ft^2)(hr)
R	Thermal resistance $= \frac{d_1}{k_1} + \frac{d_2}{k_2} + \ldots \frac{d_n}{k_n}$	$\frac{1}{BTU/(^oF)(hr)}$
s	Thickness of upper soil layer	ft
T	Time period of temperature change for 1 year	365 days
t	Time increment = duration of freezing index	day
V	Temperature amplitude in soil at depth "h"	^oF
v_f	Average air temperature during period of freezing	^oF
v_o	Average soil temperature = mean annual air temperature	^oF
v_p	Constant suddenly impressed air temperature	^oF
v_s	Variable air temperature during period "T"	^oF
x	Depth of freezing = depth of melting for rising soil temperatures	ft
x_R	Depth of freezing, when soil is overlain by an insulation layer	ft

Symbol	Definition	Unit
z	Elevation of a point from the boundary layer - measured in opposition to "h"	ft
β	Growth coefficient of melted layer = $\frac{h}{2\sqrt{24at}}$	
ω	Parameter = $2\pi/T$	
N, Z, θ	Dimensionless parameters for simplification of equations	
P, G, m, y, δ, ψ	Parameters for simplification of equations	
ϕ	Mean temperature gradient in period Δt	$^{o}F/ft$
ln	log to the base "e"	

PROBLEM NO. I

Given a homogeneous, isotropic soil mass of semi-infinite extent, with its initial temperature at temperature "v_o". Its surface temperature is suddenly changed to temperature "v_p".

(a) Find the thermal diffusivity "a", by measuring the temperature gradients at different times, neglecting latent heat.

The temperature at any depth "h" at time "t" is

$$v_{(h,t)} = v_o + (v_p - v_o) \quad [1 - \text{erf } (\beta)] \quad \ldots\ldots\ldots\ldots [1]$$

where the erf (β) is the probability-integral, also known as the Gauss "error-function" of β, and can be expressed as

$$\text{erf } (\beta) = \frac{2}{\sqrt{\pi}} \int_0^{\beta} e^{-u^2} \, du \quad \ldots\ldots\ldots\ldots [2]$$

By definition $\beta = \frac{h}{2\sqrt{24at}}$ . . . . [3]

At any time "t", the temperature gradient "i" can be expressed as the slope of the temperature

$$i = \frac{dv}{dh} = - (v_o - v_p) \frac{d}{d\beta} \text{ erf } \beta \left(\frac{d\beta}{dh}\right) \quad \ldots\ldots\ldots\ldots [4]$$

Now $\frac{d}{d\beta}\operatorname{erf}\beta = \frac{2}{\sqrt{\pi}}\frac{d}{d\beta}\int_o^\beta e^{-u^2}du = \frac{2}{\sqrt{\pi}}e^{-\beta^2}$ . . . . [5]

$$\therefore \frac{dv}{dh} = -(v_o - v_p)\frac{2}{\sqrt{\pi}}e^{-\beta^2}\cdot\frac{1}{2\sqrt{24at}} = -(v_o-v_p)\frac{e^{-\beta^2}}{\sqrt{24\pi at}} \quad \ldots\ldots [6]$$

At time "t_1", $i_1 = -(v_o - v_p)\frac{e^{-\frac{h^2}{96\,at_1}}}{\sqrt{24\pi at_1}}$ . . . . [7]

and at time "t_2", $i_2 = -(v_o - v_p)\frac{e^{-\frac{h^2}{96at_2}}}{\sqrt{24\pi at_2}}$ . . . . [8]

$$\therefore \frac{i_1}{i_2} = \frac{e^{-\frac{h^2}{96at_1}}}{e^{-\frac{h^2}{96at_2}}}\sqrt{\frac{t_2}{t_1}} = \sqrt{\frac{t_2}{t_1}}\cdot e^{\frac{h^2}{96a}\left(\frac{1}{t_2} - \frac{1}{t_1}\right)} \quad \ldots\ldots [9]$$

Let $\frac{1}{t_2} - \frac{1}{t_1} = \delta$

Then $\frac{i_1}{i_2} = \sqrt{\frac{t_2}{t_1}}\cdot e^{\frac{h^2\delta}{96a}}$ . . . . [10]

or $e^{\frac{h^2\delta}{96a}} = \frac{i_1}{i_2}\sqrt{\frac{t_1}{t_2}}$ . . . . [11]

$$\frac{h^2\delta}{96a} = \ln\left[\frac{i_1}{i_2}\sqrt{\frac{t_1}{t_2}}\right] \quad \ldots\ldots [12]$$

$$\therefore a = \frac{h^2\delta}{96\ln\left[\frac{i_1}{i_2}\sqrt{\frac{t_1}{t_2}}\right]} = \frac{k}{C} \quad \ldots\ldots [13]$$

Values of "i_1" and "i_2" may be obtained by plotting the temperature profiles for times "t_1" and "t_2" and then drawing tangents to curves at depth "h".

This problem is generally one confined to the laboratory. In nature, the soil temperature is not uniform at any time and the temperature over a given period never changes from one constant value to another.

(b) Find the thermal diffusivity "a" by noting the time required for a point at depth "h" to change its temperature by $\frac{(v_o + v_p)}{2}$.

Substituting $\frac{v_o + v_p}{2}$ for $v_{h,t}$, equation [1] becomes

$$\frac{v_o + v_p}{2} = v_o + (v_p - v_o) [1 - \text{erf} (\beta)]$$

Then $\text{erf} (\beta) = 1/2$ . . . . [14]

From tables of error functions or Fig. 5, Plate A-2 when erf

$(\beta) = 1/2$, $\beta = 0.477$.

From definition $\beta = \frac{h}{2\sqrt{24at}}$.

Then $h = 2\beta\sqrt{24at} = 2 \times 0.477\sqrt{24at}$

$$\text{or } a = \frac{h^2}{21.91\ t} = \frac{0.0458h^2}{t} \qquad [15]$$

Thus, with a soil mass of very great depth at a uniform temperature "v_o", and the surface temperature is suddenly changed to temperature "v_p", then with a thermometer or thermocouple placed in the soil at depth "h" and the time noted when the soil temperature reaches a value halfway between "v_o" and "v_p", a value of "a" can be obtained. This problem is confined to the laboratory.

PROBLEM NO. 2

Given a homogeneous, isotropic soil mass of semi-infinite extent, exposed to periodic temperature changes over a sufficiently long period so that the interior temperatures are also periodic.

Find the thermal diffusivity "a", by measuring the temperature gradients at different times, one quarter year apart, neglecting latent heat.

The surface temperature can be expressed as

$$v_s = 32 + A + B \cos \omega t \quad \ldots \quad [16]$$

The temperature at any depth "h" at any time "t" is

$$v_{(h,t)} = 32 + A + B e^{-mh} \cos (\omega t - mh) \quad \ldots \quad [17]$$

$$\text{where } m = \sqrt{\omega/48a} = \sqrt{\frac{\pi}{24aT}}$$

At any time "t", the temperature gradient "i" can be expressed as the slope of the temperature versus depth curve,

$$\text{Then } i = \frac{dv}{dh} = -mBe^{-mh} \cos (\omega t - mh) + mBe^{-mh} \sin (\omega t - mh) \quad \ldots \quad [18]$$

At time "t_1"

$$i_1 = mBe^{-mh} [\sin(\omega t_1 - mh) - \cos (\omega t_1 - mh)] \quad \ldots \quad [19]$$

and at time "t_2"

$$i_2 = mBe^{-mh} [\sin(\omega t_2 - mh) - \cos (\omega t_2 - mh)] \quad \ldots \quad [20]$$

Now let f(h) equal the sum of the squares of the thermal gradients at depth "h",

$$f(h) = i_1^2 + i_2^2 \quad \ldots \quad [21]$$

$$i^2 = m^2B^2e^{-2mh} [\sin^2 (\omega t - mh) - 2\sin(\omega t - mh)\cos(\omega t - mh) + \cos^2 (\omega t - mh)]$$

$$= m^2B^2e^{-2mh} [1 - 2\sin(\omega t - mh)\cos(\omega t - mh)] \quad \ldots \quad [22]$$

$$\therefore f(h) = m^2B^2e^{-2mh} [2 - 2\sin(\omega t_1 - mh)\cos(\omega t_1 - mh)$$

$$- 2\sin(\omega t_2 - mh)\cos(\omega t_2 - mh)] \quad \ldots \quad [23]$$

Since by hypothesis $t_2 = t_1 + T/4$; substitution in equation [23] gives

$$f(h) = 2m^2B^2e^{-2mh} \quad \ldots\ldots\ldots\ldots \quad [24]$$

At depth h_1, $f(h_1) = 2m^2B^2e^{-2mh_1}$, and at depth h_2

$$f(h_2) = 2m^2B^2e^{-2mh_2}$$

$$\text{Then } \frac{f(h_1)}{f(h_2)} = \frac{2m^2B^2e^{-2mh_1}}{2m^2B^2e^{-2mh_2}} = e^{2m(h_2-h_1)} \quad \ldots\ldots\ldots \quad [25]$$

$$\ln\frac{f(h_1)}{f(h_2)} = 2m(h_2 - h_1) \quad \ldots\ldots\ldots \quad [26]$$

$$m = \frac{1}{2(h_2 - h_1)} \ln\frac{f(h_1)}{f(h_2)} = \sqrt{\frac{\pi}{24aT}} \quad \ldots\ldots\ldots \quad [27]$$

from which the value of "a" can be computed.

Example

Temperature profiles are shown in Figure 1 on Plate A-1. Using equation [27] and drawing tangents to the temperature profiles for the months of June and September, the results of "a" are as follows:

Depth in feet	h_2-h_1	June i_1	June i_1^2	Sept. i_2	Sept. i_2^2	f(h)	$\frac{f(h_1)}{f(h_2)}$	$\ln\frac{f(h_1)}{f(h_2)}$	m	m^2	a
10.0		.38	.144	.60	.360	.504					
	4.3						2.431	.8883	.103	.0107	.0335
5.7		.96	.922	.55	.303	1.225					
	2.2						1.345	.2964	.067	.0045	.0797
3.5		1.3	1.64	.10	.010	1.648					
	2.0						2.495	.8998	.225	.0506	.0071
1.5		2.0	4.00	.23	.053	4.053					
	1.0						2.762	1.0159	.508	.2581	.0014
0.5		3.3	10.89	.55	.303	11.193					

The results of the example indicate the difficulty of determining "a" from field observations.

PROBLEM NO. 3.

Given a homogeneous, isotropic soil mass of semi-infinite extent, exposed to periodic temperature changes over a sufficiently long period so that the interior temperatures are also periodic.

Find the thermal diffusivity "a" from the temperature amplitudes at various depths, neglecting latent heat.

From equations [16] and [17],

$v_s = 32 + A + B \cos \omega t$, and

$v_{(h,t)} = 32 + A + Be^{-mh} \cos(\omega t - mh)$

At depths "h_1" and "h_2",

$$v_{h_1} = 32 + A + Be^{-mh} \cos(\omega t - mh_1), \text{ and} \quad \ldots \quad [28]$$

$$v_{h_2} = 32 + A + Be^{-mh} \cos(\omega t - mh_2) \text{ respectively} \quad \ldots \quad [29]$$

For maximum values,

$$v_{h_1} = 32 + A + Be^{-mh_1}, \text{ and } v_{h_2} = 32 + A + Be^{-mh_2} \qquad [30] \ \& \ [31]$$

$$\therefore \frac{v_{h_1}}{v_{h_2}} = \frac{32 + A + Be^{-mh_1}}{32 + A + Be^{-mh_2}} \text{ or } \frac{v_{h_1} - 32 - A}{v_{h_2} - 32 - A} = e^{m(h_2 - h_1)} \quad \ldots \quad [32]$$

$$m = \frac{1}{h_2 - h_1} \ln\left[\frac{v_{h_1} - 32 - A}{v_{h_2} - 32 - A}\right] \quad \ldots \quad [33]$$

Since $A = v_o - 32$, $v_h - 32 - A = V$

$$m = \sqrt{\frac{\pi}{24aT}} = \frac{1}{h_2 - h_1} \ln\left[\frac{V_1}{V_2}\right] \quad \ldots \quad [34]$$

Example

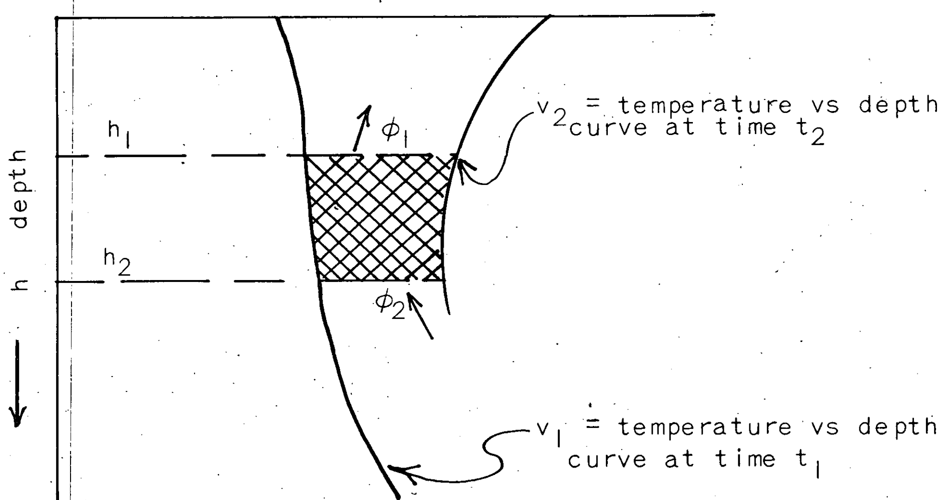
From the curves given in Figure 2, Plate A-1 the following values of "a" are derived

Depth in feet	$h_2 - h_1$	V °F	$\frac{V_1}{V_2}$	$\ln\frac{V_1}{V_2}$	m	m^2	a (ft^2/hr)
10.0		4.7					
	4.3		1.660	.5068	.1179	.01390	.0258
5.7		7.8					
	2.2		1.256	.2278	.1035	.01071	.0335
3.5		9.8					
	2.0		1.224	.2021	.1011	.01022	.0351
1.5		12.0					
	1.0		1.142	.1328	.1328	.01764	.0203
0.5		13.7					

PROBLEM NO. 4

Given a homogeneous, isotropic soil mass of semi-infinite extent, subjected to a change of temperature over a period of time.

Find the thermal diffusivity "a" from temperature variation with depth, at two or more different times, neglecting latent heat.



Let "Q" = total quantity of heat absorbed by a layer of soil of depth $(h_2 - h_1)$ and of unit cross sectional area in the period "Δt" $(\Delta t = t_2 - t_1)$.

Then $Q = C\int_{h_1}^{h_2} (v_2 - v_1)\,(dh)$ . . . . [35]

= C x Area between temperature curves and depths "h_2" and "h_1"

Let "Q_1" and "Q_2" equal quantities of heat per unit area of surface, transmitted out of and into the layer through planes "h_1" and "h_2", respectively, in time "Δt".

$Q_1 = 24k\phi_1\Delta t$ . . . . [36]

$Q_2 = 24k\phi_2\Delta t$ . . . . [37]

Now the increase in heat in the layer during the time interval "Δt" is the difference between heat input and heat output.

$Q = Q_2 - Q_1 = 24k(\phi_2 - \phi_1)(t_2 - t_1)$ = C x Area . . . . . . [38]

$$\text{or } \frac{k}{C} = \frac{\text{Area}}{24(\phi_2 - \phi_1)(t_2 - t_1)} = a \quad \ldots\ldots\ldots\ldots \quad [39]$$

In general terms

$$a = \frac{(v_2 - v_1)(h_2 - h_1)}{(\phi_2 - \phi_1)(t_2 - t_1)} = \frac{\Delta v \Delta h}{\Delta i \Delta t}$$

$$= \frac{dv}{dt} \times \frac{dh}{di} = \frac{dv}{dt} \times \frac{1}{di/dh} \quad \ldots\ldots\ldots\ldots \quad [40]$$

where $\frac{\text{"dv"}}{dt}$ is the tangent to the time-têmperature curve at a given depth and time and $\frac{\text{"di"}}{dh}$ is the tangent to the temperature-gradient curve. Time interval "Δt" must be expressed in hours.

Example

Using equation [39], and values of thermal gradient "ϕ" from Figure 1, Plate A-1 for the months of May and June (typical example is plotted in Figure 4, Plate A-1) the following values of "a" are obtained.

For May to June

$\Delta t = 31 \times 24 = 744$ hrs.

Depth in feet	h_2-h_1	V (^oF)	$\frac{V_2 + V_1}{2}$	ϕ	$\phi_2 - \phi_1$ ($\Delta\phi$)	Δt times Δφ	Area	a (ft^2/hr)
10.0		2.18		-0.23				
	4.3		3.23		.52	386.9	13.889	.0359
5.7		4.27		-0.75				
	2.2		4.81		.33	245.5	10.582	.0431
3.5		5.35		-1.08				
	2.0		5.68		.75	558.0	11.360	.0204
1.5		6.00		-1.83				
	1.0		6.11		1.72	1279.7	6.110	.0048
0.5		6.22		-3.55				

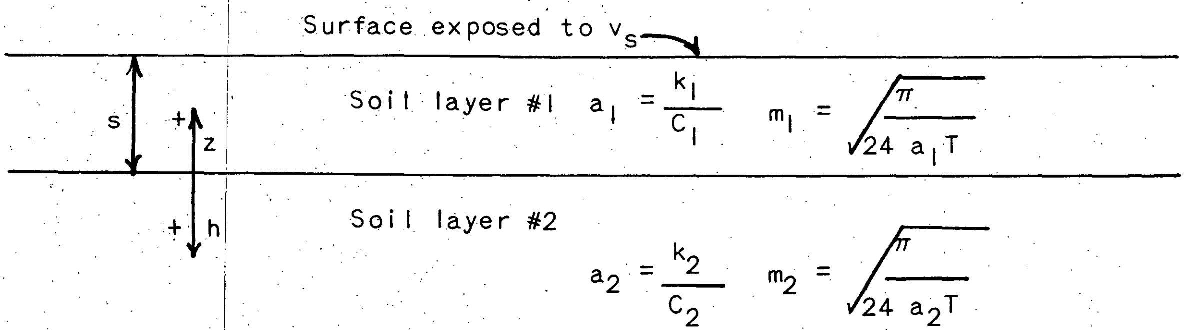
Using equation [40] and values of $\frac{\text{"dv"}}{dt}$ obtained from Figure 2, Plate A-1, and values of thermal gradient slope $\frac{\text{"di"}}{dh}$ obtained from Figure 3, Plate A-1. Values of $\frac{\text{"dt"}}{dh}$ were obtained from tangents drawn to the gradient curves.

Depth in feet	$\frac{dv}{dt}$ = °F/month			$\frac{di}{dh}$ = °F/ft²			a = ft²/hr		
	Apr.	June	Nov.	Apr.	June	Nov.	April	June	Nov.
10.0	0.7	2.5	-2.1	.035	.135	-.070	.0278	.0257	.0417
5.7	2.5	3.9	-4.3	.085	.135	-.150	.0408	.0402	.0398
3.5	3.6	4.7	-5.8	.170	.190	-.245	.0294	.0344	.0328
1.5	5.3	4.0	-5.0	.620	.720	-.355	.0119	.0097	.0125
0.5	6.5	5.0	-6.2	1.57	2.64	-.380	.0057	.0027	.0226

PROBLEM NO. 5

Given two layers of homogeneous, isotropic soils, possessing different soil properties, the uppermost of which is exposed to a periodic temperature change.

Find the thermal diffusivity "a" of both layers, neglecting latent heat.



Layer #2 of infinite extent
Arrows indicate direction of measurements for "z" and "h"

It is assumed that the impressed periodic surface temperature can be expressed by equation [16]

$$v_s = 32 + A + B\cos\omega t$$

It can then be shown that the temperature at any point "z" in layer #1 at time "t" is,

$$v_{1(z,t)} = 32 + A + \frac{B}{Z}\left[e^{m_1 z}\cos(\omega t + m_1 z - \theta) + Ne^{-m_1 z}\cos(\omega t - m_1 z - \theta)\right] \quad [41]$$

and the temperature at any point "h" in layer #2 at time "t" is,

$$v_{2(h,t)} = 32 + A + \frac{B}{Z}(1 + N)e^{-m_2 h}\cos(\omega t - m_2 h - \theta) \quad \ldots\ldots\ldots \quad [42]$$

where "N", "Z" and "θ" are parameters expressed as follows:

$$N = \frac{\sqrt{k_1 C_1} - \sqrt{k_2 C_2}}{\sqrt{k_1 C_1} + \sqrt{k_2 C_2}} \quad [43]$$

$$Z = \sqrt{e^{2m_1 s} + 2N(-1 + 2\cos^2 m_1 s) + N^2 e^{-2m_1 s}} \quad [44]$$

$$\tan\theta = \tan m_1 s\left[\frac{1-Ne^{-2m_1 s}}{1+Ne^{-2m_1 s}}\right] \quad [45]$$

Now, differentiating equations [41] and [42] and following the procedure outlined in Problem 2, equations [18] to [27] inclusive, it can be found that

$$m_1 = \sqrt{\frac{\pi}{24a_1 T}} = \frac{1}{2(z_1 - z_2)} \ln \frac{f(z_1)}{f(z_2)} \quad [46]$$

and

$$m_2 = \sqrt{\frac{\pi}{24a_2 T}} = \frac{1}{2(h_2 - h_1)} \ln \frac{f(h_1)}{f(h_2)} = \text{equation [27]}$$

However, values of "a" may be as much as 20 per cent in error.

If the data were available as to the exact location of layer boundaries and for soil temperature profiles, then, at the soil interface, we have

$$k_1 i_1 = k_2 i_2 \quad [47]$$

This ratio of thermal conductivities may be of some help.

PROBLEM NO. 6

Given a semi-infinite, homogeneous soil mass, the surface of which is exposed to periodic temperature changes over a sufficiently long period so that the interior temperatures are also periodic.

Find the depth of frost penetration "x", neglecting latent heat.

It is assumed that the periodic surface temperature can be expressed by the equation

$$v_s = 32 + A - B \sin\omega t \quad [48]$$

and that B>A, so that the temperature drops below freezing.

The temperature at depth "h" at any time "t" is

$$v_{(h,t)} = 32 + A - Be^{-mh} \sin(\omega t - mh) \quad [49]$$

To find the trace of freezing temperature (32°F) surface "x",

Then

$$32 = 32 + A - Be^{-mx} \sin(\omega t - mx) \quad [50]$$

$$\text{or } A = Be^{-mx} \sin(\omega t - mx) \quad [51]$$

$$Ae^{mx} = B \sin(\omega t - mx) \quad [52]$$

$$\text{or} \quad mx = \ln \left[\frac{B}{A} \sin(\omega t - mx)\right]$$

$$\text{and } x = \frac{1}{m} \ln \frac{B}{A} \sin(\omega t - mx) = \sqrt{\frac{24aT}{\pi}} \ln \frac{B}{A} \sin(\omega t - mx) \quad [53]$$

Now "x" is a maximum when $\sin(\omega t - mx) = 1$

$$\therefore x_{max} = \sqrt{\frac{24aT}{\pi}} \ln \frac{B}{A} \quad [54]$$

<u>Example</u>

Given: $v_o = 42°$; $B = 20°$; $a = 0.03 \text{ ft}^2/\text{hr}$

Find "x".

$$x = \sqrt{\frac{24 \times 0.03 \times 365}{3.1416}} \ln \frac{20}{10} = \sqrt{83.60} \quad \ln 2$$

$$= 9.14 \times 0.693 = 6.34 \text{ ft.}$$

PROBLEM NO. 7

Given two layers of homogeneous, isotropic soil possessing different soil properties, the uppermost of which is exposed to periodic surface temperature changes over a sufficiently long period so that the interior temperatures are also periodic.

Find the depth of frost penetration "x", neglecting latent heat.

Let the surface temperature be expressed by equation [48]

$$v_s = 32 + A - B \sin \omega t$$

and let B>A so that the temperature drops below freezing.

As indicated by equations [41] and [42], the temperature at any point "z" at time "t" in layer #1 can be expressed as

$$v_{1(z,t)} = 32 + A - \frac{B}{Z}\left[e^{m_1 z}\sin(\omega t + m_1 z - \theta) + Ne^{-m_1 z}\sin(\omega t - m_1 z - \theta)\right] \qquad [55]$$

and at any point "h" at time "t" in layer #2 by

$$v_{2(h,t)} = 32 + A - \frac{B}{Z}(1 + N)e^{-m_2 h}\sin(\omega t - m_2 h - \theta) \; . \; . \; . \; . \; . \; . \; . \; . \qquad [56]$$

where "N", "Z" and "θ" are parameters given by equations [43] [44] and [45] respectively.

Proceeding in the manner indicated in Problem #6, the trace of freezing temperature (32°F) surface "x" in layer #1 is

$$\frac{AZ}{B} = e^{m_1 z}\sin(\omega t + m_1 z - \theta) + Ne^{-m_1 z}\sin(\omega t - m_1 z - \theta) \; . \; . \; . \; . \qquad [57]$$

and in layer #2

$$\frac{AZ}{B(1 + N)} = e^{-m_2 x}\sin(\omega t - m_2 x - \theta) \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \qquad [58]$$

Solution for "x" in equations [57] and [58] is by cut and try methods only.

PROBLEM NO. 8

Given a homogeneous, isotropic soil mass of semi-infinite extent, the surface of which is exposed to periodic temperature changes over a sufficiently long period so that the interior temperatures are also periodic.

Find the depth of freezing "x", neglecting volumetric heat but considering latent heat of fusion "L".

It is assumed that the periodic temperature change can be expressed by equation [48]

$$v_s = 32 + A - B \sin\omega t$$

The temperature gradient through a frozen layer of thickness "x" is

$$i = \frac{32 - A - 32 + B \sin\omega t}{x} = \frac{B \sin \omega t - A}{x} \quad \text{. . . . . [59]}$$

Now, the heat liberated in freezing a layer of thickness "x" is

$$dH = Ldx \quad \text{. . . . . [60]}$$

The heat conducted out in time "dt" is

$$dH = 24\ ki\ dt \quad \text{. . . . . [61]}$$

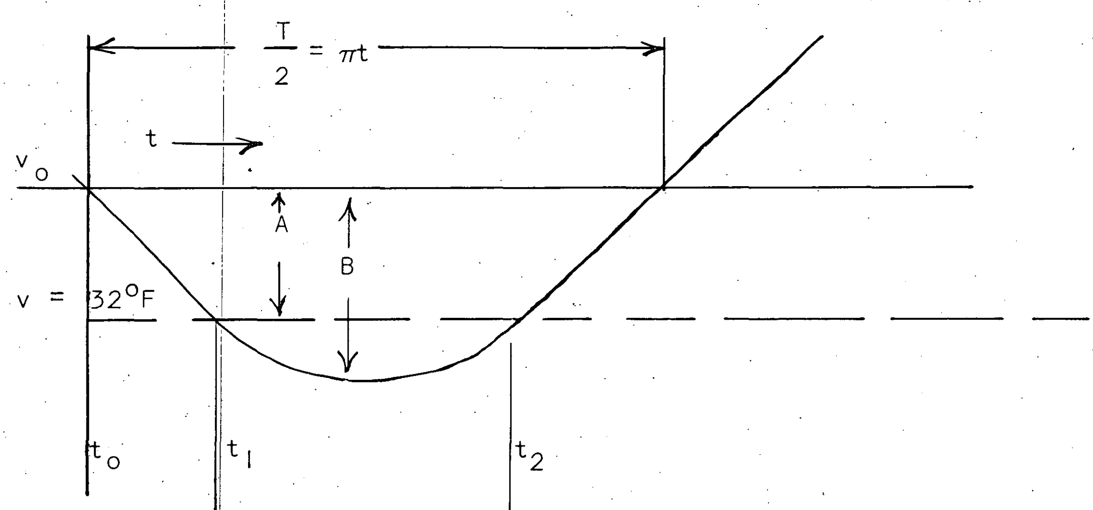
Equating [60] and [61], and substituting [59] for "i"

$$Ldx = 24kidt = \frac{24k}{x}(B\sin\omega t - A)\ dt \quad \text{. . . . . [62]}$$

$$\text{or } \frac{Lx\ dx}{24k} = (B \sin \omega t - A)dt \quad \text{. . . . . [63]}$$

Integrating

$$\frac{Lx^2}{24k} = \frac{-B}{\omega} \cos\omega t - At + \overline{K} \quad \text{. . . . . [64]}$$



From sketch, when $t = t_1$, $x = 0$ and $A = B \sin\omega t_1$

$$\therefore \sin\omega t_1 = \frac{A}{B} \text{ and } t_1 = \frac{1}{\omega} \text{arc} \sin\frac{A}{B} \quad \text{. . . . . [65]}$$

$$\text{and } \cos t = \frac{1}{B}\sqrt{B^2 - A^2}$$

$\therefore$ for [64] at time "t_1"

$$0 = \frac{-B}{\omega} \cdot \frac{1}{B}\sqrt{B^2 - A^2} - \frac{A}{\omega} \text{arc sin} \frac{A}{B} + \bar{K}$$

and $\bar{K} = \dfrac{\sqrt{B^2 - A^2}}{\omega} + \dfrac{A}{\omega}\text{arc sin}\dfrac{A}{B}$

$$\text{and } \frac{Lx^2}{24k} = -\frac{B}{\omega}\cos\omega t - At + \frac{1}{\omega}\sqrt{B^2 - A^2} + \frac{A}{\omega}\text{arc sin}\frac{A}{B} \quad \ldots\ldots\ldots \quad [66]$$

$$x = \sqrt{\frac{24k}{L}[-\frac{B}{\omega}\cos\omega t - At + \frac{1}{\omega}\sqrt{B^2 - A^2} - \frac{A}{\omega}\text{arc sin}\frac{A}{B}]} \quad \ldots\ldots \quad [67]$$

By rewriting equation [63] we have

$$\frac{dx}{dt} = \frac{24k(B\sin\omega t - A)}{Lx} \quad \ldots\ldots\ldots\ldots \quad [68]$$

Equating $\dfrac{\text{"}dx\text{"}}{dt}$ to 0, the maximum and minimum penetration is reached when

$$t = \frac{1}{\omega}\text{arc sin}\frac{A}{B} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad [69]$$

Two values of "t" satisfy equation [69] as can be seen from foregoing sketch. At time "t_1", penetration is zero and at time "t_2", melting begins and penetration is maximum.

Now $t_1 - t_o = \dfrac{T}{2} - t_2$

$$\therefore t_2 = t_{max} = \frac{T}{2} - t_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad [70]$$

Integrating equation [63]

$$\frac{L}{24\,k}\int_{o}^{x_{max}} x\,dx = \int_{t_1}^{t_2} K(B\sin\omega t - A)\,dt$$

$$\frac{Lx_{max}^2}{48k} = \left[-\frac{B}{\omega}\cos\omega t - At\right]_{t_1}^{t_2} \quad \ldots\ldots\ldots\ldots \quad [71]$$

$$= \frac{-B}{\omega}(\cos\omega t_2 + \cos\omega t_1) - A(t_2 - t_1)$$

$$= \frac{B}{\omega}(\cos\omega t_1 - \cos\omega t_2) - A(\frac{T}{2} - 2t_1) \quad . . . . \quad [72]$$

Now $\cos\omega t_1 = \frac{\sqrt{B^2 - A^2}}{B}$ and $\cos\omega t_2 = -\frac{\sqrt{B^2 - A^2}}{B}$

Substituting these values in equation [72]

$$\frac{Lx^2_{max}}{48\ k} = \frac{B}{\omega}\frac{\sqrt{B^2 - A^2}}{B} + \frac{B}{\omega}\frac{\sqrt{B^2 - A^2}}{B} - A(\frac{T}{2} - 2t_1)$$

$$= \frac{2}{\omega}\sqrt{B^2 - A^2} - A(\frac{T}{2} - 2t_1) = \frac{2}{\omega}\sqrt{B^2 - A^2} + A(2t_1 - \frac{T}{2}) \quad [73]$$

Substituting $\frac{2\pi}{T}$ for "ω" and $\frac{1}{\omega}\text{arc sin}\frac{A}{B}$ for "t_1"

Then $x^2_{max} = \frac{2k}{L}[\frac{24T}{\pi}\sqrt{B^2 - A^2} + A(\frac{24T}{\pi}\text{arc sin}\frac{A}{B} - \frac{24T}{2}\frac{\pi}{\pi})]$

$$= \frac{2kT}{\pi L}[24\sqrt{B^2 - A^2} + A(24\ \text{arc sin}\frac{A}{B} - 12\pi)]$$

$$x_{max} = \sqrt{\frac{48kT}{\pi L}[\sqrt{B^2 - A^2} + A(\text{arc sin}\frac{A}{B} - \frac{\pi}{2})]} \quad . . . . . \quad [74]$$

If the portion of the curve below 32°F is assumed to be parabolic, the equation for the surface temperature for that portion can be expressed by

$$v_s = (B - A)(\frac{4t^2}{(t_2 - t_1)^2} - 1) + 32 \quad . . . . \quad [75]$$

$$\text{or} \quad = (B - A)[(\frac{2t - t_2 - t_1}{t_2 - t_1})^2 - 1] + 32 \quad . . . . \quad [76]$$

Proceeding in the manner outlined by equations [59] through [74] inclusive, then

$$x_{max} = \sqrt{\frac{4k}{3L}(B - A)(t_2 - t_1)} \ldots\ldots\ldots \quad [77]$$

Example

Using the same data as was used for example for Problem No. 6,

$v_o = 42^o$; $B = 20^o$; $a = 0.03\ ft^2/hr$ and further

assuming C = 30 and L = 2880, then for use in equation [74]

$$k = aC = 0.03 \times 30 = 0.9$$

Then

$$x_{max} = \sqrt{\frac{48 \times 0.9 \times 365}{3.1416 \times 2880}[\sqrt{400 - 100} + 10(\arcsin\frac{10}{20} - 1.5708)]}$$

$$= \sqrt{1.74 \times (17.32 - 10.47)} = \sqrt{11.9} = 3.45\ ft.$$

for use in equation [77]

$$t_1 = \frac{12T}{\pi} \cdot \frac{\pi}{6} = 2T \text{ hours} = \frac{T}{12} \text{ days}$$

$$t_2 = \frac{T}{2} - t_1 = \frac{5T}{12} = 10T \text{ hours}$$

Then

$$x_{max} = \sqrt{\frac{4 \times 0.9}{3 \times 2880}(20 - 10)(10T - 2T)}$$

$$= \sqrt{.000417 \times 10 \times 8 \times 365} = \sqrt{12.15} = 3.49\ ft.$$

PROBLEM NO. 9

Given a homogeneous, isotropic soil mass of semi-infinite extent, the surface of which is exposed to a variable surface temperature which is a general function of time.

Find the depth of freezing "x", neglecting volumetric heat but considering latent heat of fusion "L".

The surface temperature can be expressed as

$$v_s = f(t) \ldots\ldots\ldots \quad [78]$$

Proceeding in the manner indicated by equations [59] to [62] inclusive, then

$$i = \frac{32 - f(t)}{x} \quad \text{[79]}$$

$$dH = Ldx = 24\,kidt = 24k\left[\frac{32 - f(t)}{x}\right]dt \quad \text{[80]}$$

Then $xdx = \frac{24k}{L}[32 - f(t)]dt$ . . . . [81]

Integrating

$$\frac{x^2}{2} = \frac{24k}{L}\int_o^t [32-f(t)]dt \quad \text{[82]}$$

Now $\int_o^t$ 32 - f(t)dt = F = freezing index in degree days

$$\therefore x_{max} = \sqrt{\frac{48kF}{L}} \quad \text{[83]}$$

Example

Using data from examples for Problems No. 6 and No. 8 $v_o = 42^o$; $B = 20^o$; $a = 0.03$ ft^2/hr; $C = 30$ and $L = 2880$.

$F = (32-v_s)\,t \qquad v_s = v_o - B = 42 - 20 = 22^oF.$

$t = t_2 - t_1 = \frac{T}{3} = 121.7$ days

$$x = \sqrt{\frac{48 \times 0.9 \times 1217}{2880}} = 4.26 \text{ ft.}$$

PROBLEM NO. 10

Given a homogeneous, isotropic soil mass of semi-infinite extent, the surface of which is exposed to a uniform temperature above freezing "v_o" which is suddenly reduced to below freezing "v_f".

Find the depth of freezing "x", assuming that the latent heat "L" is greatly in excess of the volumetric heat "C".

The heat liberated in freezing a small depth "dx" is "L dx", which must be conducted upwards through a distance "x".

The thermal gradient is therefore,

$$i = \frac{32 - v_f}{x} \quad \text{[84]}$$

Hence the rate of upward flow

$$= \frac{24k}{x}(32 - v_f)\,dt \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad [85]$$

Now, if the unfrozen soil has a heat capacity of "C_u" per unit volume and is originally at temperature "v_o", then the heat liberated in lowering the temperature of the layer of thickness "dx" from "v_o" to the freezing point (32^oF), is

$$dH = C_u(v_o - 32)dx \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad [86]$$

$$\text{Then, } Ldx + C_u(v_o - 32)dx = \frac{24k}{x}(32 - v_f)dt \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad [87]$$

$$\text{or } x\,dx = \frac{24k(32 - v_f)}{L + C_u(v_o - 32)}\,dt \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad [88]$$

Integrating,

$$\frac{x^2}{2} = \frac{24k(32 - v_f)\,t}{L + C_u(v_o - 32)} + \overline{K}$$

When t = 0, x = 0, therefore $\overline{K} = 0$, and

$$x = \sqrt{\frac{48k\,(32 - v_f)t}{L + C_u(v_o - 32)}} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad [89]$$

If the volumetric heat of frozen soil, "C_f", is considered, then equation [87] becomes

$$Ldx + C_u(v_o - 32)dx + \frac{1}{2}C_f(32 - v_f)dx = \frac{24k}{x}(32 - v_f)\,dt \; . \; . \; . \quad [90]$$

and equation [89] therefore becomes

$$x_{max} = \sqrt{\frac{48k\,(32 - v_f)\,t}{L + C_u(v_o - 32) + \frac{C_f}{2}(32 - v_f)}} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad [91]$$

But by definition $(32 - v_f)t = F$ (in degree days)

Therefore equation [90] becomes

$$x_{max} = \sqrt{\frac{48\,k\,F}{L + C_u(v_o - 32) + \frac{C_f\,F}{2t}}} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad [92]$$

Substituting a weighted average value "C" for "C_u" and "C_f", equation [92] becomes

$$x_{max} = \sqrt{\frac{48\ k\ F}{L + C(v_o - 32 + \frac{F}{2t})}} \quad \ldots\ldots\ldots\ldots \quad [93]$$

Example

Using same data as for Example for Problem No. 9, $v_o = 42^o$; $B = 20^o$; $a = 0.03\ ft^2/hr$; $C = 30$; and $L = 2880$ and further $C_u = 32$ and $C_f = 28$.

Using equation [92]

$$x = \sqrt{\frac{48 \times 0.03 \times 30 \times 1217}{2880 + 32\left[(10) + \frac{28 \times 1217}{2 \times 121.7}\right]}} = \sqrt{\frac{52,600}{2880 + 320 + 140}}$$

$$= \sqrt{15.75} = 3.97\ ft.$$

Using equation [93]

$$x = \sqrt{\frac{48 \times 0.03 \times 30 \times 1217}{2880 + 30(10 + \frac{1217}{243.4})}} = \sqrt{\frac{52,600}{2880 + (30 \times 15)}}$$

$$= \sqrt{15.80} = 3.98\ ft.$$

PROBLEM NO. 11

Given a homogeneous, isotropic soil mass of semi-infinite extent, the surface of which is exposed to periodic temperature changes over a sufficiently long period so that the interior temperatures are also periodic.

Find the depth of freezing "x", assuming that the latent heat "L" is greatly in excess of the volumetric heat "C".

The surface temperature is assumed to follow the form expressed by equation [48]

$$v_s = 32 + A - B \sin\omega t, \text{ in which } A = 0$$

$$\therefore v_s = 32 - B \sin\omega t \quad \ldots\ldots\ldots\ldots \quad [94]$$

The thermal gradient "i" through a frozen layer of thickness "x", is

$$i = \frac{32 - v_s}{x} = \frac{B \sin \omega t}{x} \quad \ldots\ldots\ldots\ldots \quad [95]$$

Proceeding in the same manner as in Problem #10, equations [85] to [87] inclusive,

$$Ldx + C_u(v_o - 32)\,dx = \frac{24k}{x}(B \sin \omega t)dt \quad \ldots\ldots\ldots \quad [96]$$

Transposing and integrating

$$\frac{x^2}{2} = \frac{24kB}{L + C_u(v_o-32)}\left(-\frac{1}{\omega}\cos\omega t\right) + \overline{K}$$

Now when $t = 0,\ x = 0$

$$\overline{K} = \frac{24\ k\ B}{L + C_u(v_o - 32)} \cdot \frac{1}{\omega}$$

$$\therefore\ x^2 = \frac{48\ k\ B}{\omega[L + C_u(v_o - 32)]}(1 - \cos\omega t) \quad \ldots\ldots\ldots \quad [97]$$

But $1 - \cos\omega t = 2 \sin^2 \frac{\omega t}{2}$

$$\therefore\ x^2 = \frac{96kB \sin^2 \frac{\omega t}{2}}{\omega[L + C_u(v_o - 32)]}$$

$$\text{or } x = 2 \sin\frac{\omega t}{2} \sqrt{\frac{24kB}{\omega[L + C_u(v_o - 32)]}} \quad \ldots\ldots\ldots \quad [98]$$

When $\omega t = \pi$, $\sin\frac{\omega t}{2} = 1$, "x" is max. and $t = \frac{T}{2}$

$$\therefore\ x_{max} = 2\sqrt{\frac{24\ kBT}{2\pi[L + C_u(v_o - 32)]}} = \sqrt{\frac{48\ kBT}{\pi[L + C_u(v_o - 32)]}} \quad \ldots \quad [99]$$

Example

Using values from examples for preceding Problems
$v_o = 42^o$; $B = 20^o$; $a = 0.03\ ft^2/hr$; $C = 30$; $C_u = 32$; $C_f = 28$;
and $L = 2880$

$$x = \sqrt{\frac{48 \times 0.03 \times 30 \times 20 \times 365}{3.1416(2880 + 32 \times 10)}} = \sqrt{\frac{315,000}{3.1416 \times 3200}}$$

$$= \sqrt{31.35} = 5.60\ ft.$$

PROBLEM NO. 12

Given a homogeneous, isotropic soil mass at the freezing point, but with the soil moisture unfrozen. The surface temperature varies as a general function of time but always below freezing.

Find the depth of freezing "x".

The surface temperature "v_f" can be expressed by equation [78]

$$v_f = f(t)$$

Proceeding in the manner indicated by equations [79] and [80] in Problem #9, then

$$i = \frac{32 - f(t)}{x}$$

$$\text{and } dH = Ldx = 24\ k\,i\,dt = 24k\,\frac{32 - f(t)}{x}\,dt \quad \ldots \quad [100]$$

$$\text{or } \frac{Lx}{24k}\,dx = [32 - f(t)]dt \quad \ldots \quad [101]$$

Integrating

$$\frac{x^2 L}{48k} = \int_o^t [32 - f(t)]dt \quad \ldots \quad [102]$$

$$\text{or } x = \frac{48\ k}{L}\int_o^t [32 - f(t)]dt \quad \ldots \quad [103]$$

Now considering the volumetric heats "C_u" and "C_f" and proceeding in the manner indicated in Problem #10, equations [87] to [90] inclusive, equation [100] becomes

$$Ldx + C_u[32 - f(t)]dx + \frac{C_f}{2}[32 - f(t)]dx = \frac{24k}{x}[32 - f(t)]dt \quad . \quad [104]$$

and equation [103] becomes

$$x = \sqrt{\frac{48\ k\int_o^t [32 - f(t)]dt}{L + C_u[32 - f(t)] + \frac{C_f}{2}[32 - f(t)]}} \quad \ldots \quad [105]$$

Substituting the weighted average value "C" for "C_u" and "C_f" equation [105] becomes

$$x = \sqrt{\frac{48\ k \int_o^t [32 - f(t)]dt}{L + \frac{3C}{2} [32 - f(t)]}} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \quad [106]$$

Now since "v_f" is always below freezing,

$$\int_o^t [32 - f(t)]dt = F$$

Therefore equation [106] can be written

$$x = \sqrt{\frac{48\ k\ F}{L + \frac{3C}{2} (32 - v_f)}} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \quad [107]$$

Example

Using values from examples for previous Problems

$v_f = 22^o$; $a = 0.03$; $C = 30$; and $L = 2880$

$$x = \sqrt{\frac{48 \times 0.03 \times 30 \times 1217}{2880 + 45 \times 10}} \doteq \sqrt{\frac{52{,}600}{3330}}$$

$$= \sqrt{15.80} = 3.98 \text{ ft.}$$

PROBLEM NO. 13

Given a homogeneous, isotropic, semi-infinite mass of frozen soil at freezing temperature, the surface of which is exposed to a constant temperature above freezing "v_p".

Find the depth of melting "x".

The temperature at any point "x" at any time "t" can be expressed by the equation

$$v_{(x,t)} = f(x,t) = 32 + A \int_{\frac{x}{2\sqrt{24at}}}^{\beta} e^{-u^2} du \quad . \ . \ . \ . \ . \ . \ . \ . \quad [108]$$

From equation [62]

$$-L\frac{dh}{dt} = 24\ k\frac{dv}{dx} \text{ ....(minus sign denotes melting)} \quad ... \quad [109]$$

Now, differentiating equation [108]

$$v = f(x,t)$$

$$dv = \frac{dv}{dx}dx + \frac{dv}{dt}dt \quad .... \quad [110]$$

When $x = h$, $dv = 0$

$$\therefore 0 = \left(\frac{dv}{dx}\right)_{x=h} . \left(\frac{dh}{dt}\right) + \left(\frac{dv}{dt}\right)_{x=h} \quad .... \quad [111]$$

Combining equations [109] and [111]

$$0 = \left(\frac{dv}{dx}\right)_{x=h} . \frac{24k}{L}\left(\frac{dv}{dx}\right) + \left(\frac{dv}{dt}\right)_{x=h} \quad \text{or} \quad \frac{dv}{dt} = \frac{24k}{L}\left(\frac{dv}{dx}\right)^2_{x=h} \quad .. \quad [112]$$

From equation [108] by differentiation,

$$\frac{dv}{dt} = Ae^{\frac{-x^2}{96at}} \quad \frac{x}{4t\sqrt{24at}} \quad .... \quad [113]$$

and

$$\frac{dv}{dt} = Ae^{\frac{-x^2}{96at}} \quad \frac{1}{2\sqrt{24at}} \quad .... \quad [114]$$

Substituting "h" for "x" and substituting equations [113] and [114] in equation [112],

$$Ae^{-\frac{h^2}{96at}} . \frac{h}{4t\sqrt{24\ at}} = \frac{24k\ A^2\ e^{-\frac{2h^2}{96at}}}{96\ L\ at} \quad ... \quad [115]$$

Now from equation [3]

$$\beta = \frac{h}{2\sqrt{24at}}$$

Equation [115] becomes

$$Ae^{-\beta^2} \cdot \frac{\beta}{2t} = \frac{k\,A^2\,e^{-2\beta^2}}{4\,at\,L} \qquad [116]$$

$$\text{or} \quad \beta = \frac{k\,Ae^{-\beta^2}}{2aL} \qquad [117]$$

$$\text{Hence} \quad \frac{\beta e^{\beta^2}}{A} = \frac{k}{2aL} \qquad [118]$$

Now from equation [108]

$$\frac{1}{A} = \frac{1}{v_p - 32} \cdot \int_0^{\beta} e^{-u^2}\,du \qquad [119]$$

Substituting equation [119] in equation [118]

$$\beta e^{\beta^2} \int_0^{\beta} e^{-u^2}\,du = \frac{k(v_p - 32)}{2aL} \qquad [120]$$

Now from equation [2] $\int_0^{\beta} e^{-u^2}\,du = \frac{\text{erf}\,(\beta)\sqrt{\pi}}{2}$

$$\therefore \beta e^{\beta^2}\,\text{erf}(\beta) = \frac{k(v_p - 32)}{\sqrt{\pi}\,aL} = \frac{C(v_p - 32)}{L\sqrt{\pi}} \qquad [121]$$

If β is small, then

$$\beta e^{\beta^2} \int_0^{\beta} e^{-u^2}\,du \approxeq \beta^2 \qquad [122]$$

Substituting in equation [120]

$$\beta^2 \approxeq \frac{C(v_p - 32)}{2L} \qquad [123]$$

Since from equation [3] $\beta = \frac{h}{2\sqrt{24at}}$

$$\beta^2 = \frac{h^2}{96at} = \frac{x^2}{96at} \qquad [124]$$

$$\text{Then} \quad x \approxeq \frac{48\,kt\,(v_p - 32)}{L} \qquad [125]$$

Now, consider the series expansion

$$e^{\beta^2} = 1 + \beta^2 + \frac{\beta^4}{2!} + \frac{\beta^6}{3!} \quad \ldots\ldots\ldots$$

Then

$$\beta\, e^{\beta^2} = \beta + \beta^3 + \frac{\beta^5}{2!} + \frac{\beta^7}{3!} \quad \ldots\ldots$$

and $\int_0^{\beta} e^{-u^2}\,du = \beta - \frac{\beta^3}{3 \cdot 1!} + \frac{\beta^5}{5 \cdot 2!} - \frac{\beta^7}{7 \cdot 3!} + \ldots\ldots\ldots$

Hence

$$\beta e^{\beta^2} \int_0^{\beta} e^{-u^2}\,du = (\beta + \beta^3 + \frac{\beta^5}{2} + \frac{\beta^7}{6})(\beta - \frac{\beta^3}{2} + \frac{\beta^5}{10} - \frac{\beta^7}{42} \ldots)$$

$$= (\beta^2 + \frac{2\beta^4}{3} + \ldots\ldots) \quad \ldots\ldots\ldots \quad [126]$$

Then equation [120] becomes

$$\beta^2 + \frac{2\beta^4}{3} = \frac{C(v_p - 32)}{2L} \quad \ldots\ldots\ldots \quad [127]$$

and

$$x = \sqrt{72at(\sqrt{1 + \frac{4(v_p - 32)C}{3L}} - 1)} \quad \ldots\ldots\ldots \quad [128]$$

Example

Using data from examples for previous Problems.

$a = 0.03$; $C = 30$; and $L = 2880$. Also assuming $v_p = 42^{o}$

Using equation [125]

$$x = \sqrt{\frac{48 \times 0.03 \times 30 \times 121.7 \times 10}{2880}} = \sqrt{\frac{52,600}{2880}}$$

$$= \sqrt{18.25} = 4.27 \text{ ft.}$$

Using equation [128]

$$x = \sqrt{72 \times 0.03 \times 121.7\ [\sqrt{1 + \frac{4 \times 10 \times 30}{3 \times 2880}} - 1\ ]}$$

$$= \sqrt{263(\sqrt{1.139} - 1)}$$

$$= \sqrt{263 \times .065} \qquad = \sqrt{17.09} = 4.14 \text{ ft}$$

Using equation [120] and Figure 6, Plate A-2

$$\frac{C(v_p - 32)}{L \times 2} = \frac{30 \times 1.0}{2880 \times 2} = 0.0529 = \lambda\beta$$

From Figure 6, Plate A-2, $\beta = 0.225$

$$\text{Since } x = 2\beta\sqrt{24\ at} = 2 \times 0.225\sqrt{24 \times 0.03 \times 121.7}$$

$$= 0.45\sqrt{87.62} = 0.45 \times 9.36$$

$$= 4.22 \text{ ft.}$$

The solutions by these three methods are in very close agreement, but the method using equation [120] and Figure 6, Plate A-2, gives the exact answer and is the easiest to use.

PROBLEM NO. 14

Given a homogeneous, isotropic, semi-infinite soil mass just above freezing temperature which is exposed to a constant temperature below freezing "v_p".

Find the depth of freezing "x", assuming that the thermal gradient varies uniformly from the surface to the depth of freezing.

The surface temperature can be expressed by equation [78]

$$v_p = f(t)$$

Then, as indicated in equation [100]

$$L dx = 24k \frac{[32 - f(t)]}{x} dt$$

The volumetric heat "C_f" liberated in the frozen zone of thickness "dx" in time "t", is

$$dH = \frac{C_f[32 - f(t)]}{2} dx \qquad \ldots\ldots\ldots\ldots \qquad [129]$$

$$\therefore \frac{24k}{x}[32-f(t)]dt = Ldx + \frac{C_f[32 - f(t)]}{2}dx$$

$$= L + \frac{C_f}{2}[32 - f(t)]\ dx \quad \ldots\ldots \quad [130]$$

or

$$xdx = \frac{24k[32 - f(t)]\ dt}{L + \frac{C_f}{2}[32 - f(t)]} \quad \ldots\ldots\ldots\ldots\ldots \quad [131]$$

Integrating

$$x^2 = 48k\int_{t_1}^{t_2} \frac{[32 - f(t)]dt}{L + \frac{C_f}{2}[32 - f(t)]} \quad \ldots\ldots\ldots\ldots\ldots \quad [132]$$

Now since "v_p" is always below freezing

$\int_{t_1}^{t_2} [32 - f(t)]\ dt = F$ and equation [132] becomes

$$x^2 = \frac{48kF}{L + \frac{C_f}{2}[32 - f(t)]} \quad \ldots\ldots\ldots\ldots\ldots \quad [133]$$

and

$$x = \sqrt{\frac{48k\ F}{L + \frac{C_f}{2}(32 - v_p)}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad [134]$$

If the surface temperature is expressed by the form

$$v_s = 32 + B\sin\omega t \quad \ldots\ldots\ldots\ldots\ldots \quad [135]$$

Then

$$x^2 = \frac{48k}{\omega}\{(A - \frac{DB}{G})(\frac{2}{\sqrt{D^2 - G^2}})\ [\ \text{arc tan}(\frac{G + D\tan\frac{\omega t_2}{2}}{\sqrt{D^2 - G^2}}) -$$

$$\text{arc tan}\ (\frac{G + D\tan\frac{\omega t_1}{2}}{\sqrt{D^2 - G^2}})] + \frac{B}{G}\omega(t_2 - t_1)\}. \quad [136]$$

where $D = L + \frac{C_f A}{2}$ and $G = \frac{C_f B}{2}$

Examples ·

Using data from examples for preceding Problems

$v_o = 42^\circ$; $B = 20^\circ$; $a = 0.03\ ft^2/hr$; $C = 30$; $C_f = 28$;

$C_u = 32$; $L = 2880$; and $v_p = 22^\circ$

Using equation [134]

$$x = \sqrt{\frac{48 \times 0.03 \times 30 \times 1217}{2880 \times \frac{28}{2}(32 - 22)}} = \sqrt{\frac{52,600}{3020}}$$

$$= \sqrt{17.40} = 4.17 \text{ ft.}$$

Using equation [136]

$$D = 2880 + \frac{28 \times 10}{2} = 3020$$

$$G = \frac{28 \times 20}{2} = 280$$

$$\omega = \frac{2\pi}{T} = \frac{2 \times 3.1416}{365} = 0.01724$$

$t_1 = \frac{T}{12}$ and $t_2 = \frac{5T}{12}$ (from example Problem #8)

Now $$\frac{\omega t_1}{2} = \frac{2\pi}{T} \times \frac{T}{24} = \frac{\pi}{12}$$

$$\frac{\omega t_2}{2} = \frac{2\pi}{T} \times \frac{5T}{24} = \frac{5\pi}{12}$$

$$(A - \frac{DB}{G}) = 10 - \frac{3020 \times 20}{280} = 10 - 215.7 = -205.7$$

$$\sqrt{D^2 - G^2} = \sqrt{3020^2 - 280^2} = \sqrt{9,042,000} = 3007$$

$$G + D \tan\frac{\omega t_1}{2} = 280 + 3020 + \tan\frac{\pi}{12} = 280 + 3020 \tan 15^{\circ}$$

$$= 280 + 3020 \times 0.26795$$

$$= 1089$$

$$G + D \tan\frac{\omega t_2}{2} = 280 + 3020 \quad \tan\frac{5\pi}{12} = 280 + 3020 \tan 75^{\circ}$$

$$= 280 + 3020 \times 3.84103$$

$$= 11,550$$

$$\text{arc tan } \left(\frac{G + D \tan\frac{\omega t_1}{2}}{\sqrt{D^2 - G^2}}\right) = \text{arc tan } \frac{1089}{3007} = \text{arc tan } 0.36215$$

$$= 19.91^{\circ}$$

$$\text{arc tan } \left(\frac{G + D \tan\frac{\omega t_2}{2}}{\sqrt{D^2 - G^2}}\right) = \text{arc tan } \frac{11550}{3007} = \text{arc tan } 3.84105$$

$$= 75.41^{\circ}$$

$$\frac{B}{G}\omega(t_2 - t_1) = \frac{20 \times 2\pi}{280 \times T}\cdot\frac{T}{3} = \frac{40\pi}{840} = 0.14960$$

Therefore

$$x^2 = \frac{48 \times 0.03 \times 30}{0.01724}\left[(-205.7)\left(\frac{2}{3007}\right)(75.41^{\circ} - 19.91^{\circ}) + 0.14960\right]$$

$$= 2505.8 \ [(-0.13681)(55.50^{\circ}) + 0.14960]$$

$$= 2505.8 \ [(-0.13681)(0.96866 \text{ radians}) + 0.14960]$$

$$= 2505.8 \ (-0.1325 + 0.14960)$$

$$= 2505.8 \times 0.0171 = 42.85$$

$$x = \sqrt{42.85} = 6.55 \text{ ft.}$$

PROBLEM NO. 15

Given a homogeneous, isotropic mass of frozen soil of semi-infinite extent, exposed to a surface temperature "v_s" which is below freezing.

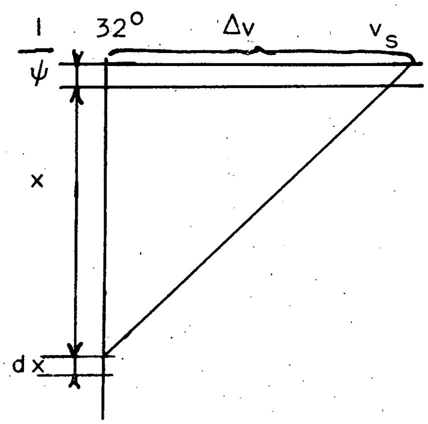
Find the effect of radiation and ground film.

In accordance with Newton's Law of cooling

$$i_{x=0} = \psi\,(v_{x=0} - v_s) = \psi\Delta v \quad \ldots\ldots [137]$$

The rate at which heat passes out through a unit area of surface is

$$\frac{dQ}{dt} = 24k\,i_{x=0} = 24k\psi(v_{x=o} - v_s) = \frac{24k}{\frac{1}{\psi}}(v_{x=o} - v_s) = 24E(v_{x=o} - v_s) \quad [138]$$



$$\frac{dQ}{dt} = L\,dx + \frac{C_f\,\Delta v}{2}\,dx = \frac{24k\Delta v}{x + \frac{1}{\psi}} \quad \ldots \quad [139]$$

$$\text{or } (x + \frac{1}{\psi})dx = \frac{24k\Delta v}{L + \frac{C_f}{2}\Delta v}(dt) \quad \ldots \quad [140]$$

Now let $y = x + \frac{1}{\psi}$

$\therefore dy = dx$

$$\text{Then } y\,dy = \frac{24k\Delta v}{L + \frac{C_f}{2}\Delta v}\,dt \quad \ldots\ldots \quad [141]$$

$$\text{or } y^2 = \frac{48k\Delta v t}{L + \frac{C_f}{2}\Delta v} + \bar{K} = (x + \frac{1}{\psi})^2 \quad \ldots\ldots \quad [142]$$

When $t = 0$, $x = 0$. $\therefore \bar{K} = (\frac{1}{\psi})^2$

$$\therefore (x + \frac{1}{\psi})^2 = \frac{48k\Delta v t}{L + \frac{C_f}{2}\Delta v} + (\frac{1}{\psi})^2 \quad \ldots\ldots \quad [143]$$

$$x = -\frac{1}{\psi} + \sqrt{\frac{48k\Delta v t}{L + \frac{C_f}{2}\Delta v} + \left(\frac{1}{\psi}\right)^2} \quad . . . . \quad [144]$$

From figure above $\Delta v = 32 - v_s$

$$\therefore \quad x = -\frac{1}{\psi} + \sqrt{\frac{48kt(32 - v_s)}{L + \frac{C_f}{2}(32 - v_s)} + \left(\frac{1}{\psi}\right)^2} \quad . . . . \quad [145]$$

The value $\frac{"1"}{\psi}$ may be regarded as an extra layer of soil having the same thermal conductivity "k" as the base soil, but having no volumetric heat capacity. The value $\frac{"1"}{\psi}$ is also a function of the velocity of air over the surface. For large values of "E" (5 or 6), the value of $\frac{"1"}{\psi}$ is small, but for small values of "E" (1 or 2), the value of $\frac{"1"}{\psi}$ becomes appreciable. The following table indicates the effect of neglecting the value $\frac{"1"}{\psi}$ in equation [145] using the following values:

$L = 800$; $t = 180$; and $C_f = 30$.

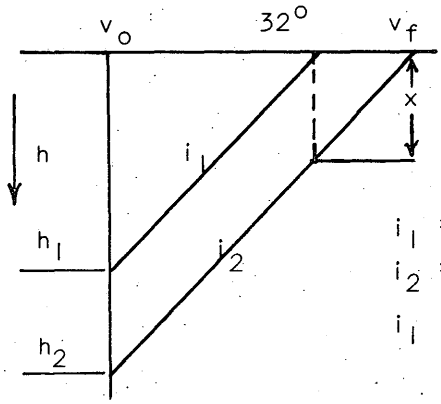
v_s (°F)	Per Cent Error in Omitting $1/\psi$ from Equation [145]											
	E = 6			E = 5			E = 2			E = 1		
	k=0.5	k=1.0	k=1.5	k=0.5	k=1.0	k=1.5	k=0.5	k=1.0	k=1.5	k=0.5	k=1.0	k=1.5
31	3.6	5.1	6.2	4.4	6.1	7.5	10.8	15.2	18.5	21.5	29.4	36.2
27	1.7	2.4	2.8	2.0	2.9	3.4	5.0	7.1	8.5	10.0	14.1	16.7
22	1.2	1.8	2.1	1.5	2.1	2.6	3.7	5.2	6.4	7.4	10.4	12.8
17	1.0	1.5	1.8	1.3	1.8	2.2	3.1	4.4	5.4	6.3	8.9	10.8
12	.9	1.3	1.6	1.1	1.6	2.0	2.8	4.0	4.9	5.7	7.8	9.7
7	.9	1.2	1.5	1.0	1.5	1.8	2.6	3.7	4.5	5.2	7.4	9.0
2	.8	1.2	1.4	1.0	1.4	1.7	2.5	3.5	4.3	4.9	6.9	8.5

The per cent error in omitting the value $\frac{"1"}{\psi}$ from equation [145] for airport runways and highways where the snow is plowed off and the surface exposed to the wind, will be small, since the value of "E" will be about 5 or 6 and the temperatures involved will be the temperatures indicated in the middle and lower portions of the above table.

PROBLEM NO. 16

Given a homogeneous, isotropic soil mass at a temperature "v_o" suddenly exposed to a surface temperature below freezing "v_f".

Find the depth of freezing "x", assuming that the temperature varies uniformly with the depth.



i_1 = thermal gradient at start of freezing

i_2 = thermal gradient at end of freezing

$i_1 = i_2$

The heat conducted out of the soil is given by equation [61]

$$dH = 24k\ i\ dt$$

and $H = \int_0^t 24ki\ dt + \overline{K}$ . . . . [146]

when $t = 0$ $H = 0$ $\therefore$ $\overline{K} = 0$ and $H = 24kit$ . . . . [147]

The total heat given up the soil as indicated in sketch is

$$H = \frac{h_2 - h_1}{2} (v_o - 32 + v_o - v_f)\ C + Lx$$

But $h_2 - h_1 = x$

$\therefore H = x\ [\frac{C}{2} (2v_o - 32 - v_f) + L] = 24kit$ . . . . [148]

Now

$i = \frac{32 - v_f}{x}$ and $32 - v_f = \frac{F}{t}$ . . . . [149]

$\therefore\ i = \frac{F}{xt}$ . . . . [150]

Substituting equation [150] in equation [148]

$$x\left[\frac{C}{2}(2v_o - 32 - v_f) + L\right] = \frac{24kF}{x} \qquad [151]$$

$$\text{and } x = \sqrt{\frac{24\ k\ F}{\frac{C}{2}(2v_o - 32 - v_f) + L}} \qquad [152]$$

From equation [149]

$$-v_f = \frac{F}{t} - 32$$

Hence equation [152] becomes

$$x = \sqrt{\frac{24\ k\ F}{L + \frac{C}{2}(2v_o - 64 + \frac{F}{t})}} \qquad [153]$$

$$\text{or } x = \sqrt{\frac{24\ k\ F}{L + C(v_o - 32 + \frac{F}{2t})}} \qquad [154]$$

Example

Using data from examples for previous Problems

$v_o = 42^o$; $C = 30$; $a = 0.03$; and $L = 2880$

Then

$$x = \sqrt{\frac{24 \times 0.03 \times 30 \times 1217}{2880 + 30(42 - 32 + \frac{1217}{2 \times 121.7})}} = \sqrt{\frac{26,300}{3330}}$$

$$= \sqrt{7.88} = 2.81 \text{ ft.}$$

PROBLEM NO. 17

Given a homogeneous, isotropic soil mass of semi-infinite extent, overlain by an insulation layer of thickness "d", all at temperature "v_o" and suddenly exposed to a surface temperature below freezing "v_f".

Find the depth of freezing "x_R", assuming that the temperature varies uniformly with the depth, that there is no significant change in temperature gradients due to the insulation layer, and neglecting latent heat "L_R" and volumetric heat "C_R" of the insulation layer.

Now equation [151] can be written as

$$x_R\left[\frac{C}{2}(2v_o - 32 - v_f) + L\right] = \frac{24\ kF}{d + x_R} \quad \ldots\ldots\ldots\ldots \quad [155]$$

$$\text{or } x_R(d + x_R) = \frac{24\ k\ F}{L + \frac{C}{2}(2v_o - 32 - v_f)} \quad \ldots\ldots\ldots\ldots \quad [156]$$

Solving for x_R

$$x_R = -\frac{d}{2} + \sqrt{\left(\frac{d}{2}\right)^2 + \frac{24\ k\ F}{\frac{C}{2}(2v_o - 32 - v_f) + L}} \quad \ldots\ldots \quad [157]$$

Substituting equation [149] for v_f

$$x_R = -\frac{d}{2} + \sqrt{\left(\frac{d}{2}\right)^2 + \frac{24\ k\ F}{L + C(v_o - 32 + \frac{F}{2t})}} \quad \ldots\ldots \quad [158]$$

Example

Using same data as for examples for previous Problems

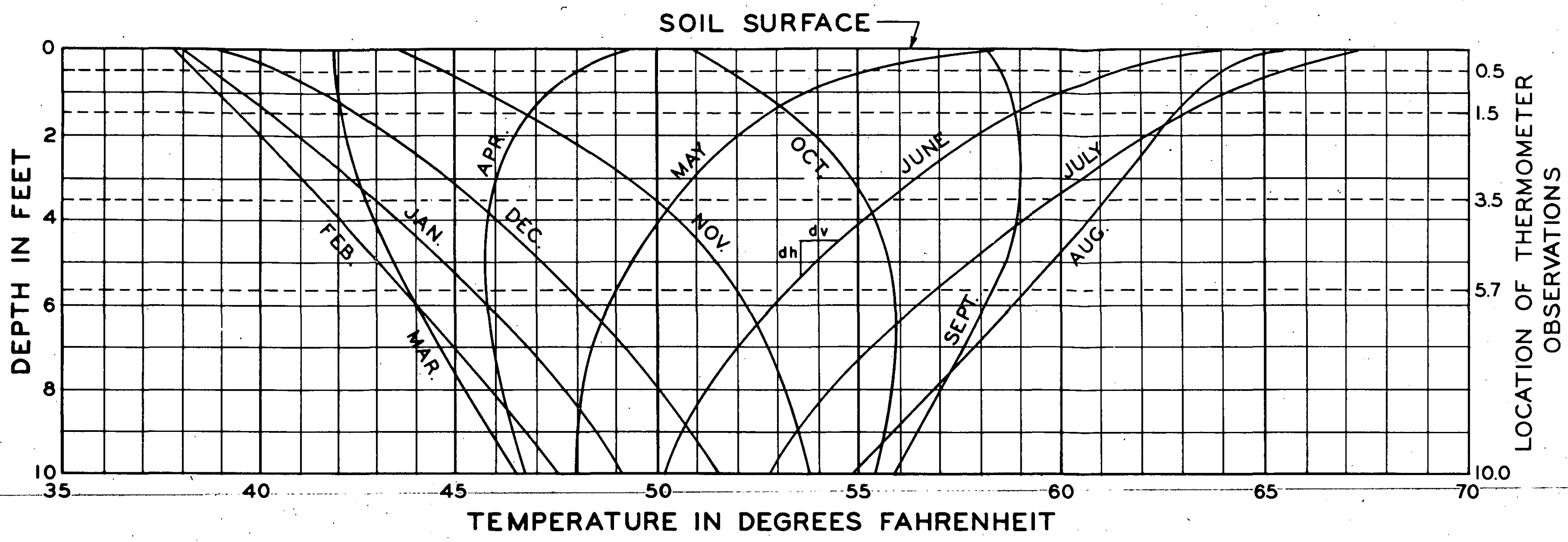
$v_o = 42^o$; $C = 30$; $a = 0.03$ and $L = 2880$; also $d = 1.0$ ft.

$$x_R = -0.5 + \sqrt{(0.5)^2 + \frac{24 \times 0.03 \times 30 \times 1217}{2880 + 30(42 - 32 + \frac{1217}{2 \times 121.7})}}$$

$$x_R = -0.50 + \sqrt{0.25 + \frac{26300}{3330}} = -0.50 + \sqrt{8.13}$$

$$= -0.50 + 2.85$$

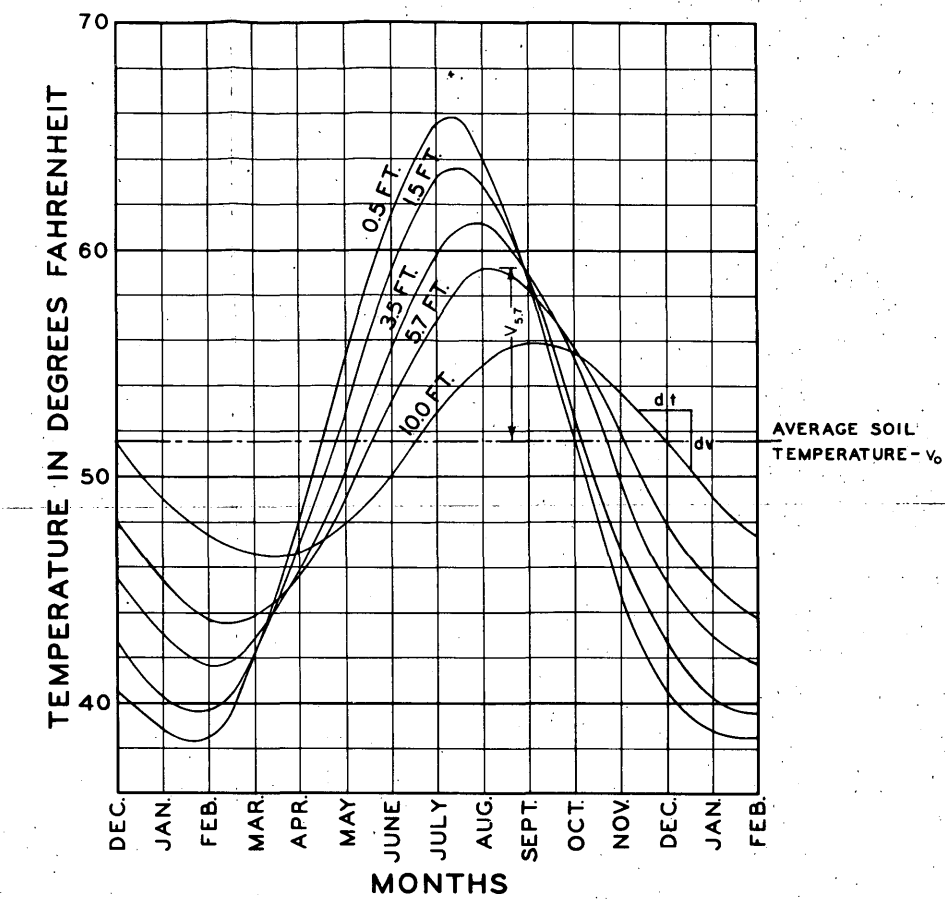
$$= 2.35 \text{ ft.}$$



MONTHLY TEMPERATURE PROFILES FOR A TURFED SOIL

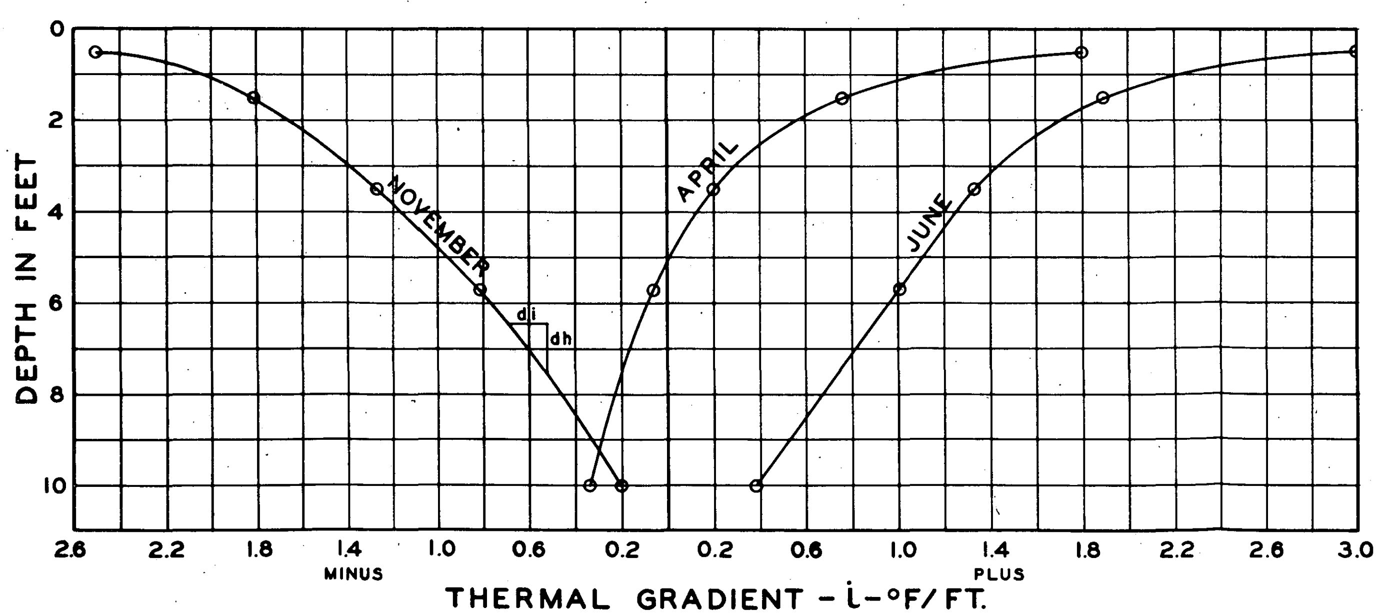
(ADAPTED FROM "RADCLIFFE OBSERVATIONS, RADCLIFFE OBSERVATORY, ENGLAND, 1915")

FIG. 1



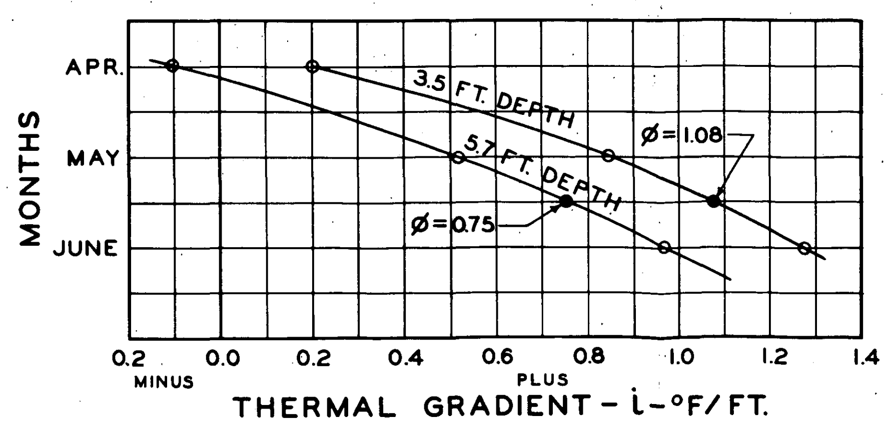
ANNUAL SOIL TEMPERATURE CURVES AT DEPTHS OF OBSERVATION

FIG. 2



THERMAL GRADIENTS FOR MONTHS OF APRIL, JUNE AND NOVEMBER

FIG. 3



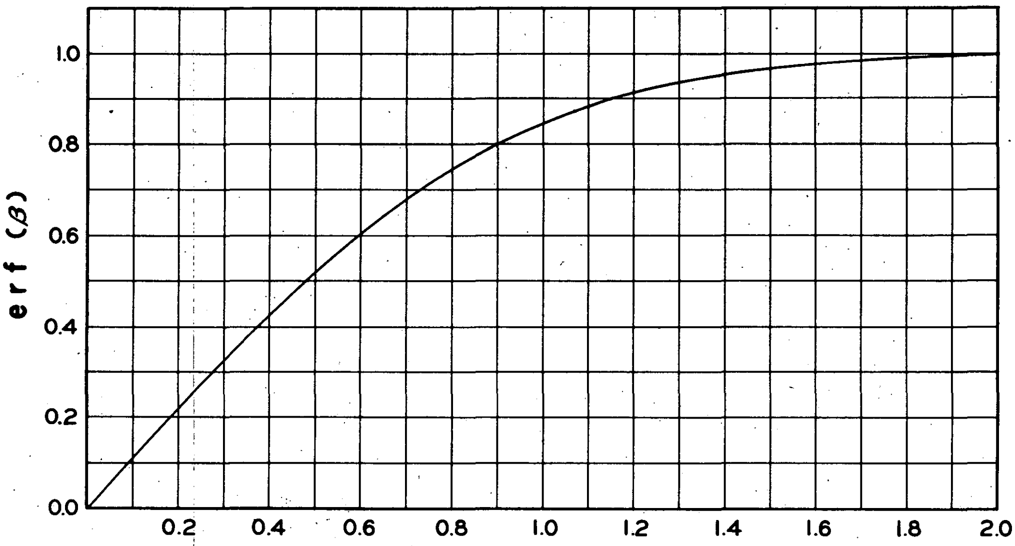
THERMAL GRADIENTS AT 3.5 AND 5.7 FOOT DEPTHS OF OBSERVATION

FIG. 4

FROST INVESTIGATION
1945 - 1946

THERMAL CURVES FOR A TURFED SOIL

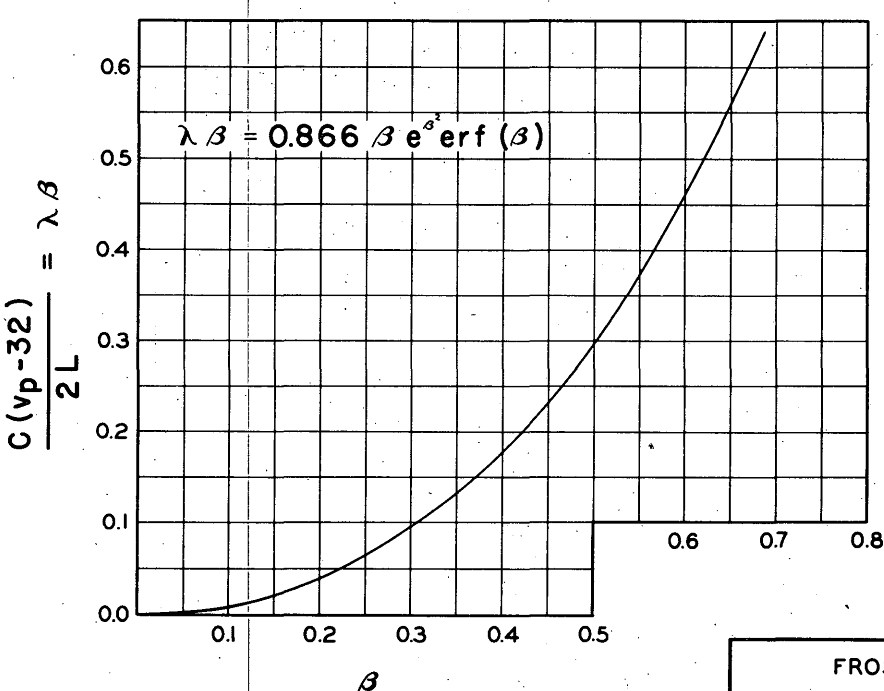
FROST EFFECTS LAB., BOSTON, MASS. JUNE 1946



$$\beta = \frac{h}{2\sqrt{24\,a\,t}}$$

THE PROBABILITY INTEGRAL (GAUSS "ERROR FUNCTION")

FIG. 5



DETERMINATION OF β FROM SOIL AND TEMPERATURE DATA

FIG. 6

FROST INVESTIGATION
1945 - 1946

CURVES FOR DETERMINATION OF erf (β) AND β

FROST EFFECTS LAB., BOSTON, MASS. JUNE 1946

TABLE OF CONTENTS

SUMMARY TABULATION OF AIRFIELD PAVEMENTS AT AIRFORCE INSTALLATIONS CONSTRUCTED ON FROST SUSCEPTIBLE SUBGRADES

I. INTRODUCTION

1-01. Authorization. This summary tabulation was authorized by the Office, Chief of Engineers, in the "Instructions and Outline for Frost Investigations" (Fiscal Year 1948) dated August 1947.

1-02. Purpose. The purpose of this summary is to present in tabular form the pavement evaluation, traffic history, pavement condition, and other pertinent data for all permanent Air Force Installations constructed on frost susceptible subgrades, and to compare the theoretical pavement evaluations, made in accordance with the Engineering Manual, with the actual performance records of the fields.

1-03. Scope. The pertinent data used in the preparation of this summary tabulation were obtained from the Airfield Pavement Evaluation Reports, the Pavement Failure Reports, the Frost Investigation Program and the latest traffic history available from each field. No field inspections or tests were made for this summary. Data relative to condition of pavements are available from only eight of the twenty-five fields summarized.

II. PREPARATION OF DATA

2-01. General. The data available to the Frost Effects Laboratory consisted principally of evaluation reports prepared by the various District and Division Offices in the Airfield Pavement Evaluation Reports. The cycles of takeoffs and landings per day or month had been summarized from the records of traffic history made available by the Office, Chief of Engineers for the period 1945 to February 1948, inclusive.

No Airfield Pavement Evaluation Report was prepared for Sherman Field, Fort Leavenworth, Kansas. The data included for this field were obtained by correspondence with the Omaha District Office through the Missouri River Division Office.

Pertinent data for each airfield are presented in Table B-1. The locations of the twenty-five Air Force installations which have been summarized are shown on Plate B-1. The plan views of individual installations are presented on Plates B-2 to B-26, inclusive.

2-02. The Evaluation Criteria. The original gross load evaluations, as taken from the Airfield Pavement Evaluation Reports and the present evaluations based on Chapter 2, dated May 1947 and Chapters 2 and 3, dated July 1946, Part XII of the Engineering Manual, are presented.

a. Flexible Pavements. The present frost condition evaluations of flexible pavements were made in accordance with Figure 4, Chapter 4, Part XII of the Engineering Manual. When the thickness of pavement and non-frost susceptible base is less than 9 inches, the evaluation is given as less than 10,000 pounds gross load.

b. Rigid Pavement.

(1) Evaluations of rigid pavements during the frost-melting period were made using Figure 5, Chapter 4, Part XII of the Engineering Manual. When the thickness of the non-frost susceptible base is less than 6 inches, the evaluation is given as less than 30,000 pounds gross load.

(2) The evaluations of the airfields were based on the modulus, k, of the subgrade. However, if the modulus of the subgrade had not been determined or was not known, the modulus, k, of the base was used to evaluate the

pavement. Fields evaluated in this manner are Dow, Mitchel, Presque Isle, Stewart, Spokane, and Wendover.

III. CONCLUSIONS

3-01. Conclusions. Pavement failures or pavement distress have occurred at all eight of the twenty-five installations on which pavement condition data are available. The traffic data indicate that seven of the eight fields had been subjected to loadings in excess of the frost condition evaluation.

The only field showing pavement distress under normal traffic load not exceeding the evaluation is Presque Isle Airfield, Presque Isle, Maine. Weaving of the flexible pavements has been observed during the frost-melting periods. Widely spaced map cracking due to frost heaving is general throughout the airfield.

When the reports of the pavement condition are available for all the installations summarized, correlation will be made between pavement evaluation, pavement condition, and traffic history. This correlation will afford qualitative information on the adequacy of present design criteria.

SUMMARY TABULATION OF AIRFIELD PAVEMENTS

BASE: % PASSING #200 SIEVE	BASE: FROST SUSCEPTIBLE (% FINER THAN 0.02MM)	BASE: CBR OR SUBGRADE MODULUS K_u	BASE: K	BASE: K_f (A)	BASE: CBR	SUBGRADE: AIRFIELD CLASSIFICATION	SUBGRADE: % PASSING #200 SIEVE	SUBGRADE: FROST SUSCEPTIBLE (% FINER THAN 0.02MM)	SUBGRADE: ATTERBERG LIMITS	SUBGRADE: CBR OR SUBGRADE MODULUS K_u	SUBGRADE: K	SUBGRADE: K_f (A)	SUBGRADE: CBR	GROUND WATER DEPTH (FEET)	SUBSURFACE DRAINAGE	APPROX. FREEZING INDEX	FROST PENETRATION (INCHES)	ORIGINAL EVALUATION: NORMAL PERIOD CAPACITY OPERATION	ORIGINAL EVALUATION: REMARKS	PRESENT EVALUATION: NORMAL PERIOD E.M. PART XII JULY 1946	PRESENT EVALUATION: FROST CONDITIONS E.M. PART XII JULY 1946
10-17	YES (4-9)	-	-	-	40	SF, ML, CL, SW, SP, SC	8-68	YES (6-60)	LL 23 PL 15 PI 8	-	-	-	3-5	≠ 90	NONE	532	33 (B)	10,000	20% REDUCTION OF EVALUATION FOR WARMUP AND TAXIING ON N-S AND NW-SE RUNWAYS AND TAXIWAYS FOR NORMAL PERIOD, CAPACITY OPERATION.	10,000	< 10,000
SUBBASE 8-68	YES (6-60)	-	-	-	4-5																
10-17	YES (4-9)	-	-	-	40	ML, SC, SF	8-68	YES (6-60)		-	-	-	4					20,000		24,000	< 10,000
SUBBASE 8-68	YES (6-60)	-	-	-	24																
10-17	YES (4-9)	-	-	-	40	SF, SC, SP ML, CL, SW	8-68	YES (6-60)		-	-	-	3					20,000		20,000	< 10,000
SUBBASE 8-68	YES (6-60)	-	-	-	21																
10-17	YES (4-9)	-	-	-	40	SF, SC, ML, SP	8-68	YES (6-60)		-	-	-	7					50,000		50,000	< 10,000
SUBBASE 8-68	YES (6-60)	-	-	-	10																
-	-	-	-	-	-	SW, CL, SC	8-68	YES (6-60)		380	279	-	-					70,000		30,000	< 30,000
-	-	-	-	-	-	CL-OL	62-87	YES (51-65)	LL 19-48 PL 16-21 PI 3-28	106	57	-	-	BELOW INFLUENCE DEPTH	OPEN JOINTED TILE DRAINS ALONG SIDE AND PARALLEL TO RUNWAYS AND TAXIWAYS, WITH PERVIOUS BACKFILL. INEFFECTIVE.	400	18 AV. 30 MAX.	25,000	THE NORMAL PERIOD, CAPACITY OPERATION EVALUATIONS HAVE BEEN REDUCED AS FOLLOWS. (1) 20% REDUCTION FOR APRON, TAXIWAYS, EW AND NW-SE RUNWAYS FOR WARMUP AND TAXIING. (2) CORRECTION FOR DEFICIENT EDGE THICKNESS– (a) 8-6-8 SECTION, BY RATIO OF SECTION MODULUS OF 8" EDGE THICKNESS TO 9" EDGE THICKNESS. (b) 8" UNIFORM SECTION, EVALUATED AS 7" INTERIOR THICKNESS.	< 30,000	< 30,000
-	-	-	-	-	-	CL-OL	62-87	YES (51-65)		106	57	-	-					32,000		< 30,000	< 30,000
-	-	-	-	-	-	CL-OL	62-87	YES (51-65)		106	57	-	-					32,000		< 30,000	< 30,000
-	-	-	-	-	-	CL-OL	62-87	YES (51-65)		106	57	-	-					32,000		< 30,000	< 30,000
4-15	YES (3-10)	130	63	-	-	CL	62-87	YES (51-65)		-	-	-	-					40,000		30,000	< 30,000
4-15	YES (3-10)	130	63	-	-	OL	62-87	YES (51-65)		-	-	-	-					56,000		30,000	< 30,000
13-18	YES (10)	-	-	-	-	ML-CL	60-83	YES (41-58)	LL 25-48 PL 17-25 PI 6-23	103	40	-	-	2-7 (APPROX.)	PERFORATED PIPE (6"-8") ALONG BOTH EDGES OF RUNWAYS AND TAXIWAYS AND AT SELECTED LOCATIONS UNDER APRON.	100	20	64,000	THE NORMAL PERIOD, CAPACITY OPERATION EVALUATIONS HAVE BEEN CORRECTED AS FOLLOWS: (1) ALL RUNWAYS, TAXIWAYS AND APRONS REDUCED 20% FOR WARMUP AND TAXIING (2) BASE COURSE TAKEN INTO EVALUATION BY ADDING 1" TO INTERIOR THICKNESS OF PAVEMENT FOR EVERY 4" OF BASE.	< 30,000	< 30,000
13-18	YES (10)	-	-	-	-	ML	60-83	YES (41-58)		36	30	-	-					74,000		30,000	< 30,000
13-18	YES (10)	-	-	-	-	ML	60-83	YES (41-58)		-	30	-	-					80,000		30,000	< 30,000
2-7	BORDERLINE	-	-	-	80	CL-GF	31-88	YES (21-70)	LL 30 PL 19 PI 11	-	-	-	8	6 (APPROX.)	OPEN JOINT DRAINS BACK FILLED WITH PERVIOUS MATERIAL ADJACENT TO RUNWAY PAVEMENTS.	1200	48 AV. 61 MAX.	102,000*	THE NORMAL PERIOD CAPACITY OPERATION EVALUATIONS FOR P.C.C. RUNWAYS, TAXIWAYS AND MAIN SERVICE APRON HAVE BEEN REDUCED 20% FOR WARMUP AND TAXIING. NO CORRECTION MADE FOR DEFICIENT EDGE THICKNESS OF CONCRETE PAVEMENT. *BITUMINOUS CONCRETE RUNWAYS EVALUATED FOR A BASE THICKNESS OF 19" AND A PAVEMENT THICKNESS OF 4".	107,000*	27,000*
2-7	BORDERLINE	315	315	65	-	CL-GF	31-88	YES (21-70)		-	-	-	-					46,000		< 30,000	< 30,000
2-7	BORDERLINE	-	-	-	80	CL-GF	31-88	YES (21-70)		-	-	-	8					67,000		72,000	24,000
2-7	BORDERLINE	315	315	60	-	CL-GF	31-88	YES (21-70)		-	-	-	-					64,000		< 30,000	< 30,000
9-20	YES (12 ±)	-	-	-	50	CL, SF, SC	71-92	YES (45-75)	LL 38-54 PL 16-26 PI 16-34	-	-	-	4	BELOW INFLUENCE DEPTH	NONE REPORTED.	750	60	14,000	THE NORMAL PERIOD CAPACITY OPERATION EVALUATION OF TAXIWAYS AND APRON HAVE BEEN REDUCED 20% FOR WARMUP AND TAXIING.	15,000	< 10,000
9-20	YES (12 ±)	-	-	-	50	CL, SF, SC	71-92	YES (45-75)		-	-	-	4					14,000		13,000	< 10,000
9-20	YES (12 ±)	-	-	-	50	CL, SF, SC	71-92	YES (45-75)		-	-	-	4					16,000		16,000	< 10,000
9-20	YES (12 ±)	-	-	-	50	CL, SF, SC	71-92	YES (45-75)		-	-	-	4					18,000		18,000	< 10,000
9-20	YES (12 ±)	-	-	-	50	CL, SF, SC	71-92	YES (45-75)		-	-	-	4					20,000		20,000	< 10,000
-	-	-	-	-	-	CL, SF, SC	71-92	YES (45-75)		37	37	-	-					40,000		< 30,000	< 30,000
10-85	YES (6-55)	-	-	-	-	SP, SF, SW	10-85	YES (6-55)	LL 20-25 PL 7-18 PI 7-14	185	185	-	-	NOT REPORTED	NONE	500	15	18,000	THE NORMAL PERIOD CAPACITY OPERATION EVALUATIONS FOR ALL PAVED AREAS HAVE BEEN REDUCED 20% FOR WARMUP AND TAXIING.	< 30,000	< 30,000
10-85	YES (6-55)	-	-	-	-	SP, SF, SW	10-85	YES (6-55)		285	285	-	-					34,000		< 30,000	< 30,000
10-85	YES (6-55)	-	-	-	-	SP, SF, SW	10-85	YES (6-55)		410	410	-	-					48,000		< 30,000	< 30,000
26-89	YES (12-55)	-	-	-	-	CL, ML, CH	82-94	YES (45-69)	LL 30-52 PL 16-24 PI 11-31	208	143	-	-	18-30	NONE REPORTED.	500	32 (B)	37,000	THE NORMAL PERIOD CAPACITY OPERATION EVALUATIONS FOR APRON AND TAXIWAYS HAVE BEEN REDUCED 20% FOR WARMUP AND TAXIING. DUE TO VARIABLE THICKNESS OF BASE AND CUSHION COURSE, SUBGRADE MODULI WERE USED FOR EVALUATION. NO ADDITIONAL STRENGTH ALLOWED FOR BASE.	< 30,000	< 30,000
26-89	YES (12-55)	-	-	-	-	CL, ML	82-94	YES (45-69)		208	143	-	-					39,000		< 30,000	< 30,000
26-89	YES (12-55)	-	-	-	-	CL, CH, ML, SF	82-94	YES (45-69)		208	143	-	-					44,000		30,000	< 30,000
26-89	YES (12-55)	-	-	-	-	CL, ML	82-94	YES (45-69)		208	143	-	-					54,000		35,000	< 30,000
26-89	YES (12-55)	-	-	-	-	CL, ML	82-94	YES (45-69)		208	143	-	-					63,000		38,000	< 30,000
23-44	YES (10-16)	-	-	-	-	CL, ML	44-67	YES (28-42)	LL 24-52 PL 13-25 PI 7-27	-	50	-	-	3-5	PERFORATED PIPE IN TRENCHES BACKFILLED WITH GRADED FILTER MATERIAL ON EITHER SIDE OF RUNWAYS.	100	25	38,000	THE NORMAL PERIOD CAPACITY OPERATION EVALUATIONS HAVE BEEN CORRECTED AS FOLLOWS: (1) ALL PAVEMENTS EXCEPT NE-SW AND E-W RUNWAYS HAVE BEEN REDUCED 20% FOR WARMUP AND TAXIING. (2) BASE COURSE HAS BEEN ACCOUNTED FOR BY ADDING 1" TO INTERIOR THICKNESS OF PAVEMENT FOR EACH 4" OF BASE. (3) EVALUATION HAS BEEN CORRECTED FOR DEFICIENT EDGE THICKNESS BY RATIO OF EDGE THICKNESS TO 1.5 TIMES INTERIOR THICKNESS.	< 30,000	< 30,000
23-44	YES (10-16)	-	-	-	-	CL, ML	44-67	YES (28-42)		76-144	50	-	-					41,000 (EXCEPT NE-SW RUNWAY-51,000)		< 30,000	< 30,000
																				36,000	< 30,000
23-44	YES (10-16)	-	-	-	-	CL	44-67	YES (28-42)		20-55	50	-	-					46,000		< 30,000	< 30,000
23-44	YES (10-16)	-	-	-	-	CL	44-67	YES (28-42)		126-142	70	-	-					73,000		30,000	< 30,000

TRAFFIC HISTORY

CYCLES OF LANDINGS & TAKEOFFS

WEIGHT CLASS (C)	1943 TOTAL	1943 APPROX DAILY	1944 TOTAL	1944 APPROX DAILY	1945 TOTAL	1945 APPROX DAILY	1946 TOTAL	1946 APPROX DAILY	1947 TOTAL	1947 APPROX DAILY	1948 JAN & FEB TOTAL	1948 JAN & FEB APPROX DAILY
C					90	45/MO.	NO DATA		1035	3	74	1
D	-	95	-	95	19	10/MO.			102	9/MO.	12	6/MO.
E	-	-	-	-	6716	112			13	1/MO.	-	-
G	-	-	-	-	-	-			2	OCC.	-	-
TRAFFIC DISTRIBUTION NE-SW, 63%; E-W, 31%; NW-SE, 4%; N-S, 2%												
C					5896	16	19,421	58	22,522	62	3602	60
D	(-	445	-	445)	2154	6	41,058	123	28,236	78	3368	56
E	(CLASSES A THRU E)				6139	17	3138	9	901	2	36	18/MO.
F	-	-	-	-	-	-	35	3/MO.	-	-	-	-
G	-	-	-	-	106	9/MO.	78	7/MO.	122	10/MO.	19	10/MO.
TRAFFIC DISTRIBUTION NE-SW, 29%; E-W, 26%; NW-SE, 19%; N-S, 26%												
C					2253	6	4464	12	7983	22	1177	20
D	-	6	-	6	1256	3	2385	7	2092	6	319	5
E	-	1	-	1	4067	11	1884	5	1849	5	292	5
F	-	-	-	-	-	-	4	OCC.	4	OCC.	-	-
G	-	-	-	-	49	4/MO.	198	16/MO.	57	5/MO.	94	47/MO.
H	-	-	-	-	-	-	14	1/MO.	-	-	-	-
TRAFFIC DISTRIBUTION NE-SW, 68%; NW-SE, 32%												
C	-	2	NO DATA		6705	22	NO DATA		26,505	73	4084	68
D	-	-			3763	13			581	2	77	1
E	-	4			4145	14			17	1/MO.	26	13/MO.
F	-	-			-	-			2	OCC.	-	-
G	-	-			29	3/MO.			-	-	-	-
TRAFFIC DISTRIBUTION NE-SW, 48%; NW-SE, 51%; E-W, 1%												
C	NO DATA		-	56	10,828	30	24,297	67	10,071	28	603	10
D			-	-	1,340	4	1,006	3	987	3	555	9
E			-	-	1,091	3	3,045	9	3,259	9	620	10
F			-	-	-	-	8	2/MO.	1	OCC.	-	-
G			-	-	27	2/MO.	182	16/MO.	210	17/MO.	71	1
TRAFFIC DISTRIBUTION NE-SW, 78%; E-W, 10%; NW-SE, 7%; N-S, 5%												
C	-	11	NO DATA		15,712	43	49,746	136	48,295	132	5272	88
D	-	18			3486	10	2182	6	3379	9	598	10
E	-	1			5612	15	1379	4	1863	5	326	5
F	-	-			1	OCC.	4	OCC.	-	-	-	-
G	-	-			334	1	262	1	448	1	145	2
TRAFFIC DISTRIBUTION E-W, 19%; NW-SE, 44%; NE-SW, 18%												
C			NO DATA		2061	6	1234	4	12,242	33	2306	38
D					478	1	170	17/MO.	470	1	72	1
E	-	45			1670	5	27	3/MO.	13	1/MO.	12	6/MO.
G	-	-			4237	12	4	OCC.	-	-	11	5/MO.
H	-	-			-	-	-	-	-	-	1	OCC.
TRAFFIC DISTRIBUTION N-S, 75%; NW-SE, 15%; NE-SW, 10%												
C			NO DATA		1405	4	15,267	42	26,237	73	3496	58
D	-	1185			1839	5	4650	13	6366	18	1160	19
E	-	1			247,131	677	405	1	13	1/MO.	-	-
F	-	-			6	OCC.	6	OCC.	-	-	-	-
G	-	-			70	6/MO.	107	9/MO.	2	OCC.	-	-
TRAFFIC DISTRIBUTION N-S, 50%; NE-SW, 28%; E-W, 13%; NW-SE, 9%												

DISTRESS OR FAILURE IN WHICH FROST ACTION WAS A CONTRIBUTING CAUSE

LOCATION	DESCRIPTION	SATURATED	DATE FIRST NOTED	REPORTED CAUSE
SCATTERED AREAS ON TAXIWAYS 1, 2, 9, 12 & 13.	CRACKING AND RUTTING, THEN COMPLETE BREAKUP OF PAVEMENT AND BASE COURSE.	BASE 46%	MARCH 1944	LOCAL POOR SUBGRADE, WATER PONDING, POOR BASE. SLIGHT FROST ACTION IN SUBGRADE.
RUNWAYS AND RUNWAY SHOULDERS.	SMALL DEPRESSED, CRACKED, AND CHECKED AREAS.	SUBBASE 44%		DIFFERENTIAL SETTLEMENT UNDER TRAFFIC, PONDING IN DEPRESSIONS.
APRON	CRACKING AND SLAB DISPLACEMENT.	SUBGRADE 37%		OVERSTRESSING ALONG TAXIING LINES.
NE-SW, E-W, NW-SE RUNWAYS	SHEARED TONGUE AND GROOVE JOINTS, CORNER CRACKS, SPALLING AND FRACTURING OF CONCRETE FOR A WIDTH OF SEVERAL INCHES.	BASE NOT REPORTED SUBGRADE 89%	JUNE 1944	INSUFFICIENT BEARING CAPACITY OF SUBGRADE SOFTENING OF SUBGRADE DURING THAWING AND FREEZING, OVERLOADING SLABS WITH HEAVY WHEEL LOADS.
NO DATA				
APRON WIDENING, TURNAROUND AND WARMUP APRON (NOT CONTROLLING PAVEMENTS)	CONCRETE DEVELOPED RANDOM CRACKS AND SOME CORNER CRACKS (9% OF SLABS CRACKED BY SPRING OF 1943 AND 30% BY FALL 1946)	BASE OBSERVED TO BE SATURATED DURING THE FROST MELTING PERIOD.	WINTER 1942-1943	SETTLEMENT OF SUBGRADE, LOW STRENGTH OF CONCRETE AND FROST ACTION.
BITUMINOUS PAVED RUNWAYS AND TAXIWAYS	FAILURES OCCURRED AT THE JOINT BETWEEN THE RUNWAY PROPER AND THE SHOULDER. THE 2" A.C. SHOULDER PAVEMENT PULLED AWAY FROM THE 6" A.C. RUNWAY PAVEMENT ALLOWING WATER TO ENTER THE LONGITUDINAL CRACKS. DEPRESSIONS BECAME EVIDENT WHEN AIRCRAFT WHEELS PASSED OVER THIS JOINT.	BASE 27% SUBGRADE 62%	NOT REPORTED	INADEQUATE DRAINAGE, WATER FLOWS ACROSS RUNWAYS. AREAS ADJACENT TO RUNWAYS BECOME SATURATED AS A RESULT OF PILING SNOW ALONG UPPER EDGES BY PLOWING. FROST ACTION CONTRIBUTES TO DETERIORATION.
NO DATA				
TAXIWAY 1a IN ORIGINAL PAVED LANES AND S.E. CORNER OF APRON.	COMPLETE FAILURE BY PAVEMENT DISINTEGRATION		MARCH 1943	POOR SUBGRADE SUPPORT AND INSUFFICIENT PAVEMENT THICKNESS.
OUTER PAVED LANES OF APRON AND TAXIWAYS 1b, 2 AND 3	EXCESSIVE CRACKING, PARTICULARLY AT THE JOINTS			MOTOR WARMUP AND FREQUENT LOAD REPITITIONS OVER CONFINED PATHS. POOR SUBGRADE PARTIALLY RESPONSIBLE. FAILURE CHIEFLY DUE TO INSUFFICIENT PAVEMENT THICKNESS.

NOTES

(A) SUBGRADE MODULUS DURING FROST MELTING PERIOD.

(B) DEPTH OF FROST PENETRATION FROM FREEZING INDEX CURVES.

(C) WEIGHT CLASSIFICATION AS SHOWN BELOW.

CLASS 1942 - 1945	GROSS WT. OF PLANES	CLASS 1946 - 1948	GROSS WT. OF PLANES
		A & B	NOT OVER 15,000 LBS.
C	25,000 - 35,000 LBS.	C	16,000 - 28,000 LBS.
D	35,000 - 50,000 LBS.	D	31,000 - 56,000 LBS.
E	50,000 - 75,000 LBS.	E	56,000 - 76,000 LBS.
F	75,000 - 90,000 LBS.	F	76,000 -123,000 LBS.
G	90,000 -135,000 LBS.	G	123,000 -135,000 LBS.
		H	135,000 AND OVER

SUMMARY TABULATION OF AIRFIELD PAVEMENTS

Group	BASE: Frost susceptible (% finer than 0.02MM)	BASE: CBR or subgrade modulus K_u	BASE: K	BASE: K_f (A)	BASE: CBR	SUBGRADE: Airfield classification	SUBGRADE: % passing #200 sieve	SUBGRADE: Frost susceptible (% finer than 0.02MM)	SUBGRADE: Atterberg limits	SUBGRADE: CBR or subgrade modulus K_u	SUBGRADE: K	SUBGRADE: K_f (A)	SUBGRADE: CBR	Ground water depth (feet)	Subsurface drainage	Approx. freezing index	Frost penetration (inches)	Original evaluation: Normal period capacity operation	Original evaluation: Remarks	Present evaluation: Normal period E.M. Part XII July 1946	Present evaluation: Frost conditions E.M. Part XII July 1946
1	-	-	-	-	-	SF-CL, SP, CH	32-69	YES (14-48)	LL 18-50 PL 15-28 PI 4-43	141	52	-	-	5	OPEN JOINT PIPE AND GRAVEL BACKFILLED TRENCHES ALONG SHOULDERS OF SOME PAVEMENTS.	200	21 (B)	20,000	THE NORMAL PERIOD CAPACITY OPERATION EVALUATIONS OF ALL PAVEMENTS EXCEPT THE N-S RUNWAY HAVE BEEN REDUCED 20% FOR WARMUP AND TAXIING. NO CORRECTION MADE FOR DEFICIENT EDGE THICKNESS.	<30,000	<30,000
	-	-	-	-	-	CL, SF	32-69	YES (14-48)		141	52	-	-					25,000		<30,000	<30,000
	-	-	-	-	-	CL, SF	32-69	YES (14-48)		141	52	-	-					30,000		<30,000	<30,000
2	-	-	-	-	-	ML, CH, CL	84-96	YES (28-54)	LL 29-67 PL 15-28 PI 4-43	202	112	-	-	0-18	NONE	200	21 (B)	25,000	THE NORMAL PERIOD CAPACITY OPERATION EVALUATIONS FOR TAXIWAYS AND APRONS HAVE BEEN REDUCED 20% FOR WARMUP AND TAXIING.	<30,000	<30,000
	-	-	-	-	-	ML, CH, CL	84-96	YES (28-54)		202	112	-	-					30,000		<30,000	<30,000
3	YES (4-32)	140	140	-	-	GF	20-87	YES (12-56)	LL 25 PL 23 PI 2	-	-	-	-	21	OPEN JOINT DRAINAGE PIPES ALONG EDGES OF PAVED AREAS.	150	18 (B)	20,000	THE NORMAL PERIOD CAPACITY OPERATION EVALUATIONS FOR TAXIWAYS AND APRONS HAVE BEEN REDUCED 20% FOR WARMUP AND TAXIING. NO CORRECTION MADE FOR DEFICIENT EDGE THICKNESS.	<30,000	<30,000
	YES (4-32)	250	250	-	-	SW	20-87	YES (12-56)		-	-	-	-					17,000		<30,000	<30,000
	YES (4-32)	160	160	-	-	GC	20-87	YES (12-56)		-	-	-	-					27,000		<30,000	<30,000
	YES (4-32)	210	210	-	-	SW	20-87	YES (12-56)		-	-	-	-					33,000		<30,000	<30,000
	YES (4-32)	240	240	-	-	GF	20-87	YES (12-56)		-	-	-	-					36,000		<30,000	<30,000
	YES (4-32)	400	400	-	-	GF	20-87	YES (12-56)		-	-	-	-					49,000		<30,000	<30,000
4	-	-	-	-	80	CL	85-94	YES (44-65)	LL 36-48 PL 18-25 PI 12-23	-	-	-	8	NOT REPORTED	OPEN CONCRETE TOE AND SHOULDER GUTTERS ON EMBANKMENTS.	740	39 (B)	15,000	THE NORMAL PERIOD CAPACITY OPERATION EVALUATIONS FOR ALL PAVEMENTS HAVE BEEN REDUCED 20% FOR WARMUP AND TAXIING. NO CORRECTION MADE FOR DEFICIENT EDGE THICKNESS. THE PAVEMENT ON THE NE-SW RUNWAY CONSISTS OF TWO LAYERS OF CONCRETE SEPARATED BY A THIN BITUMINOUS MEMBRANE. THE EFFECTIVE THICKNESS FOR EVALUATION HAS BEEN TAKEN EQUAL TO THE SQUARE ROOT OF THE SUM OF THE SQUARES OF THE THICKNESS OF THE INDIVIDUAL LAYERS.	19,000	<10,000
	-	-	-	-	-	CL	85-94	YES (44-65)		104	83	-	-					35,000		<30,000	<30,000
	-	-	-	-	-	CL	85-94	YES (44-65)		104	83	-	-					115,000		50,000	<30,000
	-	403	403	45	-	CL, ML	85-94	YES (44-65)		-	-	-	-					+ 150,000		34,000	<30,000
5	NO	-	-	-	80	CL	46-65	YES (10-25)	LL 20-22 PL 16-19 PI 3-4	-	-	-	3	NOT REPORTED	PERFORATED CONCRETE PIPE 25 FEET FROM EDGE OF PAVEMENTS IN TRENCHES, BACK-FILLED WITH CRUSHED STONE UNDER 6" OF CONSOLIDATED EARTH.	150	-	6,000	THE NORMAL PERIOD CAPACITY OPERATION EVALUATIONS FOR ALL PAVEMENTS HAVE BEEN REDUCED 20% FOR WARMUP AND TAXIING. NO CORRECTION HAS BEEN MADE FOR DEFICIENT EDGE THICKNESS.	<10,000	<10,000
	-	-	-	-	-	CL	46-72	YES (10-47)		160	100	-	-					41,500		<30,000	<30,000
6	ASSUMED NO	400	400	65	-	GW	22-90	YES (14-75)	LL 22-71 PL 17-32 PI 4-40	-	-	-	-	4-7	NONE	150	23	77,000	THE NORMAL PERIOD CAPACITY OPERATION EVALUATIONS HAVE BEEN CORRECTED AS FOLLOWS: (1) TAXIWAYS AND APRONS HAVE BEEN REDUCED 20% FOR WARMUP AND TAXIING. (2) EXCEPT FOR THE APRON, THE BASE COURSE HAS BEEN ACCOUNTED FOR BY ADDING 1" TO THE INTERIOR THICKNESS OF THE PAVEMENT FOR EACH 4" OF BASE. (3) CORRECTION FOR DEFICIENT EDGE THICKNESS HAS BEEN MADE BY MULTIPLYING EVALUATION BY THE RATIO OF EXISTING EDGE THICKNESS TO 1.5 TIMES INTERIOR THICKNESS.	<30,000	<30,000
	ASSUMED NO	-	-	-	-	CL	22-90	YES (14-75)		122	40	25	-					80,000		<30,000	80,000
	YES (-10)	-	-	-	-	ML	22-90	YES (14-75)		180	80	-	-					101,000		40,000	<30,000
	ASSUMED NO	-	-	-	-	ML, CL	22-90	YES (14-75)		116-132	80	25	-					134,000		58,000	50,000
7	BORDERLINE (0-8)	300	300	25	-	GF	18-50	YES (12-43)	LL 30 PL 20 PI 10	-	-	-	-	2-6	PERFORATED METAL PIPE IN TRENCHES BACKFILLED WITH COARSE GRADED ROCK AND V.C. OPEN JOINT PIPE WITH RUN OF BANK GRAVEL BACK-FILL LAID ALONG EDGES OF RUNWAYS.	2061	71	38,000	THE NORMAL PERIOD CAPACITY OPERATION EVALUATIONS OF APRONS AND TAXIWAYS ARE REDUCED 20% FOR WARMUP AND TAXIING. NO CORRECTION MADE FOR DEFICIENT EDGE THICKNESS OF CONCRETE PAVEMENTS. AVERAGE THICKNESS OF PAVEMENT AND BASE FOR RUNWAYS, SHOWN IN PARENTHESES, WERE USED FOR EVALUATION.	<30,000	<30,000
	BORDERLINE (0-8)	-	-	-	80	GF	18-50	YES (12-43)		-	-	-	10					59,000		63,000	13,000
8	-	-	-	-	-	GW (SMALL AREA GP, GF)	2-14	YES (1-8)	LL 22-42 PL 19-26 PI 3-16	220	220	-	-	NOT REPORTED	NOT REPORTED	750	39 (B)	62,000	THE NORMAL PERIOD CAPACITY OPERATION EVALUATIONS HAVE BEEN REDUCED 20% FOR WARMUP AND TAXIING.	30,000	<30,000
9	-	-	-	-	-	OL, CL	96-98	YES (52-74)	LL 25-43 PL 18-26 PI 3-25	95	66	-	-	BELOW INFLUENCE DEPTH	OPEN JOINT TILE DRAINS ALONG EDGES OF RUNWAY PAVEMENT.	150	12	22,000	THE NORMAL PERIOD CAPACITY OPERATION EVALUATIONS OF ALL PAVEMENTS EXCEPT THE N-S RUNWAY HAVE BEEN REDUCED 20% FOR WARMUP AND TAXIING, AND ALL PAVEMENTS HAVE BEEN REDUCED 15% FOR DEFICIENT EDGE THICKNESS.	<30,000	<30,000
	-	-	-	-	-	OL	96-98	YES (52-74)		95	66	-	-					27,000		<30,000	<30,000

TRAFFIC HISTORY — CYCLES OF LANDINGS & TAKEOFFS

Group	Weight class (C)	1943 Total	1943 Approx daily	1944 Total	1944 Approx daily	1945 Total	1945 Approx daily	1946 Total	1946 Approx daily	1947 Total	1947 Approx daily	1948 Jan & Feb Total	1948 Jan & Feb Approx daily
1	C	-	150			3246	9	50,258	138	48,986	134	6646	110
	D	-	-	-	173	13,277	36	19,655	54	5163	14	641	11
	E	-	-	-	-	20,327	56	4149	11	937	3	56	1
	F	-	-	-	-	8	OCC.	5	OCC.	-	-	1	OCC.
	G	-	-	-	2	29,180	80	327	1	158	13/MO.	34	17/MO.
		TRAFFIC DISTRIBUTION N-S, 48%; NE-SW, 27%; E-W, 25%											
2	C	-	10	-	10	-	10	NO DATA		16,918	47	2550	43
	D	-	-	-	-	-	-			727	2	53	1
	E	-	8/MO.	-	8/MO.	-	8/MO.			90	8/MO.	4	2/MO.
	F	-	-	-	-	-	-			4	OCC.	-	-
		TRAFFIC DISTRIBUTION N-S, 55%; NE-SW, 45%											
3	C			NO DATA		13,589	37	37,829	104	74,775	205	7814	130
	D					7874	21	7281	20	7598	21	1577	26
	E	-	192			8664	24	2150	6	1097	3	87	1
	F	-	-			62	5/MO.	1	OCC.	2	OCC.	-	-
	G	-				55	5/MO.	127	10/MO.	157	13/MO.	36	18/MO.
		1940 – 93 CYCLES/DAY THROUGH CLASS C; 1941, 373 CYCLES/DAY THROUGH CLASS C; 1942, 192 CYCLES/DAY THROUGH CLASS E											
		TRAFFIC DISTRIBUTION NE-SW, 48%; NW-SE, 44%; E-W, 8%; N-S, 0%											
4	C	-	55	-	-	-	-	23,392	64	28,837	80	2994	50
	D	-	-	-	18	-	18	1601	4	1955	5	493	8
	E	-	-	-	-	-	-	255	1	200	17/MO.	28	14/MO.
	G	-	-	-	17	-	17	32	3/MO.	20	2/MO.	16	8/MO.
		1942 – 20 CYCLES/DAY CLASS C											
		TRAFFIC DISTRIBUTION NW-SE, 56%; NE-SW, 30%; N-S, 14%											
5	C	-	-	-	-	9183	25	38,506	105	29,820	82	3097	52
	D	-	30	-	30	1321	4	2806	8	3088	9	505	8
	E	-	-	-	-	2106	6	1949	5	2355	7	451	17
	F	-	-	-	-	2	OCC.	-	-	-	-	-	-
	G	-	-	-	-	2	OCC.	71	6/MO.	122	10/MO.	32	16/MO.
		TRAFFIC DISTRIBUTION E-W, 64%; NW-SE, 36%											
6	C	-	87	NO DATA		21,420	59	35,683	48	29,182	80	4747	79
	D	-	15			5898	16	6178	17	6600	18	1237	21
	E	-	12			7534	21	4681	13	3185	9	526	9
	F	-	-			56	5/MO.	20	2/MO.	-	-	-	-
	G	-	-			247	1	878	2	753	2	97	2
		TRAFFIC DISTRIBUTION NE-SW (A), 58%; NE-SW (B), 17%; NW-SE, 25%											
7	C	-	-	-	8	NO DATA		2081	8	2785	7	251	4
	D	-	5	-	8			92	10/MO.	87	7/MO.	8	4/MO.
	E	-	25	-	8			186	20/MO.	53	4/MO.	24	12/MO.
	F	-	-	-	-			-	-	2	OCC.	-	-
		TRAFFIC DISTRIBUTION N-S, 45%; E-W, 31%; NW-SE, 24%											
8	C	-	-	NO DATA		3613	10	17,465	48	30,847	85	3466	58
	D	-	50			1280	4	573	2	1044	3	274	5
	E	-	-			1307	4	622	2	815	2	121	2
	F	-	-			3	OCC.	-	-	-	-	-	-
	G	-	-			12	1/MO.	53	4/MO.	82	7/MO.	-	-
		TRAFFIC DISTRIBUTION E-W, 55%; NW-SE, 38%; NE-SW, 7%											
9	C	150 CYCLES PER DAY PLANES UP TO CLASS E				14,822	41	74,871	205	85,329	234	10,041	167
	D					2839	8	7488	21	6233	17	1007	17
	E					4321	12	530	2	630	2	96	2
	F					-	-	21	3/MO.	-	-	-	-
	G					191	16/MO.	56	5/MO.	88	7/MO.	22	11/MO.
		TRAFFIC DISTRIBUTION N-S, 52%; NE-SW, 20%; NW-SE, 19%; E-W, 9%											

DISTRESS OR FAILURE IN WHICH FROST ACTION WAS A CONTRIBUTING CAUSE

Group	Location	Description	Saturated	Date first noted	Reported cause
1	NO DATA				
2	NO DATA				
3	NO DATA				
4	NO DATA				
5	NO DATA				
6	NO DATA				
7	PORTION OF N-S RUNWAY	PAVEMENT DEVELOPED WEAVING IN THE SPRING OF 1943 AS THE FROST CAME OUT OF THE GROUND	BASE 30-60% (NORMAL PERIOD) SUBGRADE 70-80%	SPRING 1943	SEVERE FROST ACTION IN THE SUBGRADE RESULTING IN ITS SOFTENING DURING THE SPRING THAW
8	NO DATA				
9	APRON AND E-W RUNWAY	EXTENSIVE FAILURE ALONG THE APRON 50 FEET FROM THE EAST EDGE ADJOINING CONCRETE BOX DRAINS. SOME CRACKING OF PAVEMENTS AT TONGUE AND GROOVE JOINTS AND AT CORNERS. LONG CRACKS ALONG THE CENTRAL PORTION OF THE E-W RUNWAY PARALLEL TO LONGITUDINAL JOINTS WHERE EDGE THICKENING COMMENCES.	SUBGRADE 100%	FALL OF 1943	LACK OF SUBSURFACE DRAINAGE OR INSTABILITY OF BACKFILL DUE TO INSUFFICIENT COMPACTION OR UNSUITABLE BACKFILLING MATERIAL. ACCUMULATION OF WATER IN THE SUBGRADE AT DRAINS. OVERSTRESSING OF PAVEMENTS DURING HEAVY TRAFFIC, FALL AND SPRING 1943, CAUSED CRACKING.

NOTES

(A) SUBGRADE MODULUS DURING FROST MELTING PERIOD.

(B) DEPTH OF FROST PENETRATION FROM FREEZING INDEX CURVES.

(C) WEIGHT CLASSIFICATION AS SHOWN BELOW.

CLASS	GROSS WT. OF PLANES
1942 – 1945	
C	25,000 – 35,000 LBS.
D	35,300 – 50,000 LBS.
E	50,000 – 75,000 LBS.
F	75,000 – 90,000 LBS.
G	90,000 – 135,000 LBS.
1946 – 1948	
A & B	NOT OVER 15,000 LBS.
C	16,000 – 28,000 LBS.
D	31,000 – 56,000 LBS.
E	56,000 – 76,000 LBS.
F	76,000 – 123,000 LBS.
G	123,000 – 135,000 LBS.
H	135,000 AND OVER

SUMMARY TABULATION OF AIRFIELD PAVEMENTS.

BASE: FROST SUSCEPTIBLE (% FINER THAN 0.02MM)	BASE CBR OR SUBGRADE MODULUS: K_u	K	K_f (A)	CBR	SUBGRADE: AIRFIELD CLASSIFICATION	% PASSING #200 SIEVE	FROST SUSCEPTIBLE (% FINER THAN 0.02MM)	ATTERBERG LIMITS	SUBGRADE CBR OR SUBGRADE MODULUS: K_u	K	K_f (A)	CBR	GROUND WATER DEPTH (FEET)	SUBSURFACE DRAINAGE	APPROX. FREEZING INDEX	FROST PENETRATION (INCHES)
-	-	-	-	-	ML	35-93	YES (18-73)	LL 24-52 PL 20-27 PI 4-25	85	85	-	-	6.5-8.2	PERFORATED TILE PIPE BACKFILLED WITH BANK RUN GRAVEL ALONG EDGES OF ALL PAVEMENTS. OPEN JOINT TILE PIPE BACKFILLED WITH GRAVEL ON 30' CENTERS IN INTERIOR OF FIELD.	520	30
YES (3-5) NO (1)	176	176	-	-	ML, CH	35-93	YES (18-73)		48	48	-	-				
YES (3-5) NO (1)	180	180	-	-	ML	35-93	YES (18-73)		48	48	-	-				
-	-	-	-	-	-	-	-	-	-	-	-	-	SHALLOW	NOT REPORTED	250	24(B)
-	-	-	-	-	-	-	-		-	-	-	-				
-	-	-	-	-	-	-	-		-	-	-	-				
-	-	-	-	-	CL, CH	66-99	YES (30-76)	LL 35-65 PL 17-29 PI 18-39	138	84	-	-	NOT REPORTED	NOT REPORTED	150	18(B)
-	-	-	-	-	CL, CH	66-99	YES (30-76)		138	84	-	-				
-	-	-	-	-	CL, CH	66-99	YES (30-76)		138	84	-	-				
-	-	-	-	-	CL, CH	66-99	YES (30-76)		138	84	-	-				
ASSUMED NO	217	217	45	-	GF, GW, SG, SP, ML	2-73	YES (2-44)	LL 16-33 PL 16-37 PI 0-7	-	-	-	-	NOT REPORTED	NOT REPORTED	250	24
ASSUMED NO	217	217	45	-	GF, GW, SG, SP, ML	2-73	YES (2-44)		-	-	-	-				
ASSUMED NO	217	217	45	-	GF, GW, SG, SP, ML	2-73	YES (2-44)		-	-	-	-				
YES (3-8)	350	350	-	-	GF	6-82	YES (4-54)	LL 19-22 PL 16-17 PI 4-8	-	-	-	-	0-7	OPEN JOINT PIPE IN PERVIOUS GRANULAR BACKFILL AT LOW POINTS.	300	30
YES (3-8)	310	310	-	-	GF	6-82	YES (4-54)		-	-	-	-				
YES (3-8)	250	250	-	-	GF	6-82	YES (4-54)		-	-	-	-				
YES (3-8)	310	310	-	-	GF	6-82	YES (4-54)		-	-	-	-				
YES (3-8)	250	250	-	-	GF	6-82	YES (4-54)		-	-	-	-				
YES (3-8)	310	310	-	-	GF	6-82	YES (4-54)		-	-	-	-				
-	-	-	-	-	CH, CL, GF, OL	53-85	YES (54)	LL 26-68 PL 14-30 PI 12-51	108	58	-	-	600 ±	NONE	1000	46(B)
YES (10)	282	282	-	-	CH, CL, GF	53-85	YES (54)		-	-	-	-				
YES (10)	282	282	-	-	CH, CL	53-85	YES (54)		-	-	-	-				
YES (10)	282	282	-	-	CH, GF, GP, SP	53-85	YES (54)		-	-	-	-				
YES (8)	396	396	-	-	CL, ML, SF, OL	87-99	YES (68-96)	LL 23-49 PL 15-40 PI 4-23	-	-	-	-	2-7	NONE REPORTED	550	
YES (8)	406	406	-	-	ML, MH	87-99	YES (68-96)		-	-	-	-				
YES (8)	406	406	-	-	CL, ML, SF, OL	87-99	YES (68-96)		-	-	-	-				
YES (8)	406	406	-	-	CL, MH	87-99	YES (68-96)		-	-	-	-				
YES (8)	440	440	-	-	CL, MH	87-99	YES (68-96)		-	-	-	-				
YES (8)	500	500	-	-	CL, MH	87-99	YES (68-96)		-	-	-	-				
NO	-	-	-	-	ML	1-90	YES (0-54)	LL 20-39 PL 15-26 PI 4-19	100	40	35	-	15-20	NW-SE AND NE-SW RUNWAYS - SIDE DRAINS OF PERVIOUS MATERIAL IN TRENCHES OVER 8" PIPE. INTERCEPTOR DRAINS FOR APRONS AND TAXIWAYS.	150	24
NO	-	-	-	-	ML	1-90	YES (0-54)		100	40	25	-				
NO	-	-	-	-	ML	1-90	YES (0-54)		100	40	25	-				
NO	-	-	-	-	ML	1-90	YES (0-54)		100	40	25	-				

EVALUATION LBS GROSS PLANE WEIGHT — ORIGINAL EVALUATION: NORMAL PERIOD CAPACITY OPERATION	REMARKS	PRESENT EVALUATION: NORMAL PERIOD E.M. PART XII JULY 1946	FROST CONDITIONS E.M. PART XII JULY 1946
32,000	THE NORMAL PERIOD CAPACITY OPERATION EVALUATIONS OF ALL PAVEMENTS EXCEPT THE N-S RUNWAY HAVE BEEN REDUCED 20% FOR WARMUP AND TAXIING. NO CORRECTION MADE FOR DEFICIENT EDGE THICKNESS OF PAVEMENTS.	< 30,000	< 30,000
115,200		34,000	< 30,000
136,000		55,000	< 30,000
-	CINDER SURFACED AREAS ARE STABLE ONLY UNDER FAVORABLE SUBGRADE CONDITIONS. WILL NOT SUPPORT NORMAL PLANE LOADS UNDER ADVERSE CONDITIONS. NO EVALUATION MADE.	-	-
-		-	-
-		-	-
48,000	THE NORMAL PERIOD CAPACITY OPERATION EVALUATIONS FOR TAXIWAYS AND APRON HAVE BEEN REDUCED 20% FOR WARMUP AND TAXIING. NO CORRECTION MADE FOR DEFICIENT EDGE THICKNESS OF PAVEMENTS.	30,000	< 30,000
54,000		35,000	< 30,000
52,000		< 30,000	< 30,000
65,000		40,000	< 30,000
42,000	THE NORMAL PERIOD CAPACITY OPERATION EVALUATIONS FOR APRON, TAXIWAYS AND NE-SW RUNWAY HAVE BEEN REDUCED 20% FOR WARMUP AND TAXIING. NO CORRECTION HAS BEEN MADE FOR DEFICIENT EDGE THICKNESS.	< 30,000	< 30,000
58,000		30,000	< 30,000
72,000		30,000	< 30,000
42,000	THE NORMAL PERIOD CAPACITY OPERATION EVALUATIONS OF TAXIWAYS AND LANDING MAT HAVE BEEN REDUCED 20% FOR WARMUP AND TAXIING. NO CORRECTION MADE FOR DEFICIENT EDGE THICKNESS OF PAVEMENT. INTERIOR THICKNESS OF PAVEMENT USED FOR EVALUATION PURPOSES IS ACTUAL MEASURED THICKNESS.	< 30,000	< 30,000
47,000		< 30,000	< 30,000
51,000		< 30,000	< 30,000
52,000		< 30,000	< 30,000
52,000		< 30,000	< 30,000
54,000		< 30,000	< 30,000
34,000	THE NORMAL PERIOD CAPACITY OPERATION EVALUATIONS FOR TAXIWAYS, APRON AND THE E-W RUNWAY HAVE BEEN REDUCED 20% FOR WARMUP AND TAXIING. NO CORRECTION MADE FOR DEFICIENT EDGE THICKNESS OF PAVEMENTS.	< 30,000	< 30,000
55,000		< 30,000	< 30,000
70,000		30,000	< 30,000
80,000		30,000	< 30,000
64,000	THE NORMAL PERIOD CAPACITY OPERATION EVALUATIONS OF TAXIWAYS AND ANCHORAGES HAVE BEEN REDUCED 20% FOR WARMUP AND TAXIING. NO CORRECTION MADE FOR DEFICIENT EDGE THICKNESS OF PAVEMENTS. *THE FOUNDATION SOILS CONTAIN A HIGH PERCENTAGE OF SOLUBLE SALTS. FROST PENETRATION IS REPORTED AS INDETERMINATE DUE TO THE INFLUENCE OF THESE SALTS. IT IS POSSIBLE THAT NO FROST ACTION OCCURS IN WHICH CASE THE NORMAL PERIOD EVALUATIONS WOULD BE THE CONTROLLING EVALUATIONS.	< 30,000*	< 30,000*
67,000		< 30,000	< 30,000
67,000		< 30,000	< 30,000
70,000		< 30,000	< 30,000
76,000		< 30,000	< 30,000
108,000		30,000	< 30,000
90,000*	THE NORMAL PERIOD CAPACITY OPERATION EVALUATIONS ARE CORRECTED AS FOLLOWS: (1) TAXIWAYS AND APRONS ARE REDUCED 20% FOR WARMUP AND TAXIING. (2) BASE COURSE ACCOUNTED FOR BY ADDING 1" TO INTERIOR THICKNESS OF PAVEMENT FOR EACH 4" OF BASE. (3) CORRECTION FOR DEFICIENT EDGE THICKNESS OF PAVEMENT MADE BY THE RATIO OF EXISTING EDGE THICKNESS TO 1.5 TIMES THE INTERIOR THICKNESS. *WEIGHTED AVERAGE OF VALUES OBTAINED FROM DESIGN COMPUTATIONS AND SLAB LOADING TESTS.	34,000	35,000
98,000*		35,000	33,000
90,000*		40,000	38,000
107,000*		48,000	46,000

WEIGHT CLASS (C)	1943 TOTAL	1943 APPROX DAILY	1944 TOTAL	1944 APPROX DAILY	1945 TOTAL	1945 APPROX DAILY	1946 TOTAL	1946 APPROX DAILY	1947 TOTAL	1947 APPROX DAILY	1948 JAN & FEB TOTAL	1948 APPROX DAILY
C	-	-	-	-	1269	3	40,186	110	50,773	139	5386	90
D	-	-	-	-	15,974	44	1578	4	1376	4	172	3
E	-	75	-	-	991	3	518	1	343	1	45	1
F	-	-	-	-	2	OCC.	-	-	-	-	-	-
G	-	-	-	-	13	1/MO.	55	5/MO.	159	13/MO.	2	1/MO.
TRAFFIC DISTRIBUTION N-S, 46%; E-W, 40%; NE-SW, 14%												
C	N	O	D	A	T	A			5582	15	674	11
D									878	2	95	2
E									55	5/MO.	2	1/MO.
TRAFFIC DISTRIBUTION N-S, 76%; NW-SW, 24%												
C	-	-	NO DATA		8994	25	NO DATA		6707	18	1022	17
D	-	-			804	2			1499	4	251	4
E	-	25			3941	11			374	1	69	1
F	-	-			-	-			11	1/MO.	-	-
G	-	-			14,994	41			7465	20	1427	24
TRAFFIC DISTRIBUTION N-S, 72%; NW-SE, 20%; NE-SW, 5%; E-W, 3%												
C	-	10	-	10	5285	14	14,400	40	13,297	37	1198	20
D	-	10	-	10	358	1	1992	5	1847	5	109	2
E	-	-	-	-	3130	9	841	2	698	2	33	17/MO.
F	-	-	-	-	-	-	115	10/MO.	-	-	-	-
G	-	-	-	-	12	1/MO.	338	1	2188	6	1307	22
TRAFFIC DISTRIBUTION NE-SW, 74%; N-S, 17%; E-W, 9%												
C	PRIOR TO 1945, 10 TO 350 CYCLES PER DAY OF PLANES UP TO 9000 LBS. GROSS WEIGHT.				916	2	89,803	246	57,076	156	2551	43
D					1103	3	2213	6	2836	8	422	7
E					227	19/MO.	115	10/MO.	215	17/MO.	8	4/MO.
F					-	-	-	-	5	OCC.	-	-
G					5	OCC.	5	OCC.	1	OCC.	-	-
TRAFFIC DISTRIBUTION E-W, 41%; NE-SW, 24%; NW-SE, 21%; N-S, 14%												
C	-	-	-	-	2248	6	9772	27	11,225	31	1775	30
D	-	-	-	-	1232	3	2657	7	1191	3	233	4
E	-	79	-	250	36,847	101	100	8/MO.	212	17/MO.	33	17/MO.
F	-	-	-	-	-	-	-	OCC.	-	-	-	-
G	-	-	-	-	21	2/MO.	47	4/MO.	1194	3	298	5
TRAFFIC DISTRIBUTION N-S, 63%; NW-SE, 32%; E-W, 5%												
C	-	-	-	-	1638	4	4245	12	2512	7	370	6
D	-	-	-	-	1278	4	528	1	615	2	102	2
E	-	90	-	-	1949	6	1426	4	300	1	8	4/MO.
G	-	-	-	-	1289	3	136	11/MO.	1614	4	397	7
TRAFFIC DISTRIBUTION NW-SE, 58%; NE-SW, 23%; E-W, 19%												
C	-	33	NO DATA		4027	17	90,400	248	41,896	115	5956	99
D	-	12			5585	15	3971	16	7325	20	1175	20
E	-	-			4355	12	3137	9	2402	7	152	3
F	-	-			57	5/MO.	214	18/MO.	258	1	103	2
G	-	-			1427	4	1800	5	1351	4	189	3
H	-	-			-	-	-	-	1	OCC.	-	-
TRAFFIC DISTRIBUTION NE-SW, 38%; NW-SE, 42%; E-W, 20%												

DISTRESS OR FAILURE IN WHICH FROST ACTION WAS A CONTRIBUTING CAUSE: LOCATION	DESCRIPTION	SATURATED	DATE FIRST NOTED	REPORTED CAUSE
NO DATA				
NO DATA				
NO DATA				
NO DATA				
NO DATA				
E-W RUNWAY AND RUNWAY SHOULDERS	RUNNING UNDER TRAFFIC IN JOINT AREA, DISPLACEMENT BY PLANE WHEELS OF 1½" A.C. PAVEMENT, 6" BASE COURSE AND SEVERAL INCHES OF SATURATED SUBGRADE. BREAKING AND CRACKING OF ORIGINAL CONCRETE APRON. NEW CONCRETE PAVEMENTS SHOW SEEPAGE OF WATER FROM JOINTS AT LOW ELEVATIONS.	BASE 65% SUBGRADE 92%	MARCH 1943	MOISTURE PENETRATION INTO BASE COURSE AND SUBGRADE AND INABILITY TO SUPPORT CONCENTRATED VIBRATORY LOADINGS UNDER EXISTING MOISTURE CONTENT. WATER LEAKED INTO BASE AND SUBGRADE THROUGH LONGITUDINAL JOINTS.
NO DATA				
NO DATA				

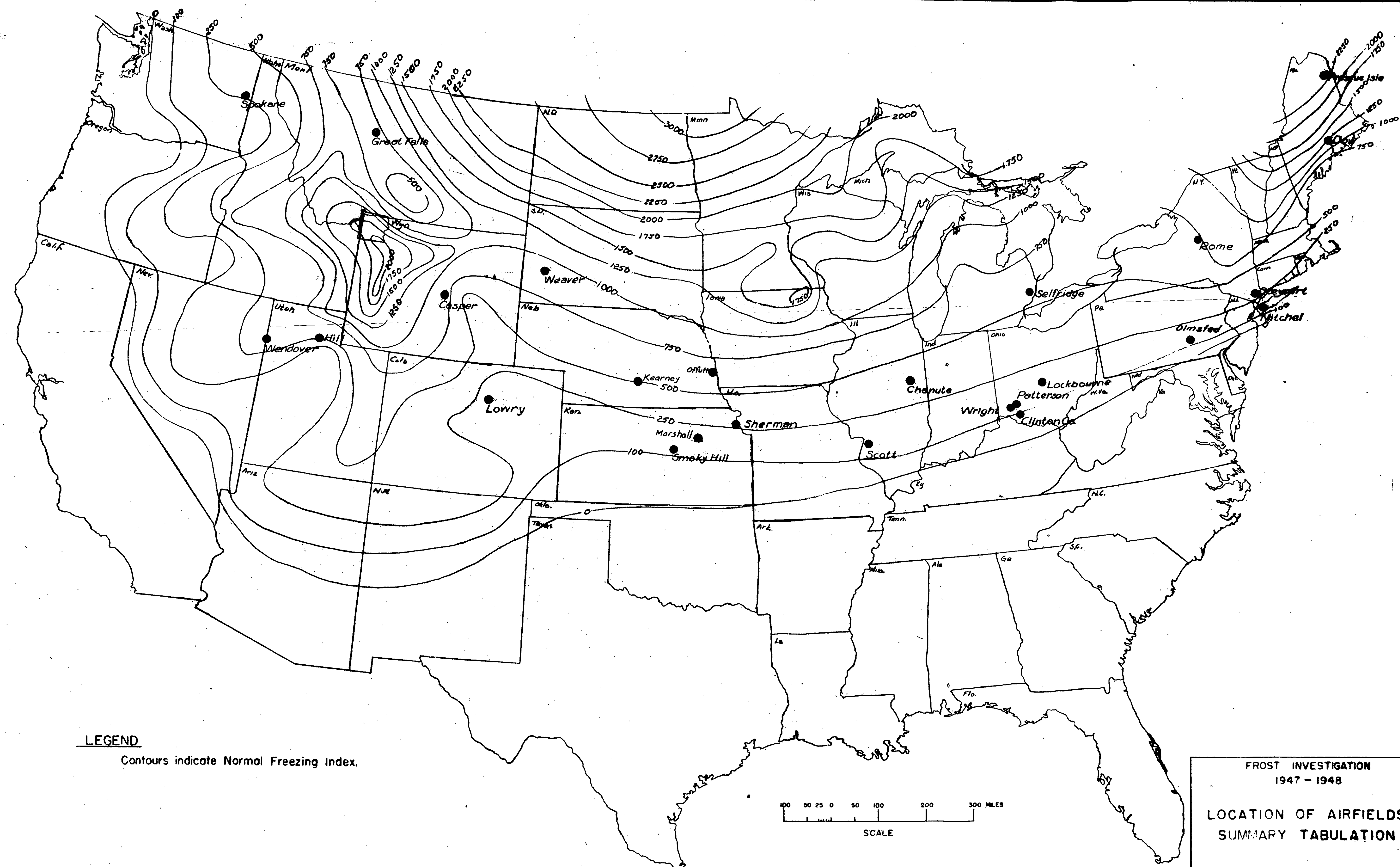
NOTES

(A) SUBGRADE MODULUS DURING FROST MELTING PERIOD.

(B) DEPTH OF FROST PENETRATION FROM FREEZING INDEX CURVES.

(C) WEIGHT CLASSIFICATION AS SHOWN BELOW.

CLASS	GROSS WT. OF PLANES
1942 - 1945	
C	25,000 - 35,000 LBS.
D	35,000 - 50,000 LBS.
E	50,000 - 75,000 LBS.
F	75,000 - 90,000 LBS.
G	90,000 - 135,000 LBS.
1946 - 1948	
A & B	NOT OVER 15,000 LBS.
C	16,000 - 28,000 LBS.
D	31,000 - 56,000 LBS.
E	56,000 - 76,000 LBS.
F	76,000 - 123,000 LBS.
G	123,000 - 135,000 LBS.
H	135,000 AND OVER



LEGEND

Contours indicate Normal Freezing Index.

FROST INVESTIGATION
1947 – 1948

LOCATION OF AIRFIELDS
SUMMARY TABULATION

SOILS LABORATORY
NEW ENGLAND DIVISION

JUNE 1948
BOSTON, MASS.

PLATE B-1

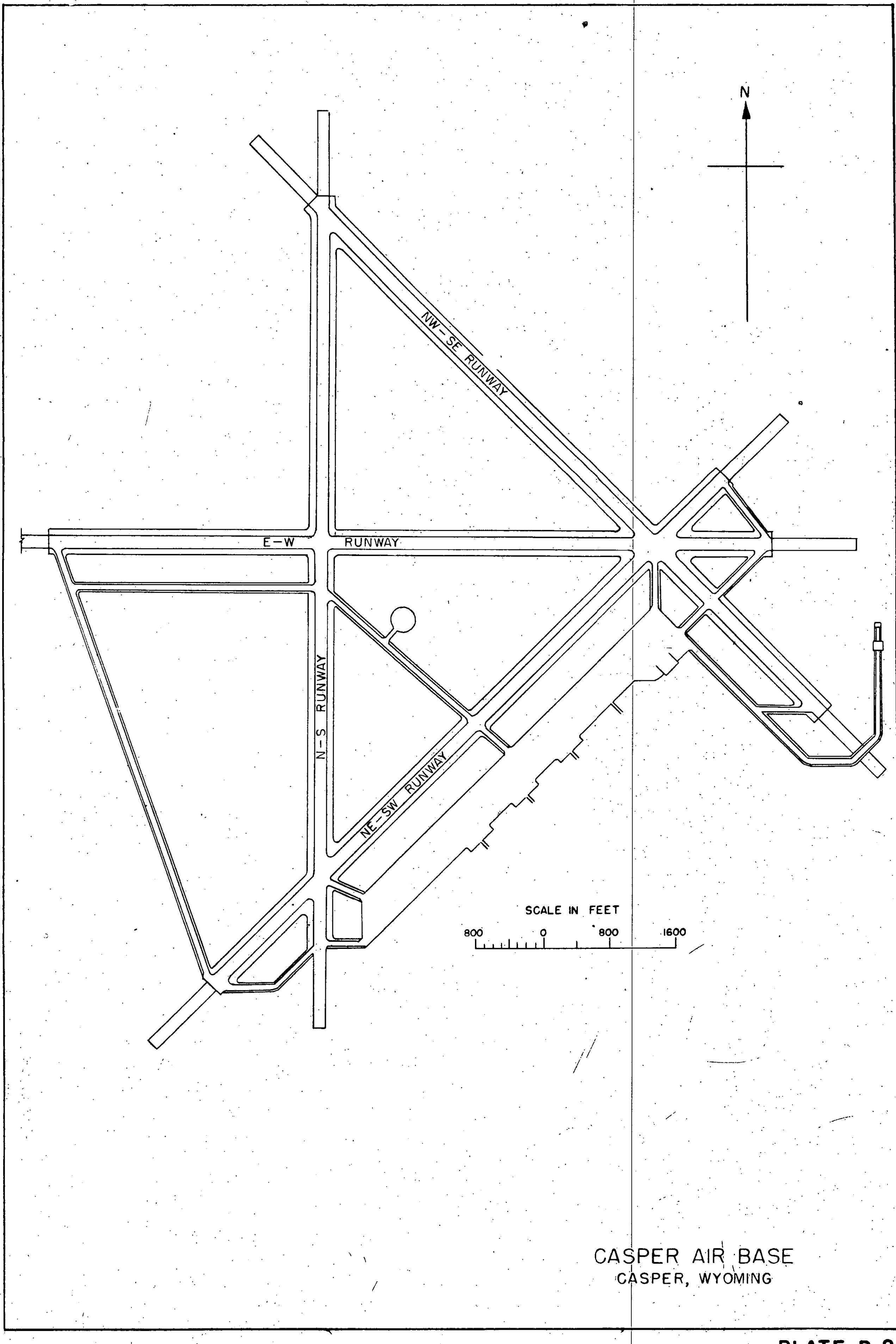
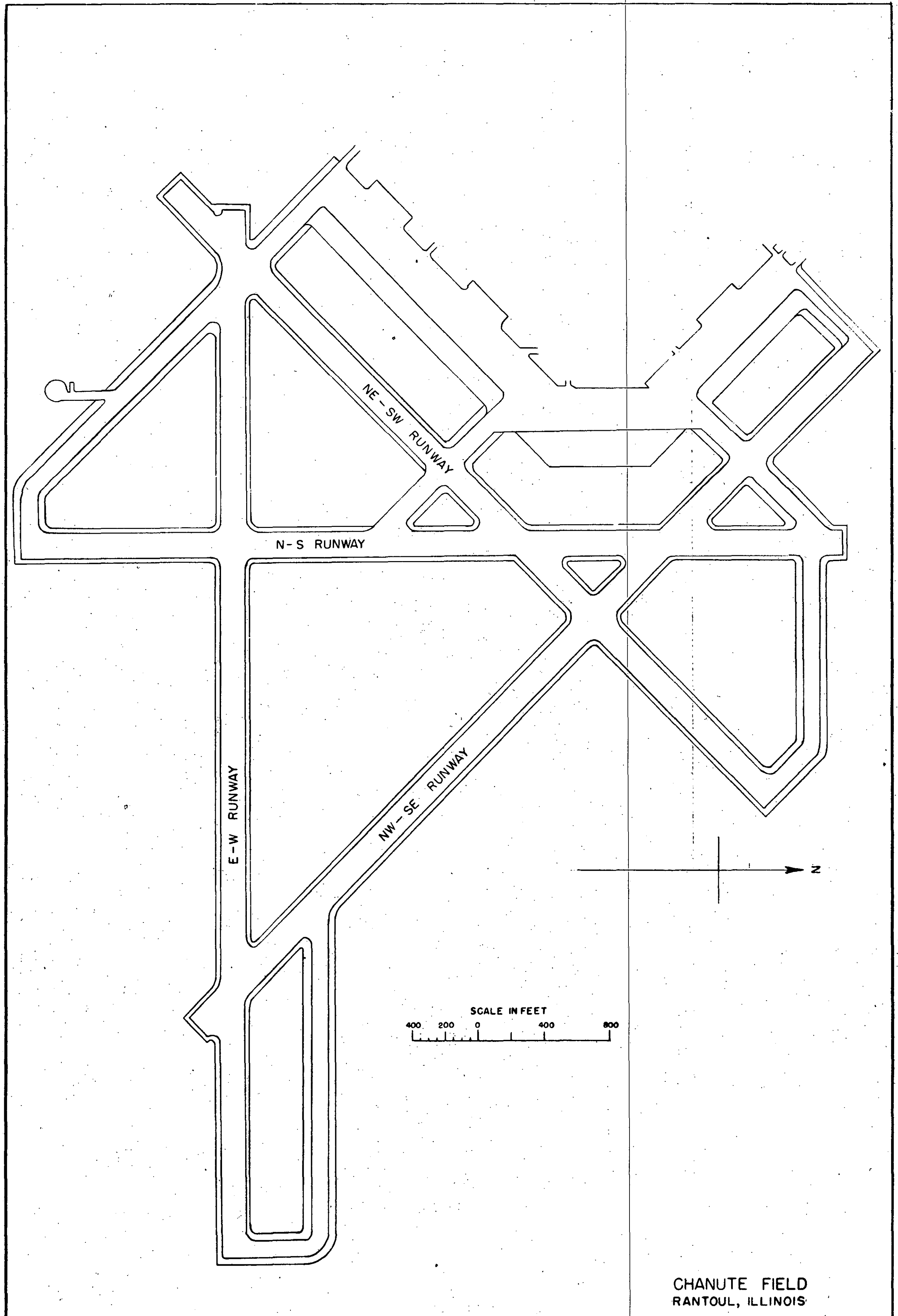
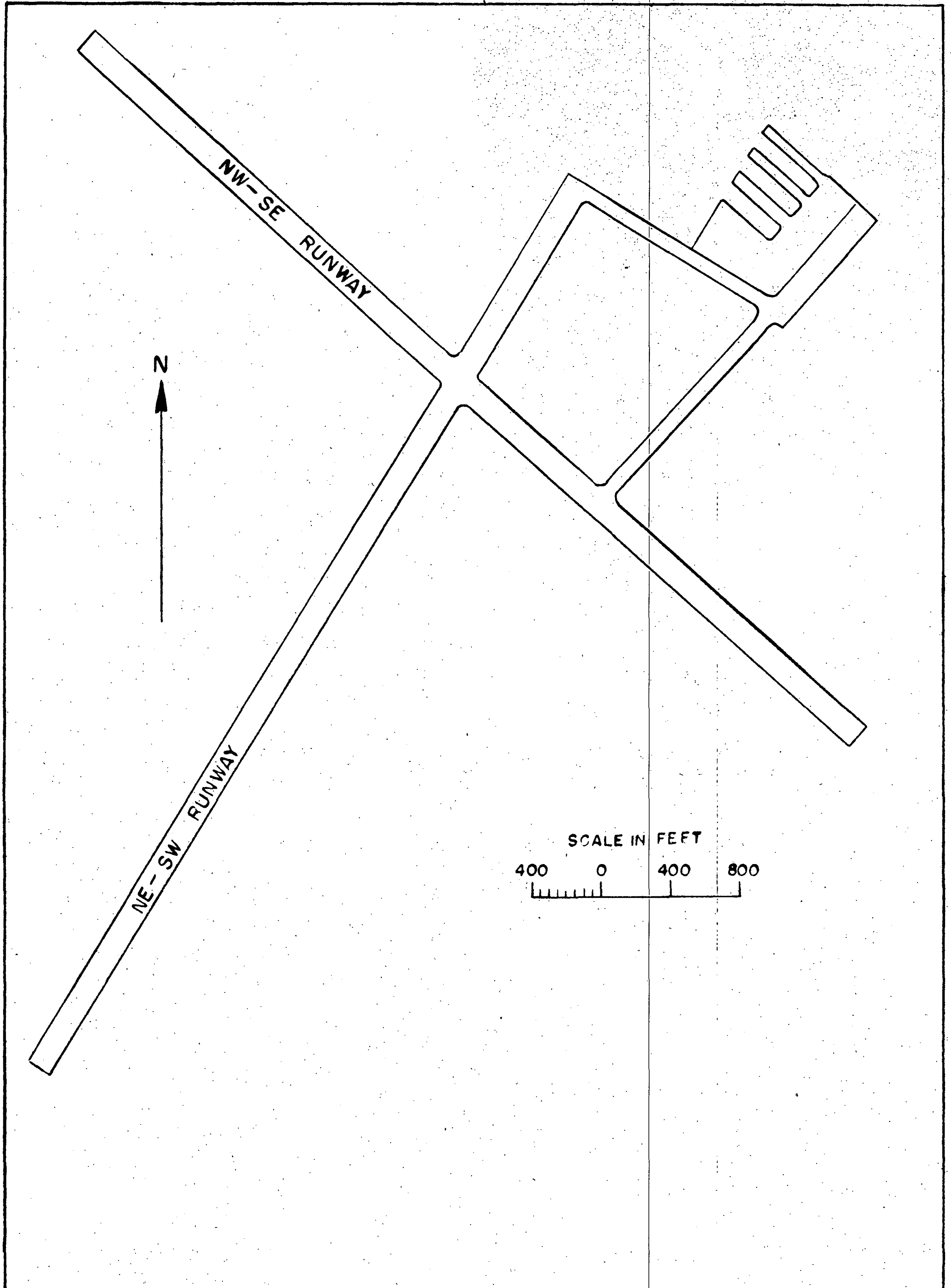

N
NW - SE RUNWAY
E-W
RUNWAY
N-S RUNWAY
NE-SW RUNWAY
SCALE IN FEET
800
0
800
1600
CASPER AIR BASE
CASPER, WYOMING

PLATE B-2



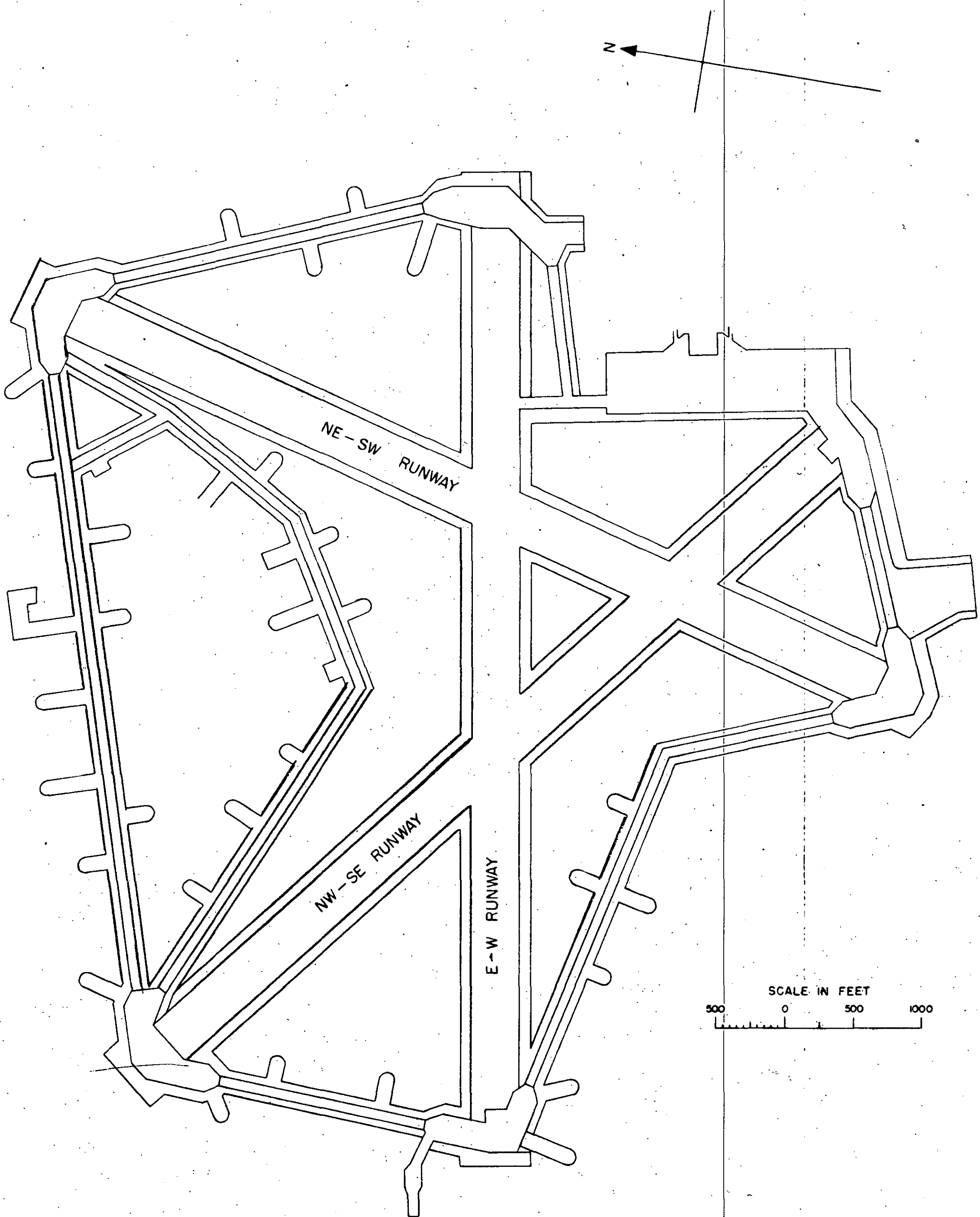
CHANUTE FIELD
RANTOUL, ILLINOIS

PLATE B-3



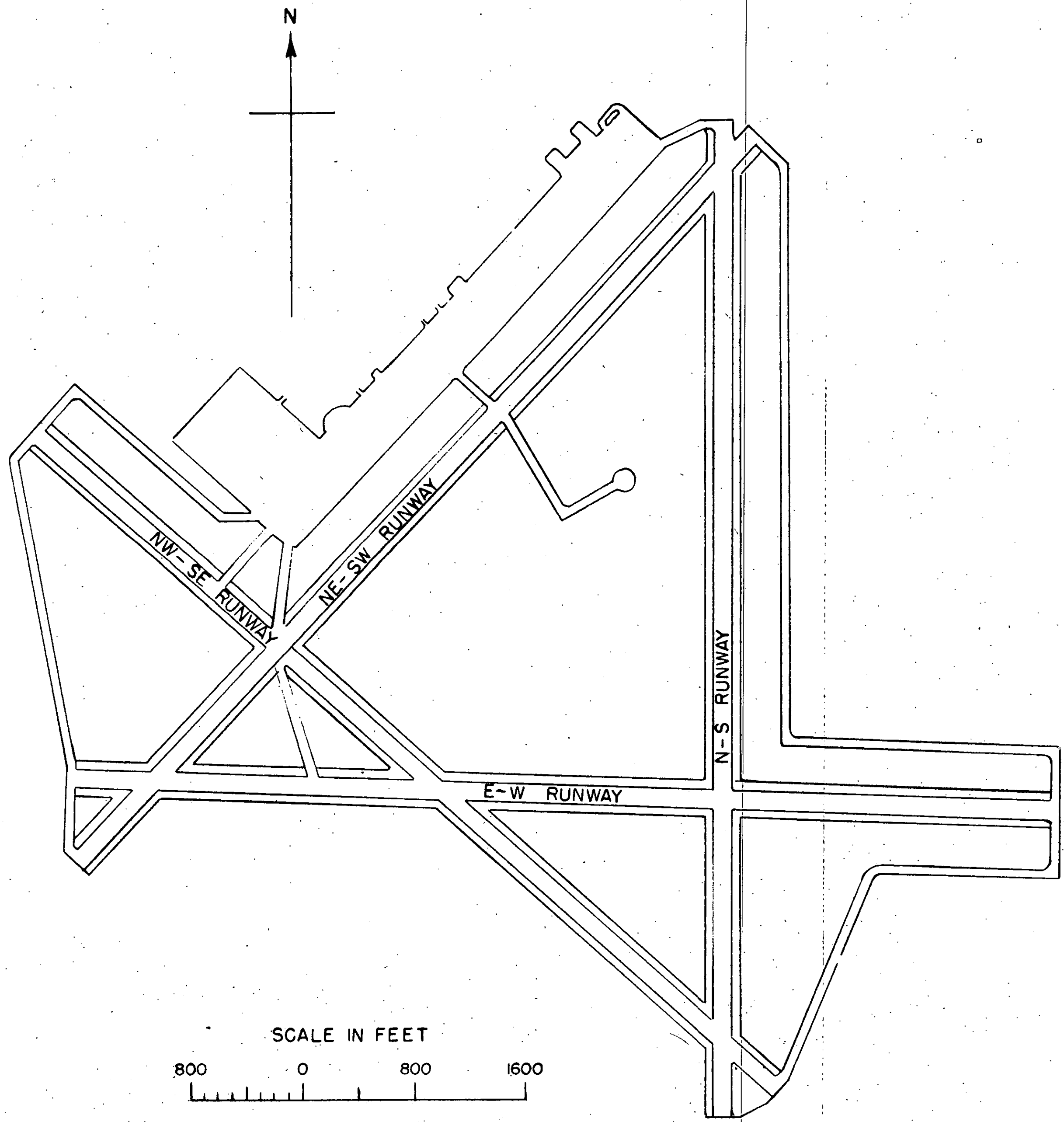
CLINTON COUNTY ARMY AIRFIELD
WILMINGTON, OHIO

PLATE B-4



DOW FIELD
BANGOR, MAINE

PLATE B-5



GREAT FALLS ARMY AIRFIELD
GREAT FALLS, MONTANA

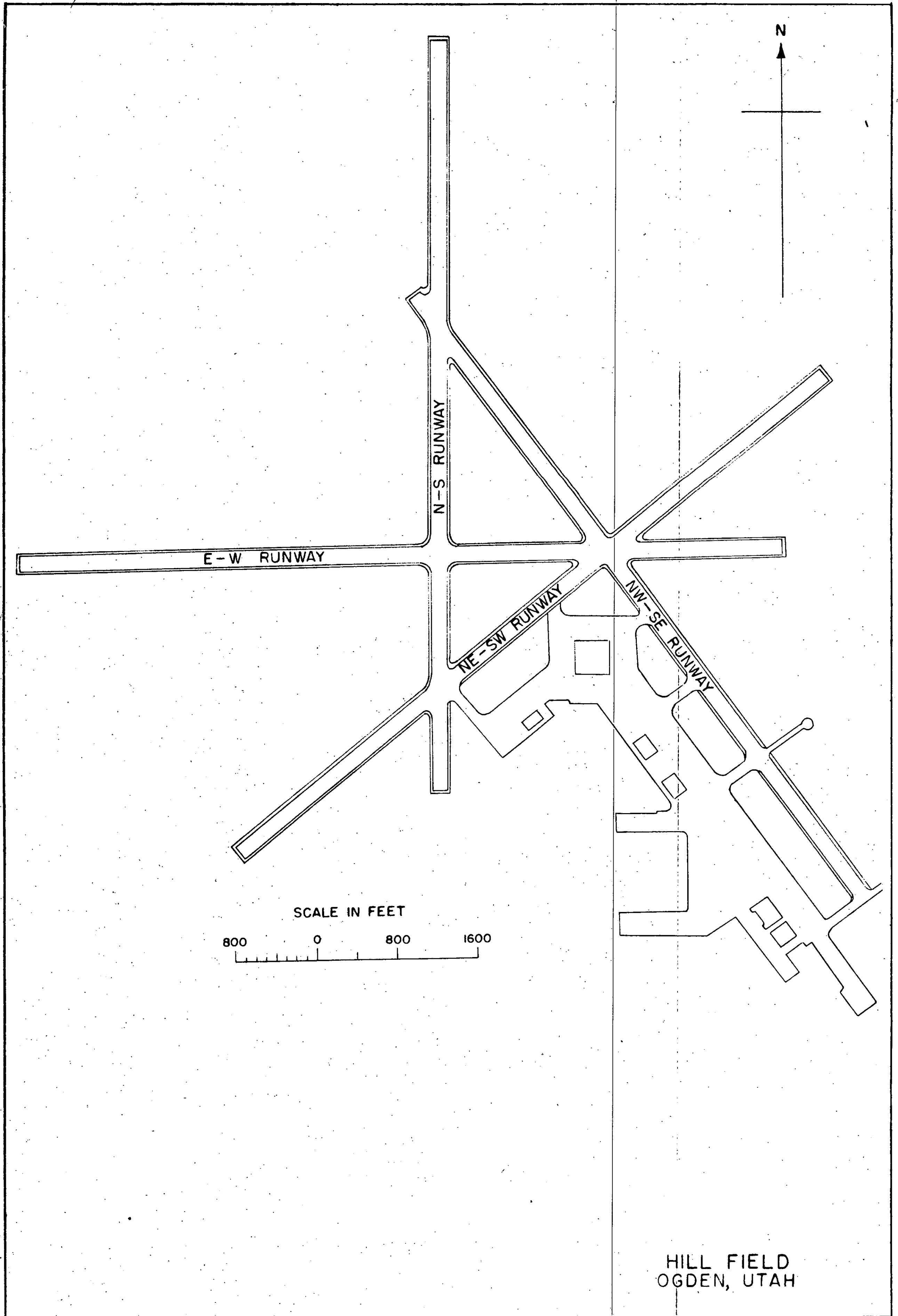

N
N-S RUNWAY
E-W RUNWAY
NE-SW RUNWAY
NW-SE RUNWAY
SCALE IN FEET
800 0 800 1600
HILL FIELD
OGDEN, UTAH

PLATE B-7

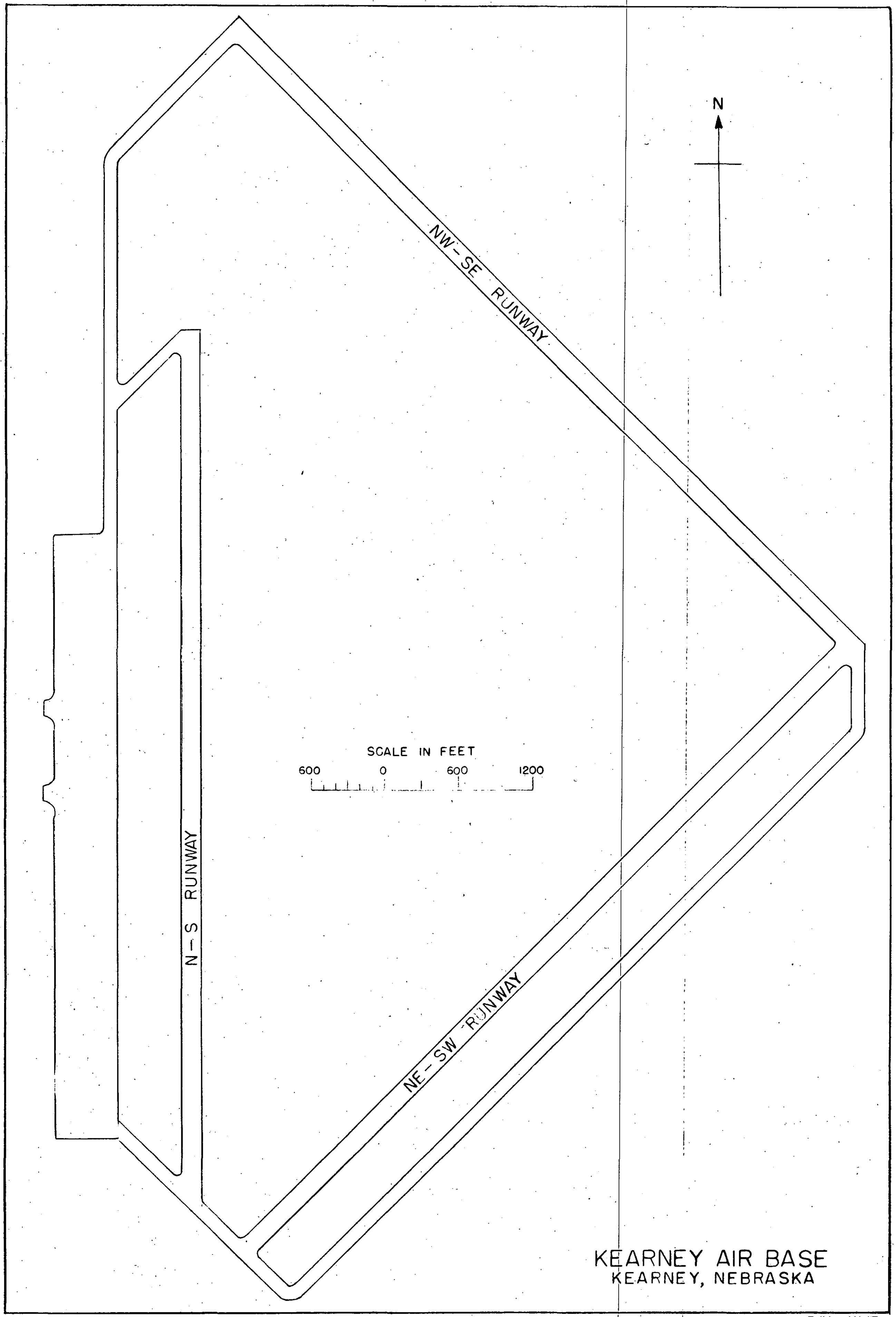
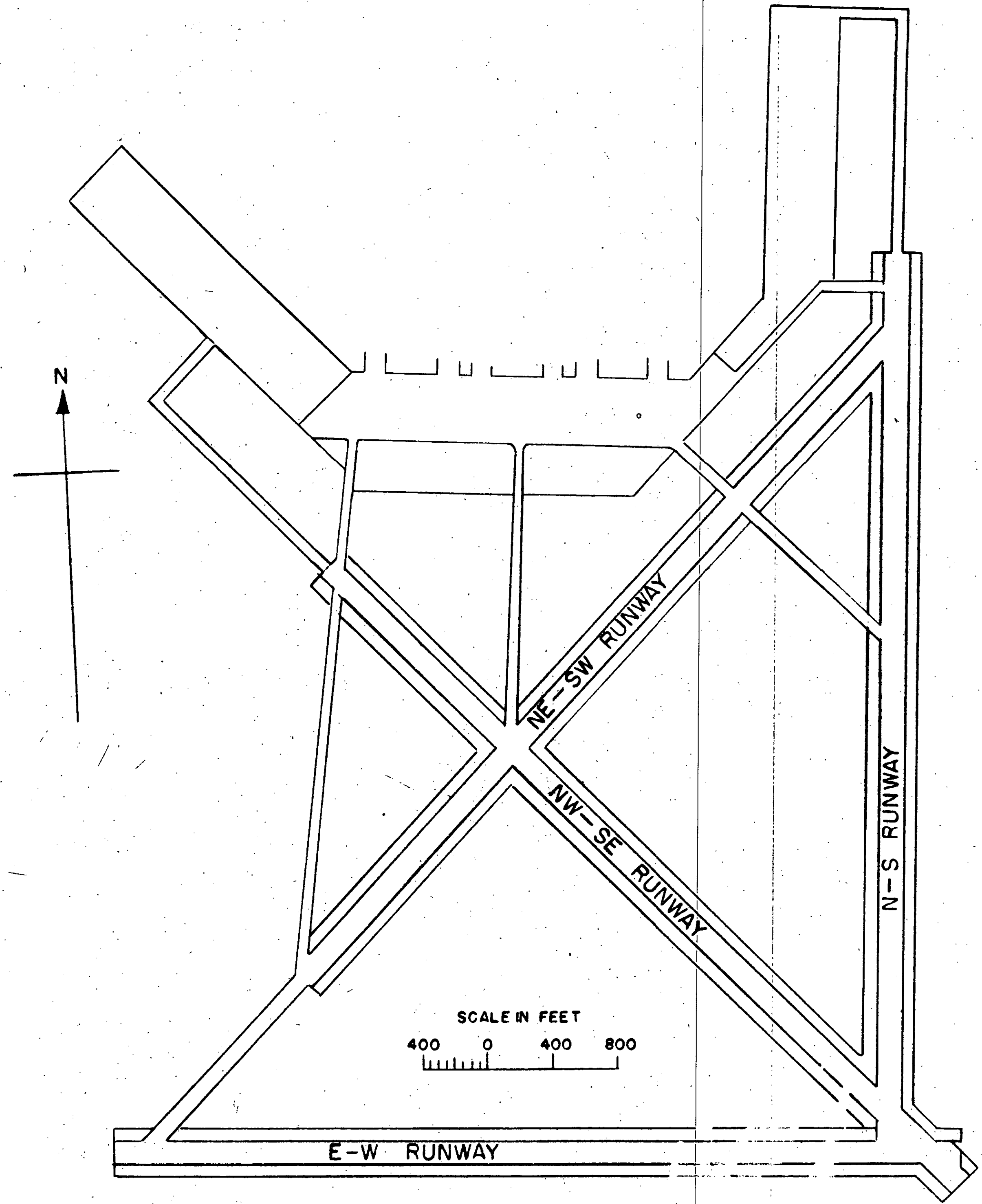

N
NW-SE RUNWAY
N-S RUNWAY
NE-SW RUNWAY
SCALE IN FEET
600 0 600 1200
KEARNEY AIR BASE
KEARNEY, NEBRASKA

PLATE B-8



LOCKBOURNE ARMY AIR BASE
COLUMBUS, OHIO

PLATE B-9

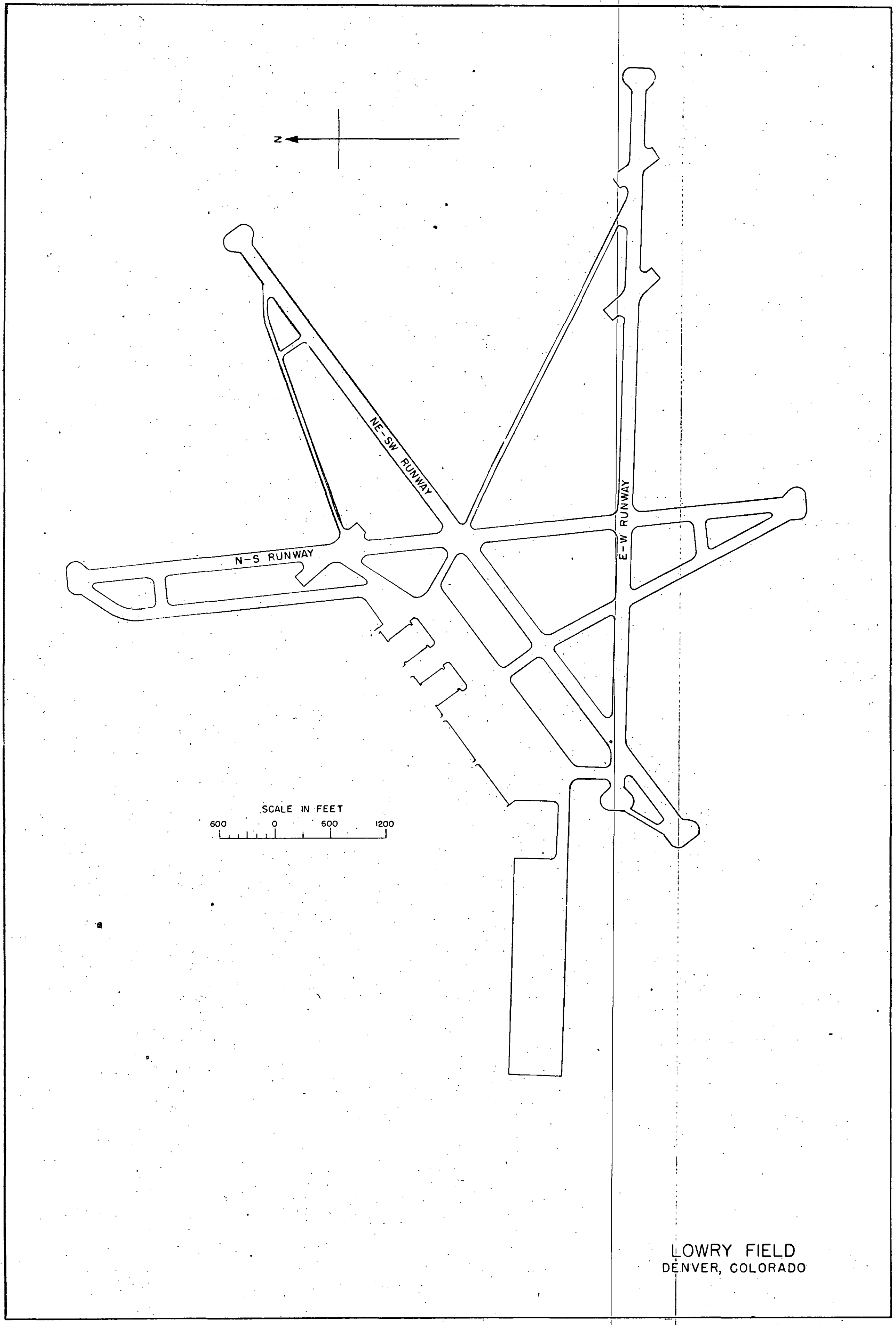

N
NE-SW RUNWAY
N-S RUNWAY
E-W RUNWAY
SCALE IN FEET
600 0 600 1200
LOWRY FIELD
DENVER, COLORADO

PLATE B-10

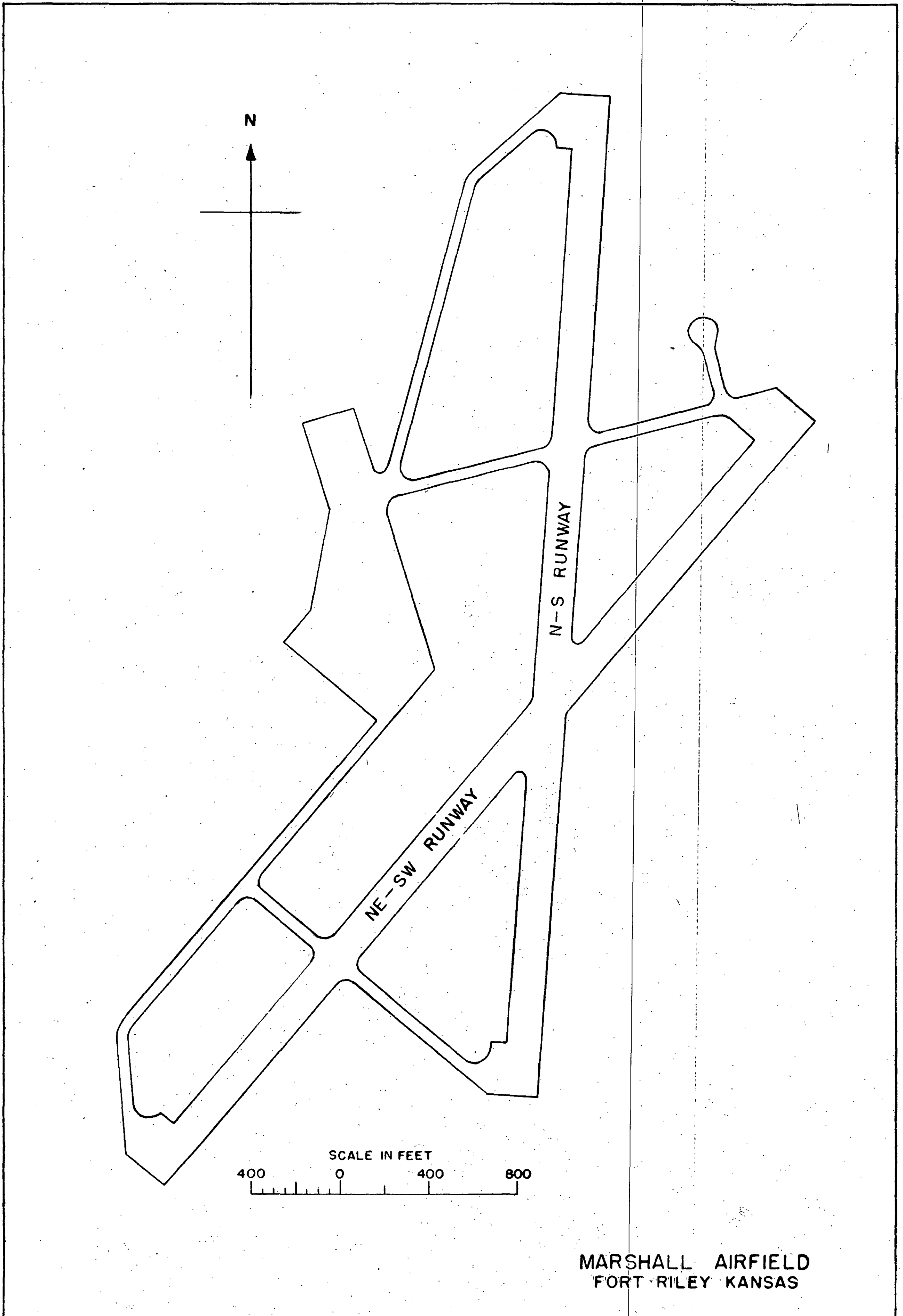

N
N-S RUNWAY
NE-SW RUNWAY
SCALE IN FEET
400 0 400 800
MARSHALL AIRFIELD
FORT RILEY KANSAS

PLATE B-11

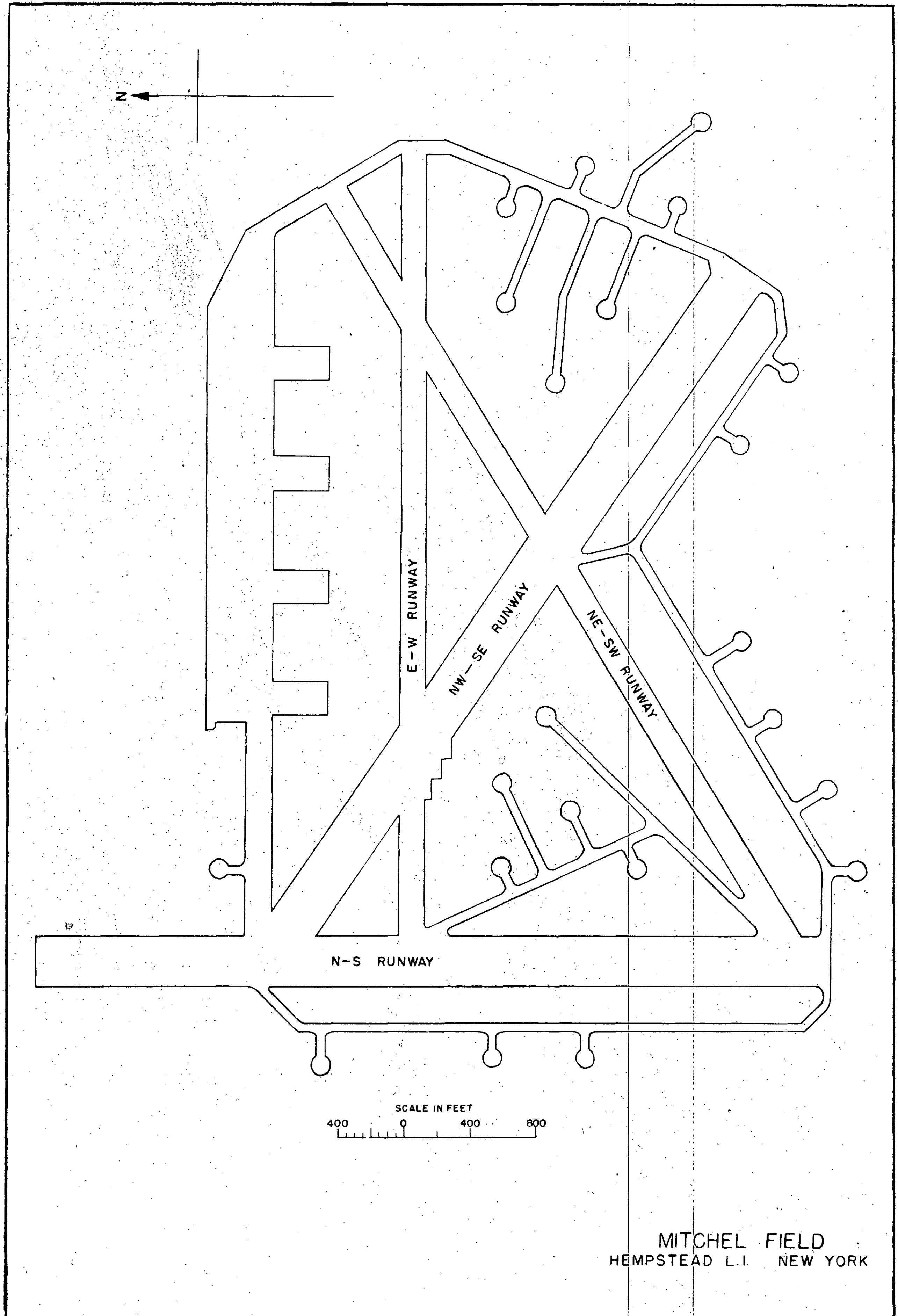
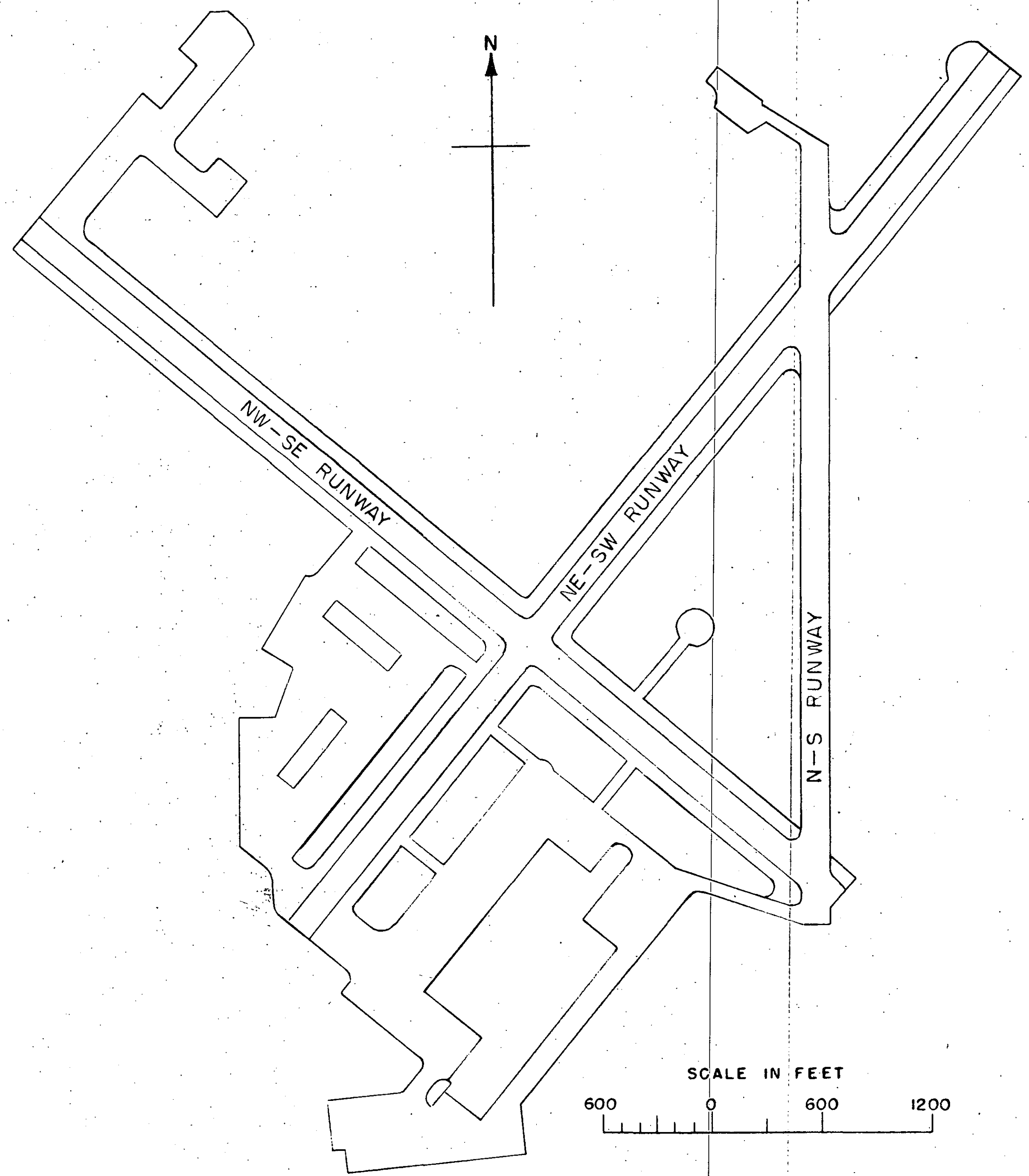
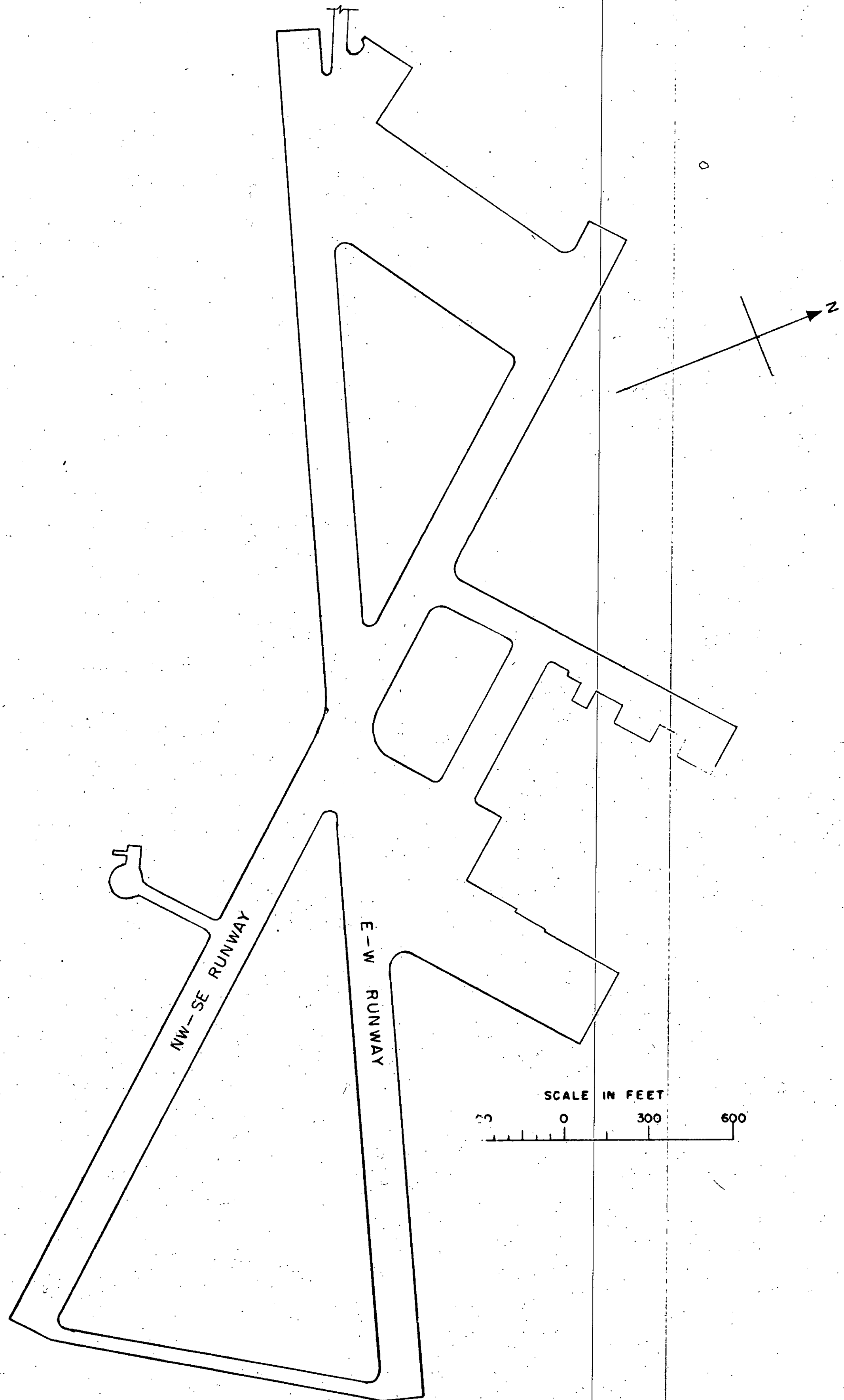

N
E-W RUNWAY
NW-SE RUNWAY
NE-SW RUNWAY
N-S RUNWAY
SCALE IN FEET
400 0 400 800
MITCHEL FIELD
HEMPSTEAD L.I. NEW YORK

PLATE B-12



OFFUTT AIRFIELD
FORT CROOK, NEBRASKA

PLATE B-13



OLMSTED FIELD
MIDDLETOWN, PENNSYLVANIA

PLATE B-14

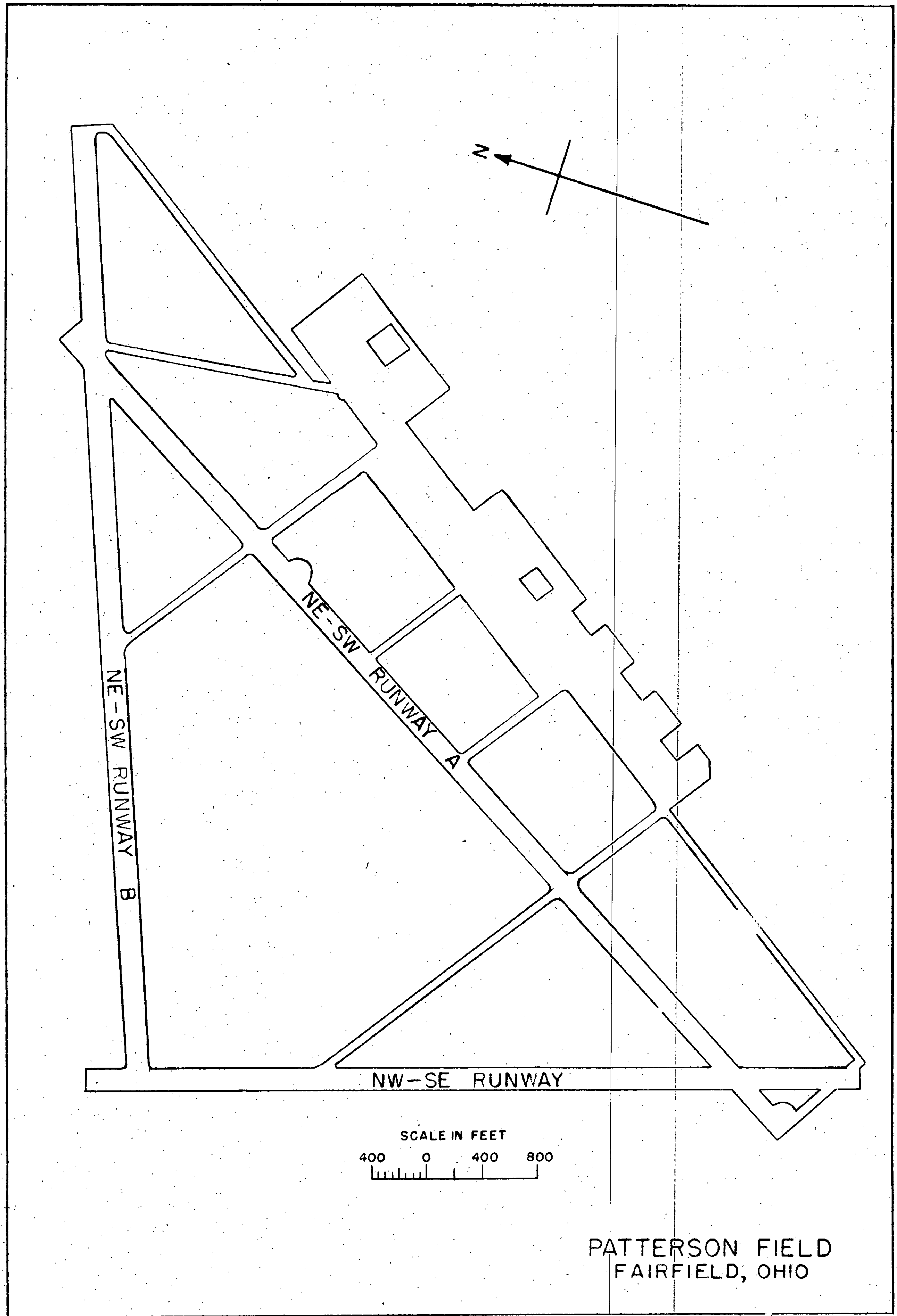
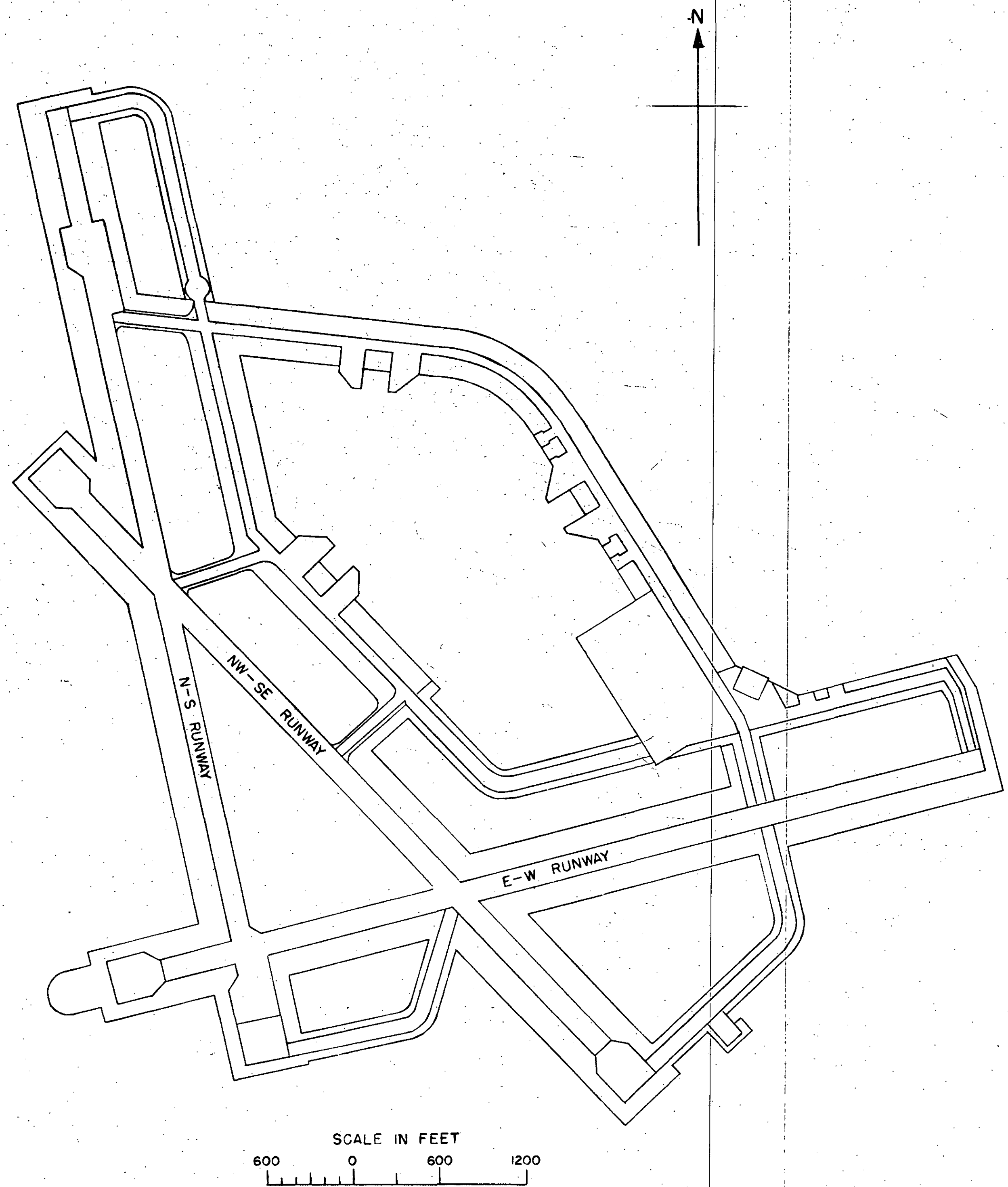
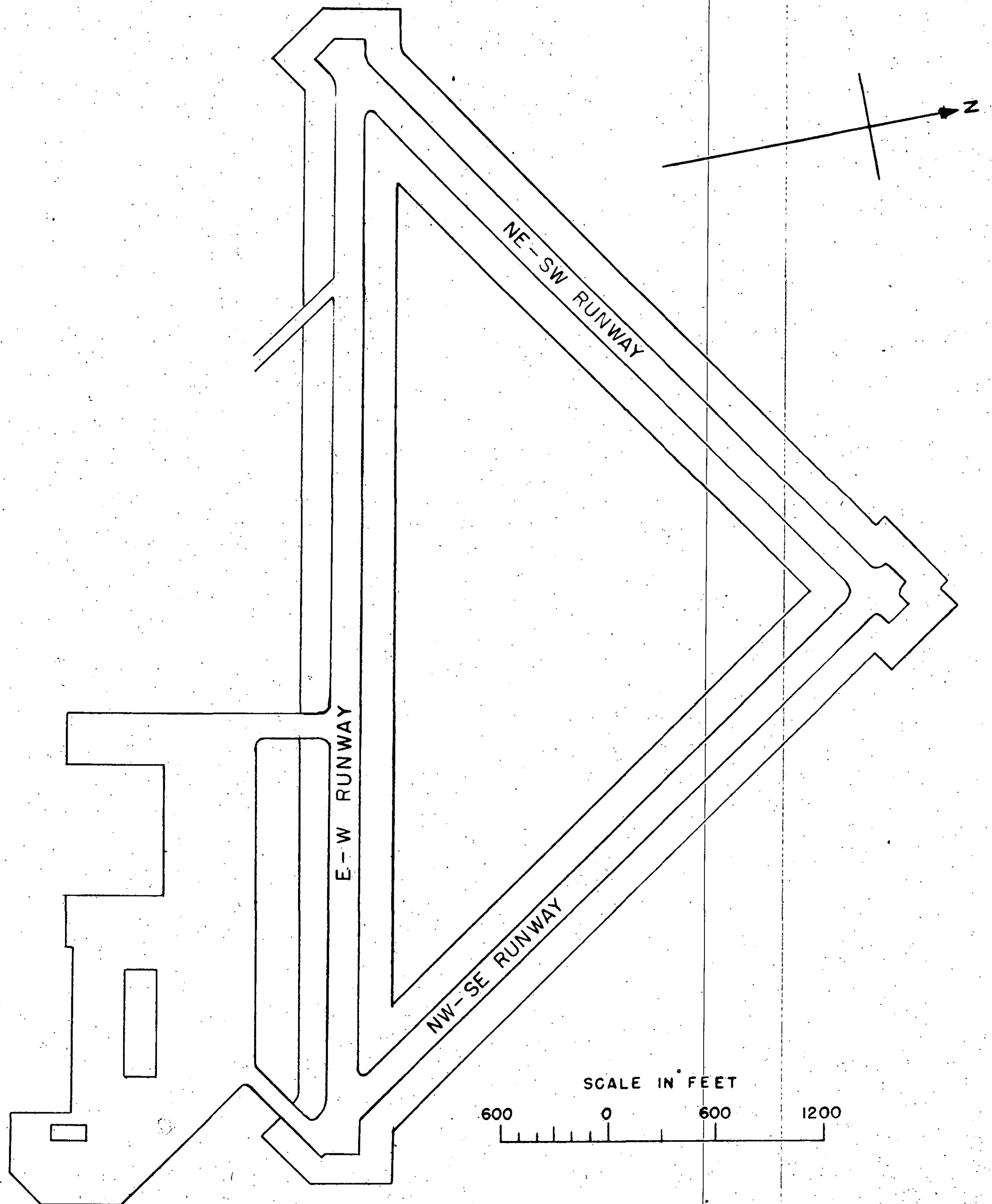

N
NE-SW RUNWAY A
NE-SW RUNWAY B
NW-SE RUNWAY
SCALE IN FEET
400 0 400 800
PATTERSON FIELD
FAIRFIELD, OHIO

PLATE B-15



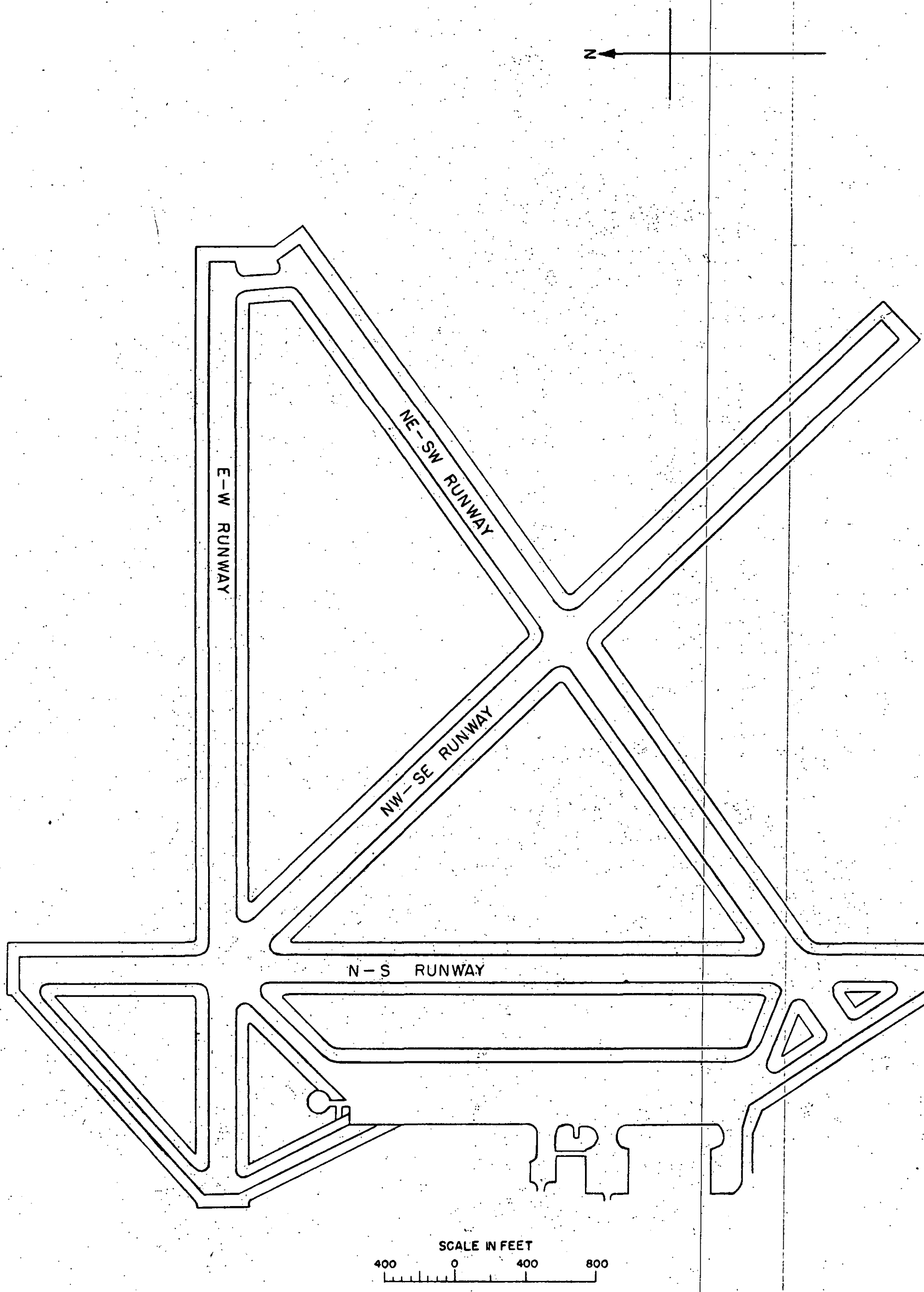
PRESQUE ISLE AIRFIELD
PRESQUE ISLE, MAINE

PLATE B-16



ROME ARMY AIRFIELD
ROME, NEW YORK

PLATE B-17



SCOTT FIELD
BELLEVILLE, ILLINOIS

PLATE B-18

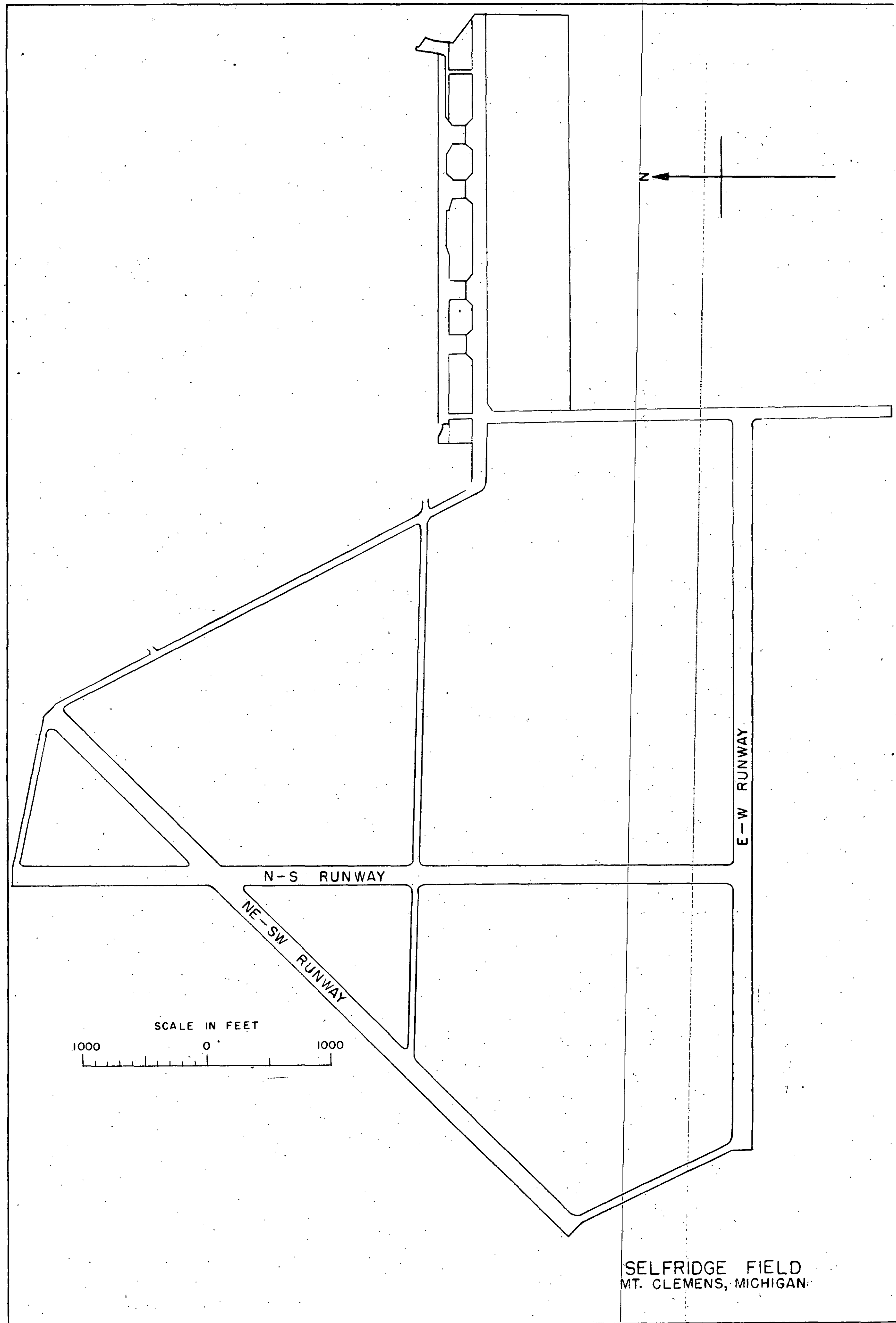
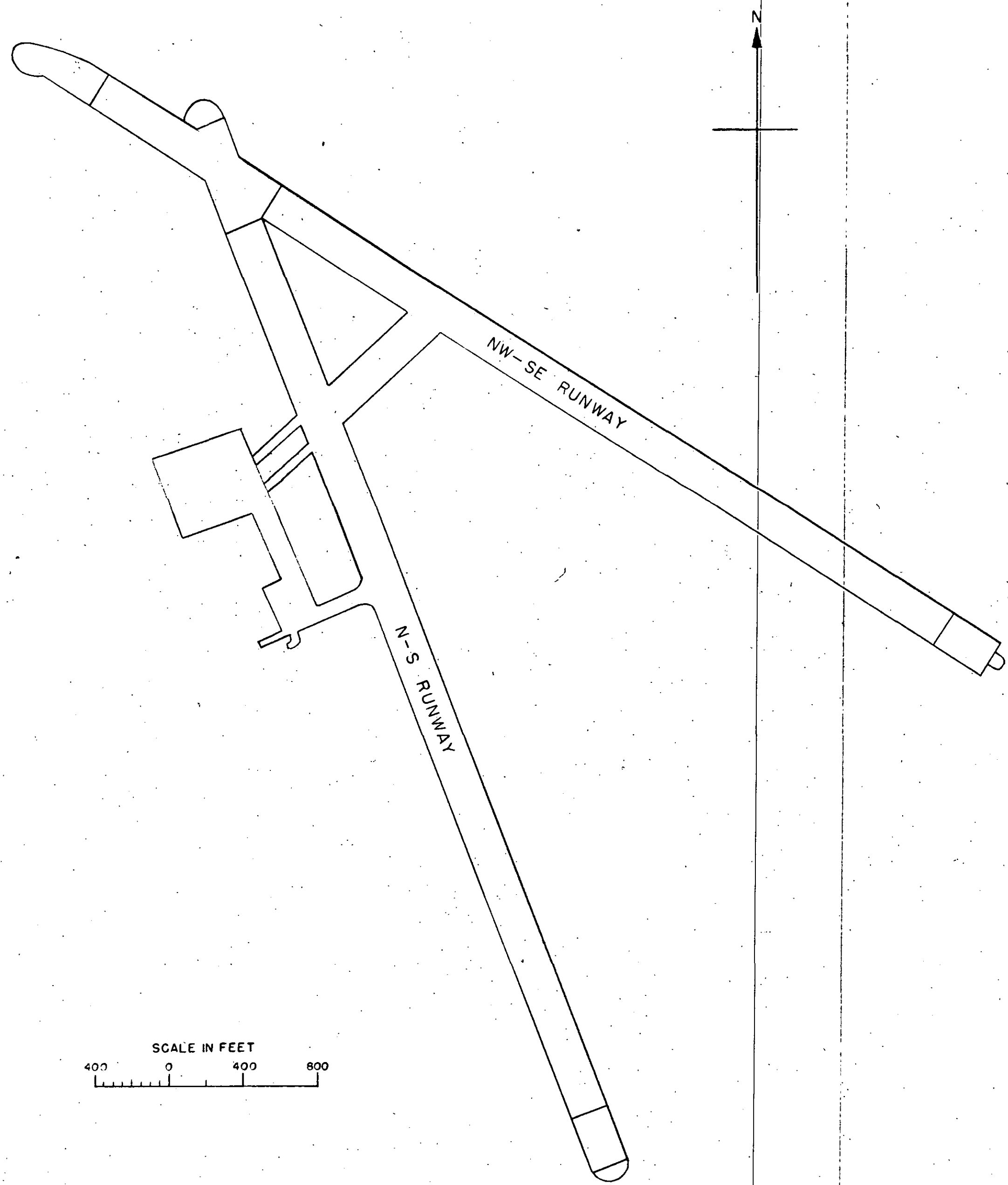
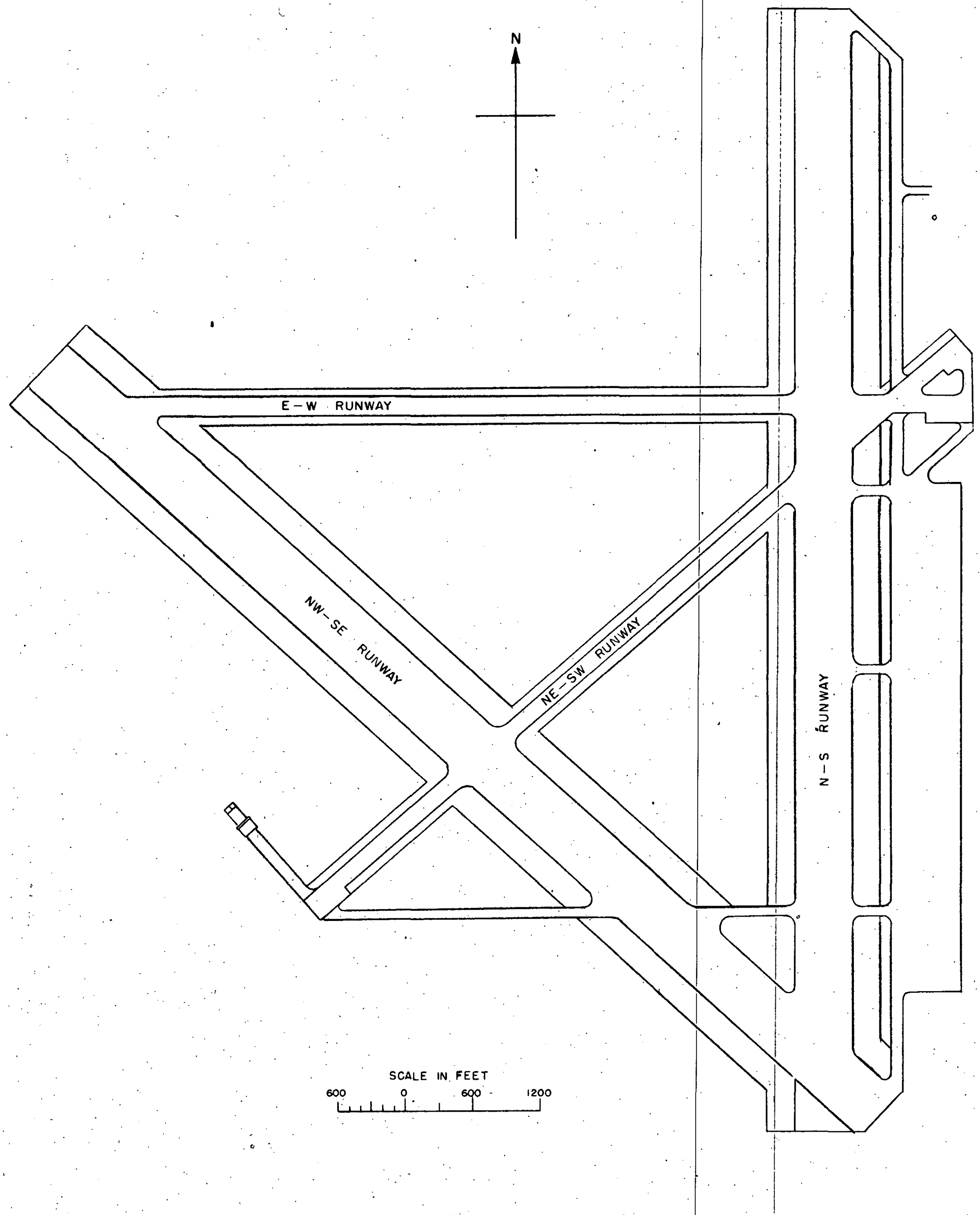

N
N-S RUNWAY
NE-SW RUNWAY
E-W RUNWAY
SCALE IN FEET
1000
0
1000
SELFRIDGE FIELD
MT. CLEMENS, MICHIGAN

PLATE B-19



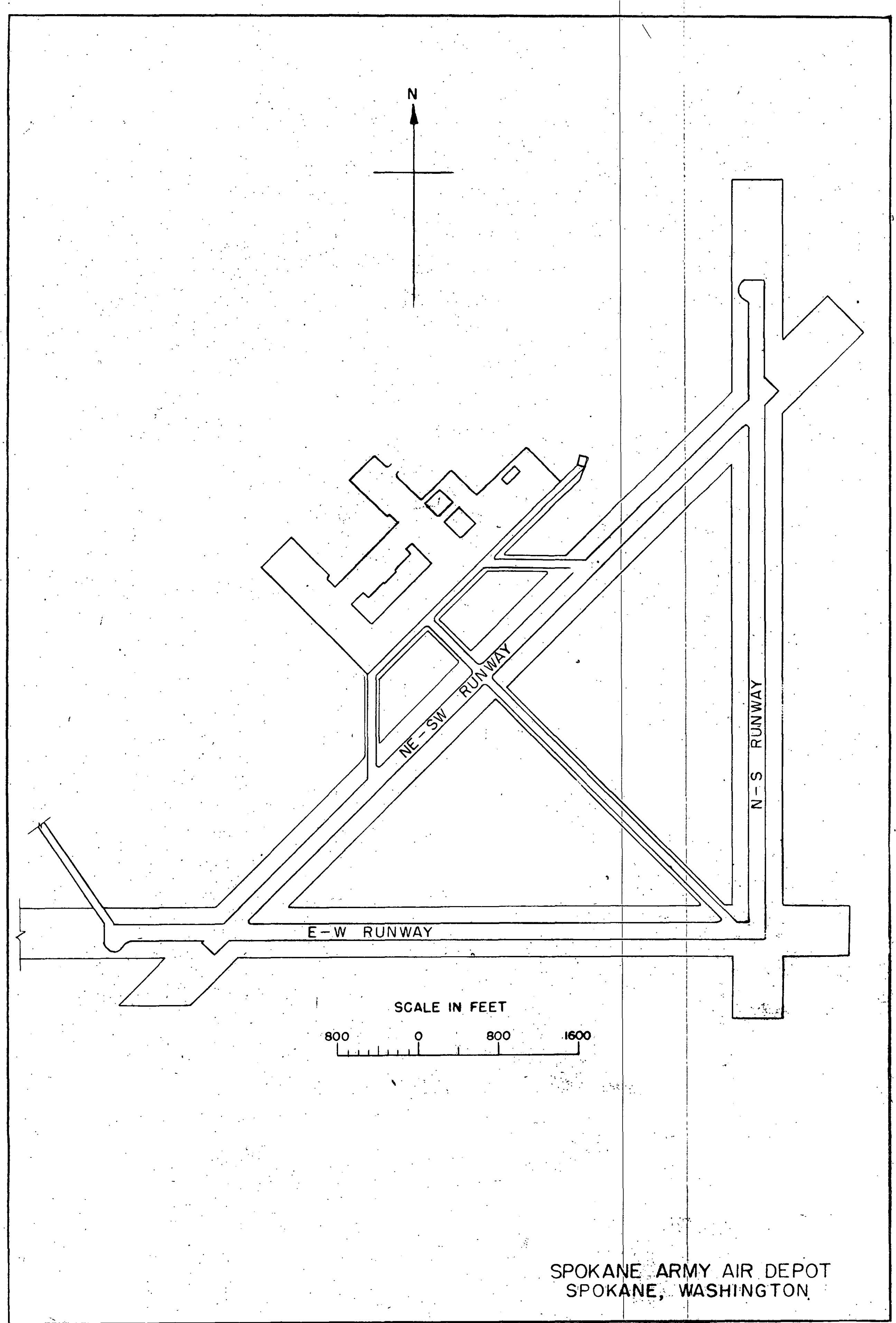
SHERMAN FIELD
FT. LEAVENWORTH, KANSAS

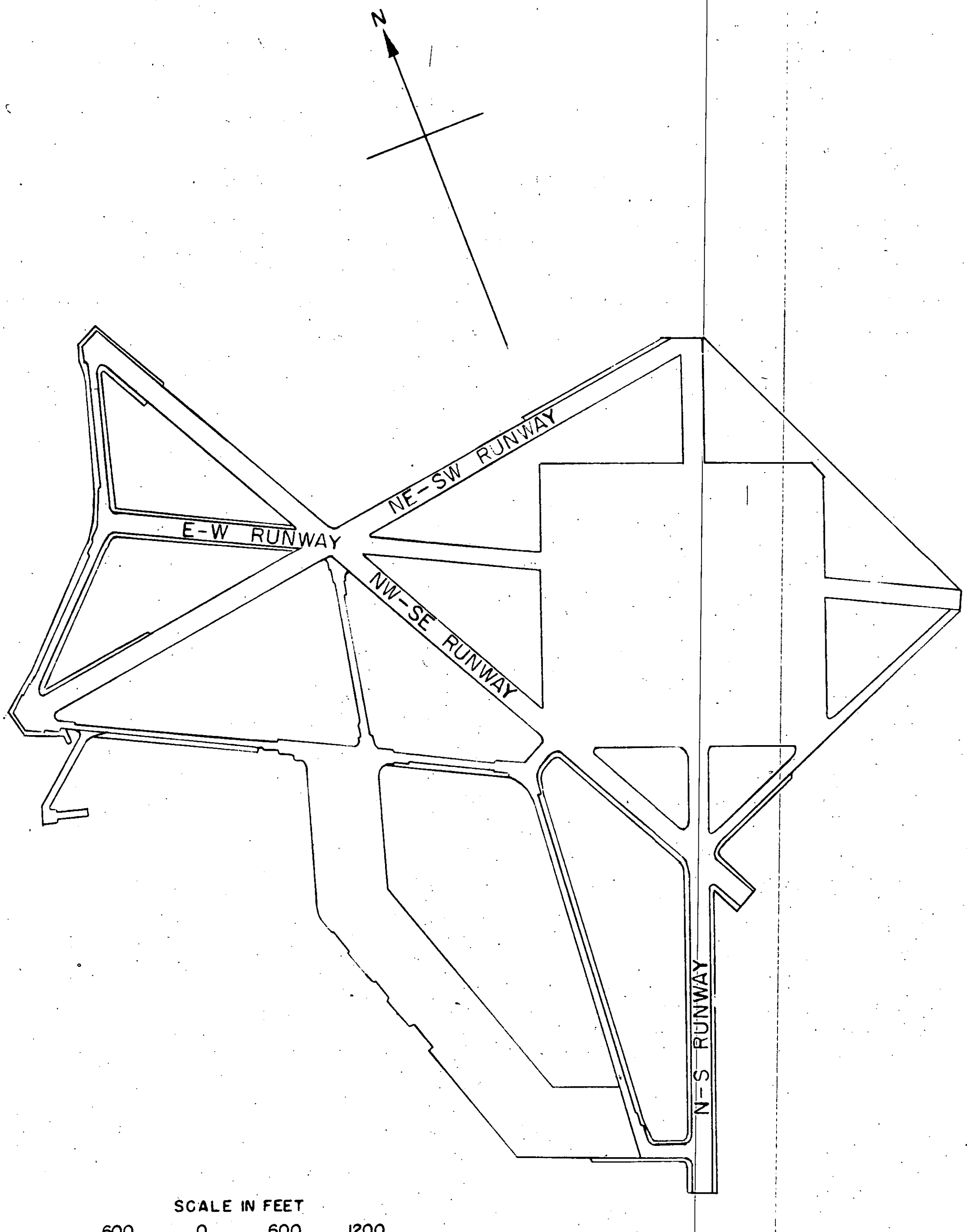
PLATE B-20



SMOKY HILL AIRFIELD
SALINA, KANSAS

PLATE B-21


N
NE-SW RUNWAY
N-S RUNWAY
E-W RUNWAY
SCALE IN FEET
800 0 800 1600
SPOKANE ARMY AIR DEPOT
SPOKANE, WASHINGTON



STEWART FIELD
NEWBURGH, NEW YORK

PLATE B-23

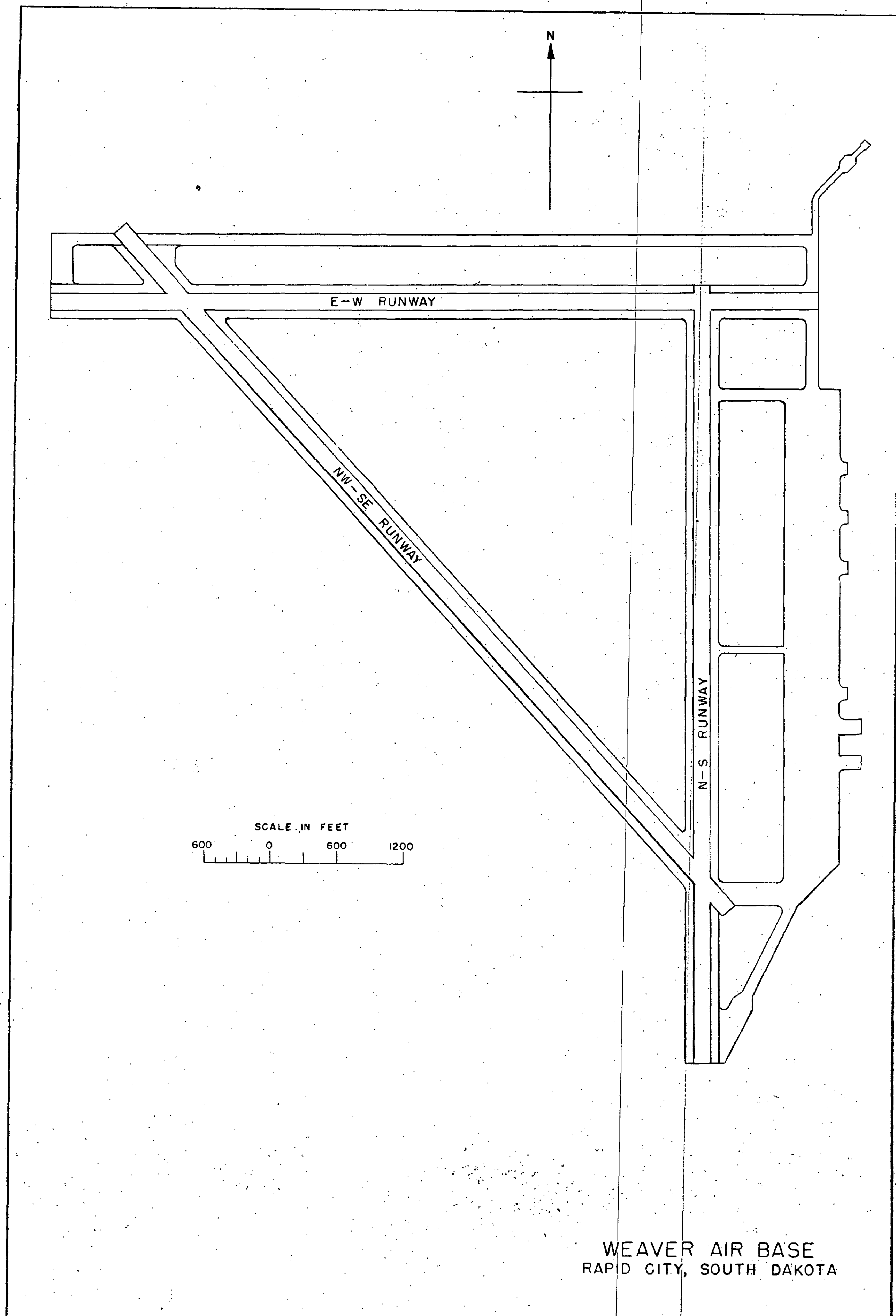

N
E-W RUNWAY
NW-SE RUNWAY
N-S RUNWAY
SCALE IN FEET
600
0
600
1200
WEAVER AIR BASE
RAPID CITY, SOUTH DAKOTA

PLATE B-24

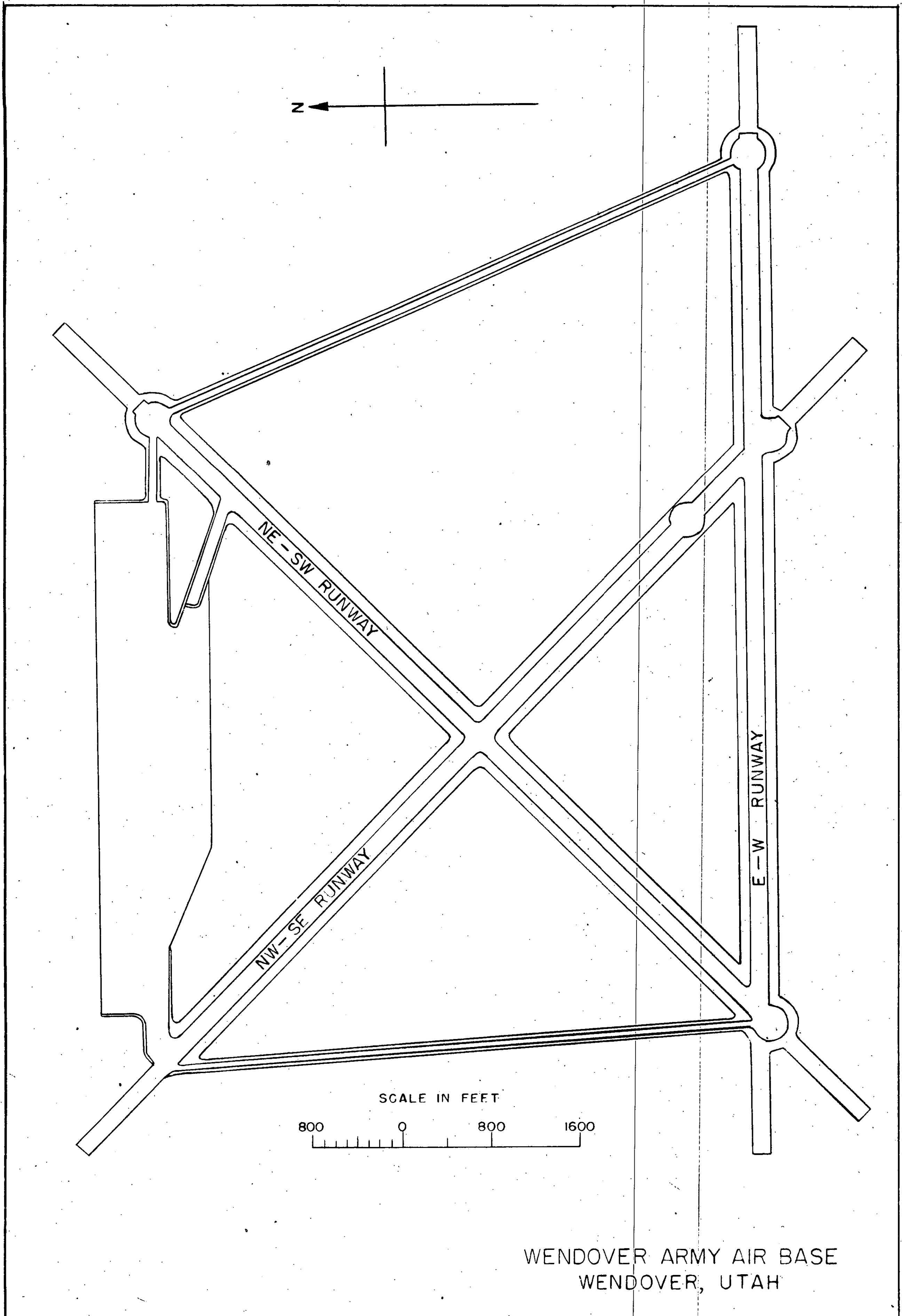
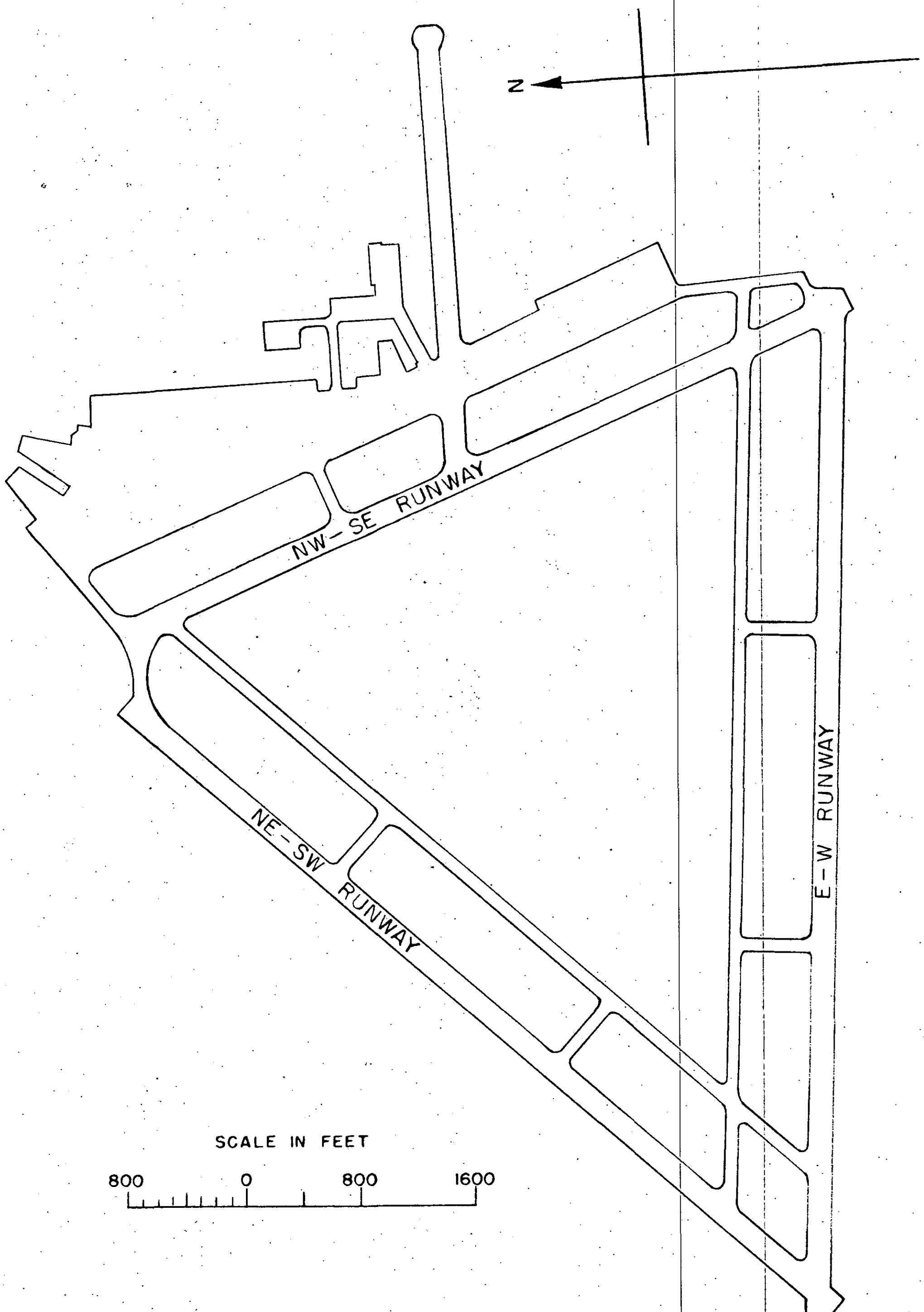

N
NE-SW RUNWAY
NW-SE RUNWAY
E-W RUNWAY
SCALE IN FEET
800 0 800 1600
WENDOVER ARMY AIR BASE
WENDOVER, UTAH

PLATE B-25



WRIGHT FIELD
DAYTON, OHIO

PLATE B-26