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FROST INVESTIGATION
1945-1946

COMPREHENSIVE REPORT

NEW ENGLAND DIVISION
CORPS OF ENGINEERS, WAR DEPARTMENT

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BOSTON, MASS.

COMPREHENSIVE

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REPORT

ON

FROST INVESTIGATION
1945 - 1946

1. Synopsis. The frost investigation program for the fiscal year 1945-1946 was conducted by the Frost Effects Laboratory in the NewEngland Division with the cooperation of the Great Lakes Division and the Missouri River Division. Field investigations were made at nine airfields, with varying subsurface conditions, located in the northern part of the United States and laboratory studies at the Frost Effects Laboratory. The purpose of the investigations was to augment the tests made and data obtained from frost investigations conducted during the years 1944 and 1945 and, if necessary, to recommend changes to Chapter 4, Part XII of the Ad Interim Engineering Manual dated July 1946. This report with nine appendices presents the data obtained during the fiscal year 1945-1946 with the conclusions based on these studies. This report contains a method of predicting the depth of frost penetration, based upon the properties of the soils encountered. A study of the pavement failures which were caused by frost action or to which frost action was a contributing cause is presented. On the basis of these studies, no changes in Chapter 4 of Part XII, Ad Interim Engineering Manual, dated July 1946, are recommended.

2. Introduction.

a. Authorization. - The frost investigation program was authorized by the Chief of Engineers by letter to the Division Engineer, NewEngland Division, dated 4 August 1945, Subject: "Frost Investigation During Fiscal Year 1945-1946." The Boston District was assigned the responsibility for

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organizing the program, obtaining the cooperation of the Missouri River Division and Great Lakes Division in the program, and analyzing and reporting on all the investigations. The Frost Effects Laboratory, established at the Boston District by direction of the Chief of Engineers, as stated in circular letter No. 3221, dated 11 August 1944, with the purpose of carrying out the frost investigation program, was continued in its function.

b. Purpose. - The purpose of the frost investigations during the fiscal year 1945-1946 was; (1) to augment the tests made and data obtained from the frost investigations conducted during the years 1944 and 1945, (2) to study in more detail the factors influencing frost action for cement concrete pavements, and (3) to correlate previous investigations for both rigid and flexible pavements. The purpose of this report is; (1) to unify and summarize the results of observations and tests made at various airfields in the United States, studies of soil properties influencing freezing, theoretical studies of frost penetration, a study of pavement failures to which one of the contributing factors was frost action and (2) with reference to Part XII Chapter 4, "Frost Conditions", Ad Interim Engineering Manual, dated July 1946, to present additional supporting data and recommend revisions, if warranted.

c. Scope. - This report with the appendices presents in detail the summary of the studies, the observations and tests made, and the supporting data for the chapter on Frost Conditions in Ad Interim Engineering Manual. The program consists of the following phases:

(1) The performance of controlled laboratory tests to determine thermal conductivity of frozen soils.

(2) The observation and testing of the effect of frost

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action during the winter of 1945-1946 under paved and turfed airfield areas.

(3) Mathematical studies of frost penetration phenomena.

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

(5) The review and analysis of the results of investigations performed.

The controlled laboratory tests consisted of an investigation of the thermal conductivity of frozen cohesionless soils with different densities and water contents under controlled temperatures to assist in the prediction of depth of frost penetration into cohesionless soils for design purposes.

The observation and testing of the effect of frost action under paved and turfed airfield areas were studied at nine airfields located in northern United States. A total of 23 test areas were investigated at those airfields. Thirteen test areas had flexible pavements and eight test areas had rigid pavements. Two turfed areas were investigated adjacent to paved test areas. The individual test areas were selected to encompass the full range of the following variables influencing frost action:

(1) Air temperature ranging from moderate to severe

(2) Ground water table varying from an elevation near the surface of the pavement to an elevation greater than 25 feet below the pavement surface.

(3) Precipitation during the fall prior to freezing period, varying from light to relatively moderate.

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(4) Base and subgrade materials of various water contents, ranging from relatively dry to saturated.

(5) Subgrades of various materials, ranging from a plastic fat clay to a nonplastic silty gravelly sand and a cohesionless clean sand.

(6) Bases of various materials ranging from a plastic sand-clay-gravel to crushed rock with soil cement at one test area.

(7) Rigid and flexible pavements.

(8) Pavement designs which would support light to heavy aircraft.

Of the 15 airfields investigated during the 1944-1945 period, the following eight were selected for investigations during the 1945-1946 period:

(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 investigations at these fields ranged from a minimum, which consisted of weather observations, heave and subsurface temperature measurements, and ground water observations to more comprehensive investigation which consisted of the above supplemented by periodic observations

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of variations in water content, density, and ice lens formations in base and subgrade soils, and plate bearing tests on the rigid and flexible pavements and on the bases beneath the rigid pavements. One additional airfield, Bedford Airfield, Bedford, Massachusetts, was selected for subsurface temperature measurements and determination of the actual frost penetrations in non-frost susceptible bases and subgrades beneath rigid and flexible pavements.

This report does not include any of the data collected at Selfridge Field, Michigan, where a detailed investigation of rigid pavement conditions, including traffic tests, was made. The investigation conducted at Selfridge Field is presented in the "Report on Frost Investigation and Traffic Tests, Selfridge Field, Michigan," June 1944.

This report does not include any data collected during the study of treatment of soils to prevent frost action. The results of the studies of treatment of soils to prevent frost action are contained in the "Report on Studies of Base Course Treatment to Prevent Frost Action," June 1944.

d. Arrangement of Report. - This report presents a summary and analysis of the data which were obtained from the field and laboratory investigations. Detailed reports of the field investigations are presented in the following appendices which are the basis for the results contained herein.

Appendix No.	Title
1	Report on Dow Field, Bangor, Maine, June 1944, U. S. Engineer Office, Boston, Mass.
2 and 3	Report on Presque Isle Airfield, Presque Isle, Maine, and Bedford Airfield, Bedford, Mass.,

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June 1946, U. S. Engineer Office, Boston, Mass.

4 Report on Truax Field, Madison, Wisconsin, June 1946. U. S. Engineer Office, Milwaukee, Wisconsin

5 and 6 Reports on Pierre airfield, Pierre, South Dakota, and Sioux Falls Airfield, Sioux Falls, South Dakota, June 1946, Missouri River Division Office, Omaha, Nebraska.

7, 8 and 9 Report on Watertown Airfield, Watertown, South Dakota; Fargo Municipal Airfield, Fargo, North Dakota; and Great Bend Airfield, Great Bend, Kansas, June 1946, Missouri River Division Office, Omaha, Nebraska.

e. Definitions. - The description of the tests and analysis of results involve a specialized use of certain terms and words. The words and terms used in this report are defined in the "Glossary" at the end of this report.

f. Acknowledgements. - These studies are based upon fundamental relations developed and presented by previous investigators, particularly S. Taber, A. Casagrande, P. C. Rutledge, and G. Beskow.

This investigation was conducted by personnel of the New England Division, assisted by personnel of the Great Lakes Division and Missouri River Division.

Dr. A. Casagrande and Dr. L. A. Pipes of Harvard University and Dr. P. C. Rutledge of Northwestern University acted in the capacity of consultants.

Acknowledgement is made to the U. S. Weather Bureau for furnishing weather data and to the Post Engineers at various test locations for assistance given in performing tests.

g. Description of Frost Action. - Frost action is defined as the physical phenomenon by which layers or lenses of ice are built up within a soil mass. Three conditions must occur simultaneously for these ice layers to form. These are as follows:

(1) Soil. - Frost action within a soil is a function of its void size which may be conveniently expressed as a function of grain size. In this investigation any soil which contains more than three per cent by weight of grains smaller than 0.02 mm. is considered frost susceptible and a soil in which frost action is possible.

(2) Water. - Frost action depends upon the availability of water either by virtue of an adjacent ground water table or a capillary supply or as water within the soil voids.

(3) Temperature. - Frost action within soils requires the maintenance of freezing temperature slightly below the lower surface of ice lens formation. The greatest accumulation of ice will occur when the penetration of the freezing temperature is slow; a rapid penetration may result in few or no ice lenses.

The process of frost action may be described as follows: The water in the void spaces becomes cooled below the normal freezing temperature of water. This super-cooled water has a high molecular attraction to ice crystals. Thus, the super-cooled water travels to ice crystals, which form in the larger voids, solidifying upon contact. Repetition of this process forms an ice lens. A single lens will continue to grow in thickness, always against the direction of heat transfer, until the formation of a lens

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at a lower elevation cuts off the source of water, or until the temperature rises above freezing.

Frost heaving is directly associated with frost action and is the visible evidence on the surface that ice lenses have formed in the soil mass. The frost boils, as referred to by highway engineers, are caused by a rapid thawing of an area of frost action beneath a flexible pavement. The thawing occurs largely from the surface down under a rapid thaw and the excess water liberated from the thawed area is prevented from draining downward by the still frozen underlying soil and ice layers. The excess water causes the thawed soil to become exceedingly soft. Likewise, the pumping of water from joints in concrete slabs during the spring, may be the result of excess water in the subgrade liberated from thawed ice layers.

3. General Conditions at Sites Investigated.

a. Locations. - The nine airfields selected for this investigation are located in the New England Division, Great Lakes Division, and Missouri RiverDivision. These airfields comprise the varied conditions of soil, temperature, rainfall, and ground water required for comparative study in an investigation of this nature.

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

AIRFIELD	NORTH LAT. (°)	WEST LONG. (°)	AGENCY	ELEV. ABOVE MSL. (ft)	PHYSIOGRAPHY
Dow, Bangor Maine	45	69	New England Div.	170	Glaciated region of rolling hills
Presque Isle, Presque Isle, Maine.	47	68	New England Div.	500	Glaciated region of rolling hills

par. 3a.

AIRFIELD	NORTH LAT.(°)	WEST LONG.(°)	AGENCY	ELEV. ABOVE MSL.(ft)	PHYSIOGRAPHY
Bedford, Bedford, Mass.	42	72	New England Div.	130	Rolling terrain of low relief
Truax, Madison, Wisconsin	43	89	Great Lakes Div.	860	Low level marsh
Pierre, Pierre, South Dakota	44	100	Missouri River Div.	1720	Ravines to predominantly flat plateau
Sioux Falls, Sioux Falls, South Dakota	44	96	Missouri River Div.	[illegible]	Flat float plain
Watertown, Watertown, South Dakota	45	97	Missouri River Div.	1730	Flat to rolling
Fargo Municipal, Fargo, North Dakota	47	97	Missouri River Div.	900	Bed of ancient lake-very flat
Great Bend, Great Bend, Kansas	39	98	Missouri River Div.	1885	Very flat river valley

b. Weather. - Of the nine airfields investigated, Fargo has the greatest normal freezing index. The nine airfields are tabulated in order of decreasing freezing indices, to show the normal freezing index and the approximate dates of the normal freezing period:

AIRFIELD	NORMAL FREEZING INDEX	NORMAL FREEZING PERIOD
Fargo	2646	1 Nov. - 1 Apr.
Presque Isle	2061	10 Nov. - 1 Apr.
Watertown	1781	1 Nov. - 20 Mar.
Pierre	1288	15 Nov. - 15 Mar.
Dow	1275	1 Dec. - 25 Mar.
Truax	1220	20 Nov. - 10 Mar.
Sioux Falls	1216	20 Nov. - 15 Mar.
Bedford	680	1 Dec. - 10 Mar.
Great Bend	50	25 Dec. - 25 Jan.

par. 3b.

Precipitation during the three months prior to the freezing period has been considered to determine its effect on water table and saturation of the subgrade during this critical period. The normal precipitation is greatest at Dow Field where a total of 11 inches is indicated for the three months prior to the start of freezing. The normal precipitation at each airfield is as follows:

AIRFIELD	NORMAL PRECIPITATION DURING 3-MONTH PERIOD PRECEDING FREEZING (Inches)
Dow	11.0
Bedford	10.2
Presque Isle	10.0
Truax	7.0
Sioux Falls	5.9
Great Bend	5.3
Fargo	4.8
Watertown	4.4
Pierre	2.4

Snowfall was greatest in the New England region during 1945-1946, where Presque Isle had a cumulative total of 74 inches; Dow, 64 inches; and Bedford, 78 inches. The cumulative total snowfall at the midwestern airfields ranged from 20 to 46 inches for the 1945-1946 winter.

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 later data from the appendices to this report.

d. Types and Condition of Pavement.- The location of the test areas at each airfield is shown on Plate 2. The thickness and type of pavement for each test area is shown in Table 1. The condition of the surfaces of the pavements prior to investigations is briefly summarized below. Crack surveys were made during the normal period and after the frost melting periods at Presque Isle, Dow, Pierre, and Sioux Falls

par. 3d.

Airfields. The surveys are presented in the respective appendices.

AIRFIELD	TYPE OF PAVEMENT AND THICKNESS IN INCHES	CONDITION
Dow Field		
Test Area F	7 P.C.C.	Fair - About 20 % of area cracked.
Test Area D and E	3.5 B.C.	Good - Scattered longitudinal cracks along construction lanes.
Presque Isle		
Test Area A	7 P.C.C.	Good - Few small cracks.
Test area C and D	3.5 B.C.	Good - Few small cracks and depressions.
Bedford		
Test Area A	6 P.C.C.	Good.
Test Area B	5 B.C.	Good.
Truax		
Test Area A	2.5 B.C.	Good - Minor cracking.
Test Area C	6 P.C.C.	Good - Minor cracking and depressions.
Test Area D	2.5 B.C.	Good.
Pierre		
Test Area A	7 P.C.C.	Good - Few cracks, minor ponding condition.
Test Area C and D	5.5 B.C.	Good - Minor cracking and depressions, ponding.
Sioux Falls		
Test Area A	2 B.C.	Fair - Numerous cracks.
Test Area B	6 P.C.C.	Good - No cracks.
Watertown		
Test Area A	8 P.C.C.	Good.
Test Area B	5 B.C.	Good.

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AIRFIELD	TYPE OF PAVEMENT AND THICKNESS IN INCHES	CONDITION
Fargo		
Test Area A	1.5 B.C.	Transverse cracking and minor deformations. Area sealed in good condition prior to start of tests.
Great Bend		
Test Area A	7 P.C.C.	Good.

e. Bases. - Sand and gravel base courses, predominately of GW classification, range in thickness from zero to 49 inches. The grain size distribution curves for these base courses, show that several samples of each test area contain more than three per cent by weight finer than the 0.02 mm. size. At Truax, the subbase underlying a crushed rock base, is a frost susceptible material because of its sandy clay content. At Presque Isle, four inches of crushed rock overlies a sand and gravel base in Test Areas C and D. A soil cement base course, 6.5 inches thick, is located under the bituminous concrete wearing surface in Test Area A at Fargo. One test area at Sioux Falls and one at Watertown have pavements constructed directly on frost - susceptible subgrades. The classification and grain size curves for base course materials in each test area are shown in Figure 4 on Plates 3 to 8 inclusive.

f. Subgrades. - A wide range of subgrade soils are found in the test areas. Predominant are the silty clays and silty-clayey gravels of CL and GC classification, respectively. All subgrade soils with the exception of Bedford are frost susceptible, with four to 97 per cent finer by weight than 0.02 mm. in size. Plates 3 to 8 inclusive show description, classification, and grain size curves of the predominating subgrade soils.

g. Ground Water. - Of the nine airfields investigated, five airfields, Dow, Presque Isle, Bedford, Truax and Fargo, have ground water tables from two to about eight feet below pavement surface. Three airfields, Watertown, Sioux Falls, and Great Bend, have water tables from about 10 to 14 feet in depth, and one airfield, Pierre, has a ground water table more than 25 feet below the ground surface.

h. Drainage. - The surface and subsurface drainage facilities at the several test areas are summarized in the following tabulation:

AIRFIELD	TEST AREA	SURFACE DRAINAGE	SUBSURFACE DRAINAGE
Dow	D and E	Surface runoff from ℄ pavement collected by catch basins located 75 feet from ℄ and spaced 225 feet longitudinally.	Eight-inch non-reinforced concrete pipes, open joints, 4-foot depth, backfilled with bank-run sand and gravel.
	F	Surface runoff from ℄ pavement collected by drains located at edge of pavement 175 feet from ℄.	Eight-inch V.C. underdrain 100 feet from taxiway ℄.
Presque Isle	A	Surface runoff from pavement collected by catch basins in valley in apron area and pavement edge.	Base course continued through shoulder to edge of fill on one edge.
	C and D	Surface runoff from pavement and shoulder collected by shallow turf or rock gutters which drain to a catch basin at end of taxiway.	Six-inch open joint pipe, five-foot depth backfilled with sand and gravel at outside edge of surface treated gravel shoulders.
Bedford	A	Surface runoff collected by catch basins located in shallow gutters in pavement area with closed joint drains.	None

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AIRFIELD	TEST AREA	SURFACE DRAINAGE	SUBSURFACE DRAINAGE
Bedford (Cont.)	B	Surface runoff collected by catch basins located at edges of original pavement and also at edges of present pavement, connected with closed joint drains.	Open joint drains 75 feet from ℄, originally part of surface drainage system.
Truax	A	Surface runoff from ℄ of pavement to edge of shoulder collected by catch basins in shallow gutter at shoulder edge.	None.
	C	Surface runoff from pavement and adjoining turf area collected by catch basins in turf area at low points.	Trench filled with sand and gravel and containing a V. C. pipe with open joints along south edge. None at north edge.
	D	Surface runoff from ℄ of pavement to edge of shoulder collected by catch basins in shallow gutter at shoulder edge.	Perforated tile pipe in trenches filled with coarse sand at edges of pavement. Top two inches is clay top soil.
Pierre	A	Surface runoff collected by shallow swales at edge of shoulders.	None
	C and D	Surface runoff collected by shallow swales at edge of shoulders.	None
Sioux Falls	A and B	Surface runoff collected by shallow swales at edge of shoulders.	None
Watertown	A and B	Surface runoff drains to shallow swales at edge of pavement.	None
Fargo	A	Surface runoff from pavement collected by combination drains at pavement edges.	Combination drains backfilled with coarse aggregate located in shoulder with open joint pipe in trench.

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AIRFIELD	TEST AREA	SURFACE DRAINAGE	SUBSURFACE DRAINAGE
Great Bend	A	Surface runoff collected by drainage swales to north and east and by drainage into sump ponds.	None

4. Results.

a. Tests for Soil Classification. Laboratory tests, including sieve analysis, hydrometer analysis and determination of Atterberg limits and specific gravity were conducted on representative base, subbase, and subgrade materials during the previous 1944-1945 investigation. Additional tests were conducted, for checking, and where required during the 1945-1946 investigation. The soils were classified in accordance with airfield classification as outlined in the Ad Interim Engineering Manual, Part XII Chapter 2, dated July 1946. The specific purpose for grain size distribution curves was to determine whether or not the base, subbase or subgrade materials were frost susceptible. Grain size distribution curves and classification data for typical materials and typical logs for each test area are shown on Plates 3 to 8 inclusive. A summary tabulation of the results of tests, including Atterberg limits, soil classification and percentage by weight of particles finer than 0.02 mm 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 airfield or from the A.A.F. Weather Officer at the specific airfield. Cumulative rainfall for the months of September to December and

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snow-fall record are shown on Plates 3 to 8 inclusive. Tabulation of the record 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 1945 to June 1946 by means of observation wells in the base and subgrade. Those measurements were augmented by excavation of test pits at periodic intervals. Depth of ground water from the surface of the pavements is plotted against time in Figure 5 on Plates 3 to 8 inclusive. Tabulation of the depth of the water table from the surface of the pavement for the various periods is 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 period, during the freezing period, during the frost melting period and during the period when subsurface conditions were normal, generally in May or June. The specific time for the excavation of the test pits was based on previous data. The variation in density and water contents for the subgrade and base materials durin these periods is shown graphically for all test areas in Figure 9 on Plates 3 to 8 inclusive. Results are also summarized in Table 1.

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(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, water content and specific gravity of the various materials. Variations in the degree of saturation during these periods are shown in Figure 9 on Plates 3 to 8 inclusive. The average degree of saturation of the base and subgrade materials for the various testing periods is summarized in Table 1.

c. Tests for Temperature. Air temperature measurements were made or obtained at all airfields investigated. At 19 test areas measurements of subsurface temperature were made.

(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 airfields, these were supplemented by U.S.E.D. thermographs, located at the test areas. Air temperature data in the form of degree day curves are shown in Figure 1 on Plates 3 to 8 inclusive, for the normal winter, winter of 1945-46, and where available, for the winter of 1944-45. The normal freezing index, the freezing index for 1945-46, and the percentage above or below normal for 1945-46 are included in Table 1.

(2) Subsurface Temperatures. Subsurface temperatures were measured by two methods: copper-constantan thermocouples and glass bulb thermometers. The thermocouples

were embedded in the pavement and the soil beneath pavement or turf at various depths up to eight feet; the temperatures were read directly from potentiometer type instruments. Partial immersion thermometers were suspended in approximately three inches of antifreeze contained in "Saran" pipes which were installed in thermometer wells excavated to various depths. A complete description of temperature measuring installations and measurements is presented in the appendices. The following table indicates the test areas at the various airfields in which thermocouple and thermometer installations were made:

AIRFIELD	TEST AREA	
	Bituminous Concrete	Cement Concrete
Dow*	Thermocouple and Thermometer	Thermocouple and Thermometer
Presque Isle*	Thermocouple and Thermometer	Thermocouple and Thermometer
Bedford	Thermometer	Thermocouple and Thermometer
Truax	Thermometer	Thermometer
Pierre**	Thermocouple and Thermometer	Thermocouple and Thermometer
Sioux Falls	Thermocouple and Thermometer	Thermometer
Watertown	Thermocouple and Thermometer	Thermocouple
Fargo	Thermometer	
Great Bend		Thermometer

*Thermocouples and thermometers were also installed in Turf areas.
**Thermocouples were also installed in a special test box.

The subsurface temperatures obtained by thermocouple and thermometer installations were compared to determine

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whether any appreciable difference existed between the two methods. At Presque Isle, Dow, and Watertown a group of thermometer wells were installed within a 10-foot radius of a thermocouple installation. A study of eight typical sets of readings through the period of this investigation show that approximately 50 per cent of the thermocouple readings are greater, 35 per cent less and 15 per cent equal to the thermometer well readings. Variations between the two methods were generally from one to two degrees, although a few readings differed by three to six degrees F. The disagreement between the two methods may be the result of actual differences in the soil temperatures between thermocouple and thermometer well locations. In general, it is indicated that thermocouples or thermometers are equally reliable for use in the measurement of subsurface temperatures. Typical subsurface temperatures as determined by both thermometers and thermocouples are plotted on Plate 9 for purposes of comparison. The variations in temperature from the surface to depths up to eight feet during the winter and frost melting periods are shown in the various appendices by plots oriented with the soil profile. In Figure 8 on Plates 3 to 8 inclusive are shown plots of the 32°F. subsurface temperatures from December to April with respect to depth. Similarly plotted on these charts are the depths of frost penetration obtained by excavation of test pits.

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d. 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 measurements of ice lenses referred to soil profile for each test area are shown in Figure 6 on Plates 3 and 8 inclusive. These data are summarized in Table 1. The ice lenses observed in the subgrade occurred in non-continuous horizontal layers, ranging from 0.75 inch to hairline in thickness, and were generally spaced irregularly less than 0.5 inch apart, with the lenses becoming thicker and more closely spaced near the bottom of the frost penetration. No ice lenses were observed in the base materials at the airfields, except in the base materials in Test Area C and sub-base materials in Test Areas A and D at Truax. 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 Test Area A at Presque Isle. Small, thin, scattered ice lenses were observed during the freezing period at all test areas at Pierre and Sioux Falls. No ice lenses were found at Bedford. No observations were made at Watertown, Fargo and Great Bend.

(2) Pavement Heave. The pavement heave was measured by means of level surveys during the normal, freezing,

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and frost melting periods at Dow, Presque Isle, Truax, Pierre, Sioux Falls, Watertown and Fargo Airfields. The amounts of heave are shown on Table 1 and in Fig. 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 foot). The average pavement heave at all test areas except those at Dow, Presque Isle, Truax 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 very small amount while the pavement at the edges heaved. This type of heaving is best illustrated at Watertown as shown by Plate 6, Appendix 7.

e. Field Measurements of Frost Penetration. The depth of frost penetration and the rate the frost entered the ground were obtained by observations in test pits, beginning at the start of freezing and extending to the end of the frost melting period. 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. It will be noted, from inspection of Figure 8 on Plates 3 to 8 inclusive, 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.

f. Studies of Soil Properties Influencing Freezing. The principal soil properties influencing freezing are: thermal conductivity, latent heat, volumetric heat, and freezing temperatures of soil moisture. The following paragraphs present the information and data obtained to date regarding these several properties.

(1) Laboratory Studies of Thermal Conductivity. Tests for thermal conductivity were continued as performed during the 1944-1945 Frost Investigation. The tests described in "Report on Laboratory Tests on Frost Penetration and Thermal Conductivity of Cohesionless Soils", Paragraph 7, pages 10-15, Appendix 13 of the 1944-1945 Comprehensive Report, pertain to material tested in the unfrozen state. During the 1945-1946 Frost Investigation, tests were made on similar materials in the frozen state.

(a) The investigations were performed in the soils laboratory cold room at Harvard University Graduate School of Engineering, Cambridge, Mass. The cold room could be regulated to any air temperature between 30° F. and 50° F. and the temperature in the air space above the drawers in a freezing cabinet could be regulated to any temperature from that of cold room to minus 10°F. The materials tested for thermal conductivity in the frozen state consisted of sand, sand and gravel, cinders, slag, and crushed rock. These materials are non-frost susceptible and are commonly used for base course construction. Gradation of materials tested is as shown in Figure 3, Plate 10. The test specimens were cylindrical in shape, 5.36 inches in diameter and 10.67 inches in height and were contained in a brass cylinder of 1/16 inch wall thickness. The materials were placed in the test cylinders at a uniform density and desired water content. The tops and the bottoms of the cylinders were sealed. A thermocouple was placed at the exact midpoint of each cylinder. Each test consisted of subjecting the test cylinder to a constant freezing temperature of approximately minus 4° F., inside the freezing cabinet until temperature equilibrium was reached, and then immersing it into a brine bath in the cold room at a constant temperature of approximately 27° 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 reached.

The data obtained from these tests are compared with similar tests made during the 1944-1945 Frost Investigation wherein unfrozen specimens were used. Table 2 contains a summary of test data showing the comparison between the unfrozen and frozen groups of thermal conductivity tests. Plate 11 contains plots of the same test results shown in Table 2 to illustrate the greater thermal conductivity for frozen material as the water content is increased. Plate 10, Figure 1 presents curves which were developed to obtain the "time factor" for temperature change at center of a cylinder. Plate 10 also shows an example, for determination of the thermal conductivity by use of these curves and data.

(b) In addition to the tests performed by this office as described in the preceding paragraphs and those reported by H. E. Patten and summarized in "Report on Laboratory Tests on Frost Penetration and Thermal Conductivity of Cohesionless Soils", Paragraph 7, pages 10-15, Appendix 13 of the 1944-1945 Frost Investigation, other investigators have made determinations of the thermal conductivity of frozen and unfrozen soil. The results of these studies are summarized in Table 3. It will be noted that values for unit dry weight of soil as tested were not determined by some investigators. Shanklin stated that in his tests the soil was well tamped. Also, it is not certain whether water content is expressed as a percentage of the dry or the wet weight in these tests.

(c) From the data collected, the following results are summarized:

1. The thermal conductivity of cohesionless soils in the frozen state is greater than in the unfrozen state, at high water contents and is approximately equal at low water contents.

2. The thermal conductivity of most types of soils increases with increasing water content and increasing unit dry weight.

3. A reasonable range of thermal conductivity of most soils frozen or unfrozen is from 0.6 to 1.5 BTU/ (ft.)(hr.)(°F.). This range does not include the organic soils such as peat, soils of volcanic origin, or other soils which may be expected to differ in thermal properties. An average value of 1.3 BTU/(ft.)(hr.)(°F.) has been used for the thermal conductivity of soil in this report as described in paragraph 6d. below.

(2) Latent Heat of Soil Moisture. The single most important property influencing depth of freezing is the latent heat of the soil moisture. Latent heat is the heat required to change water at 32° F. to ice at 32° F. The Bureau of Public Roads (1) has performed tests to determine the percentage of water in soil which freezes; this percentage determines the latent heat. In the

(1) Public Roads, February 1925, "Percentage of Water Freezable in Soils".

tests performed, the entire soil specimen was subjected to below freezing temperature and water content of the soil maintained constant during a test. These tests indicate, for the conditions tested, that all water in a clean quartz sand (standard Ottawa sand) froze at 0°C and from 32 to 83 per cent of the water in soils containing silt and clay, froze at a temperature of minus 1.5°C, (29.3°F.), the percentage of water freezing depending approximately upon the amount of fines. Based upon a few tests they concluded that the percentage of water frozen is independent of the water content.

The tests performed at Harvard University (2) (3) on a plastic clay indicate that for the conditions tested about 33 per cent of the original water in the clay froze at a temperature between minus 1.0° C and minus 2.0° C. (30.2°F. to 28.4°F.).

It is believed that the percentage of water which will freeze in a soil is primarily dependent upon:

(a) The relative quantities of free water and capillary water present.

(b) The presence of soluble salts.

(c) The temperature.

(d) The molecular attraction between soil particles and water and between ice and water.

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(2) "Ice Pressure Determinations in Clay Soils" Engineering News Record, 25 July 1935.

(3) Mackintosh "Progress Report on Investigation of Frost Action in Soils" Proceedings of International Conference on Soil Mech. and Foundation Engineering.

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Based upon the relatively few number of tests performed together with observations in the field, it is believed that, for all practical purposes, all water in clean cohesionless soils of the GW, GP, SW, and SP classification will freeze at 32°F. In silt soils of the ML classification most of the water may be expected to freeze at 32°F. In the remaining soils of GC, GF, SC, SF, CL, OL, MH, CH, and OH classification the percentage of water in the soil which will freeze will be less than its water content and will depend upon the factors listed in the preceding paragraph. It is believed that the range of values for the quantity of water frozen for usual conditions encountered may vary from 35 to 80 per cent. Figure 1, Plate 12 shows the relationship between density in pounds per cubic foot and latent heat of fusion in BTU per cubic foot for various water contents in percentage of dry weight.

Where there are several soil layers at different water contents the average latent heat may be determined using the following equation:

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

where

L is average latent heat in BTU/cu. ft.

L_1, L_2, L_3, etc., are latent heats of layers 1, 2, 3, etc.

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d_1, d_2, d_3, etc., are thicknesses of layers 1, 2, 3, etc., in feet.

It will be noted that $d_1 + d_2 + d_3 + \cdots d_n$ equals estimated depth of freezing.

(3) Volumetric Heat of Soil. The volumetric heat of a soil is the heat required to raise a unit volume of soil, including water or ice, a unit of temperature. The volumetric heat is dependent upon the unit dry weight of the soil, the specific heat of the dry soil, the water content of the soil, the specific heat of water, and the specific heat of ice. It has been demonstrated by various investigators (1) 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 12 shows the relation between unit dry weight, water content, and volumetric heat for average values of the specific heat of soil, water, and ice.

The average value for the specific heat of a dry soil has been assumed at 0.2 BTU/(lb.)(°F). There are tabulated below to substantiate this assumption a number of values for specific heat for various soils, rocks, and minerals obtained from "Handbook of Chemistry and Physics" 1945 Edition, and "Mechanical Engineers' Handbook" by Marks, 1941.

(1) H. E. Patton, "Heat Transference in Soils" Bulletin 59, U. S. Dept. of Agriculture, 1909.

MATERIAL	SPECIFIC HEAT BTU/(lb)(°F)	MATERIAL	SPECIFIC HEAT BTU/(lb)(°F)
Asbestos	0.195	Dolomite	0.222
Basalt	0.20	Gneiss	0.18
Calcspar	0.200	Hornblende	0.195
Cement	0.20	Kaolin	0.224
Chalk	0.214	Humus (soil)	0.44
Clay, dry	0.22	Salt, Rock	0.21
Granite	0.192	Sand	0.195
Marble	0.21	Sandstone	0.22
Mica	0.206	Serpentine	0.25
Quartz	0.188	Talc	0.209
Cinders	0.18		

Average values for the specific heat of ice and water of 0.5 and 1.0 BTU/(lb.)(°F.) respectively, have been used in this report.

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.

$$c = \frac{c_1 d_1 + c_2 d_2 + c_3 d_3 + \cdots c_n d_n}{d_1 + d_2 + d_3 + \cdots d_n}$$

where

c_1, c_2 etc., are volumetric heats in frozen or unfrozen state for layers.

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d_1, d_2, etc., are thicknesses in feet of layers 1, 2, etc., to a total depth of fifteen feet.

c is the weighted average volumetric heat in BTU/(cu.ft.)(°F).

When the soil is fully saturated, the volumetric heat of unfrozen soil is nearly constant, varying from 40 to 45 BTU/(cu.ft.)(°F) for reasonable limits of unit dry weight and for frozen soil it may be considered constant at approximately 33 BTU/(cu.ft.)(°F).

(4) <u>Freezing Temperature of Soil Moisture.</u> For computing the freezing index and for mathematical studies, the assumption is made that the freezing temperature of soil moisture is 32° F. This assumption is open to question, considering the tests made by various investigators, to determine the freezing temperature of soil moisture. Bouyoucos (1) found that, cohesionless soils could be super-cooled without agitation to a temperature of 24.4° F; cohesive soils to 23° F before they froze; distilled water to 21.2° F before it froze; and by constant agitation soil could be cooled to about 30.2° F before it froze.

The Bureau of Public Roads (2) has performed tests to determine the freezing point of soil moisture in fine grained soils. Their experiments led to the conclusion that the freezing temperature of fine grained

(1) Bouyoucos, G. "Degree of Temperature to which Soils Can Be Cooled Without Freezing". Journal of Agricultural Research, November 1920.

C.F. (2) Public Roads, Feb. 1925; "Percentage of Water Freezable in Soils".

soils tested is not at 0° C, but somewhat lower; in some cases it was found to be below minus 1.5° C (29.3° F). The soil moisture in one sample of clean quartz sand (standard Ottawa sand) froze at 0° C (32.0° F).

Tests performed at Harvard University (1) may be utilized to determine the temperature at which water in a plastic clay soil freezes in icelenses. The clay was placed in a container at an average water content of 42.4 per cent with a layer of powdered mica beneath, at an average water content of 75.3 per cent. This sample was gradually frozen from the top downward, resulting in the formation of ice lenses. As the ice lenses developed, water was drawn from the mica layer. Thermocouples imbedded in the test specimen were used to determine the temperature gradient. When the specimen was frozen to about two-thirds the thickness of the clay, it was removed from freezing cabinet, examined and tested for water content. The clay between the ice lenses was plastic and at a water content of 27.2 to 28.9 per cent or slightly above the plastic limit. Measurements indicated the temperature in the zone of ice lenses ranged from minus 1.0°C to minus 2.0°C (30.2°F to 28.4°F). Other tests at Harvard

(1) Engineering News Record, 25 July 1935, "Ice Pressure Determinations in Clay Soils".

(2) indicate that the temperature at the boundary between the ice lenses at the lowest elevation and the unfrozen clay below was minus 0.7° C and minus 0.5° C (30.7°F and 31.1°F) for two specimens reported. These observations indicate that the freezing temperature of soil moisture of a plastic soil is a function of the water content.

The freezing temperature of soil moisture may be determined by comparison of the depth of frozen soil as measured by test pits with the soil temperature at that depth determined from adjacent thermocouples or thermometers. In making such a comparison, it should be remembered that soil temperature is dependent upon several variables and hence soil temperatures at two separated locations may be slightly different. In Table 4, are tabulated, values for the depth of frozen soil determined by excavation of test pits and the temperature at that depth, as determined by thermocouples or thermometers located adjacent to the test pits.

A study of this tabulation indicates that, with certain exceptions, the temperature at the bottom of frozen soil was approximately 32° F, or slightly above. The arithmetic average of all observations is 33.0°F. Discounting the unreasonable values (those above 34°F) the average is 32.0° F.

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(2) Mackintosh "Progress Report on an Investigation of Frost Action in Soils"; Proceedings of the International Conference on Soil Mechanics and Foundation Engineering, 1936.

Observations by Fuller (1) at Portland, Maine, in a gravel soil and in a clay soil indicated that the temperature at the bottom of frozen layer was 32.5° F for each soil.

These date indicate the following:

(a) The freezing temperature of soil moisture in clean cohesionless soils is approximately 32°F.

(b) The freezing temperature of soil moisture in fine grained soils depends upon its water content and percentage of fines.

(c) Field measurements indicate that, pending more complete data, it is reasonable to use a value for the freezing temperature of soil moisture of 32° F.

The effect of the freezing temperature of soil moisture at the boundary between frozen and unfrozen soil upon the predicted depth of freezing may be computed using the formula developed below. If the freezing temperature of soil moisture is 31°F, the predicted depth of freezing is about two inches less than the depth for a freezing temperature of 32° F. For each additional degree F that the freezing temperature as below 32°F, the depth of freezing is about three

(1) Fuller, H.U., "Studies of Frost Penetration" Journal N. E. Water Works Association, September 1940.

inches less. Thus for a 28° F freezing temperature of soil moisture at boundary between frozen and unfrozen soil the depth of freezing would be about 11 inches less than the depth determined for a 32° F freezing temperature.

g. **Mathematical Studies of Soil Temperature Conditions.** A comprehensive mathematical study of the temperature conditions in a semi-infinite, homogeneous and isotropic soil mass due to variations in air temperature has been made. The problem would lend itself readily to such analyses if it were not for the latent heat which is given up by moist soil as it passes from above to below freezing temperatures. In pursuing these studies full use of the literature available has been made.

These studies were performed principally by Dr. L. A. Pipes, Harvard University. The results of his studies are presented in Supplement A in condensed form as problems No. 1 to 14. Problems 1, 2, 3, 4, and 5 have been placed in a form convenient for computing values for the thermal conductivity or thermal diffusivity and apply only to cases where temperatures are above freezing or where no latent heat is involved. Problem 6 has been placed in a form convenient for computing the depth of frost penetration neglecting the latent heat of fusion. Problems 5 and 7 it will be noted, deal with the case of a surface layer whose thermal properties are different from the underlying semi-infinite, homogeneous and isotropic soil mass. These solutions do not include latent heat. Problems 8, 9, and 12 are simple cases, considering that either the latent heat or the volumetric heat capacity due to specific heat are predominant. Problems 10, 11, and 14 consider both latent heat and a portion of the volumetric heat and hence are more general solutions. Problem 13 is for particular application to the melting of a layer of soil overlying permanently frozen soil at a constant temperature. The principal assumptions are included in the presentation of each problem. The detailed development of each equation is on file in the New England Division Office.

In addition to these 14 problems, supplemental studies consisting of Problems 15, 16, and 17 were made by personnel of the New England Division to further develop equations for predicting depth of freezing and thermal properties from observed data. The principal difference between Problems 1 to 14 and 16 and 17 is in the assumption of temperature distribution in the soil. The first set of problems 1 to 14 inclusive assumed (a) that the soil temperature is determined by the air temperature and may be expressed mathematically as a function of the air temperature and (b) that the volumetric heat below the depth of freezing may be neglected together with all or some of the volumetric heat in the frozen layer. Apparently, these two assumptions do not express adequately, the results of limited observed data. These data indicate that the temperature gradients in a soil mass subjected to surface temperatures below freezing are reasonably constant during the period of soil freezing as illustrated by Figure I, Plate A-1, Supplement A. Problems 15 and 16 are based upon the assumption of a constant temperature gradient and, in addition, include the total volumetric heat above and below depth of freezing, together with the total latent heat. Problem 15 is an attempt to evaluate the effect of the air film at a pavement surface on depth of freezing. Problem 17 considers the effect of a surface insulation layer.

h. Tests for Flexible Pavement Supporting Capacity.- The supporting capacity of flexible pavements was investigated by means of

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plate bearing tests conducted during the normal period and the frost melting period. The field test procedures for plate bearing tests were the same as used during the 1944-1945 investigations and are described briefly in the following paragraphs.

(1) The static load tests were conducted in the manner described in the Engineering Manual, Chapter XX, Paragraph 20-41 except that a 30-inch diameter plate was placed directly on top of the bituminous concrete pavement.

(2) The repeating load test used the same type and arrangement of testing apparatus as required for the static load test except that a 24-inch diameter plate was used which was also placed on top of the bituminous pavement. The repeating load test was conducted in the following manner. A seating load of 3500 pounds was applied for five minutes and released. A load of 20,000 pounds was then rapidly applied in one increment. The load was maintained for ten minutes during which the deformation was measured at the end of 0.25, 1, 2.25, 6.25, and 10 minutes. The load was rapidly released and deformation readings taken at the end of a 5-minute period. The foregoing procedure was then repeated until ten load repetitions had been made.

Plate bearing tests were conducted at Dow, Presque Isle, Truax, Pierre and Sioux Falls Airfields. At these airfields tests were conducted during the fall and during and after the frost melting period, except at Presque Isle where tests were not made during the frost melting period.

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Figure 10, Plates 3 to 8 inclusive, presents the average results of the static tests. Detailed results of all plate bearing tests are presented in the appendix for the specific airfield. In general, the results are summarized for each field as follows:

(1) Dow. Results of the static-load plate bearing tests, as plotted on Plate 16, indicate that the ratio of loads to produce a 0.1-inch deflection of the plate in the normal period to the frost melting period at the average thickness of frozen subgrade of 0.8 foot is 1.7. The repeating-load plate bearing tests show that the same load in the normal period produced about 0.7 of the deflection obtained during the frost melting period.

(2) Presque Isle. Results of the static-load plate bearing tests, as plotted on Plate 16, indicate that the ratio of loads to produce 0.1-inch deflection of the plate in the normal period to the frost melting period at the average thickness of frozen subgrade of 3.1 feet is 2.2. The repeating-load plate bearing test shows that the 20,000-pound load in the normal period produced about 0.4 of the deflection obtained during the frost melting period.

(3) Truax. Results of static-load plate bearing tests, as plotted on Plate 16, indicate that the ratio of the loads to produce a 0.1-inch deformation of the plate during the normal period to the frost melting period

at an average thickness of frozen subgrade of 1.3 feet is 4.3. The repeating-load plate bearing tests show that the 20,000-pound load in the normal period produced from 0.24 to 0.54 of the deflection obtained during the frost melting period. The repeating-load plate bearing tests indicate that the reduction in pavement supporting capacity extends over a period of about three months after the sudden decrease during the frost melting period.

(4) **Pierre.** Results of the static-load plate bearing tests, as plotted on Plate 16 indicate that the ratio of loads to produce 0.1-inch deflection of the plate in the normal period to the frost melting period at the average thickness of frozen subgrade of 2.6 feet is 1.6. The repeating-load plate bearing tests show that the 20,000 load in the normal period produced about 0.9 of the deflection obtained during the frost melting period.

(5) **Sioux Falls.** Results of the static-load plate bearing tests, as plotted on Plate 16 indicate that the ratio of loads to produce 0.1-inch deflection of the plate in the normal period to the frost melting period at the average thickness of frozen subgrade of 2.9 feet is 2.7. The repeating-load plate bearing tests show that the 20,000-pound load in the normal period produced about 0.4 of the deflection obtained during the frost melting period.

i. Tests for Rigid Pavement Supporting Capacity.- The supporting capacity of rigid pavements was investigated by means of plate bearing tests conducted during the normal period and the frost melting period. Additional investigations of rigid pavement conditions at Selfridge Field consisting of traffic tests, explorations, pavement rupture tests, subgrade modulus tests and ground water and subsurface temperature measurements are reported separately in a report "Frost Investigations and Traffic Tests, Selfridge Field, Michigan", U. S. Engineer Office, Detroit, Michigan, June 1946.

The field test procedures for the plate bearing tests were the same as used during the 1944-1945 investigations and are described briefly as follows: (1) The rupture tests were made directly on the surface of the pavement using a 24-inch diameter plate placed at a corner of a slab made by the intersection of a longitudinal construction joint and transverse expansion joint. The edge of the plate was about three inches from the slab edges. The following test procedure was followed: The plate was seated on a thin layer of sand. Two extensometers were placed in a line bisecting the right angle formed by the pavement joints. The load was applied in successive totals of 20, 30, 35, 40, 45, 50, 55 and 60 thousand pounds. If the available load was not sufficient to cause failure, the loading was released in one decrement and reloaded by increments to the maximum total load. This procedure was repeated until rupture occurred or for a total of five repetitions. (2) The subgrade modulus tests were conducted on the surface of the base material after the removal of part of the slab at the same location as the rupture tests. The tests were conducted as far from the location of the plate for the rupture test as practicable.

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The surface of the base was carefully leveled and a thin layer of fine, dry sand, was used to seat the bearing plate. A load equivalent to five pounds per square inch, rapidly applied and released, was used to obtain additional seating of the plate before beginning the test. Deflections were measured by two extensometers bearing on opposite sides of the bearing plate, the extensometers being mounted on a beam independent of the influence of deflections caused by test loads. Load increments were applied at the rate of five pounds per square inch, each increment being held constant until the increase in deformation for that increment of loading, during a five minute period, was less than three per cent of the total deformation for that increment. Loadings were applied until either a total deformation of 0.3 inch was obtained or the capacity of the loading equipment reached. Only single cycle loadings were used to determine subgrade modulus. The load deflection data obtained from the subgrade modulus tests were used to determine subgrade modulus by means of the formula $K_u = \frac{P}{0.05''}$; "K_u" is the subgrade modulus and "P" is equal to the pressure in pounds per square inch required to give a vertical deflection of 0.05 inch in the plate bearing test. Rupture tests and subgrade modulus tests were conducted at Dow, Presque Isle, Truax, Sioux Falls and Pierre during the fall and again during the frost melting period in order that the difference in bearing capacity between these periods could be obtained. Detailed results of all tests conducted are presented in the appendicies for the specific airfields.

In general the results are summarized for each airfield as follows:

(1) Dow - The rupture tests did not break the pavement with five repetitions of the available maximum load of

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60,000 pounds with deflections as great as 0.27 inch inch during the frost melting period. The ratio of loads at 0.1-inch deflection during the normal period to the frost melting period was 1.5. The subgrade modulus tests conducted on the top of the gravel base indicate an average subgrade modulus of 200 lbs/sq. in./ in., during the normal period and 150 lbs/sq. in./in., during the frost melting period. The results of the subgrade modulus tests during the frost melting period are plotted on Plate 15.

(2) Presque Isle.- The rupture tests did not break the pavement with five repetitions of the available maximum load of 60,000 pounds with deflections up to 0.18 inch during the frost melting period. The ratio of loads at 0.1-inch deflection during the normal period to the frost melting period was 1.2. The subgrade modulus tests conducted on the top of the gravel base indicate an average subgrade modulus of 400 lbs/sq. in./ in., during the normal period and 145 lbs/sq. in./in., during the frost melting period. The results of the subgrade modulus tests during the frost melting period are plotted on Plate 15.

(3) Truax.- The rupture tests did not break the pavement with five repetitions of the available maximum load of 46,000 pounds with deflections of 0.12 inch during the frost melting period. The ratio of loads at 0.1-

inch deflection during the normal period to the frost melting period was 1.3. The subgrade modulus tests conducted on the top of the gravel base indicate an average subgrade modulus of 240 lbs/sq. in./in., during the normal period and 120 lbs/sq. in./in., during the frost melting period. The results of the subgrade modulus tests during the frost melting period are plotted on Plate 15.

(4) Pierre.- The rupture tests conducted during the frost melting period caused failure in the pavement at total loads ranging from 52,000 pounds at 0.145 inch deflection to two load applications on one test, first load of 80,000 pounds with deflection of 0.22inch without failure and second load of 70,000 pounds with failure at 0.245 inch. The ratio of loads at 0.1-inch deflection during the normal period to the frost melting was 1.2. The subgrade modulus tests conducted on the top of the gravel base indicate an average subgrade modulus of 158 lbs/sq. in./in., during the normal period and 120 lbs/sq. in./in., during the frost melting period. The results of the subgrade modulus tests during the frost melting period are plotted on Plate 15.

(5) Sioux Falls. - The rupture tests conducted during the normal and frost melting period cracked the pavement at total loads ranging from 60,000 to 80,000 pounds. Deflections ranged from 0.29 to 0.33 inch during the

normal period and increased to 0.45 inch during the frost melting period. The ratio of loads at 0.1-inch deflection during the normal period to the frost melting period was 1.5. The subgrade modulus tests gave an average value of 87 lbs/sq. in./in., during the normal period and 71 lbs/sq. in./in., during the frost melting period. The results of the subgrade modulus tests during the frost melting period are plotted on Plate 15.

j. Tests for Insulation Qualities of Turf and Snow Cover.- Investigations were conducted at two turfed areas, one at Presque Isle and one at Dow. The tests conducted and observations made were for soil classification, availability of water for frost action, air and subsurface temperature, frost action, depth of frost penetration and snow cover. The snow was not plowed at the turfed areas. It was the purpose of these tests to obtain a comparison of test results particularly frost penetration in turfed areas against paved areas. Results of tests in turfed areas are summarized in Table 1 and included on Plates 3 to 8 inclusive. Detailed results of all tests are contained in the respective appendices for Dow and Presque Isle. 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 to the bare pavement with the result that during the winter months, depending upon weather conditions, a layer of packed snow or ice from 0.5 inch to two inches in thickness covered the paved test areas. At the turfed areas measurements of snow cover were made periodically.

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5. <u>Airfield Pavement Failure Review.</u>- A study was made of all airfield pavement failure reports which were submitted to the Frost Effects Laboratory to determine the failures to which frost action was a contributing cause. Of the reports studied, frost action was believed to have contributed to the failure at 30 airfields as listed in Table 6. Relatively few of all the failure reports show frost action as a cause, however, it is believed that frost action has been a contributing factor to all the failures listed in Table 6.

At these airfields 24 failures were on flexible pavement and 16 failures were on rigid pavements. In 17 of the failure areas 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 failure areas and more than 18 feet below the pavement surface in 13 failure areas. The ground water elevation was not reported in 17 failure 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 evaluation for frost conditions of the failure areas based upon Chapter 4, Part XII of the Engineering Manual dated July 1946, compared with the traffic using the areas indicate that the pavement was overloaded or loaded to the evaluation load in 27 of the 40 failed areas.

6. <u>Analyses.</u>

a. <u>Effect of Water Source on Frost Action.</u>- For frost action to occur there must be a source of water. This water source may consist of a ground water table at the depth of freezing, a rise of water by capillarity from a relatively close ground water table to the freezing soil, or a flow of water from adjoining soil resulting in a depletion of its water content. There are a number of different methods by which the availability of water for frost action can be measured or indicated. These methods consist of measuring depth to ground water, measuring precipitation occurring prior to freezing period and measuring soil water content and degree of saturation before freezing. Results of these measurements at all test areas are included in summary form in Table 1. In addition, there have been added to this table, data which show the character and extent of frost action. From a study of these data, the following conclusions are presented:

(1) At locations where the water table is less than 16 feet from the ground surface and there is no stratum which will prevent the upward flow of water when freezing starts (such as a layer of clean sand) extensive to slight frost action occurred in frost susceptible soils.

(2) At locations where the water table is below 25 feet or where there is a stratum of clean sand above the water table which cuts off upward flow of water, slight to no frost action occurred in frost susceptible soils.

(3) Ice lens formation varied from an exceedingly few thin lenses to many thin to thick lenses, depending upon two related factors: the degree of saturation at start of freezing and the relationship between the natural water content at start of freezing and the Atterberg limits. The greater the degree of saturation, the greater the frost action. Soils with natural water

contents below the plastic limit during the fall, prior to freezing, had negligible frost action. As the natural water content approached the liquid limit, frost action increased.

(4) The degree of saturation beneath paved areas varied generally with the climatic conditions, the lower degree of saturation occurring in the areas of low annual rainfall. The degree of saturation also varied generally with the depth to ground water, the higher the ground water table the greater the degree of saturation.

(5) At the following four test areas: Test Area D, Presque Isle; Test Area A, Truax; Test Area A, Sioux Falls; and Test Area B, Watertown; frost heaving was at a maximum at the pavement edge and decreased toward the center with some test areas showing a slight settlement during the winter. This type of heaving is believed to be a result of flow of water from adjoining turf area into the subgrade beneath the pavement. Greater heaving at edges than at center of pavements occurred only at test areas with bituminous concrete pavements without subsurface drains at pavement edges, except at Presque Isle, where subsurface drains are installed.

(6) At all concrete paved test areas, it is believed that surface water infiltrating through joints into the base

and subgrade prior to freezing augmented to a slight degree the available water for frost action. The pavement heave was more uniform in portland cement concrete test areas compared with the heave in the bituminous concrete paved test areas.

b. Effect of Temperature on Frost Action.- The freezing index at five airfields was greater during 1945-1946 than during the previous winter and less at two airfields. At the five fields where the freezing index was greater, two had greater heave and three had less heave during 1945-1946 than during 1944-1945. One of the airfields with a lower freezing index had greater heave and the other field had less heave. In general, the observations made do not indicate the effect of below freezing air temperature on frost action. It will be necessary to carry out observations over a number of years at the same locations to isolate the effect of freezing temperatures from the other factors influencing frost action.

c. Effect of Soil on Frost Action.- For the occurrence of frost action in a given soil, it must have not less than three per cent by weight of sizes smaller than 0.02 mm in diameter. In general, the observations reported herein substantiate this criterion. However, with the exception of Bedford, which has a non-frost susceptible base, the base materials, except crushed rock, at all fields have more than three per cent by weight finer than 0.02 mm. in diameter, yet only occasional ice crystals were reported and in one instance a few ice lenses. These results may be considered a contradiction of the criterion, however, it may be explained by the absence of a readily available water supply except in the one instance where a few ice lenses were observed. In this case water is believed to have entered the base through joints in the pavement just prior to freezing and during the early stages of freezing when surface thawing occasionally occurred. This conclusion appears reasonable, since the ice lenses were observed in the base immediately beneath the pavement and not in depth.

The observations performed 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. However, other factors constant, the observations indicate that the finer grained soils are more susceptible to frost action than those with gravel and coarse sand sizes.

d. Analysis of Frost Penetration.

(1) Laboratory Studies. Laboratory studies of thermal conductivity conducted upon selected samples of non-frost susceptible base materials in the frozen and unfrozen states show that the thermal conductivity increases with an increase in water content as shown in Figures 1 to 5 inclusive, Plate 11. At water contents less than one per cent by dry weight, the thermal conductivity for the Lowell sand, Winchester crushed trap rock, Somerville cinders, and Mystic slag were all approximately the same, 0.2 BTU/(ft)(hr)(^{o}F), in both frozen and unfrozen states. For Bangor sand and gravel the value increases rapidly from 0.3 to 0.6 BTU/(ft)(hr)(^{o}F) up to a water content of one per cent. Above one per cent water content there is no correlation between the thermal conductivities of the various substances

in either the frozen or unfrozen conditions. The ratios of the thermal conductivities of the cinders and slag to the thermal conductivities of the other non-frost susceptible materials vary between 1.5 and 4.5. This indicates that cinders and slag may be used to reduce the thickness of base courses required to prevent frost penetrating into a frost susceptible material.

(2) Mathematical Studies.- The depth to which a pavement, base, and subgrade will be frozen during a winter will depend principally upon the magnitude and duration of freezing air temperature, the thermal properties of the materials and the subsurface temperature conditions at the start of freezing. All these factors have been used in this study and methods of predicting the depth of frost penetration are presented which are reasonably close to the measured values at the various test areas. Observations of depths of freezing have been made over a period of one to three years at 15 sites. The results of these observations together with pertinent data influencing depth of freezing are summarized on Table 5. In addition, there are also tabulated the values for predicted depth of freezing based upon equations (83), (93), (154), (158), and the empirical formula for the several variables as indicated. These equations were selected from the Problems in Supplement A except the

empirical formula which was derived from all observations of frost penetration; as they are considered to represent in the most usable form, the principal variations in assumptions. The values of predicted depth of frost penetration tabulated were determined in the following manner:

(a) Thermal Conductivity.- The thermal conductivity used for computations of depth of freezing is for all cases 1.3 BTU/(ft)(hr)(^{o}F). Based upon tested values for thermal conductivity, as discussed in paragraph 4f.(1), this value may be somewhat high as an average value for all soils to a depth of 16 feet; however, it is believed to be a reasonable value for the pavement, base, and subgrade soils which are frozen or unfrozen.

(b) Mean Soil Temperature.- The mean soil temperature is equal to the mean annual air temperature at the particular location. At a depth of about 16 feet below ground surface the amplitude of soil temperature change approaches zero. Values for the mean air temperature in the United States are given in Figure 1 on Plate 13 which was plotted from Weather Bureau data.

(c) Latent Heat.- In cohesionless soils, all water in the voids will be frozen and thus the latent heat may be determined from the water content using the graph in Figure 1 on Plate 12. For cohesive soils, there will be a portion of the measured water content (in percentage of dry weight of soil) which will not freeze at 32°F as discussed in paragraph 4.f(2). Thus for some soils, not all the water content contributes latent heat. In Table 5, it is considered all of the water freezes, the value for latent heat as tabulated being determined from Figure 1, Plate 12.

(d) <u>Volumetric Heat</u>.- The average volumetric heat at each location was determined using the equation given in paragraph 4.f(3). Values for the volumetric heat for each different soil were determined using the average water content and unit dry weight as tabulated on Table 5 and Figure 2 on Plate 12. Soils within the depth of freezing were considered to be totally frozen in determining the average volumetric heat.

Based upon comparisons contained in Table 5, it is concluded that values determined from equation 154, paragraph 4g and the empirical formula compare most favorable with measured depth of freezing. In Table 5, an arrow pointing to the left has been placed beside the predicted values which fall within six inches of the measured depth. An arrow pointing to the right has been placed adjacent to the value closest to the measured depth.

The prediction of depth of freezing at a particular location may be accomplished with reasonable accuracy from the Design curve from the Engineering Manual Part XII, Chapter 4, July 1946 as shown on Figure 3, Plate 14 using the Freezing Index "F" obtained from Figure 2, Plate 13. If there is an insulation layer present, such as slag or cinder base, sawdust, peat or tundra layer, the depth of freezing may be determined by equation (158).

(3) Field Observations.- A study of the actual frost penetrations in non-frost susceptible soils shows that the depth of frost penetration varies approximately as a straight line function vs. freezing index when it is plotted on log log plot as shown on Plate 14. On Plate 14 there are plotted all observations of depth of frost penetration in non-frost susceptible soils against freezing index for the years 1944-1945 and 1945-1946. Figure 1 shows data for portland cement concrete pavements, Figure 2 for bituminous concrete pavements, and Figure 3 contains all results. 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 of non-insulating and non-frost susceptible materials such as sand, gravel, or crushed rock. On the basis of the additional data obtained during these investigations, as plotted on Plate 14, no change in the design curve

is recommended.

The results of frost penetration measured in the turfed areas with snow cover are summarized in the following table and compared with frost penetrations in adjacent paved areas.

Location of Turf Test	Average Snow Cover During Winter In Turfed Areas (Feet)	Average Total Frost Penetration in Feet Turfed	Pavement Bit.	Pavement P.C.C.
Dow Field	1.5	2.2	4.3	4.4
Presque Isle	1.3	4.2	5.8	6.5

These data indicate that snow cover and turf together provide an insulating blanket which retards frost penetration to a considerable magnitude.

e. Effect of Frost Action on Rigid Pavement Supporting Capacity.- The results of the subgrade modulus tests as plotted on Plate 15 indicate that the additional data obtained from these investigations tends to substantiate the design curves as they are shown on Plate 15. All the subgrade soils at the airfields where tests were performed fall into group 3 which is defined as all frost susceptible soils which have more than 25 per cent passing #200 mesh sieve. Additional tests are required to eliminate the scattering of the test data before any revisions can be made in the design curves. The rupture tests performed on the top of the pavement indicate a reduction in load required for 0.1-inch deflection during and immediately after the frost melting period. From the study of the pavement failure reports it is concluded that frost action was a substantial contributing cause to the failures of the rigid pavement.

f. Effect of Frost Action on Flexible Pavement Supporting Capacity.- The plate bearing tests performed at Presque Isle, Dow, Truax, Pierre, and Watertown 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 data as plotted on Plate 16 indicates that in general there is about the same reduction in strength caused by frost action regardless of the thickness of the zone in which frost action occurs. From the study of the pavement failure reports it is concluded that frost action was substantial contributing cause to the failures of the flexible pavements. Since no traffic tests were conducted on flexible pavements no check on the design curves for flexible pavements in the Ad Interim Engineering Manual, Part XII, Chapter 4, Airfield Pavement Design, "Frost Conditions", dated July 1946, can be made.

7. Conclusions.-On the basis of the results obtained from the frost investigation conducted during 1945-1946 the following general conclusions are presented:

a. A method of predicting the depth of frost penetration based upon the soil and weather characteristics at the site was developed.

b. The temperature at which soil freezes is approximately 32°F.

c. There is a definite lowering of the supporting capacity of rigid and flexible pavements caused by frost action.

d. Pavement bearing capacity for both flexible and rigid is reduced about the same magnitude irrespective of the depth of frost penetration.

e. The curves presented for the design of rigid pavements in Part XII, Chapter 4, Airfield Pavement Design "Frost Conditions" Ad Interim Engineering Manual and dated July 1946 are satisfactory.

f. The curve to determine the combined thickness of pavement and base required to prevent freezing in the subgrade in Part XII, Chapter 4, Airfield Pavement Design, "Frost Conditions", Ad Interim Engineering par. 7f.

Manual dated July 1946 is satisfactory.

g. No revisions to Part XII, Chapter 4, Airfield Pavement Design "Frost Conditions" Ad Interim Engineering Manual dated July 1946 are recommended at this time.

h. Frost action has been a contributing factor in numerous pavement failures in both rigid and flexible pavements.

8. Recommendations.- From the data and analyses presented herein the following recommendations are submitted:

a. Continue collection of data to check the curve for the prediction of frost penetration in non-frost susceptible materials.

b. Continue tests to check the design curves for rigid pavement.

c. Study and correlate all data obtained to date.

GLOSSARY

The body of the report contains certain terms and words which are defined below as to their special use relative to frost investigation.

(1) Test Area. - The test area is the portion of the airfield selected for observations and investigations.

(2) Pavement. - The term pavement is defined as a covering of a prepared or manufactured product superimposed upon subgrade or base to serve as an abrasive and weather resisting structural medium.

(3) Base. - The term base applies to the course of specially selected soils, minerals, aggregates, or treated soils placed and compacted on the natural or compacted subgrade.

(4) Subgrade. - The term subgrade applies to the natural soil in place or to fill material, upon which a pavement or base is constructed.

(5) Frozen Soil. - Frozen soil as referred to in this report is as follows:

(a) Homogeneously Frozen Soil.- A homogeneously frozen soil is a soil in which all the water in the soil is frozen within the natural voids existing in the soil, without observable accumulation of ice lenses or frost forms, exceeding in volume, such natural void spaces.

(b) Stratified Frozen Soil.- A stratified frozen soil is a soil in which a part of the water in the soil is frozen in the form of observable ice lenses, occupying space in excess of original soil voids.

(6) Ice Crystals. - The formation of ice particles found in the pores of homogeneously frozen soil is referred to as ice crystals.

(7) Ice Lenses.- Ice lenses are the ice formations in stratified frozen soil, occurring in repeated layers, in general, parallel to each other and normal to the direction of heat loss.

(8) Frozen Zone.- The limits of depth within which the soil is frozen is designated as the frozen zone.

(9) Frost Penetration.- The depth from the surface to the bottom of the frozen soil.

(10) Depth of Freezing Temperature Penetration.- The depth of freezing temperature penetration is the maximum depth below the surface of freezing temperature.

(11) Frost Action.- Frost action is the accumulation of water in the form of ice lenses in the soil under natural freezing conditions.

(12) Frost Heave.- Frost heave is the raising of the pavement surface due to the accumulation of ice lenses. The amount of heave in most soils is approximately equal to the cumulative thickness of ice lenses.

(13) Frost Susceptible Soil.- Frost susceptible soil is a soil in which frost action is possible. Any soil which contains three per cent or more by weight of grains smaller than 0.02 mm. diameter shall be considered susceptible to frost action.

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(14) Non-Frost Susceptible Materials.- Non-frost susceptible materials are crushed rock, sand and gravel, gravel, slag, cinders, or any other cohesionless material in which frost action is not possible.

(15) Degree Day.- Degree day for one day is the algebraic difference between 32° Fahrenheit and the daily mean temperature. The degree day is plus when the daily mean temperature is below 32° Fahrenheit and minus when above. For any one day there are as many degree days as there are degrees Fahrenheit difference in temperature between the mean temperature for the day and 32° Fahrenheit. Cumulative degree days-time curve is obtained by plotting the cumulative degree days versus time.

(16) Freezing Index.- Freezing index is a measure of the combined duration and magnitude of below-freezing air temperatures occurring during any given winter and is the maximum ordinate of the degree days-time curve

(17) Normal Freezing Index.- Normal freezing index is the index computed for normal air temperatures based upon a long period of record, usually 10 years or more.

(18) Ground Water Table.- The ground water table is the free water surface nearest to the ground surface.

(19) Density.- Density is the unit dry weight, in pounds per cubic foot.

(20) 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.

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(21) 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.

(22) Frost Melting Period.- The frost melting period is the time of year during which the frost in the foundation materials is returning to a liquid state. In frost susceptible materials it is the period when melting of the ice lenses causes a temporary increase in the water content of the material resulting in a reduction in the supporting capacity of the pavement.

(23) Water Content.- Water content is the ratio, expressed as a percentage, of the weight of water in a given soil mass to the weight of solid particles.

SITE	TEST AREA	SURFACE TYPE	SURFACE THICKNESS (INCHES) (a)	UNDERLYING MATERIAL CLASSIFICATION	UNDERLYING MATERIAL THICKNESS (INCHES)	UNDERLYING MATERIAL PERCENT FINER THAN 0.02 MM	WATER CONTENT (PERCENT DRY WEIGHT) NORMAL PERIOD	WATER CONTENT FREEZING PERIOD (b)	WATER CONTENT FROST MELTING PERIOD (b)	DENSITY (DRY WEIGHT - LBS/CU. FT.) NORMAL PERIOD	DENSITY FREEZING PERIOD (b)	DENSITY FROST MELTING PERIOD (b)	PERCENT SATURATI[ON] NORMAL PERIOD	PERCENT SATURATION FREEZING PERIOD (b)	FRO[ST] MELT[ING] PER[IOD]
DOW	D	BIT. CONC.	3.5	BASE GW SUBGRADE CL	36 - 48 -	2 - 8 48 - 87	13.5 17.7	- -	(5.8), 6.8 (22.8), 21.7	128 115	- -	129 107	100 100	- -	9 10
	E	BIT. CONC.	3.5	BASE GW SUBGRADE CL	32 - 41 -	2 - 8 49 - 87	10.1 22.4	- -	(7.8), 8.4 (23.0), 22.3	136 101	- -	136 109	100 93	- -	10 10
	F	P.C. CONC.	7, 10	BASE GW SUBGRADE CL	19 - 23 -	2 - 8 40 - 87	8.1 22.5	(7.8) (25.0), 17.5	10.7 33.0	138 110	- -	137 95	100 100	- -	10 10
	TURF	TOPSOIL	2 - 8	SUBGRADE CL	-	40 - 87	-	(43.0), 19.8	-	-	-	-	-	-	-
PRESQUE ISLE	A	P.C. CONC.	7, 10	BASE GW SUBGRADE GC	24 - 37 -	0 - 7 10 - 35	10.4 17.0	(8.0) (16.8)	(8.1), 8.4 (17.6), 16.4	133 117	- -	140 114	100 100	- -	10 10
	C	BIT. CONC. & BIT. PEN. CA.	3.5 2 - 4	BASE GW SUBGRADE GC	22 - 38 -	0 - 7 10 - 35	8.2 13.6	(10.3) (13.6), 11.0	11.2 15.6	132 115	- -	138 114	84 84	- -	10 9
	B	BIT. CONC. & BIT. PEN. CA.	3.5 2 - 4	BASE GW SUBGRADE GC	25 -	0 - 7 10 - 35	9.1 16.0	- -	(9.8), 10.5 (16.8), 16.4	124 129	- -	142 120	71 100	- -	10 10
	TURF	TOPSOIL	3 - 5	SUBGRADE GC	-	10 - 35	-	(18.3)	-	-	-	-	-	-	-
BEDFORD	A	P.C. CONC.	6, 9	BASE GW SUBGRADE SW	18 -	3 0 - 10	4.8 5.3	(10.6) (8.0), 4.5	- -	119 103	- -	- -	33 23	- -	- -
	B	BIT. CONC.	5	BASE GW SUBGRADE SW	13 - 19 -	3 0 - 10	- -	(5.8) (8.0), 4.6	- -	- -	- -	- -	- -	- -	- -
TRUAX	A	BIT. CONC.	2.5	BASE (CRUSHED RK) SUBBASE GF SUBGRADE CL SUBGRADE SF	8 18 26, >7.5 FT 36	0 8 - 21 80 - 90 7	- 8.0 27.5 19.8	(8.5) (8.0) (31.2), 28.4 19.8	5.2 8.1 27.7 -	- 140 95 118	- - - -	- 138 96 -	- 85 100 100	- - - -	- 7 10 -
	C	P.C. CONC.	7, 9	BASE GF SUBGRADE CL SUBGRADE SF	28 - 36 32 -	8 - 21 80 - 90 7	10.1 35.5 20.4	(13.1) (23.0), 36.0 22.5	11.8 34.6 -	128 87 113	- - -	125 88 -	85 100 100	- - -	3 10 -
	D	BIT. CONC.	2.5	BASE (CRUSHED RK) SUBBASE GF SUBGRADE CL	20 24 - 33 -	0 8 - 21 80 - 90	- 5.6 25.9	(8.1) (8.3) (24.8), 34.5	7.4 6.8 27.2	- 130 90	- - -	- 138 95	- 70 100	- - -	- 6 8
PIERRE	A	P.C. CONC.	7, 10	BASE GF SUBBASE CL SUBGRADE CL SUBGRADE CH	5 - 11 5 - 12 16 - 38 -	8 - 15 28 - 53 34 - 57 38 - 78	7.4 15.9 21.8 -	(8.5) (13.1) (15.3), 24.3 -	7.5 12.9 (17.2), 19.1 21.7	142 110 97 -	- - - -	141 117 (103), 102 97	100 82 80 -	- - - -	10 8 (73) 7
	C & D	BIT. CONC.	6	BASE GF SUBBASE CL SUBGRADE CL	5 - 11 6 - 12 -	7 - 10 37 - 50 40 - 54	6.7 13.6 12.7	(5.5) (10.6) (12.2), 10.4	6.4 12.6 14.1	126 115 92	- - -	137 118 95	56 70 41	- - -	7 8 4
SIOUX FALLS	A	BIT. CONC.	2	BASE GC SUBBASE CL SUBG CL OR CH SUBG SF-CL & SC	10 12 48 VARIES (h)	7 - 12 37 - 41 55 - 60 4 - 28	7.1 21.4 28.0 15.8	(7.0) (18.3), 21.8 (26.0), 28.0 -	8.2 16.0 (31.0), 26.1 27.3	137 103 89 97	- - - -	133 110 95 90	80 83 86 58	- - - -	7 9 9 8
	B	P.C. CONC.	6, 9	SUBGRADE CH SUBGRADE CL SUBGRADE SC	80 10 - 12 -	60 - 77 56 14	33.0 - -	(33.0), 33.0 - -	(34.0), 33.0 27.5 -	85 - -	- - -	84 87 -	92 - -	- - -	9 8 -
WATERTOWN	A	P. C. CONC.	9, 12	SUBGRADE SF-OL & SF-CL SUBGRADE OL-CL, OL & SF-CL SUBGRADE GP & SP	22 - 25 18 - 26 -	18 - 28 31 - 38 2 - 4	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -
	B	BIT. CONC.	5	BASE GF SUBGRADE SF-OL & OL-CL SUBGRADE SP OR GP	10 - 12 18 - 44 -	8 - 12 21 - 42 3	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -
FARGO	A	BIT. CONC.	1.5	SOIL CEMENT BASE SUBG CL - SF SUBG OH - CH SUBGRADE CH	6 - 7 10 - 12 10 - 12 -	- 11 - 16 45 - 58 75 - 92	- - - -	- - - -	- - - -	- - - -	- - - -	- - - -	- - - -	- - - -	- - - -
GREAT BEND	A	P.C. CONC.	7, 10.5	BASE SF OR SW, SP SUBGRADE CL-SF OR SF-CL SUBGRADE CL SUBGRADE SP, SW & SF	5 - 8 VARIES (h)	2 - 17 23 - 33 32 - 60 1 - 17	- - - -	- - - -	- - - -	- - - -	- - - -	- - - -	- - - -	- - - -	- - - -

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 TRUAX 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.

NOTES:

(h) TEST PITS INDICA

(i) DEPTH OF FROST
PITS DUG IN WIN

\- DASHES IN COLU
SPECIFIC INFORMA

(c)

PERCENT SATURATION: NORMAL PERIOD	PERCENT SATURATION: FREEZING PERIOD (b)	PERCENT SATURATION: FROST MELTING PERIOD	ATTERBERG LIMITS: LIQUID LIMIT	ATTERBERG LIMITS: PLASTICITY INDEX	PRECIPITATION (3 MO PRIOR TO FREEZING): NORMAL (INCHES)	PRECIPITATION 1945-1946: INCHES	PRECIPITATION 1945-1946: PERCENT OF NORMAL	GENERAL DRAINAGE CONDITIONS	DEPTH OF WATER TABLE (FT.): NORMAL PERIOD	DEPTH OF WATER TABLE (FT.): FREEZING PERIOD	DEPTH OF WATER TABLE (FT.): FROST MELTING PERIOD	FREEZING INDEX: NORMAL (DEGREE DAYS)	FREEZING INDEX 1945-1946: DEGREE DAYS	FREEZING INDEX 1945-1946: PERCENT OF NORMAL	MAX. DEPTH OF FROST (FEET)	ICE SEGREGATION: CRYSTALS	ICE SEGREGATION LENSES: THICKNESS (INCHES)	ICE SEGREGATION LENSES: DESCRIPTION
100 100	- -	92 100	NONPLASTIC 29-36	NONPLASTIC 11-17	11	11	100	DRAINAGE SYSTEM CONSISTS OF PAVED GUTTERS, DITCHES, CULVERTS, PIPE DRAINS AND CATCH BASINS. SURFACE WATER FROM LANDING STRIPS IS GENERALLY COLLECTED BY LONGITUDINAL OPEN DITCHES PARALLEL TO OUTER EDGES	3.4	7.0	3.0	1275	1421	111	4.2	FOUND FOUND	- 0-1/16	NONE ISOLATED
100 93	- -	100 100	NONPLASTIC 29-36	NONPLASTIC 11-17					3.4	7.0	3.3				4.0	FOUND FOUND	- 0-1/16	NONE ISOLATED
100 100	- -	100 100	NONPLASTIC 29-36	NONPLASTIC 11-17					-	7.5	1.3				4.5	FOUND FOUND	- 0-1/8	NONE ISOLATED
-	-	-	29-36	11-17					-	5.6	0.2				2.2	01-17FT	1/4-3/4	17FT-2.2FT
100 100	- -	100 100	NONPLASTIC 29	NONPLASTIC 8	10	11	110	SURFACE WATER GENERALLY COLLECTED BY OPEN DITCHES AT OUTER EDGES OF SAFETY STRIPS RUNWAYS HAVE COMBINED SURFACE AND SUBSURFACE DRAINAGE. UNDER DRAINS INSTALLED TO CONTROL SPRINGS AND WET AREAS. ALL OPEN AND CLOSED JOINT PIPE 5FT. BELOW SURFACE	1.2 3.5	- 5.6-7.1	0.7 4.4-8.0	2061	2304	112	6.5	FOUND FOUND	- -	NONE HAIRLINE
84 84	- -	100 94	NONPLASTIC 30	NONPLASTIC 10					- 4.9	- 6.4-8.5	1.4 3.5-6.5				5.7	FOUND FOUND	- -	NONE NONE
71 100	- -	100 100	NONPLASTIC 30	NONPLASTIC 10					- 2.5	- 4.3-6.6	0.8 0.0-5.?				5.75	FOUND FOUND	- -	NONE NONE
-	-	-	28	8					6.5	6.5	5.0				4.2	FOUND	-	NONE
33 23	- -	- -	NONPLASTIC NONPLASTIC	NONPLASTIC NONPLASTIC	10.2	10.1	99	DRAINAGE SYSTEM CONSISTS OF DITCHES DRAIN PIPES AND CATCH BASINS. SURFACE WATER FROM PAVED AREAS COLLECTED BY CATCH BASINS. SUBSURFACE DRAINS AT EDGES OF ORIGINAL 150 FT. RUNWAYS	(d) 4.5	3.5-5.5	3.5-4.0	680	825	121	3.3	NONE NONE	- -	NONE NONE
- -	- -	- -	NONPLASTIC NONPLASTIC	NONPLASTIC NONPLASTIC					(d) 4.5	3.5-5.5	3.5-4.0				2.2	NONE NONE	- -	NONE NONE
- 88 100 100	- - -	- 78 100 -	- 19-30(e) 43 NONPLASTIC	- 2-9(e) 20 NONPLASTIC	7	7.8	111	SUBSURFACE DRAINAGE CONSISTS OF 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 SOUTH WEST CORNER OF FIELD	4.5	1.6-3.3	1.3	1220	1060	87	3.8	FOUND NONE NONE	- - 0-1/10	NONE HAIRLINE NUMEROUS
83 100 100	- - -	83 100 -	19-30(e) 38 -	2-9(e) 18 -					6.3	5.7-8.7	5.0				4.0	FOUND NONE	0-0.05 0.01-0.02	NUMEROUS -
- 70 100	- - -	- 83 87	- 19-30(e) 44	- 2-9(e) 20					7.5	5.8-7.6	6.0				4.8	FOUND FOUND NONE	- 0-002 0-002	NONE FEW NUMEROUS
100 82 80 -	- - - -	100 80 (73), 83 78	28-33 34-42 38-46 52-66	8-18 16-26 20-28 23-40	2.4	2.08	87	DRAINAGE SYSTEM CONSISTS OF SURFACE DRAINAGE SUPPLEMENTED BY STORM SEWER SYSTEM DISCHARGING INTO OPEN DITCHES OUTSIDE THE LANDING STRIPS.	- (f)	-	-	1288	1026	80	4.0	FOUND FOUND 08-37 FT.	- - -	NONE(g) NONE NONE
56 70 41	- - -	78 81 49	23-29 48-43 38-41	7-12 18-23 19-23				AIRFIELD AREA IS NATURALLY WELL DRAINED NORMAL CONDITION OF SOIL IN TURF AREA IS DRY.	- (f)	-	>11.0				3.7	NONE NONE NONE	- - -	NONE NONE NONE
80 93 88 58	- - - -	78 90 93 88	23 36-44 81 16-28	8 15-21 30 0-11	5.9	3.2	54	DRAINAGE OBTAINED BY SURFACE RUN-OFF TEMPORARY PONDING RELIEVED BY SEEPAGE INTO PERMEABLE STRATA. DRAINAGE POOR DURING FLOOD STAGE AND INTENSIVE RAINFALL PERIODS NATURAL WATER COURSES NEAR FIELD MAINTAIN HIGH MOISTURE CONTENT IN SUBGRADE.	6.0	6.5	4.0	1216	1311	108	3.9	NONE NONE 3.6-3.9 FT.	- 0-1/8	NONE HOR & VERT (1.0-3.6 FT)
92 - -	- - -	90 83 -	50-68 44 17	27-41 25 4					14.2	15.2	11.8				3.5	NONE	0-1/8	HOR & VERT (1/2-3 IN APART)
- - -	- - -	- - -	32-41 38-50 NONPLASTIC	12-14 12-18 NONPLASTIC	4.4	3.2	73	DRAINAGE SYSTEM CONSISTS OF SURFACE DRAINAGE SUPPLEMENTED BY STORM SEWERS DISCHARGING TO OPEN DITCHES OUTSIDE THE LANDING AREA. PONDED SURFACE WATER RELIEVED BY SEEPAGE.	-	-	-	1781	2017	113	8.25 (i)	-	-	-
- - -	- - -	- - -	16-24 30-43 NONPLASTIC	5-9 12-18 NONPLASTIC					10.6	11.2	8.5				8.8 (i)	-	-	-
- - -	- - -	- - -	30-31 62-64 73-80	12 28-31 40-58	4.8	3.9	81	DRAINAGE OBTAINED BY ELEVATION OF PAVEMENT AND COMPLETE UNDERGROUND DRAINAGE AND STORM SEWER SYSTEMS OPEN DITCH SERVES AS OUTLET FOR THESE SYSTEMS	5.3	6.4	3.0	2648	2483	93	6.0 (i)	-	-	-
- - - -	- - - -	- - - -	18-22 18-28 25-43 17-20	0-8 3-14 9-24 0-5	5.3	4.6	87	DRAINAGE OBTAINED BY DITCHES AND DRAINAGE INTO PONDS AND SUMPS SURFACE CONDITIONS POOR DURING PERIODS OF HIGH PRECIPITATION.	10.5	12.2	12.0	50	207	414	2.0 (i)	-	-	-

NOTES:

(h) TEST PITS INDICATE EXTREMELY VARIABLE SUBGRADE SOIL STRATA.

(i) DEPTH OF FROST DETERMINED ONLY BY THERMOMETER OR THERMOCOUPLE OBSERVATIONS, NO TEST PITS DUG IN WINTER OF 1945-1946.

\- DASHES IN COLUMNS INDICATE THAT NO OBSERVATIONS HAVE BEEN MADE TO DETERMINE THE SPECIFIC INFORMATION.

(c)

GENERAL DRAINAGE CONDITIONS	DEPTH OF WATER TABLE (FT.) NORMAL PERIOD	FREEZING PERIOD	FROST MELTING PERIOD	FREEZING INDEX NORMAL (DEGREE DAYS)	1945 - 1946 DEGREE DAYS	PERCENT OF NORMAL	MAX. DEPTH OF FROST (FEET)	ICE SEGREGATION CRYSTALS	LENSES THICKNESS (INCHES)	LENSES DESCRIPTION	PAVEMENT HEAVE (FEET) MIN	MAX.	AVG.	TRAFFIC HISTORY PERIOD	GROSS PLANE WEIGHT (LBS.)	CYCLES PER DAY
SYSTEM CONSISTS OF PAVED ITCHES, CULVERTS, PIPE DRAINS BASINS. SURFACE WATER FROM RIPS IS GENERALLY COLLECTED DINAL OPEN DITCHES PARALLEL EDGES	3.4	7.0	3.0	1275	1421	111	4.2	FOUND FOUND	- 0-1/16	NONE ISOLATED	0.05	0.10	0.08	5/42-10/42	ALL WTS TO	14
	3.4	7.0	3.5				4.0	FOUND FOUND	- 0-1/16	NONE ISOLATED	0.10	0.20	0.12	1/43-12/43	60 000 MAX	10
	-	7.5	1.3				4.5	FOUND FOUND	- 0-1/8	NONE ISOLATED	0.20	0.30	0.25	8/44 1945	NO DATA	17
	-	3.8	0.2				2.2	0.1 - 1.7 FT.	1/4 - 3/4	1.7 FT. - 2.2 FT.	-	-	-	1946	NO DATA	
WATER GENERALLY COLLECTED ITCHES AT OUTER EDGES OF RIPS RUNWAYS HAVE COMBINED ND SUBSURFACE DRAINAGE NS INSTALLED TO CONTROL D WET AREAS ALL OPEN AND IT PIPE 5 FT. BELOW SURFACE	1.2 3.5	- 5.6-7.1	0.7 4.4-6.0	2061	2304	112	6.5	FOUND FOUND	- -	NONE HAIRLINE	0.10	0.25	0.16	1943	27-36 000 65 000	5 25
	- 4.9	- 6.4-8.5	1.4 3.5-8.5				5.7	FOUND FOUND	- -	NONE NONE	0.05	0.10	0.06	1944	< 5 - 15 000 29-65 000	22 20
	- 2.5	- 4.5-6.6	0.8 0.0-5.2				5.75	FOUND FOUND	- -	NONE NONE	0.15	0.40	0.22	1945	46-65 000 <10 - 30 000	21 16
	6.5	6.5	5.0				4.2	FOUND	-	NONE	-	-	-	1946	NO DATA	
SYSTEM CONSISTS OF DITCHES AND CATCH BASINS. SURFACE M PAVED AREAS COLLECTED BY NS. SUBSURFACE DRAINS AT ORIGINAL 150 FT. RUNWAYS	(d) 4.5	3.5-5.5	3.5-4.8	880	825	121	3.3	NONE NONE	- -	NONE NONE	-	-	-	1943 - 1944	10-36 000 35-60 000	7 3
	(d) 4.5	3.5-5.5	3.5-4.8				2.2	NONE NONE	- -	NONE NONE	-	-	-	1944 - 1945 1946	30-100 000 10 - 30 000 NO DATA	7 20
CE DRAINAGE CONSISTS OF AINS ALONG EDGES OF RUNWAYS , DRAINING INTO LATERAL URFACE RUNOFF IS COLLECTED AT THE EDGES OF THE GRADED EN PERIMETER DITCHES INTO DRAINAGE DITCH AT T CORNER OF FIELD.	4.5	1.6 - 5.3	1.5	1220	1060	87	3.8	FOUND NONE NONE	- - 0 - 1/10	NONE HAIRLINE NUMEROUS	0.10	0.18	0.13	1942 - 1944	ALL WTS TO 60 000 MAX	10 - 100
	6.3	5.7 - 6.7	5.0				4.0	FOUND NONE	0 - 0.05 0.01-0.02	NUMEROUS -	[illegible]	0.18	0.12	1945 - 1946	NO DATA	
	7.9	6.8-7.6	6.0				4.9	FOUND FOUND NONE	- 0 - 0.02 0 - 0.02	NONE FEW NUMEROUS	0.02	0.05	0.04			
SYSTEM CONSISTS OF SURFACE SUPPLEMENTED BY STORM TEM DISCHARGING INTO OPEN UTSIDE THE LANDING STRIPS REA IS NATURALLY WELL ORMAL CONDITION OF SOIL REA IS DRY.	- (f)	-	-	1286	1026	80	4.0	FOUND FOUND 0.8-3.7 FT.	- - -	NONE (g) NONE NONE	0.00	0.03	0.01	12/42 - 8/43 8/43 - 8/44	29 - 60 000 10 - 15 000	5 - 200 50
	- (f)	-	>11.0				3.7	NONE NONE NONE	- - -	NONE NONE NONE	-0.02	0.04	-0.01	8/44 - 8/46	5 - 10 000	4
OBTAINED BY SURFACE RUN- RARY PONDING RELIEVED BY NTO PERMEABLE STRATA. POOR DURING FLOOD STAGE SIVE RAINFALL PERIODS ATER COURSES NEAR FIELD IGH MOISTURE CONTENT IN	6.0	8.5	4.0	1216	1311	108	3.9	NONE NONE 3.8 - 3.9 FT.	- 0 - 1/8	NONE HOR & VERT (1.0 - 3.6 FT.)	0.05	0.16	0.08	6/42 - 11/45	35-65 000 10-15 000	50 20
	14.2	15.2	11.6				3.5	NONE	0 - 1/8	HOR & VERT. (1/2 - 3 IN. APART)	0.02	0.10	0.06	1946	NO DATA	
SYSTEM CONSISTS OF SUR- NAGE SUPPLEMENTED BY WERS DISCHARGING TO OPEN OUTSIDE THE LANDING AREA. URFACE WATER RELIEVED BY	-	-	-	1761	2017	115	8.25 (i)	-	-	-	0.00	0.08	0.05	12/42 - 12/43 3/44 - 12/44 1945 - 1946	60 000 15 - 60 000 COMMERCIAL	100 100 4
	10.6	11.2	8.5				6.6 (i)	-	-	-	-0.02	0.07	0.02			
OBTAINED BY ELEVATION OF AND COMPLETE UNDERGROUND ND STORM SEWER SYSTEMS SERVES AS OUTLET FOR TEMS	5.3	6.4	3.0	2646	2463	93	6.0 (i)	-	-	-	0.02	0.09	0.05	1941 - [illegible] 1941 - 1946	60 000 5 - 29000	2 28
OBTAINED BY DITCHES AND NTO PONDS AND SUMPS ONDITIONS POOR DURING HIGH PRECIPITATION.	10.3	12.2	12.0	50	207	414	2.0 (i)	-	-	-	-	-	-	3/43 - 6/43 6/43 - 7/44 7/44 - 1/45 1/45 - 4/46 1946	LT. PLANES 47 - 120 000 47 - 120 000 47 - 120 000 NO DATA	< 20 130 115 53

RVATIONS, NO TEST

TERMINE THE

FROST INVESTIGATION
1945 - 1946

SUMMARY OF FACTORS INFLUENCING FROST ACTION OTHER AIRFIELD DATA

FROST EFFECTS LABORATORY, BOSTON, MASS. JUNE 1946

CR-45-46

TABLE I

SERIES NO.	MATERIAL	SPECIFIC GRAVITY G	SPECIFIC HEAT DRY SOIL BTU/(LB)(°F) (1) c	NON-FROZEN LABORATORY SAMPLE NO.	NON-FROZEN UNIT DRY WEIGHT LBS./CU.FT. γ	NON-FROZEN WATER CONTENT PER CENT DRY WEIGHT w	NON-FROZEN VOLUMETRIC HEAT CAPACITY TOTAL SAMPLE BTU/(CU.FT.)(°F) C_u	NON-FROZEN THERMAL CONDUCTIVITY BTU/(FT)(°F)(HR) k_u
3A	LOWELL SAND (Well graded - medium to coarse sand) (2)	2.66	0.20	3A-4	105.0	0.2	21.2	0.188
				3A-4a	105.0	0.2	21.2	0.188
				3A-5 (3)	101.0	0.2	20.4	0.169
				3A-6a	106.5	16.4	38.8	1.025
				3A-7	101.0	20.9	41.3	1.000
				3A-8	103.0	4.5	25.3	0.718
				3A-9	83.5	4.9	20.8	0.469
				3A-10(3)	84.5	2.3	18.8	0.335
				3A-11(3)	91.1	1.9	19.9	0.352
				3A-12	109.0	2.2	24.3	0.582
				3A-13	103.0	2.0	22.7	0.476
				3A-15	89.3	2.1	19.7	0.463
				3A-16	105.0	5.1	26.4	0.777
				3A-17	90.8	2.1	20.1	0.437
3B	BANGOR SAND & GRAVEL (Well graded - 1½" maximum)	2.70	0.20	3B-1	127.0	3.4	29.8	0.890
				3B-2	131.5	1.1	27.7	0.673
				3B-3	127.0	9.3	36.3	1.125
				3B-11	133.3	0.32	27.1	0.472
3C	SOMERVILLE CINDERS (Well graded - 1" maximum.)	2.27	0.18	3C-1	60.9	20.7(5)	23.6	0.353
				3C-2	60.0	36.6	32.8	0.462
				3C-3	60.8	21.2(6)	23.9	0.354
				3C-4	61.7	11.3	18.1	0.297
				3C-8	61.9	1.1	11.9	0.173
3D	MYSTIC SLAG (1½" maximum.)	2.45	0.17	3D-1	79.1	9.1	17.5	0.222
				3D-2(7)	81.2	33.5	40.9	0.553
				3D-6	92.3	0.6	16.3	0.146
3E	WINCHESTER CRUSHED TRAP ROCK (3/4" maximum.)	2.91	0.20	3E-1	99.4	1.9	21.7	0.350
				3E-2	100.0	2.1	22.1	0.371
				3E-3	98.5	4.4	23.6	0.403
				3E-4	98.5	27.2	46.5	0.849
				3E-5(7)	99.3	28.4	48.0	2.320
				3E-6a(7)	100.0	27.7	47.7	1.850
				3E-7	102.0	2.5	23.0	0.371
				3E-8(7)	102.0	26.7	47.7	1.479
				3E-21	112.4	0.21	2[illegible].7	0.196

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% at top of sam
w = 27.3% at bottom of
(6) Non-uniform water content.
(7) Test results are not consistent w
(8) Cover lifted off cylinder due to
affected by leaking of brine
(9) Average heave 0.08". Slight leak

RANGE OF STONE SIZES - SERIES 3E

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

NON-FROZEN			FROZEN				
WATER CONTENT PER CENT DRY WEIGHT w	VOLUMETRIC HEAT CAPACITY TOTAL SAMPLE BTU/(CU.FT.)(°F) C_u	THERMAL CONDUCTIVITY BTU/(FT)(°F)(HR) k_u	LABORATORY SAMPLE NO.	UNIT DRY WEIGHT LBS./CU.FT. γ	WATER CONTENT PER CENT DRY WEIGHT w	VOLUMETRIC HEAT CAPACITY TOTAL SAMPLE BTU/(CU.FT.)(°F) C_f	THERMAL CONDUCTIVITY BTU/(FT)(°F)(HR) k_f
0.2	21.2	0.188	3A-18	106.2	0.17	21.3	0.185
0.2	21.2	0.188	3A-19	102.9	0.17	20.7	0.164
0.2	20.4	0.169	3A-20	102.5	5.4	23.3	0.885
16.4	38.8	1.025	3A-21	106.2	16.5	30.0	1.755
20.9	41.3	1.000	3A-22	102.6	18.5	30.0	1.540
4.5	25.3	0.718	3A-23	102.5	20.5	31.0	1.610
4.9	20.8	0.469	3A-24	105.0	2.2	22.2	0.460
2.3	18.8	0.335	3A-25	106.0	4.2	23.4	0.912
1.9	19.9	0.352	3A-26(4)	111.8	0.66	22.4	0.265
2.2	24.3	0.582	3A-27(4)	111.1	0.98	22.8	0.314
2.0	22.7	0.476					
2.1	19.7	0.463					
5.1	26.4	0.777					
2.1	20.1	0.437					
3.4	29.8	0.890	3B-4(4)	130.8	2.1	27.5	0.725
1.1	27.7	0.673	3B-5	127.1	3.6	30.2	1.038
9.3	36.3	1.125	3B-6	130.8	9.9	32.8	1.528
0.32	27.1	0.472	3B-7	127.1	10.6	32.2	1.489
			3B-8	130.2	1.8	27.2	0.665
			3B-9	130.2	10.3	32.8	1.475
			3B-10	132.9	0.23	26.7	0.465
20.7(5)	23.6	0.353	3C-5	60.8	11.7	14.5	0.372
36.6	32.8	0.462	3C-6	60.8	35.5	21.7	0.700
21.2(6)	23.9	0.354	3C-7	63.4	0.09	11.4	0.152
11.3	18.1	0.297					
1.1	11.9	0.173					
9.1	17.5	0.222	3D-3	87.2	5.5	17.2	0.245
33.5	40.9	0.553	3D-4	87.2	27.7	26.9	0.673
0.6	16.3	0.146	3D-5	89.3	0.21	15.3	0.122
1.9	21.7	0.350	3E-9	102.8	1.5	21.3	0.328
2.1	22.1	0.371	3E-10(8)	102.8	25.8	33.8	1.189
4.4	23.6	0.403	3E-11	106.5	2.2	22.5	0.417
27.2	46.5	0.849	3E-12	103.6	1.2	21.3	0.334
28.4	48.0	2.320	3E-13(9)	106.5	22.1	33.1	0.989
27.7	47.7	1.850	3E-14(8)	103.5	25.0	33.6	1.060
2.5	23.0	0.371	3E-15	104.7	2.0	22.0	0.375
26.7	47.7	1.479	3E-17	102.5	0.21	20.6	0.157
0.21	22.7	0.196	3E-18	111.3	0.12	22.3	0.196

ft.
ter leaked
test.

(5) Average - w = 14.2% at top of sample
w = 27.3% at 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

3E-7 and 3E-15	1/2" - 3/4"	50%
	3/8" - 1/2"	25%
	1/8" - 3/8"	25%
3E-8 and 3E-17	1/2" - 3/4"	
3E-21 and 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.

C.R.-48-46
F.R.-48-46

TABLE 2

INVESTIGATOR	SOIL TESTED	WATER CONTENT %	THERMAL CONDUCTIVITY WATTS / CM/°C	BTU / FT/°F/HR	UNIT DRY WEIGHT LBS/CU.FT.
Shanklin	Clean yellow builders sand	0.15	0.003	0.174	
		1.6	0.0035	0.202	
		4.2	0.0048	0.278	
		9.0	0.013	0.752	
	Yellow sandy clay	0.89	0.0025	0.145	
		3.87	0.0029	0.168	
		8.5	0.0032	0.185	
		15.0	0.014	0.810	
Kennelly (a)	Fine white quartz sand (b)	0.2	0.0025	0.145	
		7.0	0.0044	0.255	
		13.8	0.0062	0.359	
	Fine sandy soil	0.2	0.0021	0.121	
		4.0	0.0023	0.133	
		8.0	0.0024	0.139	
		15.0	0.0028	0.162	
Teichmuller	Clean yellow sand	0.2	0.0031	0.179	
		4.1	0.0125	0.729(c)	
		9.8	0.0161	0.932	
	Average sandy soil	12.0	0.0085	0.492	
Ingersoll and Koepp	Quartz	0.0		0.42	103
	Medium fine sand	8.3		0.94	109
	Sandy clay	15.0		1.47	111
	Calcareous earth	43.0		1.14	104
Berggren	Dry soil	0.0		0.19	
	Moist soil (frozen)			0.68	
	Moist soil (unfrozen)			0.48	
	Wet soil (frozen)			1.21	
	Wet soil (unfrozen)			0.97	

(a) Test equipment considered unsatisfactory by Shanklin.
(b) Passing 0.25 mm mesh.
(c) Shanklin believes water content for this value should be about nine per cent.

FROST INVESTIGATION
1945 - 1946

THERMAL CONDUCTIVITY TESTS
BY OTHER INVESTIGATORS

BOSTON, MASS.
FROST EFFECTS LABORATORY, JUNE 1946

AIRFIELD	YEAR	TEST AREA	TYPE OF TEMPERATURE MEASURING INSTALLATION	THICKNESS OF PAVEMENT AND BASE (INCHES)		CLASS OF FROZEN SUBGRADE SOIL	MEASURED DEPTH OF FROST PENETRATION (INCHES)	TEMPERATURE AT DEPTH OF FROST PENETRATION (°F)	DISTANCE BETWEEN NEAREST TEMPERATURE INSTALLATION AND TEST PIT (FEET)
				AT TEMPERATURE INSTALLATION	AT TEST PIT				
Presque Isle	1944-45	A	Thermocouple	31	37	GC	64	32.1	47
					40	GC	56	33.0	51
					41	GC	70	34.2	33
					31	GC	65	33.5	320
		B	Thermocouple	30	30	GC	68	33.0	40
					31	GC	46	31.6	45
					30	GC	64	32.5	552
					24	GW	24	32.1	1118
					31	GC	71	32.7	37
					31	GC	68	32.6	277
					31	GC	70	32.6	655
					31	GC	70	32.1	1062
	1945-46	A	Thermocouple	31	42	GC	48	33.4	25
					42	GC	52	32.2	15
					40	GC	78	34.4	30
					31	GC	32	32.7	47
					31	GC	68	33.2	47
					38	GC	40	37.2	8
					38	GC	46	35.0	8
		C	Thermocouple	30	31	GC	42	32.9	12
					35	GC	50	31.5	15
					46	GC	62	31.6	20
					30	GC	68	31.7	35
					29	GC	65	31.9	48
		Turf	Thermocouple	-	5(TS)	GC	18	32.1	25
					2(TS)	GC	36	30.7	10
					4(TS)	GC	32	29.8	50
					2(TS)	GC	50	31.6	173
Dow	1944-45	A	Thermocouple	20	19	CL	47	35.1	39
					24	CL	54	34.9	182
					22	CL	52	35.6	163
					24	CL	53	35.8	144
					20	CL	44	34.9	45
					24	CL	47	34.0	124
					22	CL	46	35.6	56
					24	CL	44	35.8	148
					24	CL	43	40.6	43
		B	Thermocouple	30	32	CL	46	34.3	50
					24	CL	41	33.2	92
					40	CL	52	35.0	166
					37	CL	48	34.7	198
					29	CL	46	34.6	80
					38	CL	48	34.7	142
					37	CL	47	35.2	122
					29	CL	49	35.5	140
					26	CL	47	34.9	72
					29	CL	44	34.2	56
					26	CL	38	35.4	80
					32	CL	52	35.5	156
		C	Thermocouple	41	49	CL	60	33.0	38
					66	GW	48	35.2	280
					60	CL	62	35.8	294
					49	GW	44	34.1	62
					48	CL	55	34.9	218
					30	CL	48	33.6	-
		Turf	Thermocouple	-	2(TS)	CL	13	31.8	124
					0	CL	20	32.6	46
					7(TS)	CL	24	34.0	14
	1945-46	D	Thermometer	42	41	CL	50	33.1	28
		B	Thermocouple	38	37	GW	31	32.4	38
					36	GW	36	32.5	28
					42	CL	44	32.5	32
					37	CL	19	31.4	22
					37	CL	48	32.0	22
		F	Thermocouple	20	28	CL	36	32.7	117
					28	CL	54	35.6	131
					29	CL	53	33.1	116
					26	CL	26	35.1	100
					26	CL	52	35.3	100
		Turf	Thermocouple	-	2(TS)	CL	15	33.0	70
					2(TS)	CL	24	33.3	14
					2(TS)	CL	24	32.9	14
					1(TS)	CL	26	33.4	130

AIRFIELD	YEA
Sioux Falls	1944-
	1945-
Pierre	1944-
	1945-
Great Bend	1944-
Fargo	1945-
Watertown	1944-
Truax	1945-
Bedford	1945-
Selfridge	1945-

NO

EMPERATURE AT DEPTH OF FROST ENETRATION (°F)	DISTANCE BETWEEN NEAREST TEMPERATURE INSTALLATION AND TEST PIT (FEET)
32.1	47
33.0	51
34.2	33
33.5	320
33.0	40
31.6	45
32.5	552
32.1	1118
32.7	37
32.6	277
32.6	655
32.1	1062
33.4	25
32.2	15
34.4	30
32.7	47
33.2	47
37.2	8
35.0	8
32.9	12
31.5	15
31.6	20
31.7	35
31.9	48
32.1	25
30.7	10
29.8	50
31.6	173
35.1	39
34.9	182
35.6	163
35.8	144
34.9	45
34.0	124
35.6	56
35.8	148
40.6	43
34.3	50
33.2	92
35.0	166
34.7	198
34.6	80
34.7	142
35.2	122
35.5	140
34.9	72
34.2	56
35.4	80
35.5	156
33.0	38
35.2	280
35.8	294
34.1	62
34.9	218
33.6	-
31.8	124
32.6	46
34.0	14
33.1	28
32.4	38
32.5	28
32.5	32
31.4	22
32.0	22
32.7	117
35.6	131
33.1	116
35.1	100
35.3	100
33.0	70
33.3	14
32.9	14
33.4	130

AIRFIELD	YEAR	TEST AREA	TYPE OF TEMPERATURE MEASURING INSTALLATION	THICKNESS OF PAVEMENT AND BASE (INCHES)		CLASS OF FROZEN SUBGRADE SOIL	MEASURED DEPTH OF FROST PENETRATION (INCHES)	TEMPERATURE AT DEPTH OF FROST PENETRATION (°F)	DISTANCE BETWEEN NEAREST TEMPERATURE INSTALLATION AND TEST PIT (FEET)
				AT TEMPERATURE INSTALLATION	AT TEST PIT				
Sioux Falls	1944-45	A	Thermocouple	12	12	CL	39	33.0	110
				12	12	CL	38	32.5	110
	1945-46	A	Thermocouple	12	10	CL,CH	19	32.4	63
					10	CL,CH	44	32.2	63
					12	CL,CH	31	33.8	36
					12	CL,CH	41	32.4	36
		B	Thermometer	6	6	CH	19	32.0	52
					6	CH	40	32.0	52
Pierre	1944-45	A	Thermocouple	14	14	CL	42	32.8	65
		B	Thermocouple	14	13	CL	25	28.8	215
	1945-46	A	Thermocouple	14	12	CL - SF	48	33.1	25
					14	CL	44	33.0	65
					14	CL,CH	44	36.7	60
Great Bend	1944-45	A	Thermometer	12	13	GP	13	37.0	37
Fargo	1945-46	A	Thermometer	8	7	SF,OH-OH,CH	46	31.0	15
Watertown	1944-45	A	Thermocouple	10	10	SF-CL,SP	36	34.5	100
					10	SF-CL,OL	38	34.8	60
		Turf	Thermocouple	-	-	SF-OL,CL	42	35.6	18
Truax	1945-46	C	Thermometer	42	43	GF	41	31.5	16
					42	CL	48	32.0	20
		D	Thermometer	23	22	GF	48	31.9	14
					23	GF	59	32.1	20
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	32.4	33
		B	Thermometer	18	18	SW	26	31.8	8
					18	SW	20	31.4	16
					24	SW	26	32.4	33
					18	SW	25	32.1	24
Selfridge	1945-46	A	Thermometer	26	21	ML	24	30.8	210
					21	ML-SF	34	31.5	260
					24	ML	35	32.5	220
					20	ML	31	32.7	280
					22	ML	29	32.5	370
					20	ML-SF	28	32.7	335

NOTE

"(TS)" after figures in column headed "THICKNESS OF PAVEMENT AND BASE (INCHES) - AT TEST PIT" indicates top soil.

FROST INVESTIGATION
1945-1946

OBSERVED TEMPERATURES AT DEPTHS OF FROST PENETRATION

FROST EFFECTS LABORATORY BOSTON, MASS. JUNE 1946

C.R.- 46- 46 TABLE 4

B

SITE	TEST AREA	YEAR	MEAN ANNUAL AIR TEMP. °F (v_0)	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)
DOW	I AND III	1943 - 1944	42.5	1515	108	B.C.	4.0	GW	17	9.8	135	CL	-	30.5	81
	II			1890	123	B.C.	3.5	GW	36	4.2 *	135 *	CL	-	19.3 *	107 *
	III TO VII			1745	130	P.C.C.	7.0	GW	15	9.2	133	CL	38	28.4	92
												GC	-	28.4 (1)	92 (1)
	A	1944 - 1945		1445	104	P.C.C.	7.0	GW	15	11.1	119	CL	42	25.7	98
												GC	-	25.4 NF	103 NF
	B			1445	104	B.C.	3.5	GW	31	8.9	131	CL	-	31.1	93
														24.2 NF	92 NF
	C			1345	88	B.C.	3.5	GW	42	9.2	121	CL	-	19.3	109
	C			1445	104	B.C.	3.5	GW	42	9.2	121	CL	-	19.3	109
	TURF			1445	104	T.S.	6.0	-	-	-	-	CL	-	23.4	99
														15.2 NF	112 NF
	D	1945 - 1946		1420	99	B.C.	3.5	GW	40	13.5 *	128 *	CL	-	17.7 *	115 *
	E			1420	99	B.C.	3.5	GW	36	10.1 *	136 *	CL	-	22.4 *	101 *
	E			1000	75	B.C.	3.5	GW	38	10.1 *	136 *	CL	-	22.4 *	101 *
	F			1080	74	P.C.C.	7.0	GW	20	8.1 *	138 *	CL	-	22.5 *	110 *
	TURF			1420	99	T.S.	6.0	-	-	-	-	CL	-	22.4 (1)	101 (1)
PRESQUE ISLE	A	1944 - 1945	39.0	2060	115	P.C.C.	7.0	GW	33	6.3	134	GC	-	17.9	108
														16.2 NF	113 NF
	B			2060	115	B.C.	4.0	C.R.	4	-	-	GC	-	14.8	114
								GW	30	8.5	134			14.2 NF	114 NF
	TURF			140	25	T.S.	5.0	-	-	-	-	GC	-	18.6	105
														15.9 NF	110 NF
	A	1945 - 1946		2240	128	P.C.C.	7.0	GW	32	10.4 *	133 *	GC	-	17.0 *	117 *
	C			2230	120	B.C.	3.5	C.R.	3.5	-	-	GC	-	13.6 *	115 *
								GW	28	6.3 *	* 132				
	D			2230	124	B.C.	3.5	C.R.	3.5	-	-	GC	-	10.4 **	120 **
								GW	25	10.5 **	** 142				
	TURF			2240	128	T.S.	5.0	-	-	-	-	GC	-	13.8 (1)	115 (1)
BEDFORD	A	1945 - 1946	46.5	625	99	P.C.C.	6.0	GW	18	4.8 *	119 *	SW	-	3.3 *	103 *
	B			695	87	B.C.	5.0	GW	14	4.8 (1)	119 (1)	SW	-	3.3 (1)	103 (1)
	B			345	41	B.C.	5.0	GW	14	4.8 (1)	119 (1)	SW	-	3.3 (1)	103 (1)
OTIS	A	1944 - 1945	48.7	300	60	B.C.	6.0	-	-	-	-	SF OR	30	9.5 **	** 124
												ML		23.5 **	** 87
												SP	24	1.2	119
												GP	-	0.8	128
HOULTON	A	1944 - 1945	40.5	1605	107	B.C.	1.5	B.CEM.	6	16.3	113	GF	30	14.7	110
												GC	-	6.3	134
														10.1 NF	NF 118
TRUAX	A	1944 - 1945	46.0	1210	88	B.C.	2.5	C.R.	8	-	-	CL	23	21.1 *	108 *
								GF	15	5.3 *	* 141	SF	38	6.1 *	118 *
												CL	-	21.1 *	108 *
	B			1245	95	B.C.	2.5	C.R.	10	-	-	CL	-	27.0	99
								GF	25	7.7	122				
	C			1245	97	P.C.C.	8.0	GF	48	12.7	112	CL	-	30.0	92
	A	1945 - 1946		1020	93	B.C.	2.5	C.R.	8	-	-	CL	28	27.5 *	95 *
								GF	18	6.0 *	* 140	SF	38	10.8 *	118 *
												CL	-	27.5 *	95 *
	C			1060	100	P.C.C.	7.0	GF	30	10.1 *	* 129	CL	32	35.5 *	87 *
												SF	-	20.4 *	113 *
	D			1055	99	B.C.	2.5	C.R.	20	-	-	CL	-	25.9 *	99 *
								GF	30	5.6 *	* 130				
SELFRIDGE	B	1945 - 1946	47.0	645	81	P.C.C.	10.0	GF	12	11.5	99	ML	13	18.0	112
												SF	30	22.3 *	108 *
												CL	-	36.2 *	85 (1)
PIERRE	A	1944 - 1945	47.5	860	104	P.C.C.	7.0	GF	7	6.7 *	135 *	CL	32	15.1 *	105 *
												CH	-	23.5 *	99 *
	B			695	71	B.C.	5.5	GF	8	6.4 *	140 *	CL	-	14.1 *	97 *
	TURF			860	69	T.S.	4.0 (1)	-	-	-	-	CL	60	12.1 *	98 *
												CH	-	18.7 *	98 *
	A	1945 - 1946		1025	99	P.C.C.	7.0	GF	7	7.4 *	* 142	CL	27	21.6 *	97 *
								CL	8	15.9 *	* 110	CH	-	21.7 **	97 **
	C			1025	99	B.C.	6.0	GF	8	8.7 *	* 120	CL	-	12.7 *	92 *
								CL	7	13.9 *	* 115				
SIOUX FALLS	A	1944 - 1945	46.2	915	76	B.C.	2.0	GC	10	7.0 *	* 132	CL OR	-	23.8 *	95 *
								CL	12	16.7 *	* 112	CH		30.9 *	84 *
	A	1945 - 1946		1220	82	B.C.	2.0	GC	10	7.1 *	* 137	CL OR CH	48	29.0 *	89 *
								CL	12	21.4 *	* 103	SF-CL	-	15.9 *	97 *
	B			1310	100	P.C.C.	6.0	-	-	-	-	CH	90	33.0 *	85 *
												CL	11	27.5 **	87 **
												SC	-	15.9 (1)	97 (1)
WATER-TOWN	A	1944 - 1945	42.5	860	62	P.C.C.	6.0	-	-	-	-	SF-OL	32	14.9 *	112 *
												OL-CL	26	23.8 *	87 *
												GP	-	3.8 *	120 (1)
	B			840	59	B.C.	5.0	GF	8	4.9 *	130 *	SF-OL	22	14.1 *	103 *
												OL-CL	11	22.1 *	88 *
												GP	-	4.4 *	120 (1)
	TURF			860	64	T.S.	6.0	-	-	-	-	SF-OL	52	6.4 *	138 *
												GP	-	4.4 *	120 (1)
	A	1945 - 1946		1715	98	P.C.C.	6.0	-	-	-	-	SF-OL	24	14.6 (1)	112 (1)
												OL-CL	22	23.8 (1)	87 (1)
												GP	-	3.8 (1)	120 (1)
	B			1715	98	B.C.	5.0	GF	12	4.0 (1)	130 (1)	SF-OL	30	14.1 (1)	103 (1)
												GP	-	4.4 (1)	120 (1)
FARGO	A	1944 - 1945	39.2	1395	70	B.C.	1.5	B.CEM.	6.5	11.1 *	* 122	OH-CH	6	28.7 *	90 *
								CL-SF	14	10.6 *	* 126	CH	-	31.1 *	89 *
	A	1945 - 1946		2465	125	B.C.	1.5	B.CEM.	6.5	11.1 (1)	122 (1)	OH-CH	12	28.7 (1)	90 (1)
								CL-SF	11	10.6 (1)	126 (1)	CH	-	31.1 (1)	89 (1)
GREAT BEND	A	1944 - 1945	55.0	50	5	P.C.C.	7.0	SW OR SF	6	2.0 *	120 *	SF-CL	35	15.1 *	109 *
												OR			
												CL-SF		13.1 *	102 *
												CL	-	17.0 *	100 *
	A	1945 - 1946		130	11	P.C.C.	7.0	SF	5	2.0 (1)	120 (1)	SF-CL	35	15.1 (1)	109 (1)
												OR			
												CL-SF		13.1 (1)	102 (1)
												CL	-	17.0 (1)	100 (1)
BISMARCK	A	1944 - 1945	39.0	1280	86	B.C.	4.5	SC	6	4.7 *	130 *	CL-ML	40	16.6 *	97 *
												SP	-	8.1 *	99 *
CASPER	A	1944 - 1945	47.4	355	55	P.C.C.	7.0	-	-	-	-	SF-CL	20	11.4 *	114 *
												SF	12	8.8 *	120 *
												SP	-	5.3 *	111 *
	B			355	55	B.C.	5.0	GW	7	3.0 *	131 *	SF-CL	12	8.2 *	117 *
												SP	32	3.5 *	109 *
												SF-CL	-	8.2 *	117 *
FAIRMONT	A	1944 - 1945	52.0	360	70	P.C.C.	6.0	-	-	-	-	CL	25	20.9 *	98 *
												CH	-	23.0 *	98 *
GARDEN CITY	A	1944 - 1945	55.0	25	7	B.C.	1.5	SC	18	5.0 *	128 *	CL	30	15.0 *	107 *
												CH	-	10.1 *	95 *
												OR			
												CH-CL		10.3 *	97 *

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	EMP.
81 / 107 R	38.8	2920	48	88	82	44◀	▶48◀		55
92	39.5	1300	50	106	87	▶62	65		▶62
92 (I)	42.8	3900	48	83	58	41	▶48◀		63
88 / 103 NF	44.1	3035	54	85	58◀	41	48◀		▶57◀
93 / 92 NF	39.2	2310	52	75	88	47◀	▶50◀		57◀
109	40.0	1880	60	79	87	47	50		▶55◀
109	40.0	1985	62	81	89	49	52		▶57◀
88 / 112 NF	39.0	3500	24					37	
115 R	42.1	2530	50	71	82	44◀	▶47◀		56◀
101 R	41.5	2205	48	76	88	▶47◀	50◀		58
101 R	41.6	2110	44	88	59	42◀	▶43◀		50◀
110 R	44.8	2700	54	58◀	▶52◀	37	44		49◀
101 (I)	42.0	3210	26						
108 / 113 NF	36.7	1945	70	98	85	60	67◀	37	▶66◀
114 / 114 NF	37.4	1870	71	99	87	62	▶70◀		68◀
105 / 110 NF	39.1	2790	13					12◀	
117 R	41.1	2450	78	91	▶80◀	57	64		71
115 R	37.0	1785	68	106	92	▶65◀	72◀		▶71◀
120 RR	44.0	2740	69	85	76	54	61		▶71◀
115 (I)	37.5	2230	60						
103 R	28.0	800	40	88	78	54	60	58◀	▶43◀
103 (I)	28.0	805	18	88	70	49	54		▶40
103 (I)	28.0	605	28	62	49	35	40		▶28◀
124	27.4	2265	28	34	31◀	22◀	28◀		▶28◀
	34.6	2180	49	61	72	▶51◀	52◀		60
	39.9	2305	48	88	58	41	▶51◀		52◀
	43.9	1605	56	78	64	45	65		▶53◀
	38.8	2070	55	74	62	44	50◀		▶53◀
	43.7	2430	48	82	53	37	▶47◀		48◀
	43.9	2550	48	61	53◀	37	44◀		▶49◀
	43.2	1580	59	78	▶63◀	44	60		49
	44.6	2200	35	50	43	30◀	40◀		▶38◀
	37.9	2150	42	63	54	▶39◀	46◀		46◀
	32.8	1640	25	62	52	▶37	42		40
	35.8	1480	8					34	
	39.1	2625	48	59	52◀	37	44◀		▶48◀
	30.0	1670	44	74	63	▶45◀	51		48◀
	40.8	2840	40	56	49	35◀	▶37◀		45◀
	36.5	3020	47	60	53◀	38	40		▶52◀
	38.0	3080	42	54	50	35	▶41◀		54
	30.7	2325	36	56	52	▶37◀	45		44◀
	29.9	1870	42	62	55	39◀	44◀		▶43◀
	30.6	1240	42					43◀	
	28.7	2010	75 TH	88	▶77◀	55	64		62
	29.6	1330	79 TH	108	90	64	▶69		62
	43.2	2065	46	85	38	42◀	▶43◀		58
	42.3	3395	72 TH	81	▶73◀	52	53		74◀
	30.4	325	15	37	16◀	▶13◀	20		11◀
	30.2	1600	24 TH	27◀	21◀	15	▶22◀		17
	28.7	1905	48	78	70	▶50◀	54		54
	29.2	1850	30	42	36◀	26◀	33◀		▶28◀
	28.7	870	16	61	47	34	38		▶28
	38.1	3550	15	51	26	▶20◀	28		29
	36.2	990	12	15◀	▶11◀	8◀	9◀		6◀

EQUATIONS:

$$83 \quad x = \sqrt{\frac{48kF}{L}}$$

$$93 \quad x = \sqrt{\frac{48kF}{L + C\left(v_0 - 32 + \frac{F}{2t}\right)}}$$

$$154 \quad x = \sqrt{\frac{24kF}{L + C\left(v_0 - 32 + \frac{F}{2t}\right)}}$$

$$158 \quad x = -\frac{d}{2} + \sqrt{\left(\frac{d}{2}\right)^2 + \frac{24kF}{L + C\left(v_0 - 32 + \frac{F}{2t}\right)}}$$

EMPIRICAL $x = 0.125\sqrt{F}$

- 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./FT³
- C = AVERAGE VOLUMETRIC HEAT IN B.T.U./(FT³)(°F)
- v_0 = 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)

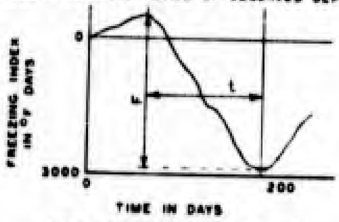
(II) VALUES USED FOR WATER CONTENT AND DENSITY ARE FOR FREEZING PERIOD WHEN AVAILABLE. EXCEPTIONS ARE NOTED AS FOLLOWS:
- R - VALUES FOR NORMAL PERIOD
- RR - VALUES FOR FROST MELTING PERIOD
- (I) - ASSUMED VALUES
- NF - VALUES FOR NON-FROZEN SUBGRADE SOIL (FREEZING PERIOD)

(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

SUMMARY OF AIRFIELD PAVEMENT FAILURES WHERE FROST

AIRFIELD	LOCATION OF DISTRESSED AREA	PAVEMENT: TYPE	PAVEMENT: THICKNESS INCHES	PAVEMENT: WORKING STRESS IF CONCRETE (LIMITED OPERATION) 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 PL.	SUBGRADE: ATTERBERG LIMITS L.L.	SUBGRADE: CBR OR SUBGRADE MODULUS (k) IN PLACE UNLESS OTHERWISE NOTED	GROUND WATER DEPTH (FEET)	SUB SURFACE
DOW FIELD, BANGOR, MAINE	Apron widening, turnaround and warm-up apron 10,000 sq. yds.	Non-reinforced concrete	7	429	Bank run sand and gravel	17	During frost melting period base observed to be saturated	Borderline	k = 315 (1)	CL	100%	Yes	19	30	CBR = 4 (1)	Approx. 2 to 4	[illegible]
PRESQUE ISLE AIRFIELD PRESQUE ISLE, MAINE	Portion of N-S Runway 500 sq.yds.	Asphaltic concrete	3		Bank run sand and gravel	18 to 20	30% to 60% (1)	Borderline	CBR = 50 (1)	GP	70% to 80%	Yes	20	30	CBR = 10 (1)	Approx. 2 to 6	[illegible]
BRIDGETON - MILLVILLE AIRFIELD MILLVILLE, N. J.	Portions of NE-SW and NW-SE Runways from 50 to 1,000 sq. ft. at intervals.	Asphaltic concrete	2		None					GP, SF and GC	80% to 90%	Yes	19	28	CBR = 50✓ (1)	Not given	[illegible]
		Portland Cement Concrete	6-4-6	325	None										k = 350 (1)		
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	Not reported calculated from the evaluation report as 100% +.	No	Not reported	Micaceous clays CH	Not reported calculated from evaluation report as 85%.	Yes	15 to 30	41 to 63	CBR = 8 (1)	Not given	[illegible]
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 19% oversize crushed.	8	Not reported.	No	CBR = >80 (1)	CL	Not reported	Yes	20	35	3 (1) (laboratory tests on soaked samples)	Indefinite but deep	[illegible]
HARVARD AIRFIELD HARVARD, NEBRASKA	Taxiway 2 and small areas of south and north ends of N-S Runway	Portland cement concrete	11-8-11	Taxiway 2 350	None					CL, ML CH, OL	90% to 100%	Yes	22	44	k = 96 (2)	20	[illegible]
				300	None										k = 190 (2)		
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 56%	Yes	CBR = 25 to >50 CBR of 25 under taxiway 1 and 3.	ML	32% to 63%	Yes	11.6 to 20.1	19.6 to 35.1	CBR = 3 (1) to 6 (1)	>15	[illegible]
BUCKLEY FIELD, DENVER, COLORADO	E-W and NW-SE Runway, taxiways A, B, C, D, E, F, G, W and X also landing apron	Portland cement concrete Areas over fill reinforced	6-6-6 9-6-9	250	None					CH, CL, SF SF-CL CL-SF	Average [illegible]	Yes	21	43	k = 53 (1) k = 27 (2)	Not reported	[illegible]
CAMP WILLIAMS AIRFIELD, CAMP DOUGLAS, WISCONSIN	Lane in Apron.	Portland cement concrete	8	525	None					GP, SF		Yes	Non-plastic		k = 117 (1)	[illegible]	[illegible]
	Lane on taxiway at east end of apron edges of bituminous pavement.	Bituminous concrete	2½-3		Varies from 6" gravel - sand to 6" gravel - sand on 6" broken shale.	6 to 12 Variable	Free Draining	No	CBR = 31.4 (1) Average	SP, [illegible]	45% Average				CBR = 23.3 (1) Average saturated	[illegible]	
OTIS FIELD, CAMP EDWARDS, MASS.	Main service apron, extension to service apron, runways	Apron-non-reinforced Portland cement concrete	7	335	Bank run and gravel	6	14% to 80%	No	k = 415 (1)	SW, GW SP, GP	60% to 100%	Yes	[illegible]	41	CBR = 35 (1)	2 to 40	[illegible]
		Bituminous concrete	4.5 - 6.2		Gravel	6 to 12		1942 construction contains some areas that are frost susceptible	CBR = 65 (1)	SW, GW SP, GP							
BILLY MITCHELL FIELD CUDAHY, WISCONSIN	600 ft. at West end of E-W runway, 1200 ft. at [illegible] of NE-SW runway, entire 2500 ft of apron taxiway	Bituminous concrete	[illegible]		Pit run gravel crushed stone	7 to 12		No	CBR = 75 (1) to >80 (1)	CL	[illegible]% to 91%	Yes	14.4 to 20.6	23.6 to 42.9	CBR = 6.2 (1) to 8.0 (1)	>6 ft.	[illegible]

[illegible]ILURES WHERE FROST ACTION WAS CONTRIBUTING CAUSE

[illegible]ADE: Atterberg Limits P.L.	[illegible]ADE: Atterberg Limits L.L.	[illegible]ADE: 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	Probable Depth of Frost Penetration into Subgrade	Traffic: Period of Use Prior to Last Dated Report of Distress	Traffic: Predominate Gross Plane Wt. Using Field Immediately Preceding Distress (Lbs.)	Evaluation (Lbs Gross Plane Wt.): Normal Period	Evaluation (Lbs Gross Plane Wt.): Frost Melting Period (Limited Operation) (Based upon Revised Engr. Manual)	Remarks
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		Fall 1942 to 1946	[illegible],000	111,000	[illegible],000	
20	30	CBR = 10 (1)	Approx. 2 to 6	At edges of runway	Pavement developed heaving 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.	2260		Not given	60,000	59,000	25,[illegible]	
19	29	CBR = 50+ (1) k = 350 (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	Low CBR of base. 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		Jan. 1943 to Aug. 1943	13,000	15,000 74,000	Very low [illegible],000	
15 to 38	41 to 63	CBR = 8 (1)	Not given	Not adequate where filled.	Heaving of subgrade and overlending 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		June 1941 to Aug. 1945	1942-118 cycles per day-[illegible],000 # 1943-151 cycles per day-[illegible],000 #	20,000	Very low	
20	35	3 (1) (laboratory tests on soaked samples)	Indefinite but deep	Not reported	Area showed no signs of distress until frost left the ground when when depressions began to appear which in some instances increased to a depth of 6" with accompanying cracking.	Not reported	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		May thru July 1943	56,000	15,000	[illegible],000	
22	41	k = 96 (2) k = 19[illegible] (2)	20	Limited no details	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		Aug. 1943 to June 1944	60,000	75,000	55,000	
1[illegible] to 2[illegible].1	1[illegible] to [illegible].1	CBR = 3 (1) to [illegible] (1)	>15	[illegible]oor at [illegible] 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 the first the load was run over them. Utility trenches settled when frost left ground.	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	Reported as from 3-5 ft.	Spring '43 to August 31, 1943	50,000	8,000 to 18,000	5,000	
[illegible]1	43	k = 5[illegible] (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)		Jan. 1942 to 1 Aug. 1944	20,000	20,000	10,000	
None [illegible]		[illegible] = 117 (1) CBR = 23.5 (1) Average saturated	[illegible] [illegible] below [illegible]	[illegible] and edge of pavement	[illegible] and cracking of concrete apron along lanes cleared of snow. Additional cracks in other sections of apron. B-17 landing rutted flexible pavement.	April 1943	Frost action caused cracking of apron. Head of water under apron causing bleeding at cracks and joints.	1942-1943 1896	40-55 [illegible] maximum penetration below paved areas	1942-1943	55,000 64,000	98,000 74,000	90,000 18,000	
[illegible]1		CBR = 3[illegible] (1)	2 to 40	At edge of runways, and taxiways	[illegible] during winter of 1944 [illegible] severe. Surface stones in [illegible] portions of runways loosened and were picked out by traffic. Apron cracked and heaved as much as 1" at joints between slabs. Runway heaves of 4-[illegible]" found in 1[illegible] of pavement.	Feb. 1944 March 1943 Jan. Feb. Mar. 1944	Additional drainage and seal coat prevented surface and underground water destroying pavement. Frost and traffic over unsealed portions. Frost action caused cracking; [illegible] and inorganic matter in base. Poor drainage and lack of seal coat, pockets of poor material found in 1944 constructed areas.	1942-1943 4[illegible] 1943-1944 [illegible]	[illegible] ft.	Jan. 1942 to Jan. 1944 May 1944 to Nov. 1944	32,000 [illegible],000 to [illegible],000	74,000 to 120,000 120,000+	25,000 30,000	
[illegible] to [illegible]	23.6 to [illegible]	CBR = [illegible].2 (1) to [illegible].0 (1)	>[illegible] ft.	[illegible]	[illegible] 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 1[illegible]		June to Sep. 1942 April to June 1943	2[illegible],000 to 6[illegible],000 60,000	[illegible] runway [illegible],000	10,000	

SHEET 1 OF 3 SHEETS TABLE 6

SUMMARY OF AIRFIELD PAVEMENT FAILURES WHERE FROS

AIRFIELD	LOCATION OF DISTRESSED AREA	PAVEMENT			BASE					SUBGRADE						GROUND WATER DEPTH (FEET)
		TYPE	THICKNESS INCHES	WORKING STRESS IF CONCRETE (LIMITED OPERATION) 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	
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.	12.75-8.5-11	280 to 355	Semi-Soil base Sand cushion 8" sand-gravel base 2" asphalt 3" sand cushion	8 15	Not reported	No	Not reported	CL, [illegible] ML, [illegible]	96%	Yes	21 (Average)	37	k = 145 (1) k = 101 (2)	Reported as low as 18 to 30
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.	Asphaltic concrete	1.5 to 2		Cement treated gravel on clay gravel subbase. Clay gravel under taxiway Nos. 2 and 2a.	6 4 7½	Base = [illegible]% Average subbase = [illegible]% 91%	Base / Yes Subbase / Yes	CBR for cement gravel base = 90+ (1) CBR for subbase = 20 (1) CBR for 7.5" base under taxiway 2 and 2a = 20 (1)	CL, CH	61%	Yes	16 to 24	30 to 54	CBR = 7 (1)	High water table not prevalent
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 construction	1½		Gravel water bound chat subbase	6 to 8	Highly Saturated 21%	Yes	CBR = 45% (1)	CL, CH ML	75%	Yes	11	28	CBR = 7 (1)	High water table not prevalent
COFFEYVILLE AUXILIARY FIELD NO. 3 COFFEYVILLE, KANSAS	Areas on NE-SW and NW-SE runways.	Portland cement concrete	6	525	None					CL-ML CL, CH	96%	Yes	21 to 29	32 to 72	k = 39 (1) k^f = 24 (1)	Not reported
RAPID CITY AIRBASE, RAPID CITY, SOUTH DAKOTA	E-W runway and runway shoulders.	3½" asphalt concrete on original pavements. Portland cement concrete	3½ 7	465	Asphalt and gravel	1½ to 3½ 6 to 8	59%	Borderline	k^f = (2) 51 to 159	CL, CL CH, CL GP, SP MP, CH GP, CL [illegible]	92%	Yes	21 (Average)	48	CBR = 6 est. for taxiway "G" k^f = 39	Reported as very deep
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	Asphaltic concrete	1 to 3½		Penetration and water bound macadam	3 to 5	Not reported	No	Not reported	CL	Not reported	Yes	23.7	37.9	CBR = 6 (1) to 12 (1)	Undetermined (Not a factor)
BUFFALO MUNICIPAL AIRPORT, BUFFALO, NEW YORK	Portions of E-W runway NE-SW runway, NW-SE runway and east taxiway	Bit. conc. P.C.C. Penetration surface course	4 6 2	Not reported	Stone Stone	7 7	Not reported	No	CBR on crushed stone averaged 77.5 (1)	ML (A-4) Slightly plastic group	100% for fill section and 95% for natural ground.	Yes	14.1 to 17.8	22 to 25.4	CBR = 9(1) to 34 (1)	
WATERTOWN AIRPORT, WATERTOWN, N. Y.	Taxiways Nos. 1 and 3.	Asphalt concrete	2		Bank run gravel.	15	100%	Yes	CBR = 7.8 to 27.2 Laboratory tests.	[illegible]-ML	100%	Yes	2[illegible].3 to 34.5	41 to 48.4	CBR = 7 Average lab. tests	Not reported
SCHENECTADY AIRPORT, SCHENECTADY, N. Y.	Sections of E-W, N-S, NW-SE runway and NE-SW taxiway and N-S taxiway	Asphalt concrete	3		Stabilized run of bank gravel.	7 to 12	63%	Yes	CBR = field 24.7(1) Lab = 80	SP-SF	77%	Yes	Non-plastic		CBR = field 25(1) to 38 Lab. 10 to 27	Not reported
LEWISTON AIRFIELD, LEWISTON, MONTANA	NW end of NE-SW runway NE end of NW-SE runway perimeter taxiways "D-E" taxiway, "A" taxiway east end of E-W runway	Asphalt concrete	4.75 to 6		Gravel	6 to 12	76%	Yes	CBR = 80+ (1)	CL	71%	Yes	14.3 to 24.5	30.8 to 51.5	CBR = 7 (1)	100' ± below surface

T FAILURES WHERE FROST ACTION WAS CONTRIBUTING CAUSE

(SUB)GRADE: Frost Susceptible	(SUB)GRADE: Atterberg Limits P.L.	(SUB)GRADE: Atterberg Limits L.L.	(SUB)GRADE: 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	Probable Depth of Frost Penetration into Subgrade	Traffic: Period of Use Prior to Last Dated Report of Distress	Traffic: Predominate Gross Plane Wt. Using Field Immediately Preceding Distress (Lbs.)	Evaluation (Lbs Gross Plane Wt.): Normal Period (Limited Operation)	Evaluation (Lbs Gross Plane Wt.): Frost Melting Period (Based upon Revised Engr. Manual)	Remarks
Yes	21 (Average)	37	k = 143 (1) k = 101 (2)	Reported as low 16 to 30	Not 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		Feb. 1943 to Aug. 1943	74,000	110,000	55,000	
Yes	16 to 24	30 to 54	CBR = 7 (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.	Fall 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		16 Dec. 1942 to 1 June 1944	5,000 to 15,000	< 10,000 to 45,000	20,000	
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 F.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)		Nov. 1942 to Dec. 1943	8,000	< 10,000	< 10,000	
Yes	21 to 29	32 to 72	k = 39 (1) k^f = 24 (1)	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)		Feb. 1943 to Feb. 1944	4,500	< 20,000 to 55,000	< 20,000 to 30,000	
Yes	21 (Average)	48	CBR = 6 est. for taxiway "G" k^f = 39	Reported as very deep	No subsurface drainage system	Running under traffic in joint area, displacement by plane wheels of 1½" A.C. pavement, the 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.	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.	1097		Oct. 1942 to June 1943	48,000	50,000 to 95,000	50,000	Original 3½" A.C. pavement rebuilt July 1943 with 7" concrete slab.
Yes	23.7	37.9	CBR = 6 (1) 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		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	7,000	< 10,000	
Yes	14.1 to 17.8	22 to 25.4	CBR = 9(1) to 34 (1)		At edge 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 bitumen. Low density of fill areas frost penetration deep.	1943-1944 629	3 ft. approx.	1944 Principally P-40, C-47, C-46 51,795 landings and take-offs.	45,000		< 10,000	No evaluation report.
Yes	[illegible] to 24.5	41 to 44	CBR = 7 Average lab. tests	Not reported	At edge of runways. No subsurface drainage in taxiway areas.	Soft spongy surfaces 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 seeping into base course weakening the subgrade. Pavement not thick enough. Poor base course.	1943-1944 1042		1943 Slightly used snow removal equipment was main abuse of field.	1,200 to 2,100	Not reported	15,000	No evaluation report.
Yes	Non-plastic		CBR = field 25 (1) to 28 Lab. 10 to 27	Not reported	Edge of pavement	Badly failed areas characterized by a rutty, soft, spongy surface with considerable cracks. Bird baths.	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		16,000	No evaluation report.
Yes	14.3 to 24.5	30.8 to 51.5	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	28,000	10,000	180,000 sq. yds. of pavement failed during 5 months of use by Very Heavy Bombers.

B

SUMMARY OF AIRFIELD PAVEMENT FAILURES WHERE F

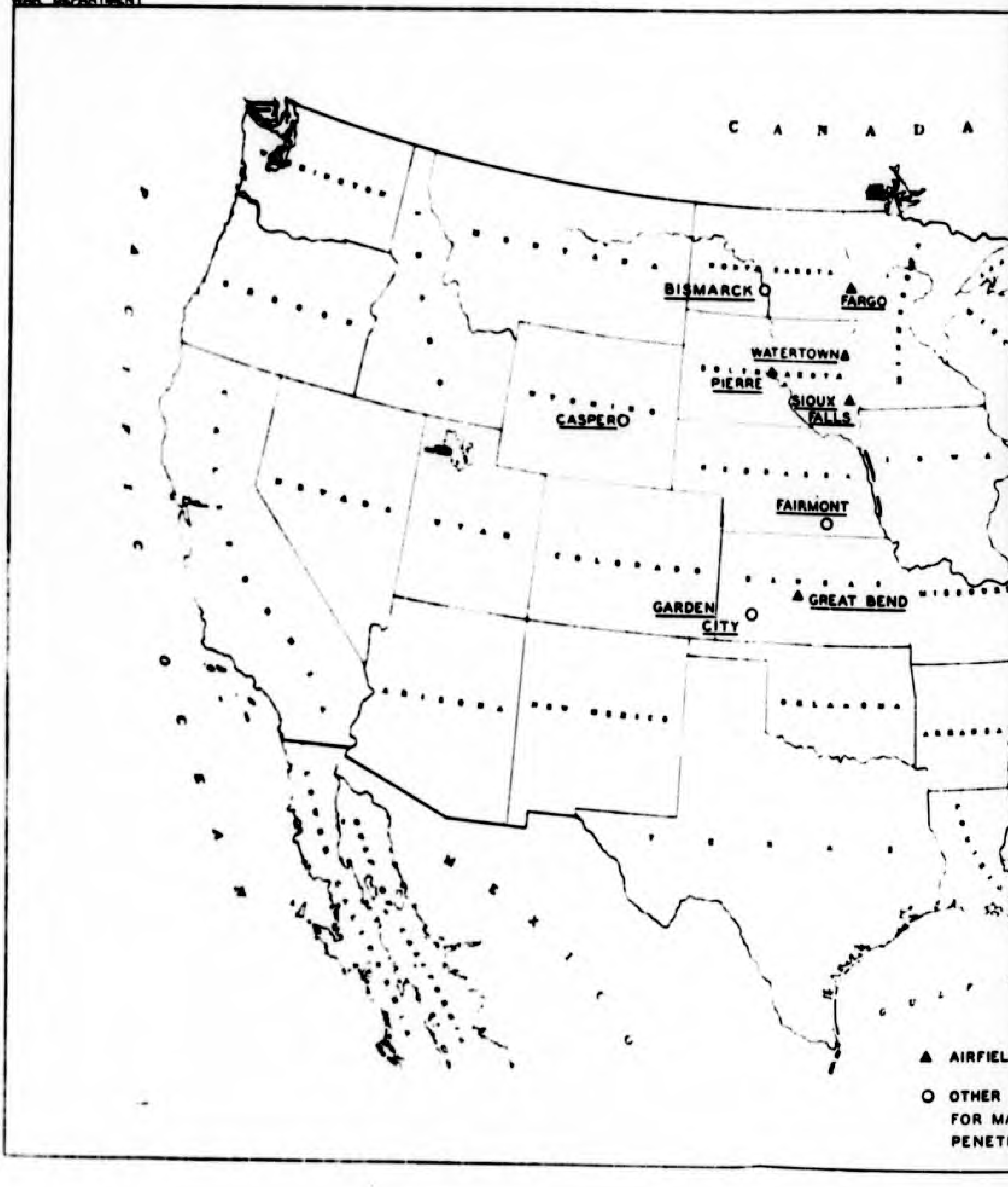
AIRFIELD	LOCATION OF DISTRESSED AREA	PAVEMENT			BASE					SUBGRADE						GROUND WATER DEPTH (FEET
		TYPE	THICKNESS INCHES	WORKING STRESS IF CONCRETE (LIMITED OPERATION) LBS./SQ.IN.	TYPE	THICKNESS INCHES	SATURATED	FROST SUSCEPTIBLE	CBR OR SUBGRADE MODULUS (k)	AIRFIELD CLASSIFICATION	SATURATED	FROST SUSCEPTIBLE	ATTERBERG LIMITS P.L.	ATTERBERG LIMITS L.L.	CBR OR SUBGRADE MODULUS (k) IN PLACE UNLESS OTHERWISE NOTED	
GREAT FALLS A.A. BASE GREAT FALLS, MONTANA	Bituminous Pavements showing failure paved taxiways and runways.	Asphalt concrete	6		Pit run gravel	9 to 11	27%	Yes	CBRs 50(1)	Predominately CL, SF and SC	62%	Yes	16 to 26	38 to 54	CBRsL(1)	Possibly 200 / r below su face
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	60%	Yes	CBRs(1) 10 to 75 50$(AV.)	SF, GF, GC ML, and CL	80%	Yes	3 to 21	20 to 34	CBRs(1) 15 to 30 20$(AV.)	Not rep ed
GEIGER FIELD WASHINGTON STATE	10,000 sq. ft. of taxiway No. 2	Asphalt concrete	3		Gravel sand and silt (14%)(silty loam)	8 to 12	100% (Ponded water seeped under pavement)	Yes	CBRs 17.5(2)	GF to SF	100%	Yes	10	29	CBRs 35(2)	12' to below su face
PUEBLO AIRFIELD PUEBLO, COLORADO	Concrete apron, N-S, NW-SE, E-W runways, Taxiways T-1, T-2, T-3 and T-6	P. C. concrete Asphalt concrete	8-6-8 12-8-12 15-10-15 2 to 4	364 304 480	Sand gravel Stabilized gravel	6 to 10 8 to 12	43%	Yes	k = 49(2) to 58.9(2) CBRs 8(1) to 47(1)	CL CH	60%	Yes	20	40	k = 49(2) CBRs3% to 6%	Artesian springs countere
CHANUTE FIELD RANTOUL, ILLINOIS	NE-SW, E-W, NW-SE runways	Portland cement concrete	8-6-8 10-7-10	502 500	Pit run sand and gravel	From none to 6 to 15	Not reported	Borderline	k(1) = 63 to 72	ML to OL	89%	Yes	14.8 to 20	18.8 to 48	k(1) = 57	Below in area dep (not repor ed)
SCOTT FIELD BELLEVILLE, ILLINOIS	N-S, E-W, NE-SW, NW-SE runways and apron	Portland cement concrete	8-6-8 9-6-9	420 500	None to compacted gravel	6				OL and CL	100%	Yes	17.9 to 26	25.5 to 42.8	k = (1)66	Depth no reported (believed low infl ence dep
GREAT BEND AIRFIELD GREAT BEND, KANSAS	West edge apron. Original taxiway No. 1. Taxiway at end of N-S runway.	Portland cement concrete	10½-7-10½	385	Sand cushion	3 to 12	No data	No	No data	ML, CL, CH, and SF in this strata	86%	Yes	15 (Av. values)	22	k = 86(Av.)	5' to 2' at apron
CASPER AIRBASE CASPER, WYOMING	Scattered areas on taxiways 1, 2, 9, 12 and 13. Runways and runways shoulders. Apron	Asphalt concrete Bituminous material P. C. C.	6 3 9-7-9	 482	BASE: Sand (9% pass. .02) SUBBASE: SF, ML, SP, SC, SW, CL.	6 to 8 BASE P.I.= 14 L.L.= 39 9 to 14 No base	44% 44%	Yes Yes	CBRs 40 CBRs 10 (Av.)	SP, SC, SF, ML, CL, SW. SW, CL, SC.	37%	Yes	15 (Av.)	23	CBRs 5(Av.) k = 277	> 90'
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

FAILURES WHERE FROST ACTION WAS CONTRIBUTING CAUSE

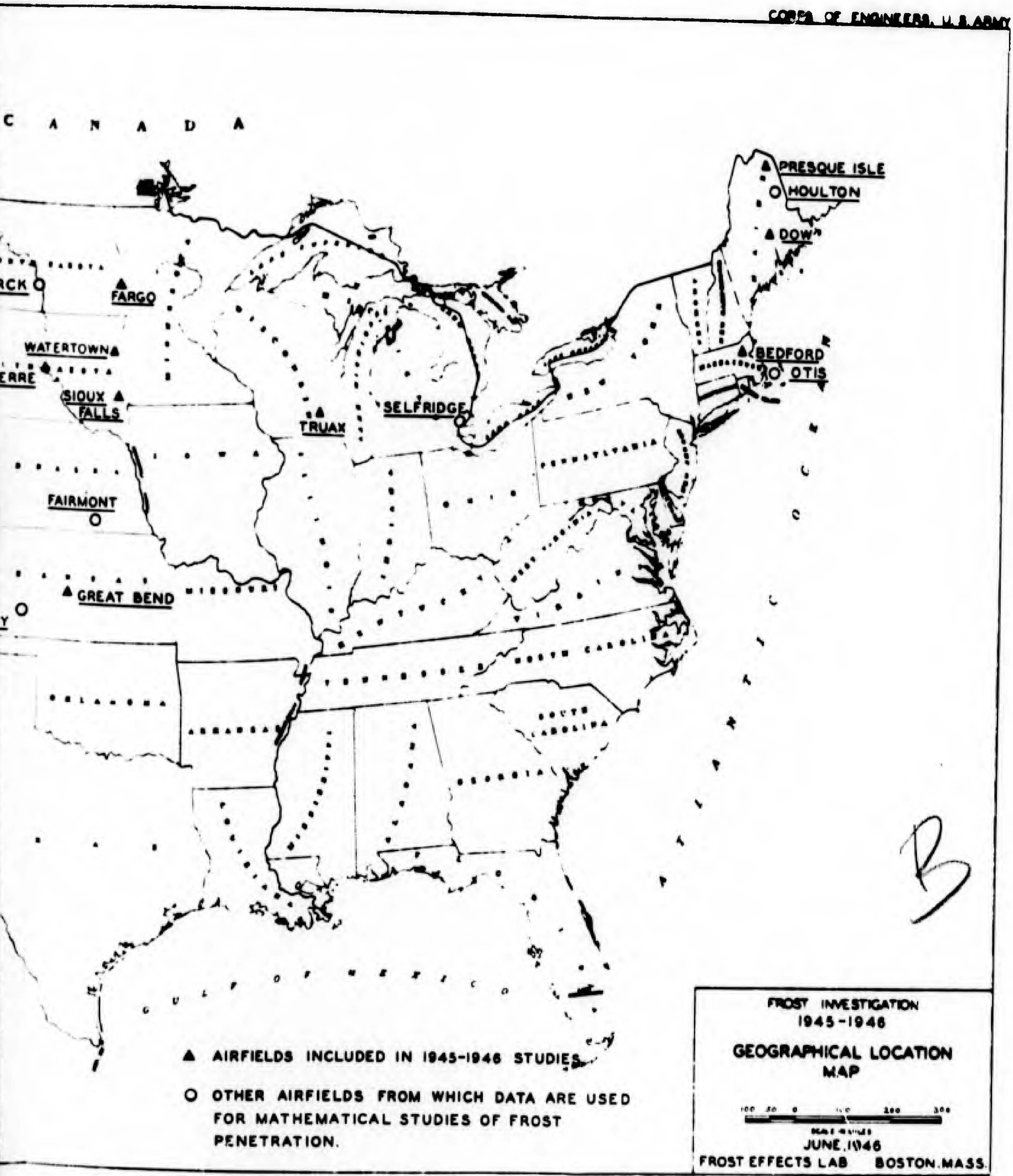
GRADE: SUSCEPTIBLE	ATTERBERG LIMITS P.L.	ATTERBERG LIMITS L.L.	CBR OR SUBGRADE MODULUS (k) IN PLACE UNLESS OTHERWISE NOTED	GROUND WATER DEPTH (FEET)	SUB SURFACE DRAINAGE	DISTRESS OR FAILURE: DESCRIPTION	DATE FIRST NOTED	REPORTED CAUSE	FREEZING INDEX FOR WINTER PRECEDING DISTRESS	PROBABLE DEPTH OF FROST PENETRATION INTO SUBGRADE	TRAFFIC: PERIOD OF USE PRIOR TO LAST DATED REPORT OF DISTRESS	TRAFFIC: PREDOMINATE GROSS PLANE WT. USING FIELD DURING PERIOD OF DISTRESS (LBS.)	EVALUATION LBS GROSS PLANE WT.: NORMAL	EVALUATION: PERIOD OF LIMITED OPERATION FROST MELTING PERIOD (BASED UPON REVISED ENGR. MANUAL)	REMARKS
Yes	16 to 26	36 to 54	CBR[illegible](1)	Possibly 200 ± ft. below surface	Reported as poor	Failures became apparent at the joint between the runway proper and the shoulder. Shoulder construction 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 planting. Frost action contributes to deterioration.	1942-1943 1093	5" Average 30"	January to Sept. 1943 / Dec. 1943 to Jan. '44	40,000 / 9,500 to 35,000	20,000	11,000	
Yes	5 to 23	20 to 34	CBR(1) 15 to 30 20(Av.)	Not reported	Poor	Pavement becoming wavy, weakness along edges of the pavement, complete failure of taxiways "B" and "C", 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 1093	5"	Jul. 1942 to Oct. '43	9,500 to 50,000 (50% very heavy bombers)	55,000	15,000	55,000 cycles since occupancy. Very heavy bombers.
Yes	17	29	CBR 35(2)	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 556		May 1943 to July 1943	60,000	70,000 (Field)	17,000	
Yes	20	40	k = 40(2) CBR 35 to 65	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 135 (Alternate freezing and thawing)		Oct. 1942 to Aug. 1943	60,000	25,000 / 367,000 / 270,000 / 14,000	70,000 / 15,000 / 120,000 / < 17,000	
[illegible]	14.7 to 20	17.8 to 48	k(1) = 57	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	Jan. 1944	Insufficient bearing capacity of subgrade, softening of subgrade during thawing and freezing, overloading slabs with heavy wheel loads.	1943-1944 500	12 to 18" Average max. equals 30"	1942 to 1944	60,000	75,000 / 75,000	60,000 / 60,000	
[illegible]	17.6 to 26	21.5 to 42.8	k = (1)66	Depth not reported (believed below influence depth)	None	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 140	12 to 16" average 24 to 30" Maximum	Mar. 1942 to Aug. 1943 / Aug. 1943 to Jul. 1944	6,000 / 60,000	30,000	30,000 / 40,000	
[illegible]	15 (Av. values)	22	k = 96(Av.)	5' to 8' at apron	None	Extensive cracking, pavement broken up at local areas into small patterns.	1944 to May 1945	Pavement used extensively for taxiing and warm up. Pavement apparently has insufficient load carrying capacity.	1944-1945 44	3"	1944 to May 1945	47,000	50,000	44,000	No heaving noticed after one winter cycle.
[illegible]	15 (Av.)	23	CBR 5(Av.) / k = 279	> 50'	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 B.C., water ponding, poor base. Slight frost action in subgrade. Different settlement under traffic, ponding in depressions. Overstressing, overtaxing lines.	5 Year av. equals 532 1944 = 770	24"	Nov. 1942 to Mar. '45	50,000	25,000 / 130,000	< 10,000 / 60,000	
[illegible]	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 1442		No data	25,000	< 10,000	No data	No evaluation report.

B

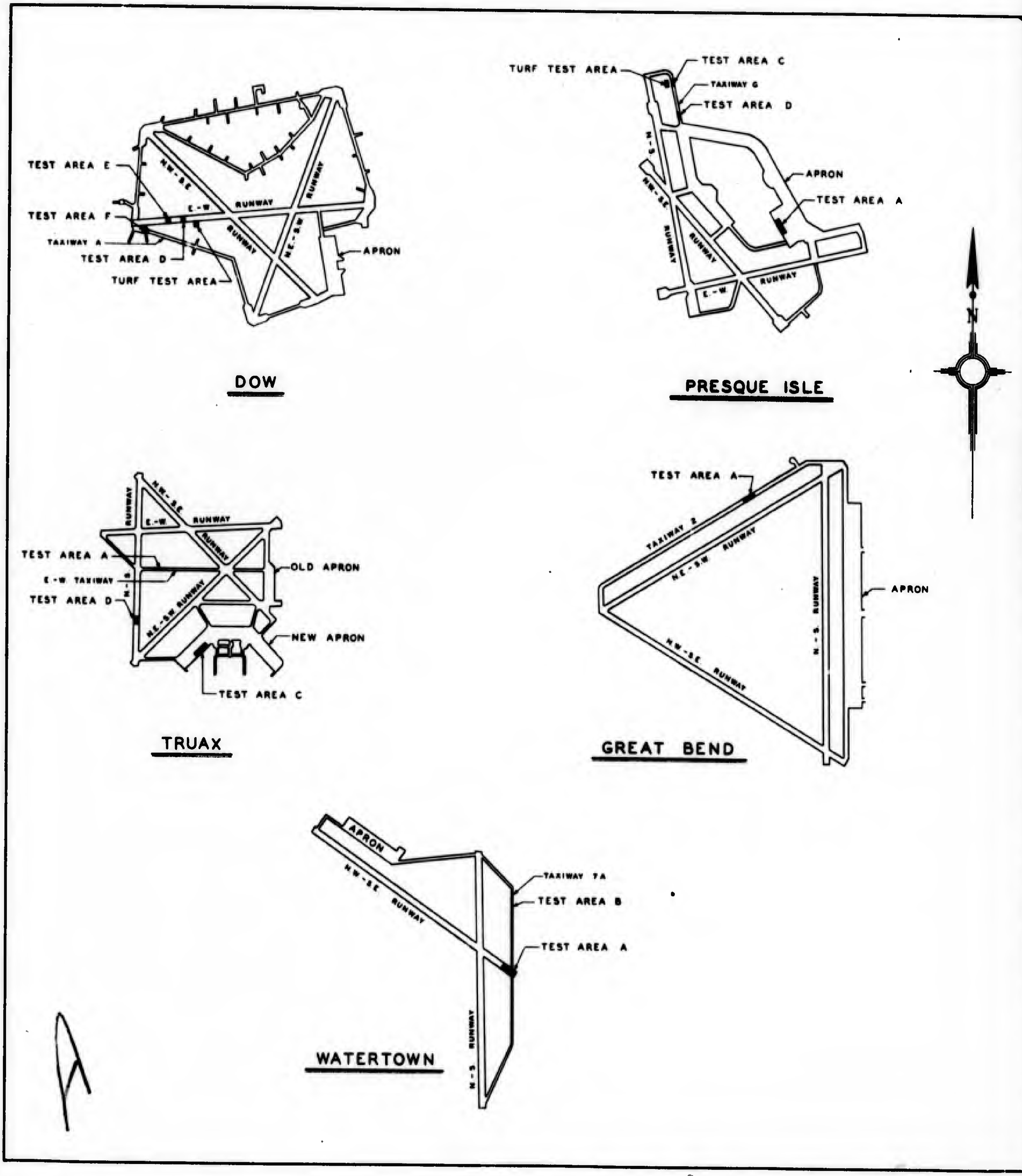
WAR DEPARTMENT

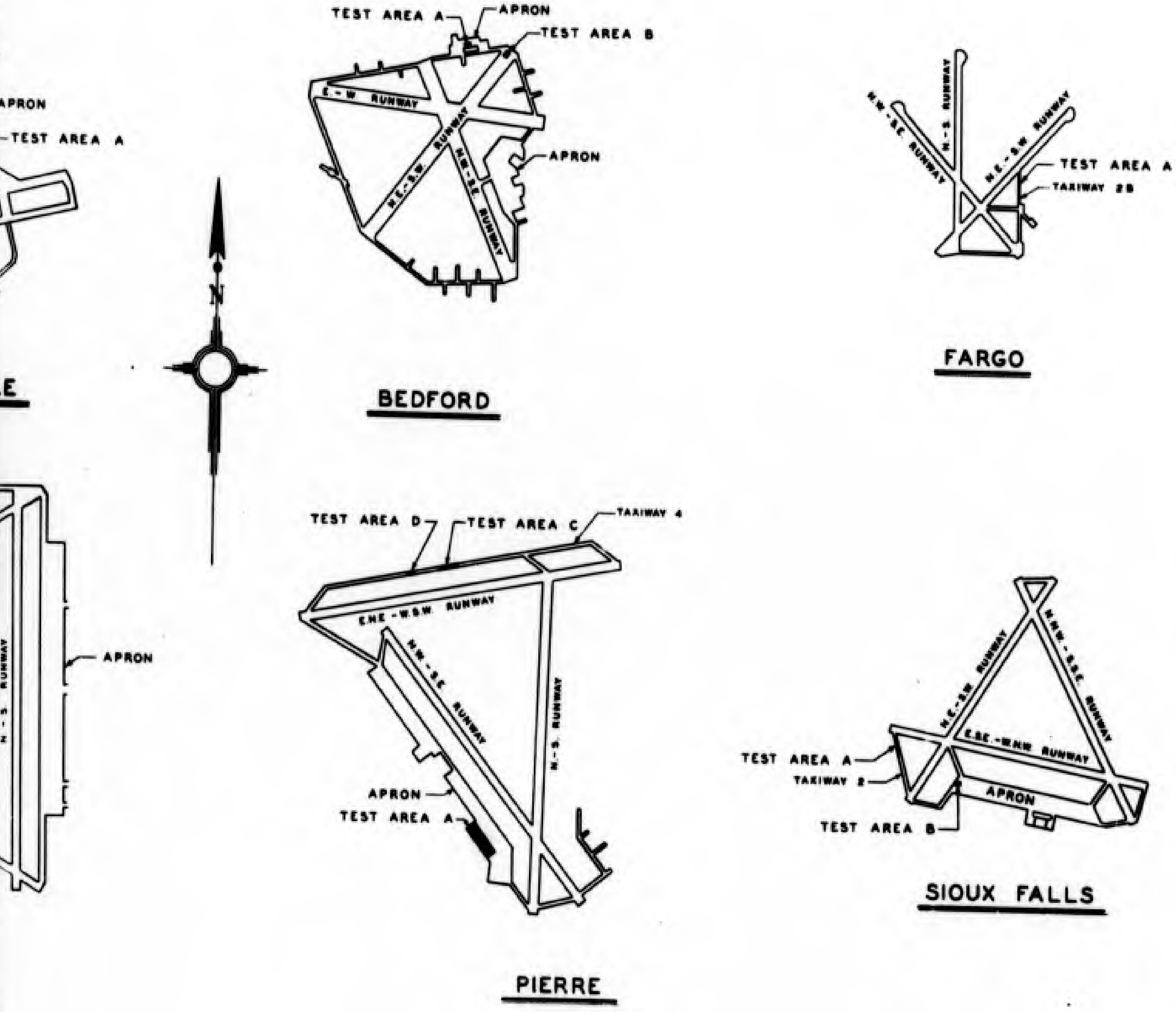


CORPS OF ENGINEERS, U.S. ARMY



C.R. - 45-46 PLATE I


TEST AREA E
TEST AREA F
TAXIWAY A
TEST AREA D
TURF TEST AREA
NW-SE
E-W RUNWAY
RUNWAY
NE-SW
RUNWAY
APRON
DOW
TURF TEST AREA
TEST AREA C
TAXIWAY G
TEST AREA D
N-S
NW-SE
RUNWAY
RUNWAY
APRON
TEST AREA A
E-W
RUNWAY
PRESQUE ISLE
N
RUNWAY
NW-SE
E-W
RUNWAY
RUNWAY
TEST AREA A
E-W TAXIWAY
N-S
TEST AREA D
NE-SW RUNWAY
OLD APRON
NEW APRON
TEST AREA C
TRUAX
TEST AREA A
TAXIWAY 2
NE-SW RUNWAY
N-S RUNWAY
NW-SE RUNWAY
APRON
GREAT BEND
APRON
NW-SE RUNWAY
TAXIWAY 7A
TEST AREA B
TEST AREA A
N-S RUNWAY
WATERTOWN



B

FROST INVESTIGATION
1945 - 1946

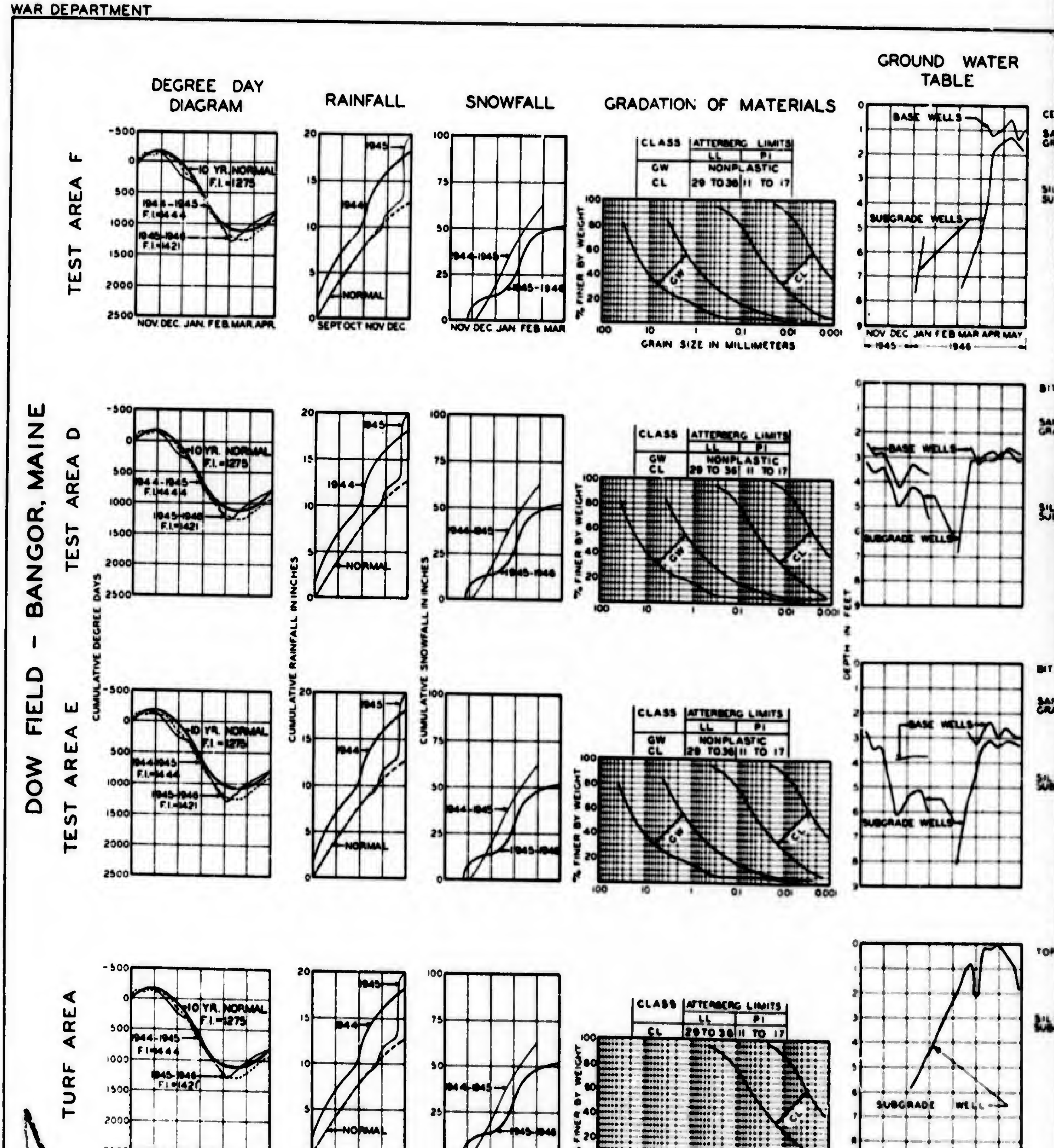
LOCATION OF TEST AREAS
AT AIRFIELDS

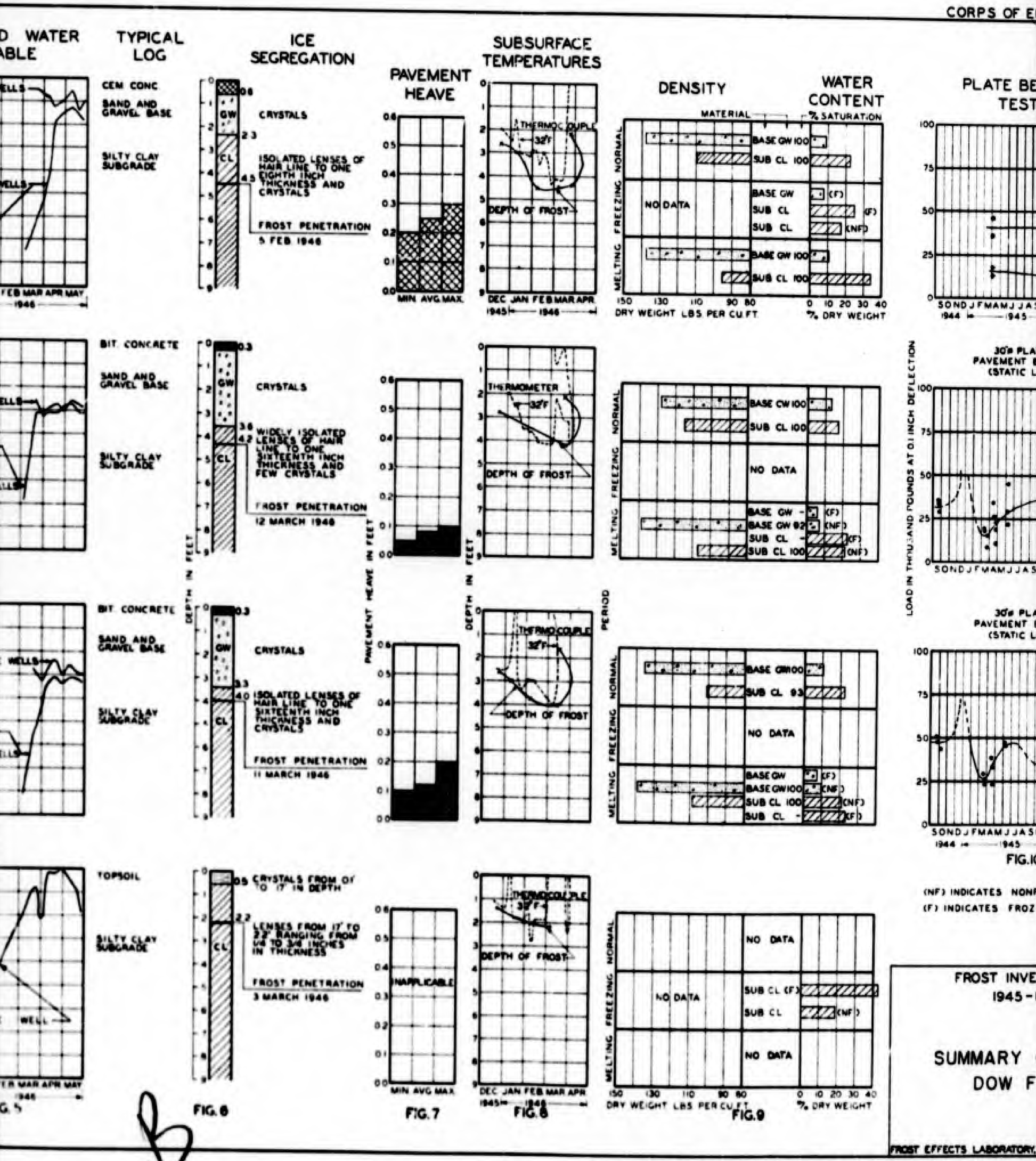
1600 0 1600 3200 4800 FT

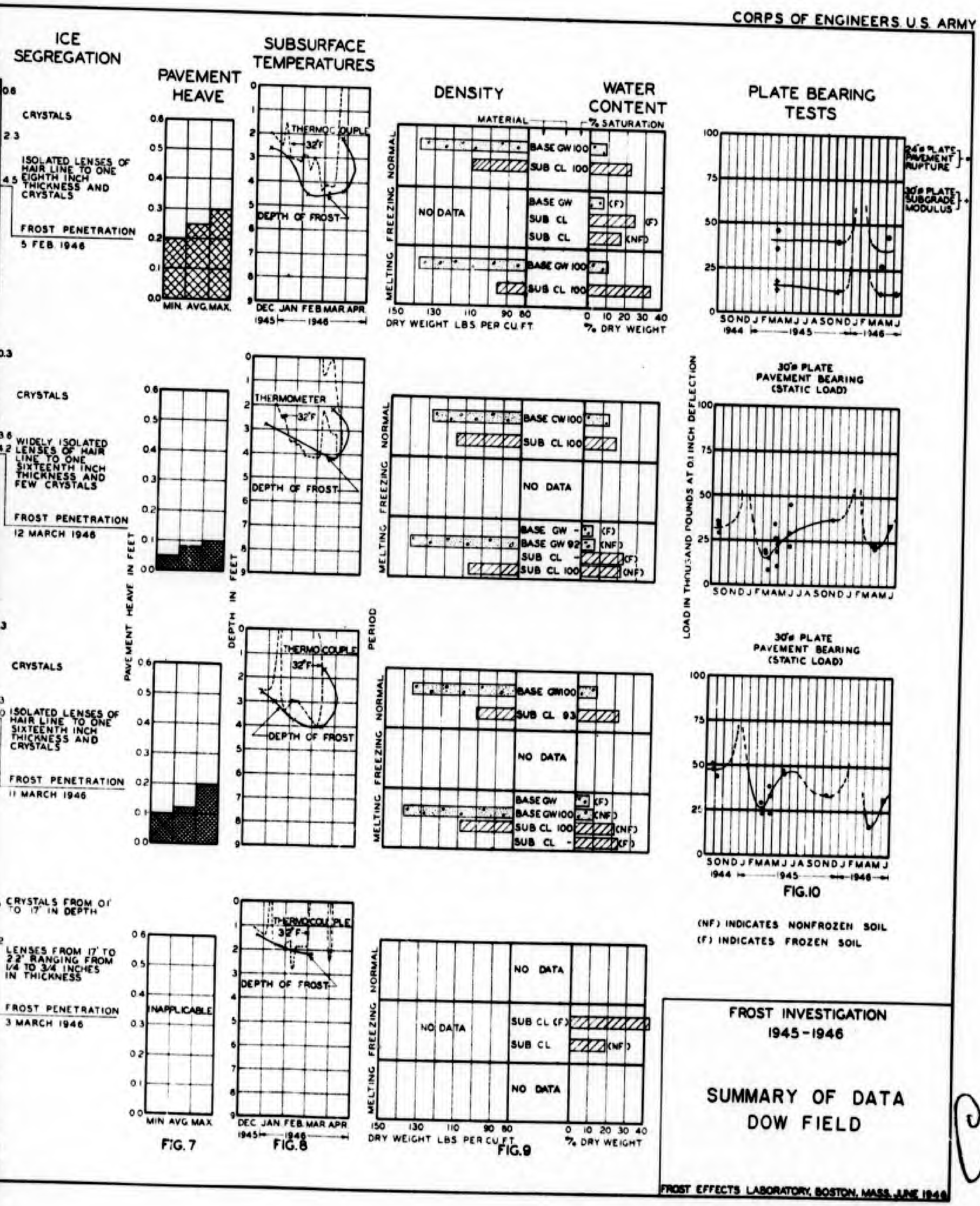
FROST EFFECTS LABORATORY, BOSTON, MASS. JUNE 1946

CR 45-46 PLATE 2

WAR DEPARTMENT



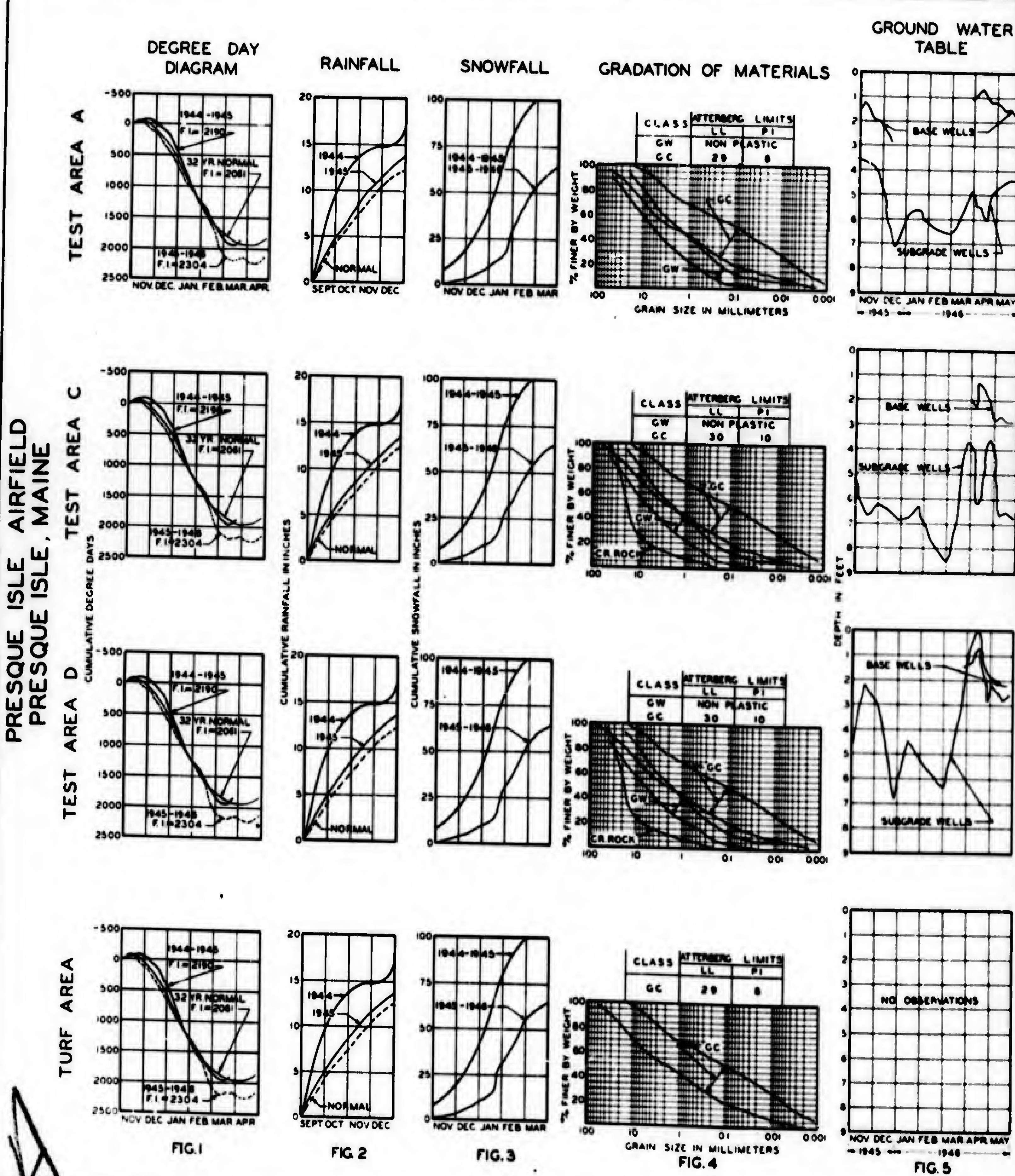

CORPS OF E
D WATER
BLE
TYPICAL LOG
ICE SEGREGATION
PAVEMENT HEAVE
SUBSURFACE TEMPERATURES
DENSITY
WATER CONTENT
PLATE BE
TEST
CEM CONC
SAND AND GRAVEL BASE
SILTY CLAY SUBGRADE
CRYSTALS
ISOLATED LENSES OF HAIR LINE TO ONE EIGHTH INCH THICKNESS AND CRYSTALS
FROST PENETRATION 5 FEB 1946
BIT. CONCRETE
WIDELY ISOLATED LENSES OF HAIR LINE TO ONE SIXTEENTH INCH THICKNESS AND FEW CRYSTALS
FROST PENETRATION 12 MARCH 1946
ISOLATED LENSES OF HAIR LINE TO ONE SIXTEENTH INCH THICKNESS AND CRYSTALS
FROST PENETRATION 11 MARCH 1946
TOPSOIL
CRYSTALS FROM 0' TO 17" IN DEPTH
LENSES FROM 17" TO 2.2' RANGING FROM 1/4 TO 3/4 INCHES IN THICKNESS
FROST PENETRATION 3 MARCH 1946
DEPTH IN FEET
PAVEMENT HEAVE IN FEET
MIN AVG MAX
INAPPLICABLE
THERMOCOUPLE
THERMOMETER
32°F
DEPTH OF FROST
DEC JAN FEB MAR APR
1945 1946
MATERIAL
% SATURATION
NORMAL
FREEZING
MELTING
PERIOD
BASE GW 100
SUB CL 100
NO DATA
(F)
(NF)
DRY WEIGHT LBS PER CU FT
% DRY WEIGHT
LOAD IN THOUSAND POUNDS AT 0.1 INCH DEFLECTION
30" PLA
PAVEMENT
(STATIC L
SONDJFMAMJJAS
1944 1945
(NF) INDICATES NON
(F) INDICATES FROZ
FROST INVE
1945-
SUMMARY
DOW F
FROST EFFECTS LABORATORY
FIG. 5
FIG. 6
FIG. 7
FIG. 8
FIG. 9
FIG. 10



C.R. 45-46
P.R. -45-46

PLATE 3

WAR DEPARTMENT



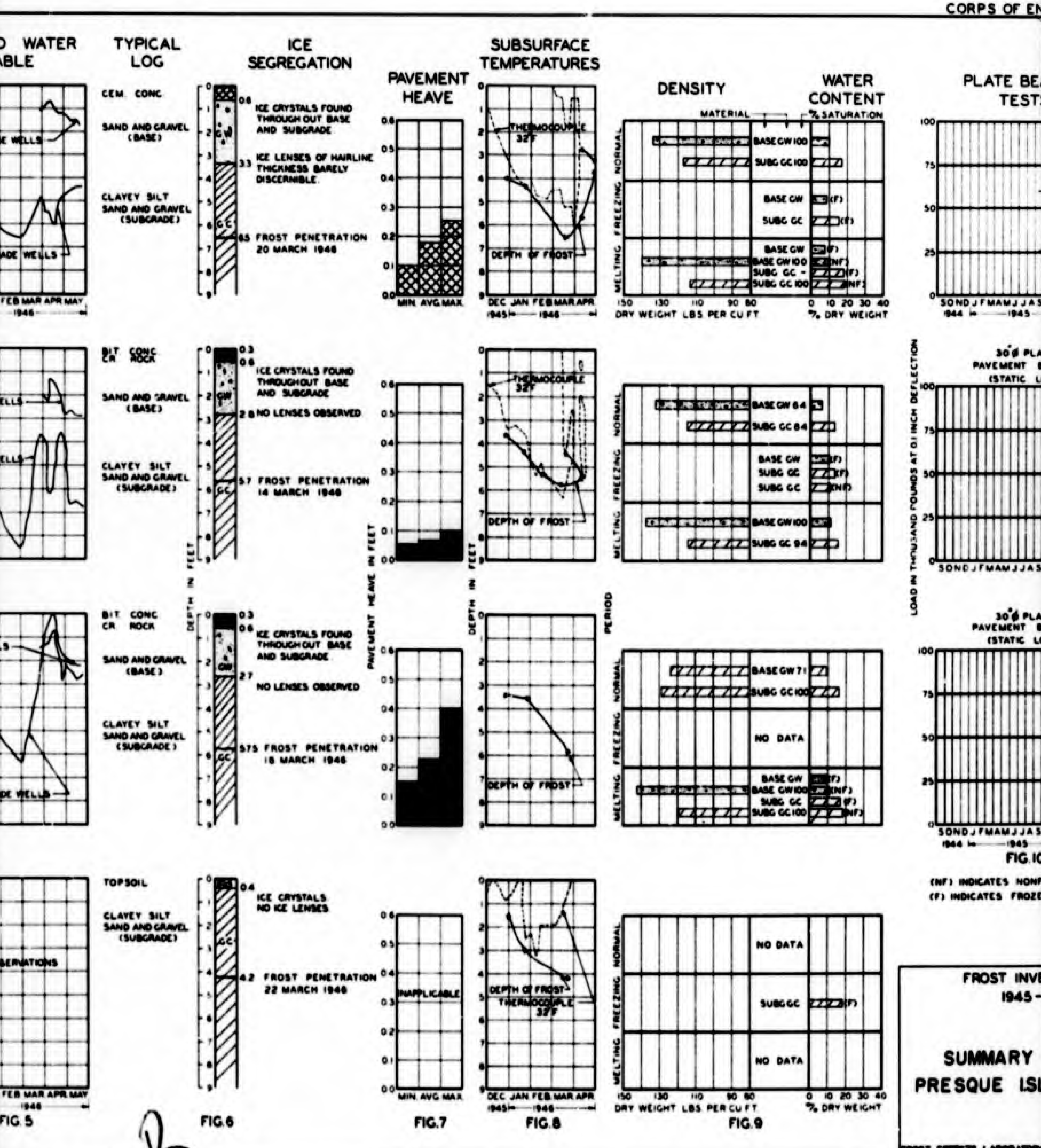


FIG.5 FIG.6 FIG.7 FIG.8 FIG.9 FIG.10

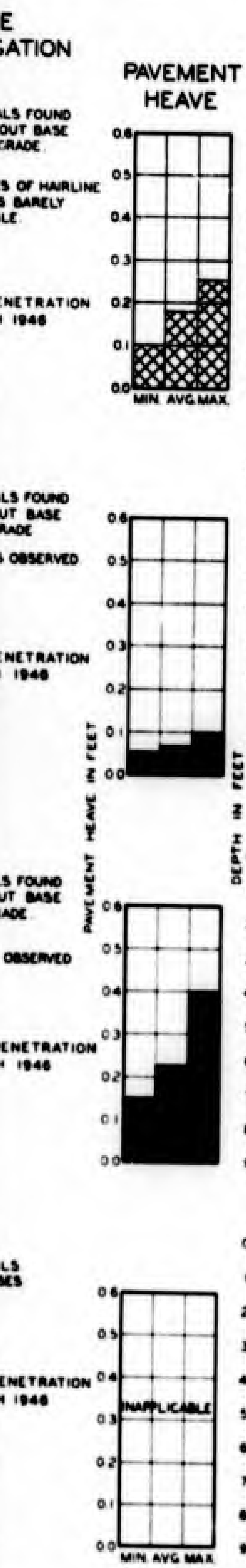


FIG.7

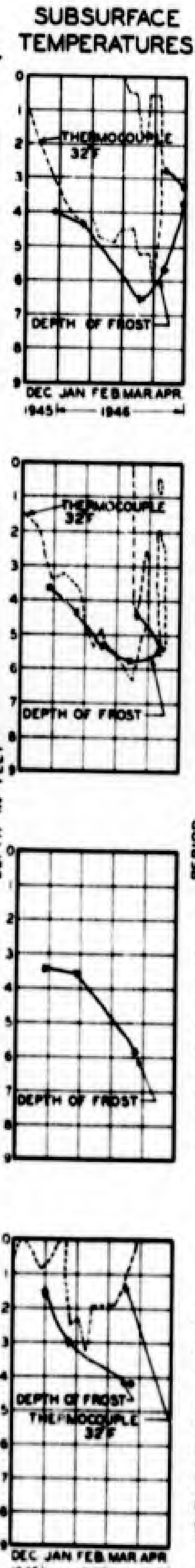


FIG.8

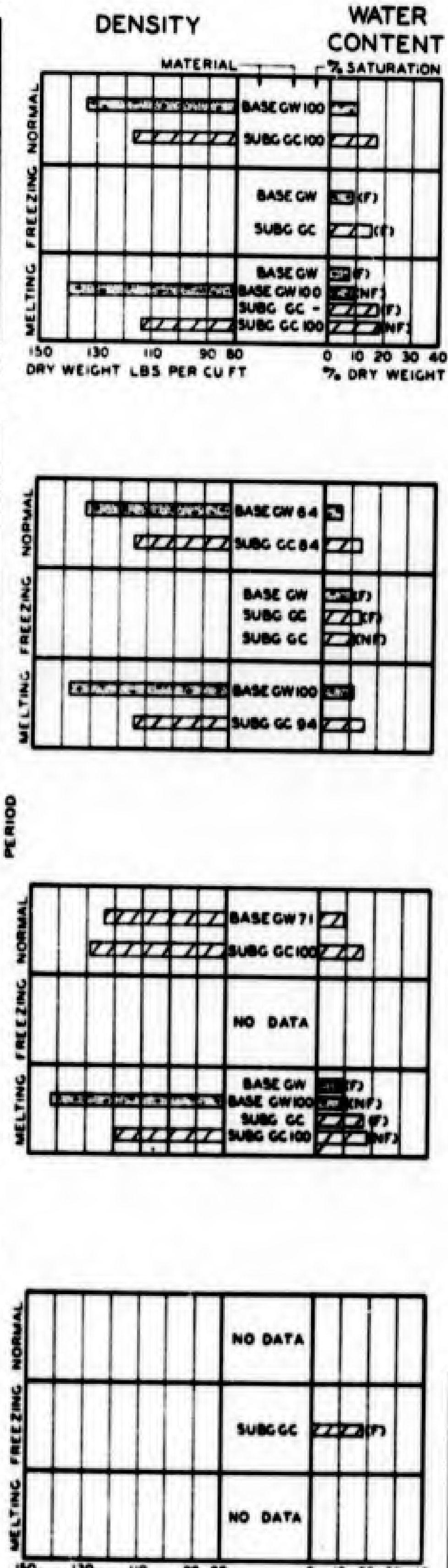


FIG.9

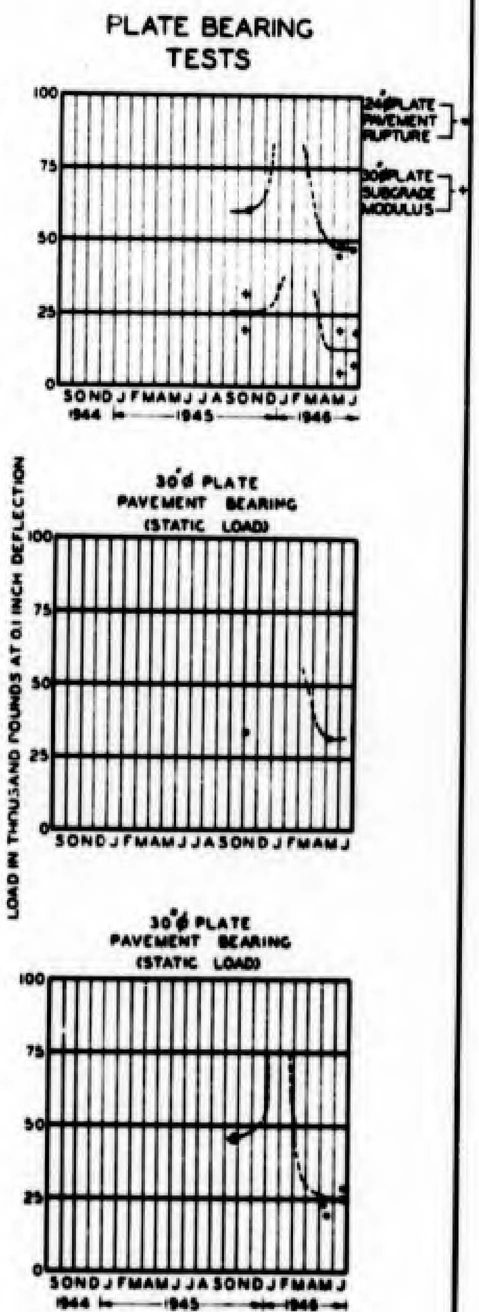


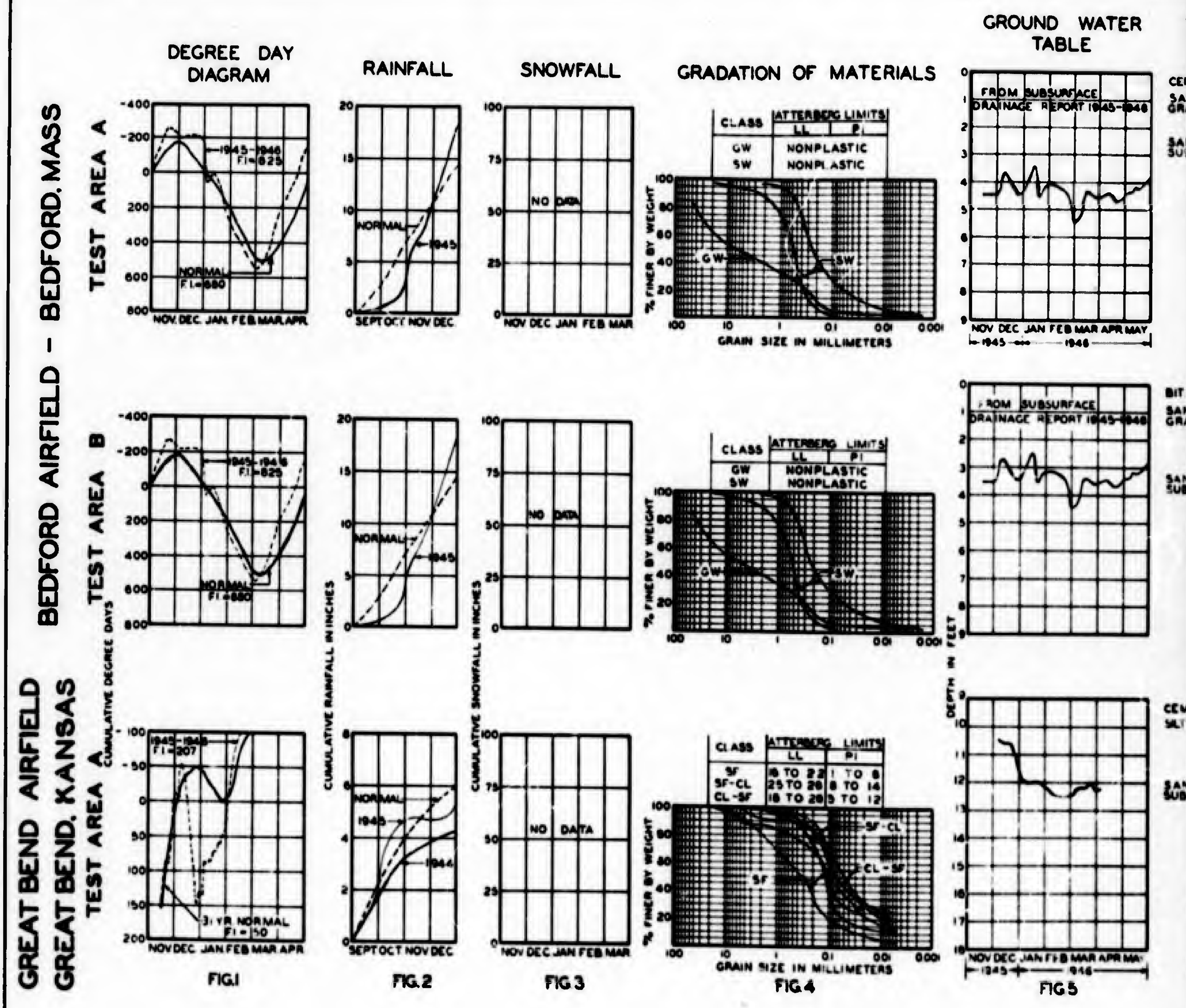
FIG.10

(NF) INDICATES NONFROZEN SOIL
(F) INDICATES FROZEN SOIL

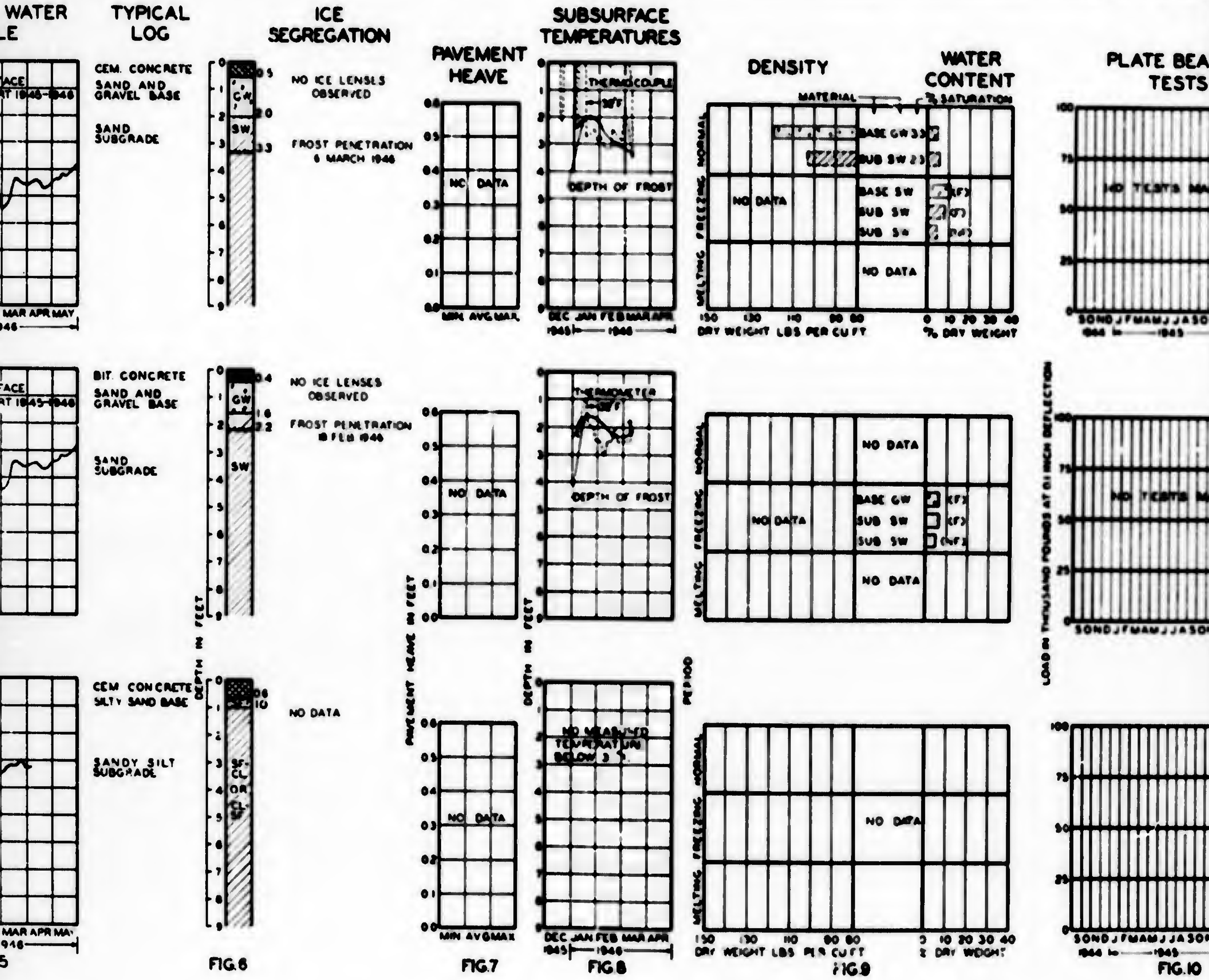
FROST INVESTIGATION 1945-1946

SUMMARY OF DATA PRESQUE ISLE AIRFIELD

FROST EFFECTS LABORATORY, BOSTON, MASS. JUNE 1946


BEDFORD AIRFIELD - BEDFORD, MASS
TEST AREA A
TEST AREA B
GREAT BEND AIRFIELD
GREAT BEND, KANSAS
TEST AREA A
DEGREE DAY DIAGRAM
RAINFALL
SNOWFALL
GRADATION OF MATERIALS
GROUND WATER TABLE
1945-1946 FI=825
NORMAL FI=880
1945-1946 FI=207
31 YR NORMAL FI=150
NOV. DEC. JAN. FEB. MAR. APR.
CUMULATIVE DEGREE DAYS
NORMAL
1945
1946
SEPT OCT NOV DEC
CUMULATIVE RAINFALL IN INCHES
NO DATA
NOV DEC JAN FEB MAR
CUMULATIVE SNOWFALL IN INCHES
CLASS
ATTERBERG LIMITS
LL
PI
GW NONPLASTIC
SW NONPLASTIC
SF 16 TO 22 1 TO 8
SF-CL 25 TO 26 8 TO 14
CL-SF 16 TO 28 5 TO 12
% FINER BY WEIGHT
GRAIN SIZE IN MILLIMETERS
FROM SUBSURFACE DRAINAGE REPORT 1945-1946
NOV DEC JAN FEB MAR APR MAY
1945
1946
DEPTH IN FEET
FIG.1
FIG.2
FIG.3
FIG.4
FIG.5

CORPS OF ENG



(F) INDICATES FROZEN SO
(NF) INDICATES NON-FROZ

FROST INVES
1945-19

SUMMARY C
BEDFORD A
GREAT BEND

FROST EFFECTS LABORATORY

B

1

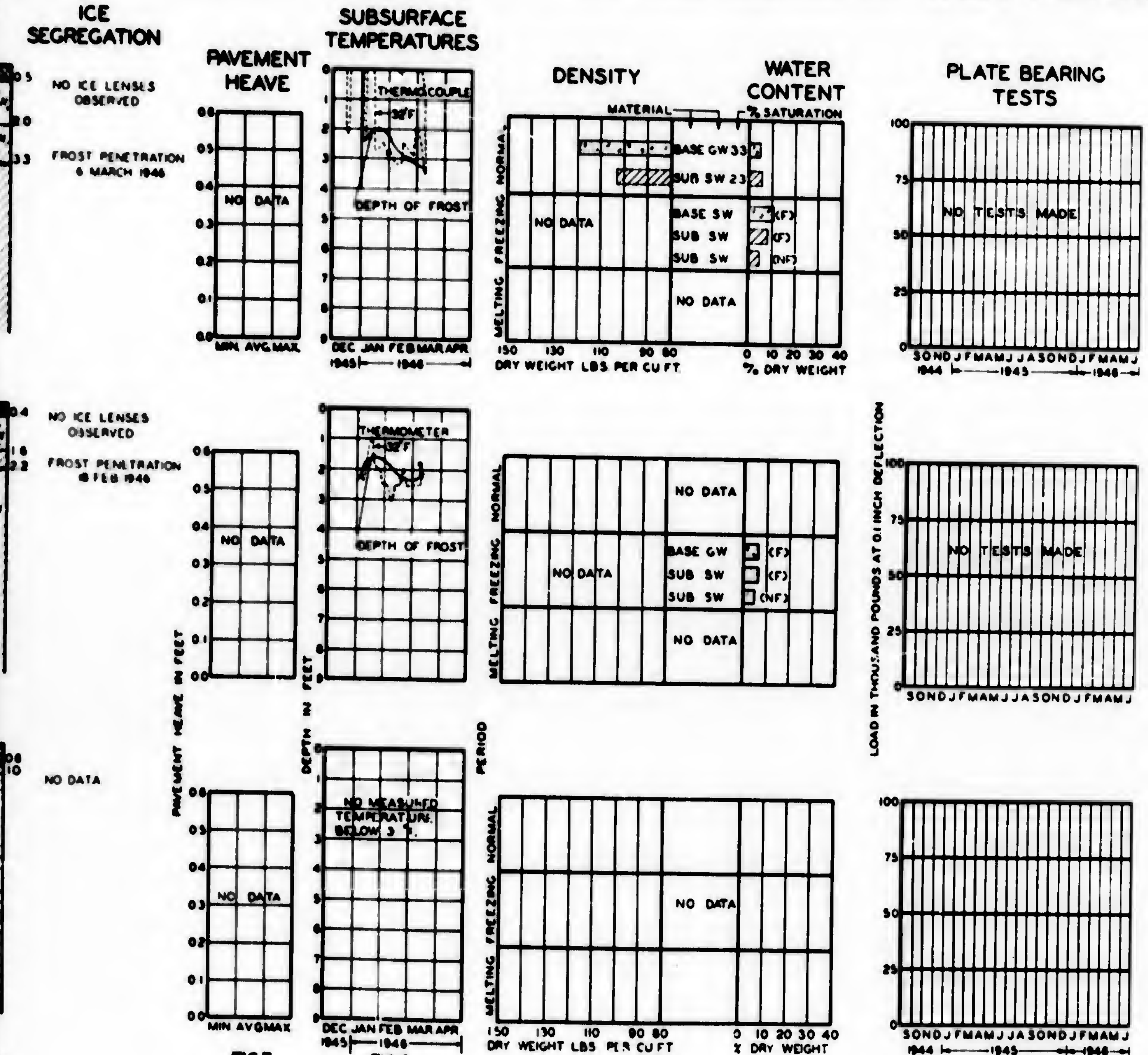


FIG.7 FIG.8 FIG.9 FIG.10

(F) INDICATES FROZEN SOIL
(NF) INDICATES NON-FROZEN SOIL

FROST INVESTIGATION
1945-1946

SUMMARY OF DATA
BEDFORD AIRFIELD
GREAT BEND AIRFIELD

FROST EFFECTS LABORATORY, BOSTON, MASS. JUNE 1946

WAR DEPARTMENT

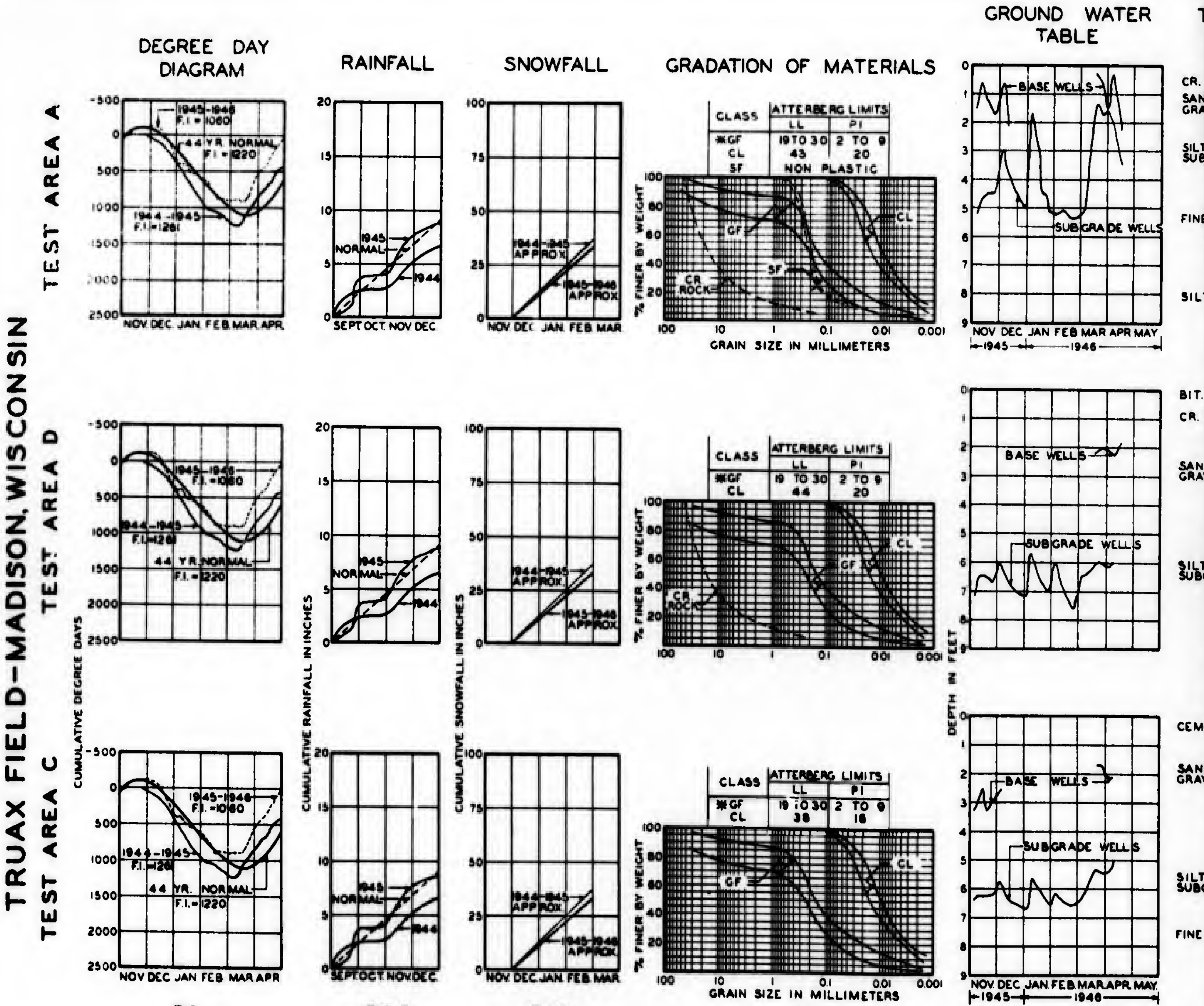


FIG.1 FIG. 2 FIG.3 FIG.4 FIG.5

* ON PORTION PASSING NO. 200 SIEVE

CORPS OF

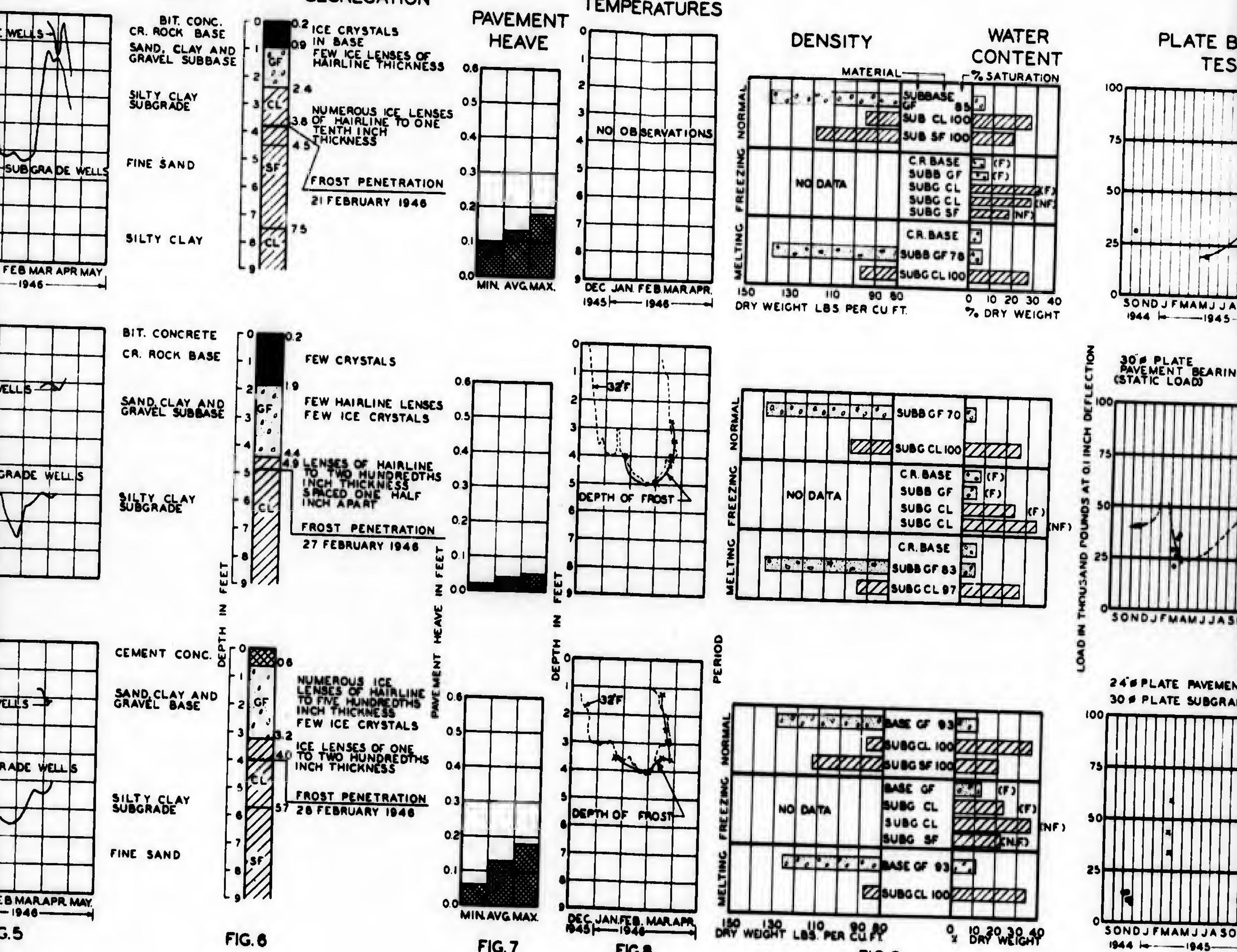


FIG.5 FIG.6 FIG.7 FIG.8 FIG.9 FIG.10

(NF) INDICATES NONF

(F) INDICATES FROZE

FROST INVES
1945-19

SUMMARY O
TRUAX F

FROST EFFECTS LABORATORY, B

CR-45-46
PR-45-46

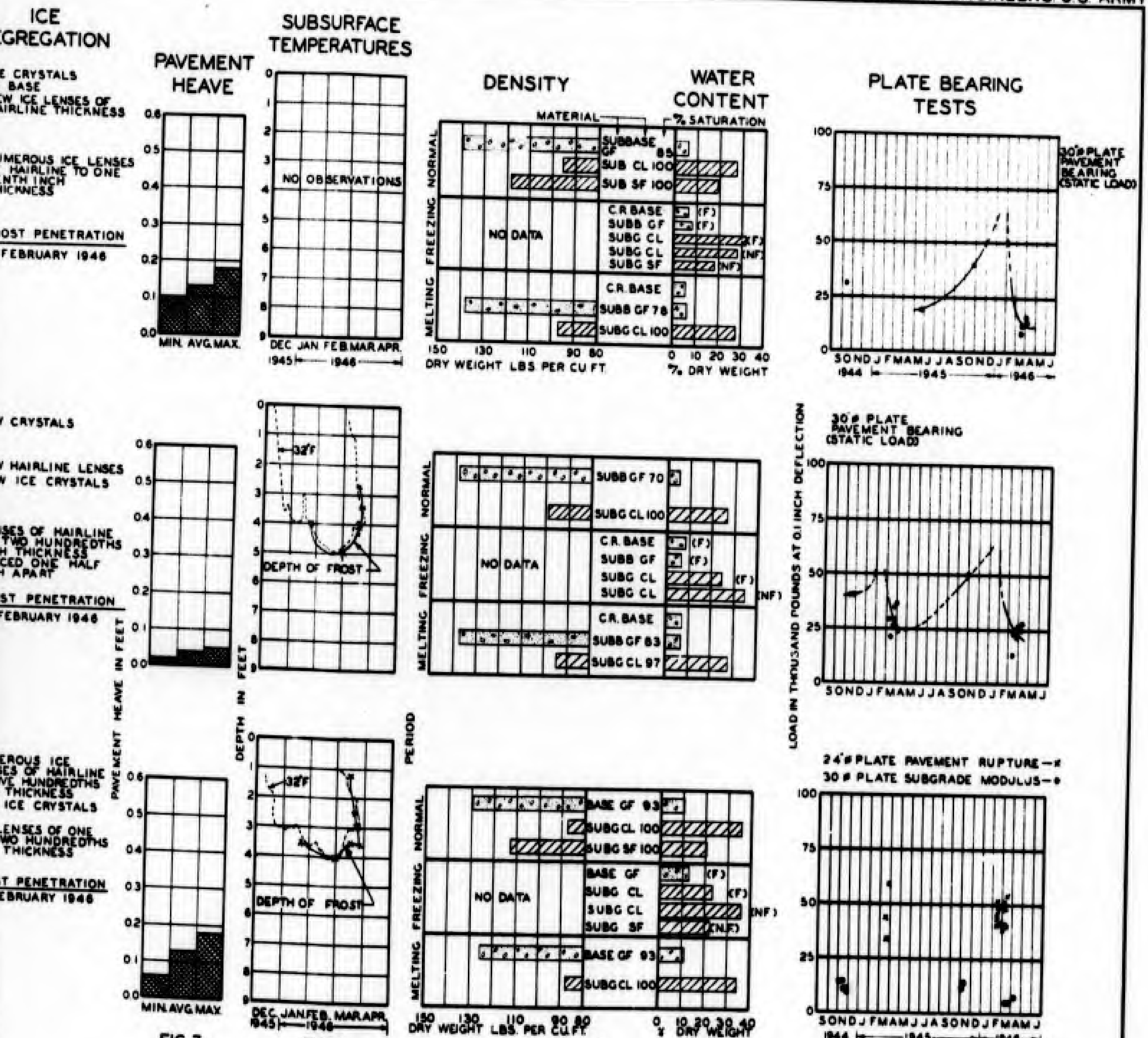


FIG.7 FIG.8 FIG.9 FIG.10

(NF) INDICATES NONFROZEN SOIL
(F) INDICATES FROZEN SOIL

FROST INVESTIGATION
1945-1946

SUMMARY OF DATA
TRUAX FIELD

FROST EFFECTS LABORATORY, BOSTON, MASS. JUNE 1946

WAR DEPARTMENT

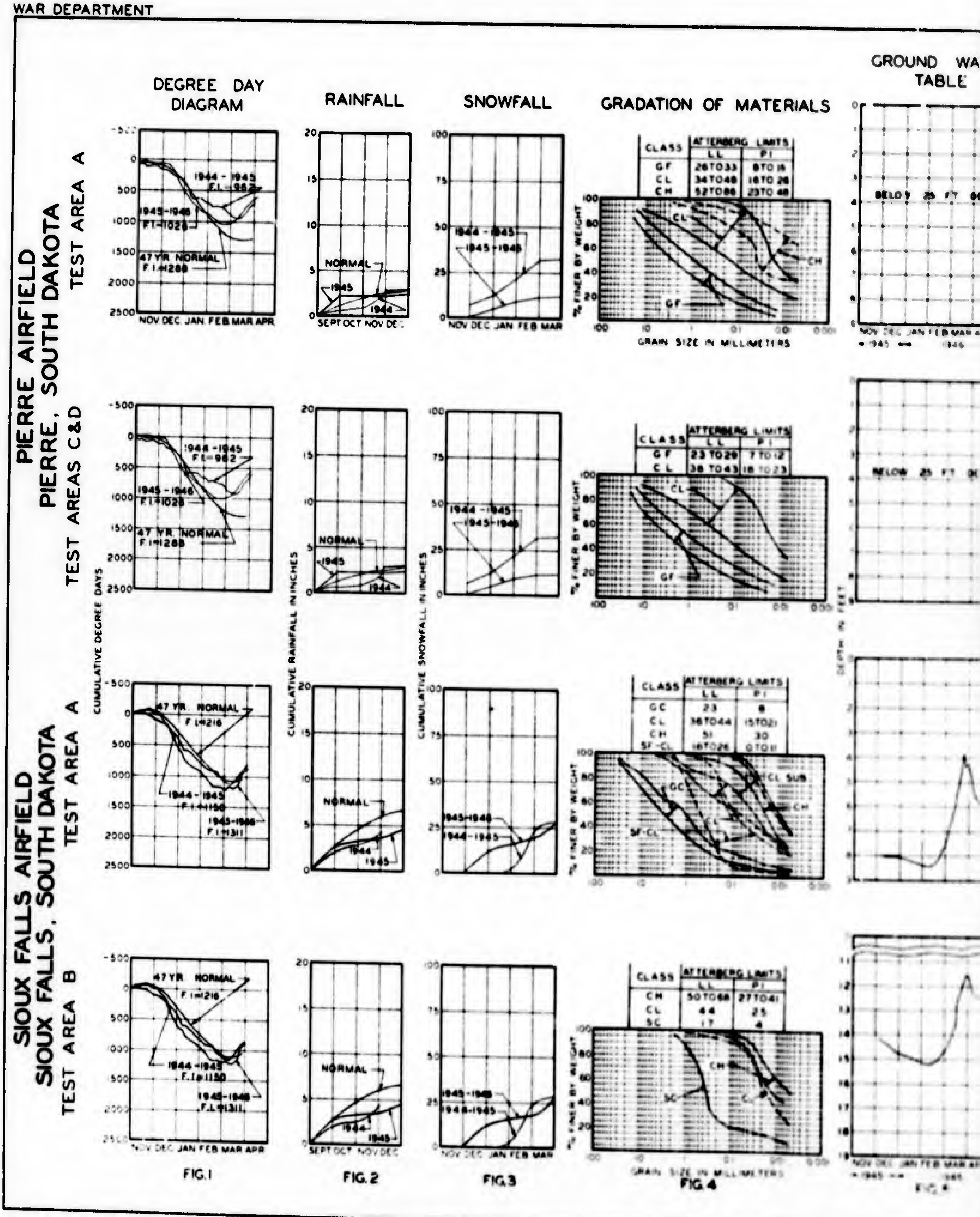


FIG.1 FIG.2 FIG.3 FIG.4 FIG.5

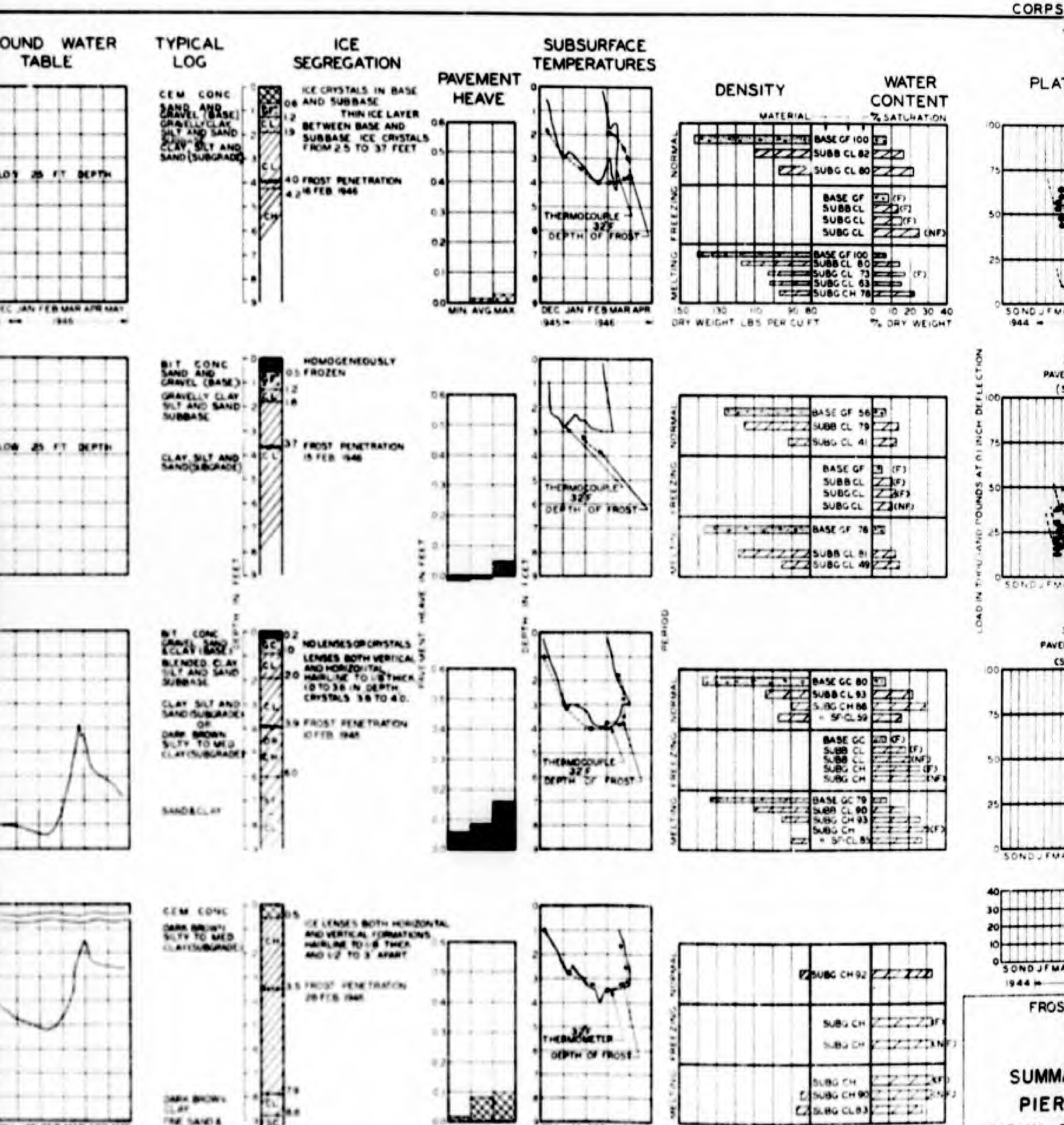
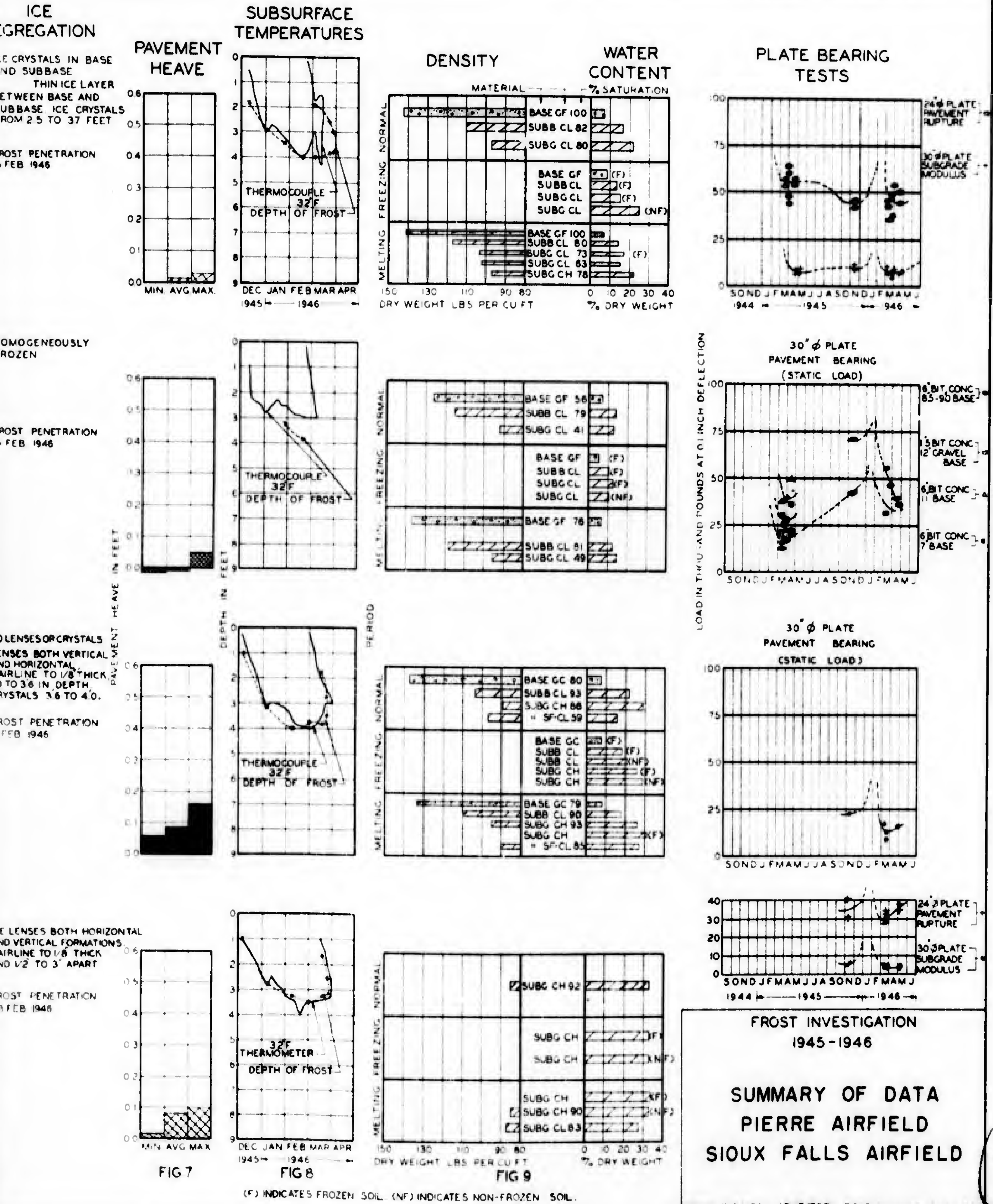


FIG 5   FIG 6   FIG 7   FIG 8   FIG 9

(F) INDICATES FROZEN SOIL (NF) INDICATES NON-FROZEN SOIL



FROST INVESTIGATION
1945-1946

SUMMARY OF DATA
PIERRE AIRFIELD
SIOUX FALLS AIRFIELD

FROST EFFECTS LABORATORY, BOSTON, MASS. JUNE 1946

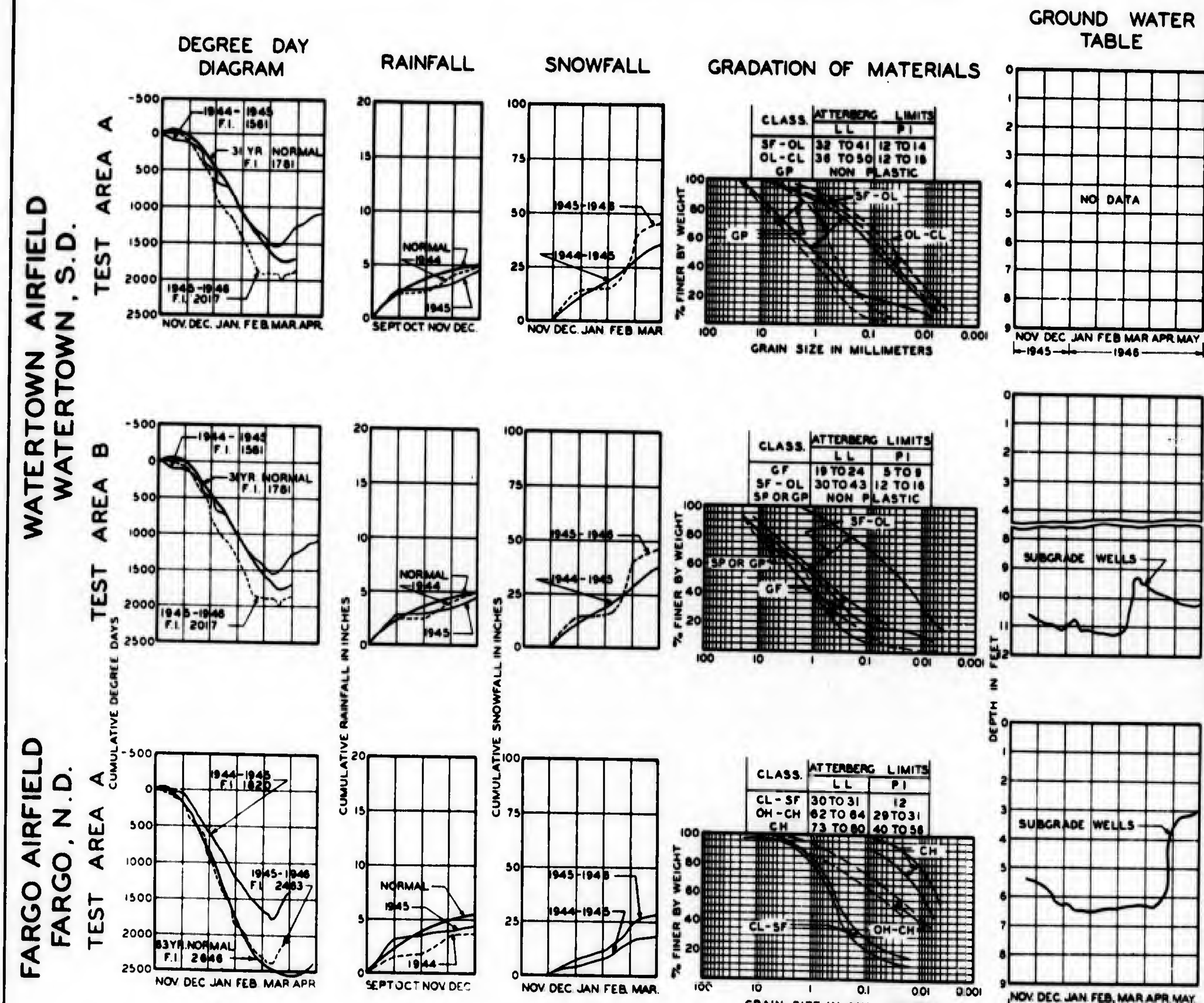
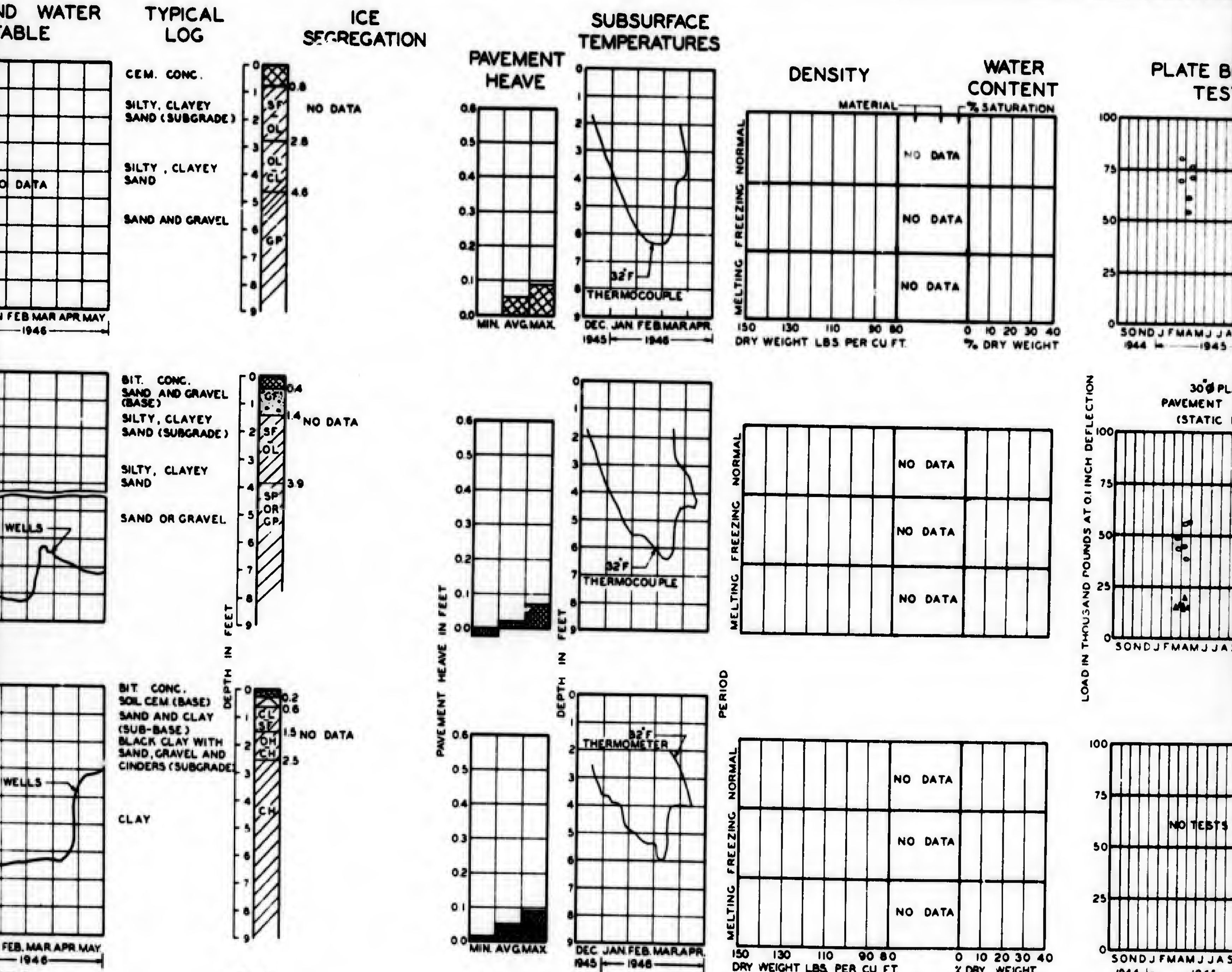


FIG.1 FIG.2 FIG.3 FIG.4 FIG.5



IG.5 FIG.6 FIG.7 FIG.8 FIG.9 FIG.1

FROST INVE
1945-

SUMMARY
WATERTOWN
FARGO A

FROST EFFECTS LABORATORY

B

CR -
PR -

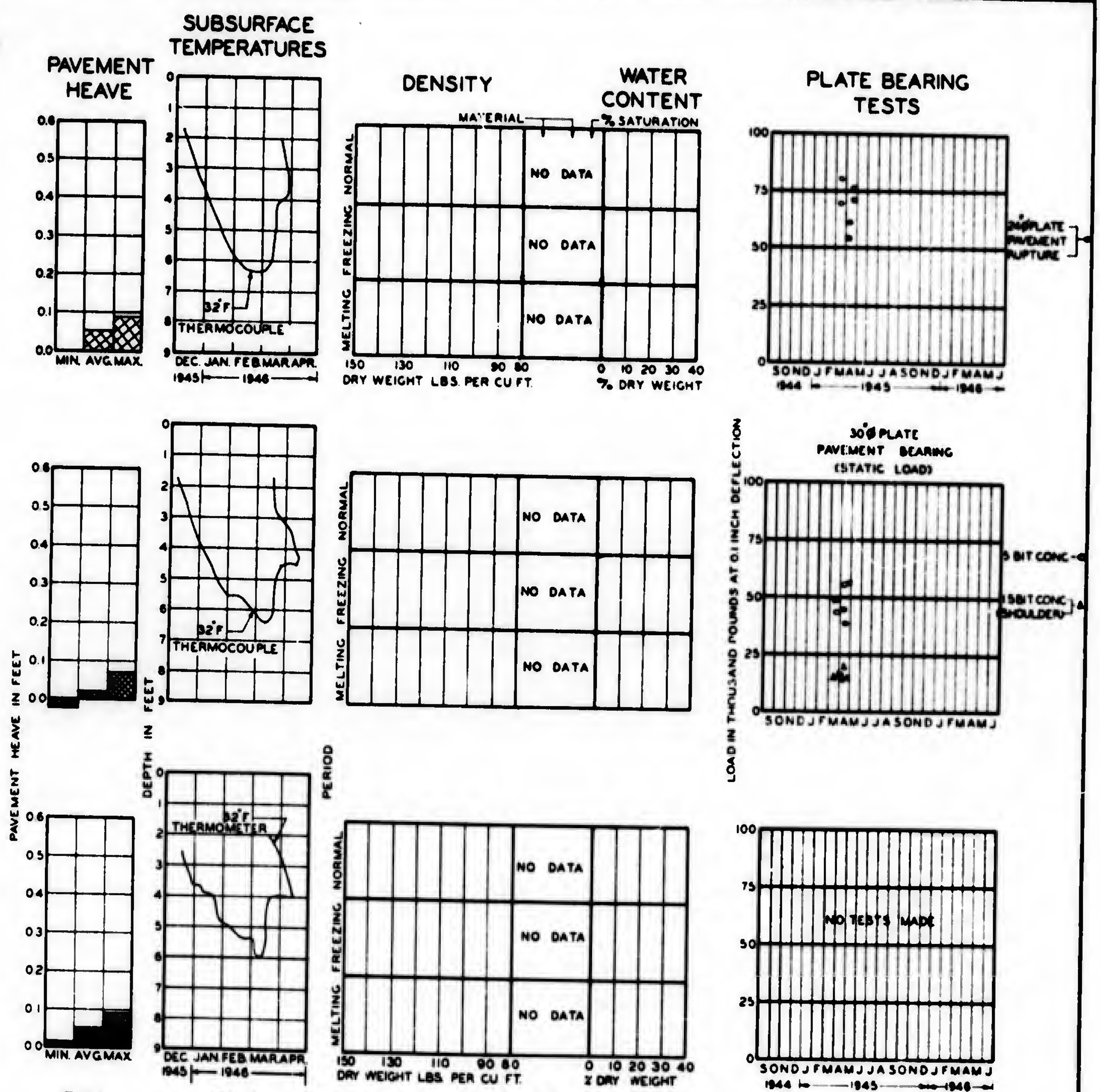
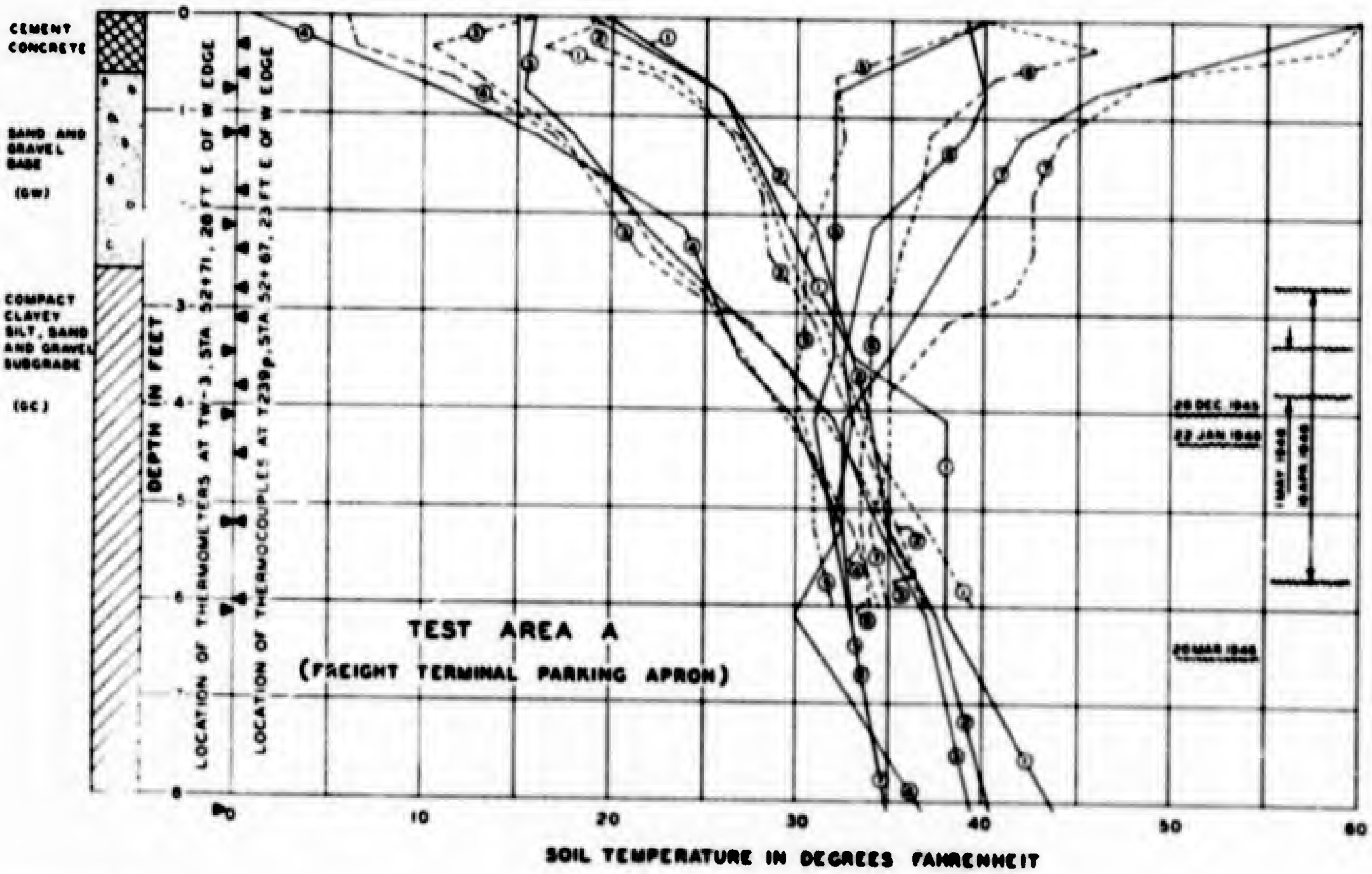


FIG.7 FIG. 8 FIG.9 FIG.10

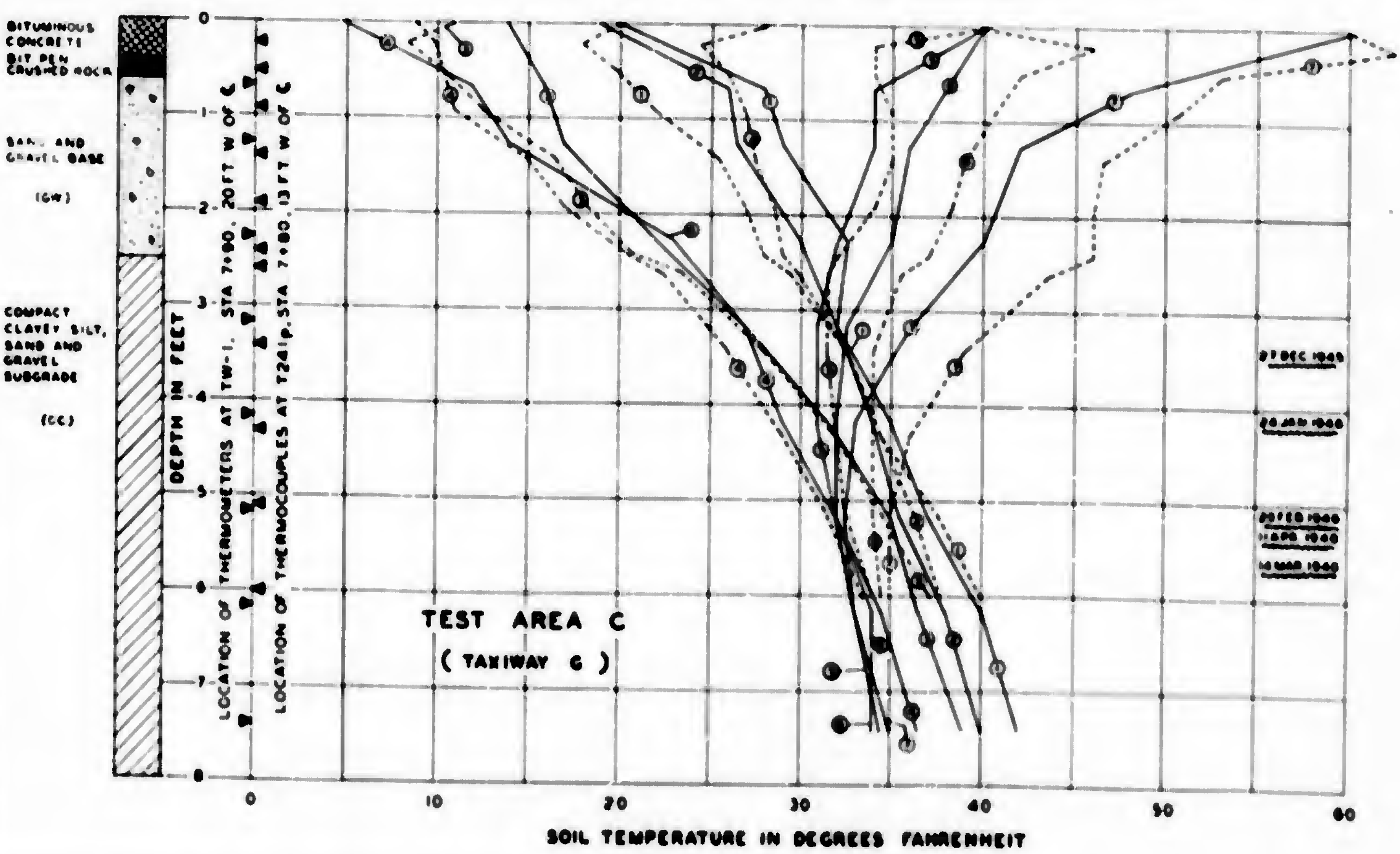
FROST INVESTIGATION
1945-1946

SUMMARY OF DATA
WATERTOWN AIRFIELD
FARGO AIRFIELD

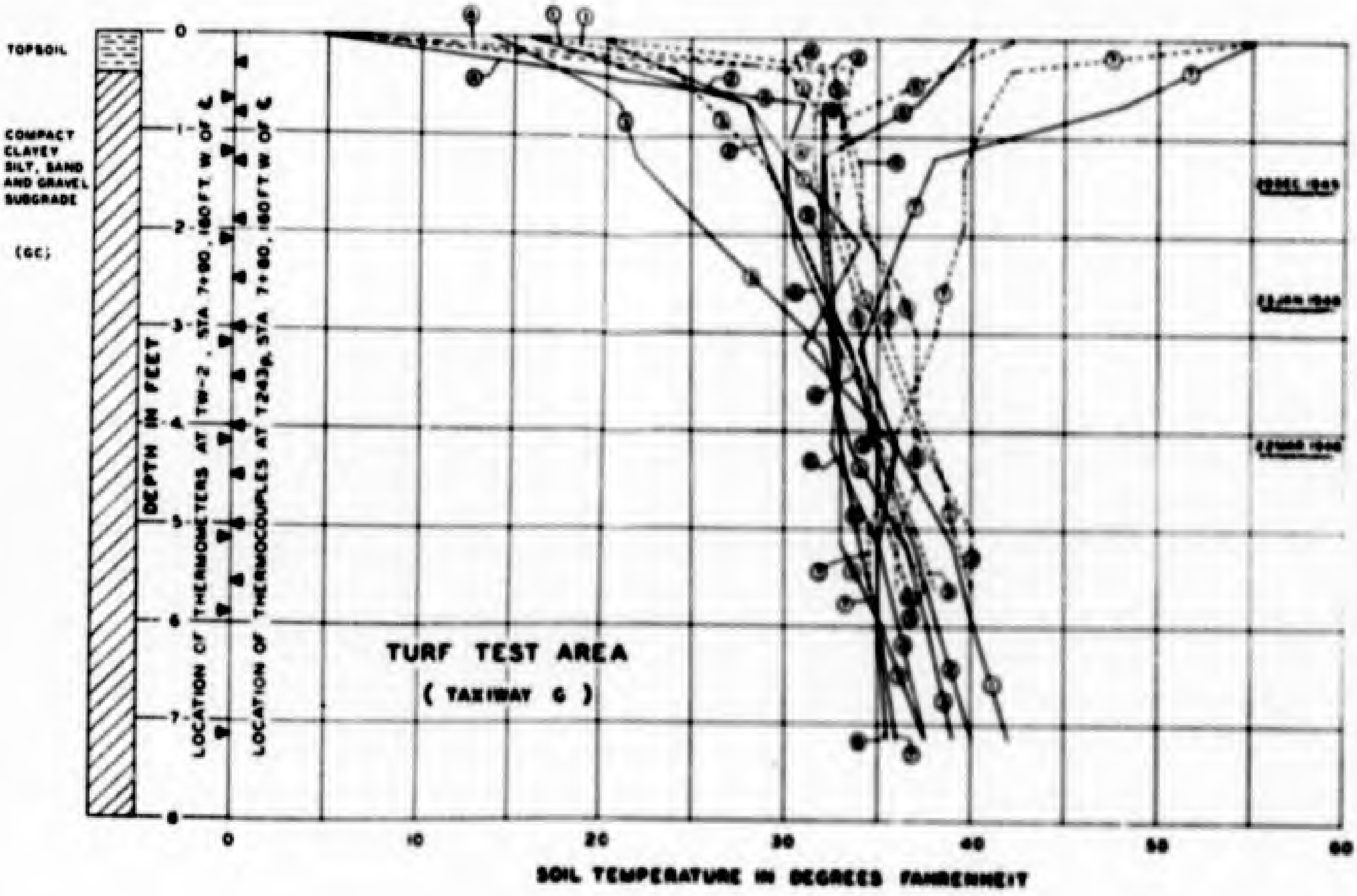
FROST EFFECTS LABORATORY, BOSTON, MASS. JUNE 1946



CEMENT CONCRETE
SAND AND GRAVEL BASE
(GW)
COMPACT CLAYEY SILT, SAND AND GRAVEL SUBGRADE
(GC)
DEPTH IN FEET
LOCATION OF THERMOMETERS AT TW-3, STA 52+71, 28 FT E OF W EDGE
LOCATION OF THERMOCOUPLES AT T239p, STA 52+67, 23 FT E OF W EDGE
TEST AREA A
(FREIGHT TERMINAL PARKING APRON)
0
10
20
30
40
50
60
SOIL TEMPERATURE IN DEGREES FAHRENHEIT



BITUMINOUS CONCRETE
BIT PEN CRUSHED ROCK
SAND AND GRAVEL BASE
(GW)
COMPACT CLAYEY SILT, SAND AND GRAVEL SUBGRADE
(GC)
DEPTH IN FEET
LOCATION OF THERMOMETERS AT TW-1, STA 7+90, 20 FT W OF C
LOCATION OF THERMOCOUPLES AT T241p, STA 7+80, 13 FT W OF C
TEST AREA C
(TAXIWAY G)
0
10
20
30
40
50
60
SOIL TEMPERATURE IN DEGREES FAHRENHEIT



NOTE:-

DATA TAKEN FROM OBSERVATIONS MADE AT PRESQUE ISLE AIRFIELD DURING THE 1945-1946 INVESTIGATIONS

CURVE NO	DATE OF OBSERVATION
1	20 DEC 1945
2	11 JAN 1946
3	23 JAN 1946
4	19 FEB 1946
5	20 MAR 1946
6	16 APR 1946
7	1 MAY 1946

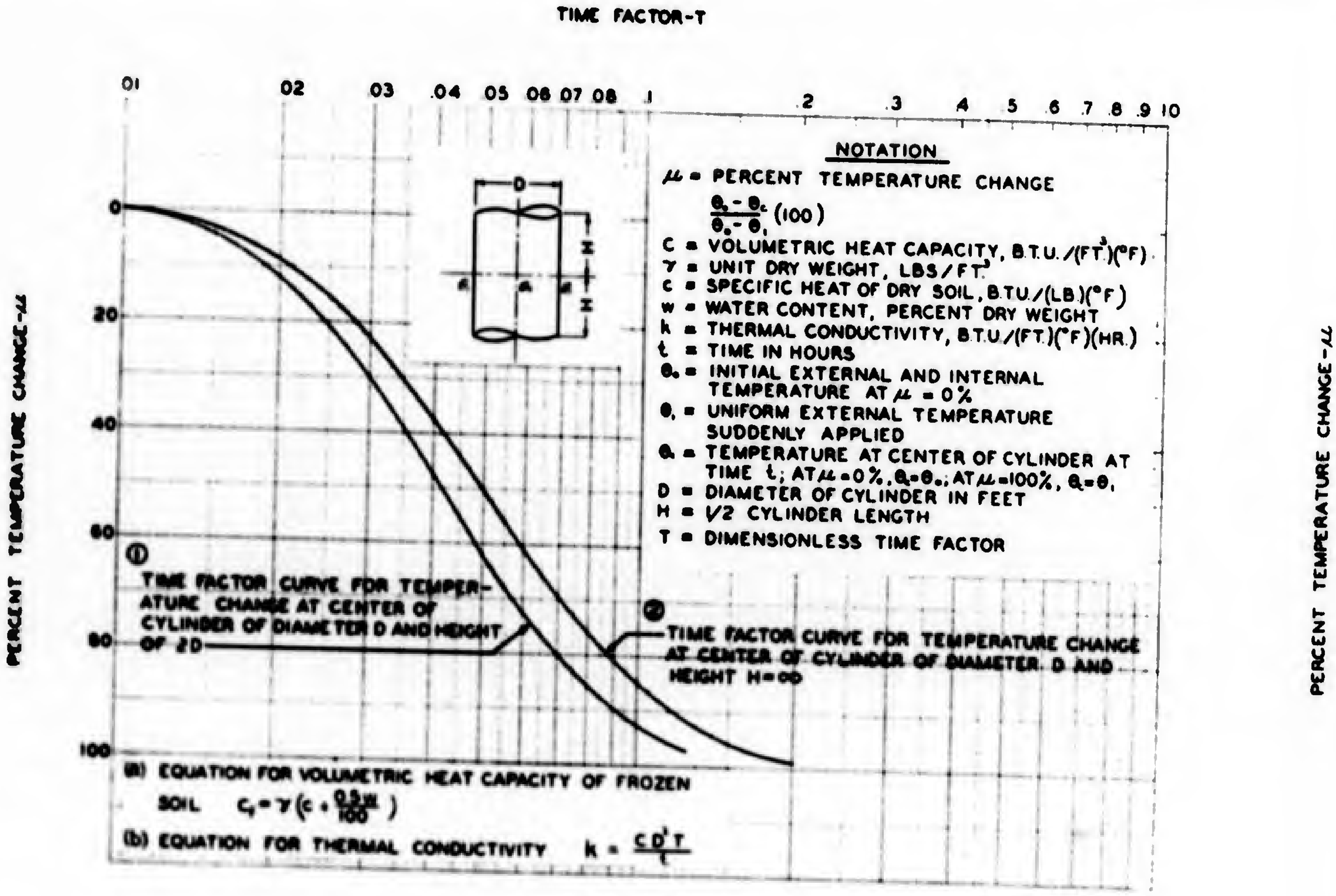
------- THERMOCOUPLE OBSERVATIONS
——— THERMOMETER OBSERVATIONS
~~~~~ DEPTH OF FROST PENETRATION MEASURED IN TEST PITS EXCAVATED ON INDICATED DATES

B

FROST INVESTIGATION
1945-1946

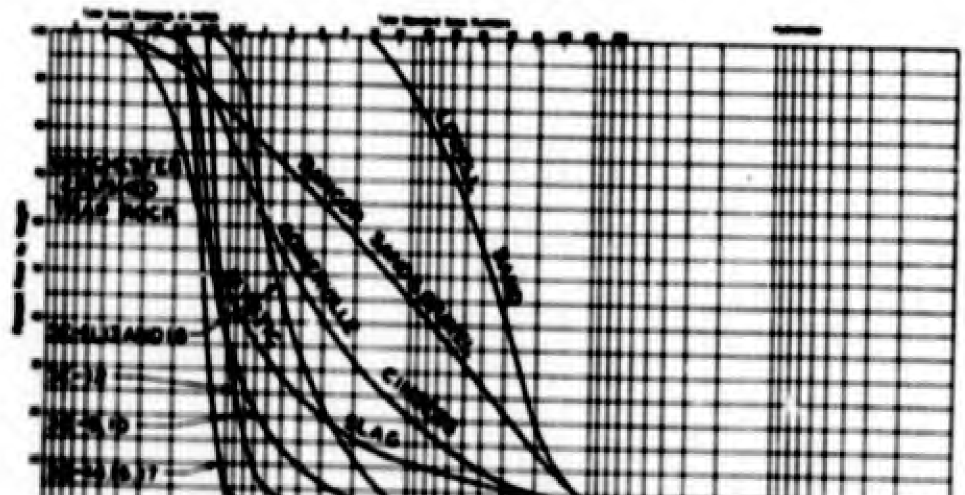
COMPARISON OF TYPICAL THERMOMETER AND THERMOCOUPLE OBSERVATIONS

JUNE 1946
FROST EFFECTS LABORATORY, BOSTON, MASS
~~~~~



TIME FACTOR CURVES FOR TEMPERATURE CHANGE AT CENTER OF CYLINDER

FIG 1



GRADATION OF BASE MATERIALS

FIG 3

EXAMPLE FOR DETERMIN

GIVEN: μ = 50%

TEST DATA FOR S

c = 0.20 B.T.U./

γ = 127.1 LBS/F

w = 3.6%

EQUATIONS:

(a) $C_1 = \gamma\left(c + \frac{0}{10}\right.$

(b) $k = \frac{C_1 D^2 T}{t}$

SUBSTITUTING IN (a)

$C_1 = 127.1(0.20 +$

FROM FIG 2

D = 5.36 IN = 0.4

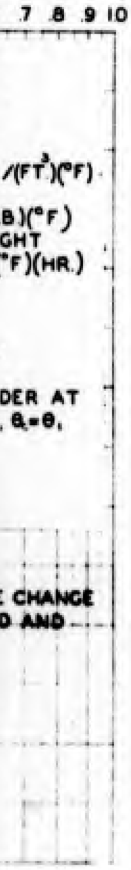
t = 0.224 HR

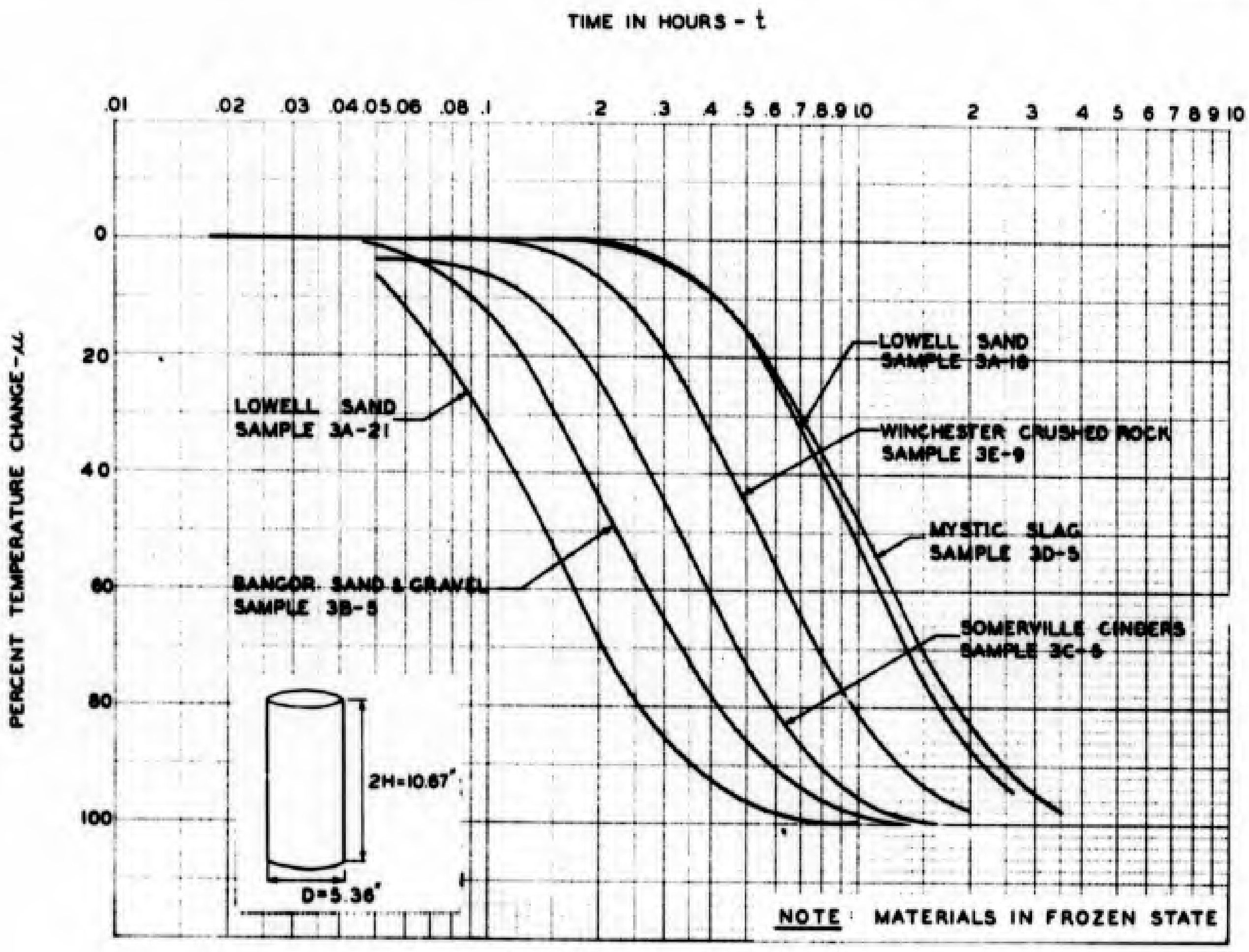
FROM FIG 1, CURVE 1

T = 0.042

SUBSTITUTING IN (b)

$k = \frac{(27.7)(0.1995)}{0.224}$





TYPICAL TIME CURVES
THERMAL CONDUCTIVITY DETERMINATIONS

FIG. 2

EXAMPLE FOR DETERMINATION OF THERMAL CONDUCTIVITY

GIVEN: $\mu = 50\%$

TEST DATA FOR SAMPLE NO. 3B-5, TABLE 6, 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}

$t = 0.22<$ HR.

FROM FIG. 1, CURVE ! !

$T = 0.042$

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

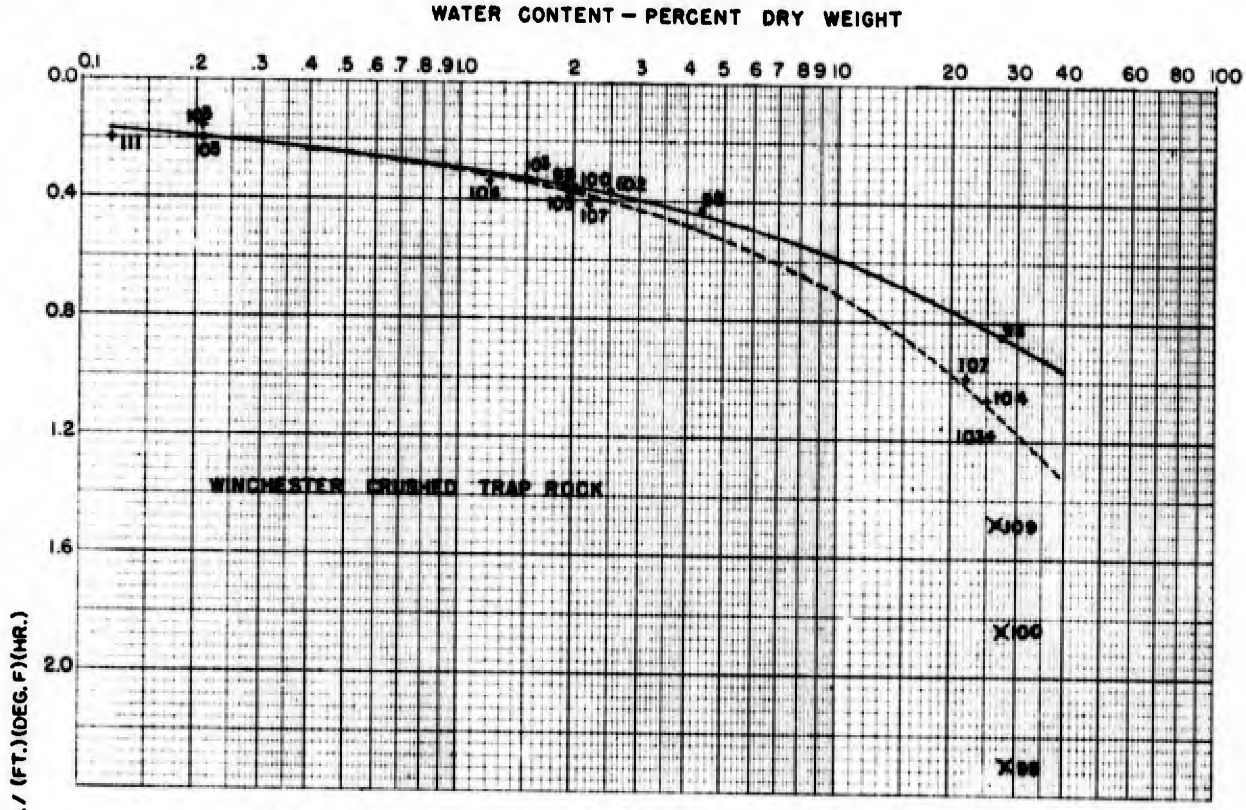


FIG. 1

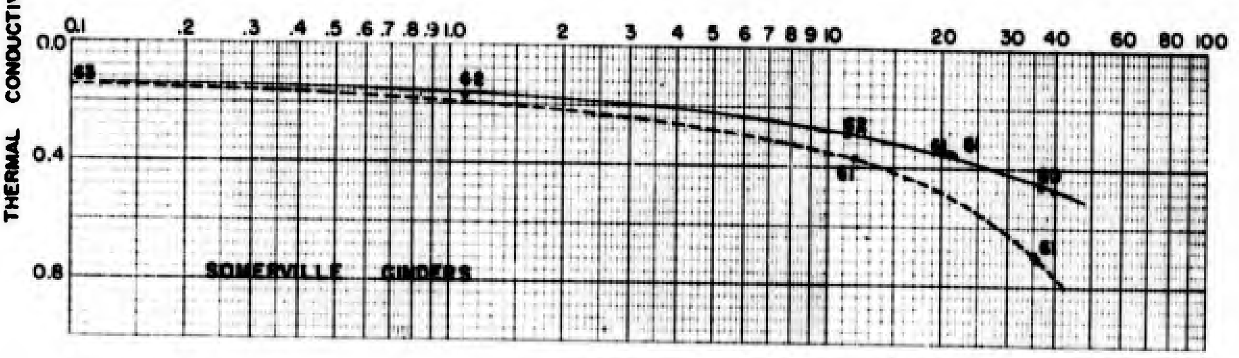


FIG. 2

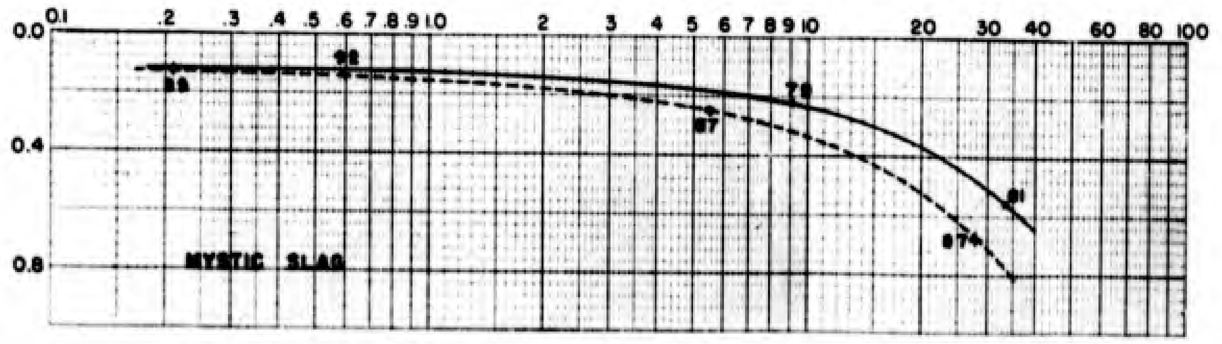


FIG. 3

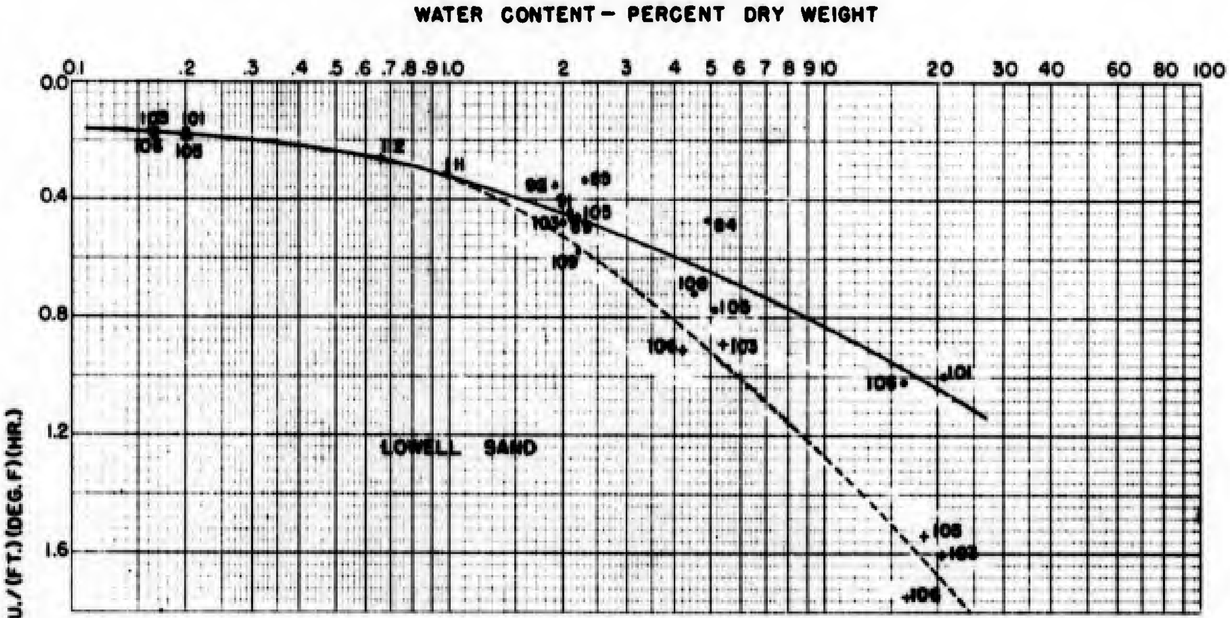


FIG. 4

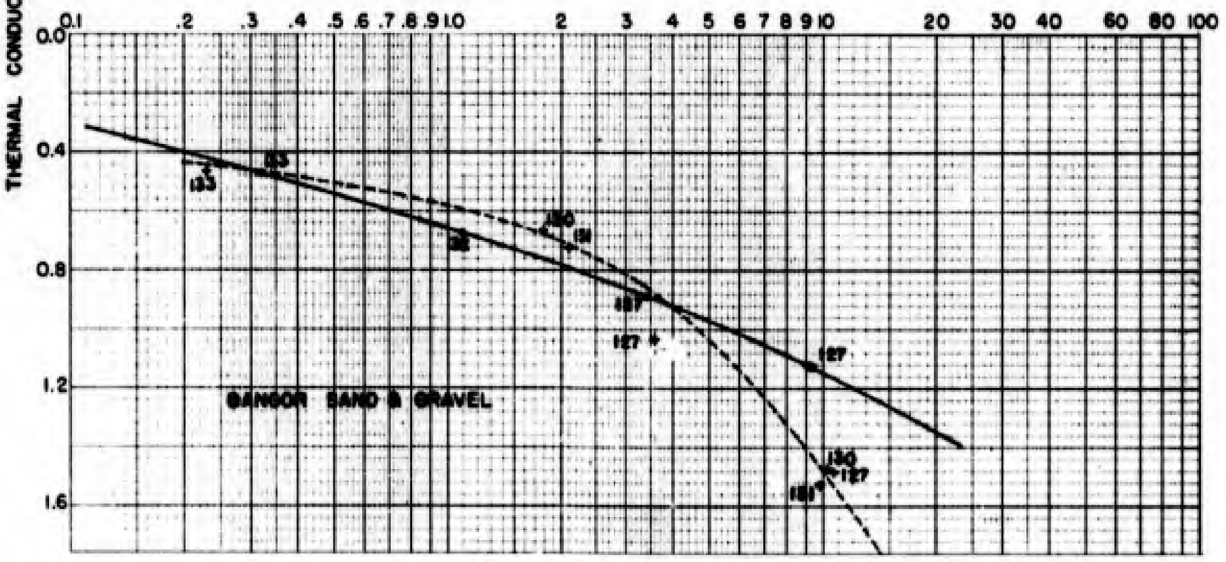


FIG. 5

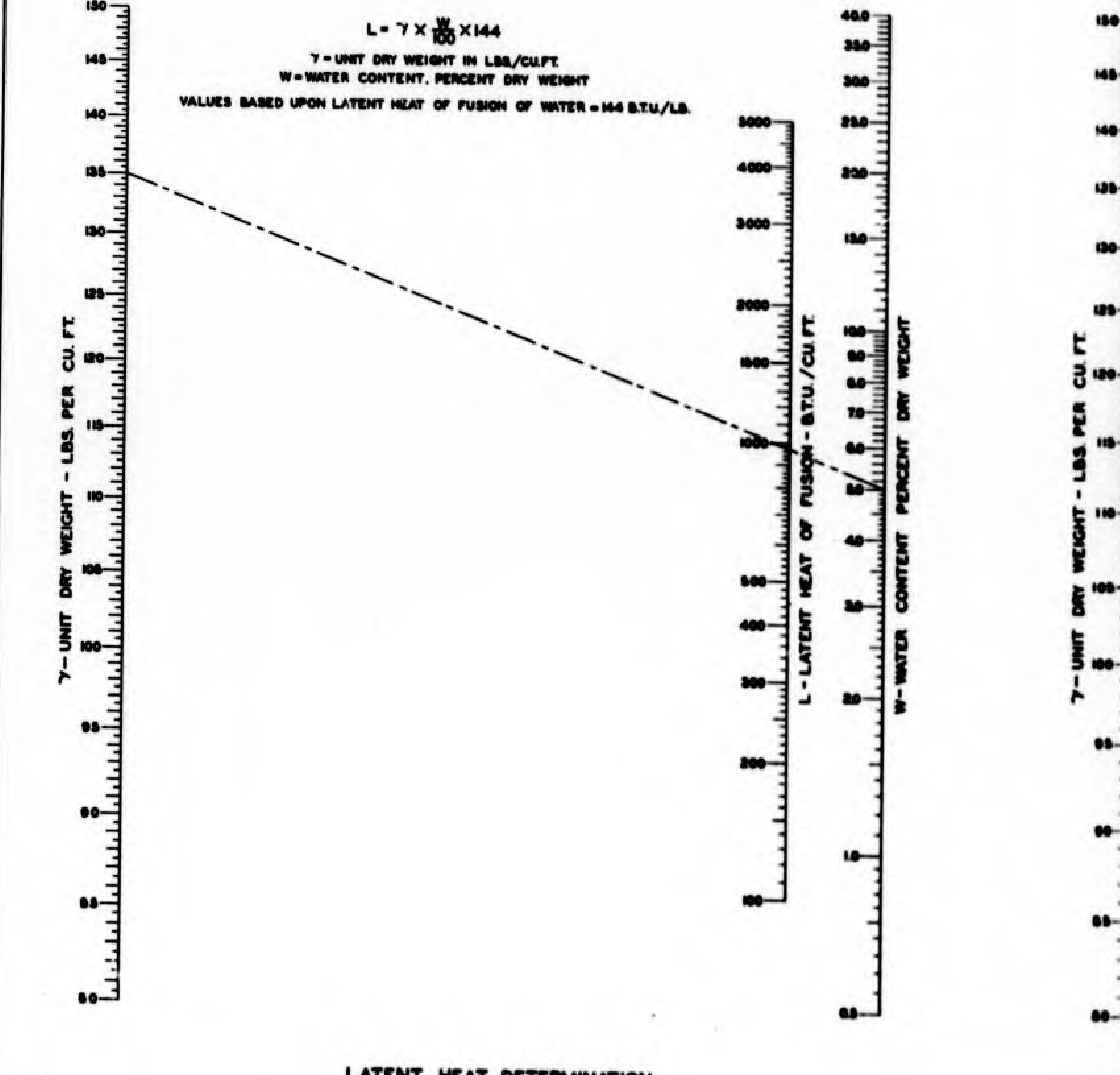
NOTES:
NUMBERS BESIDE PLOTTED POINTS INDICATE UNIT DRY WEIGHT OF SAMPLE IN POUNDS PER CUBIC FOOT.
—●— UNFROZEN MATERIAL
--+-- FROZEN MATERIAL
X OBSERVATION IN ERROR

FROST INVESTIGATION
1945-1946

THERMAL CONDUCTIVITY VS. WATER CONTENT OF BASE MATERIALS

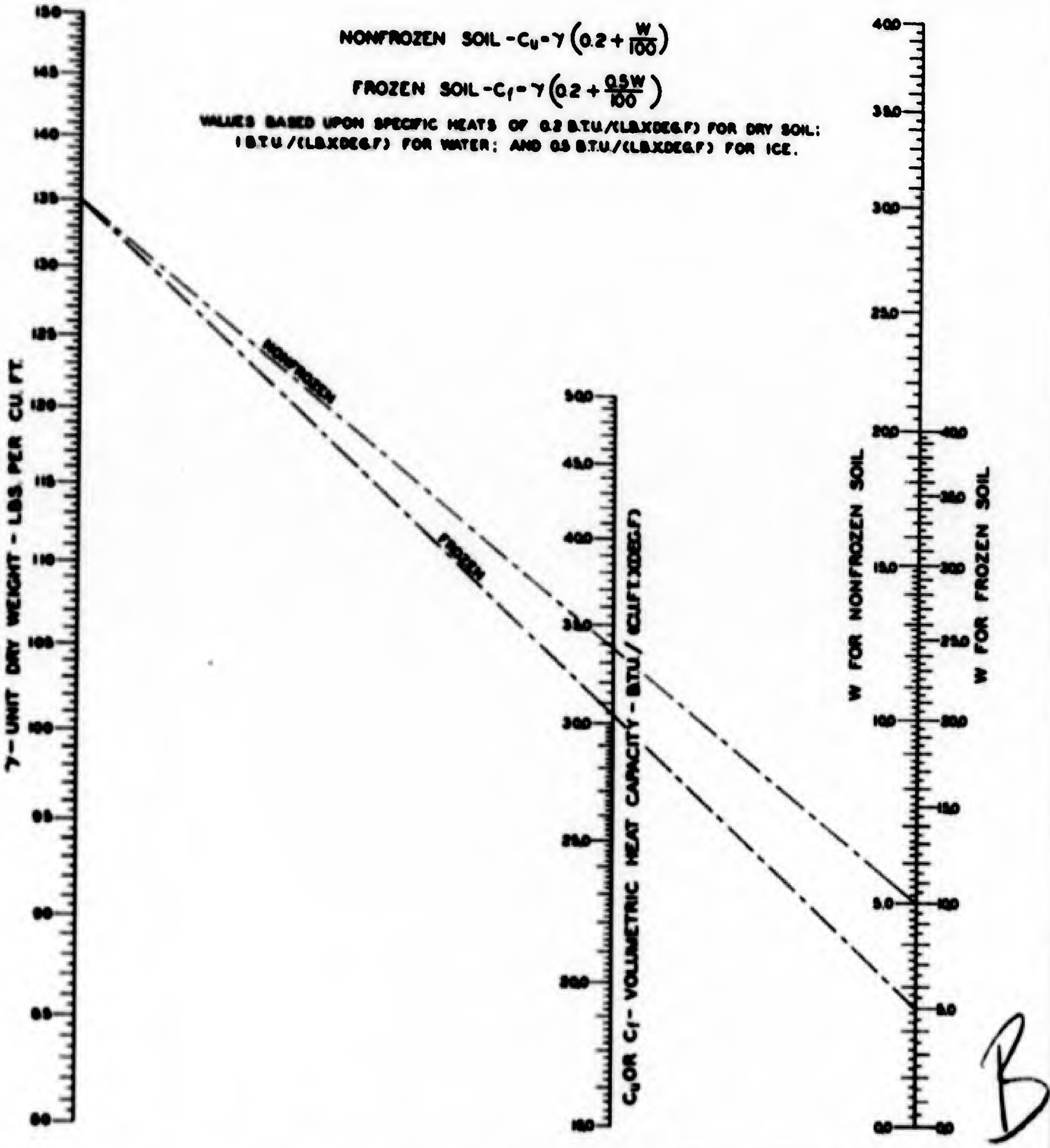
FROST EFFECTS LABORATORY, BOSTON, MASS. JUNE 1946

C.R.-45-46



LATENT HEAT DETERMINATION

FIG. 1



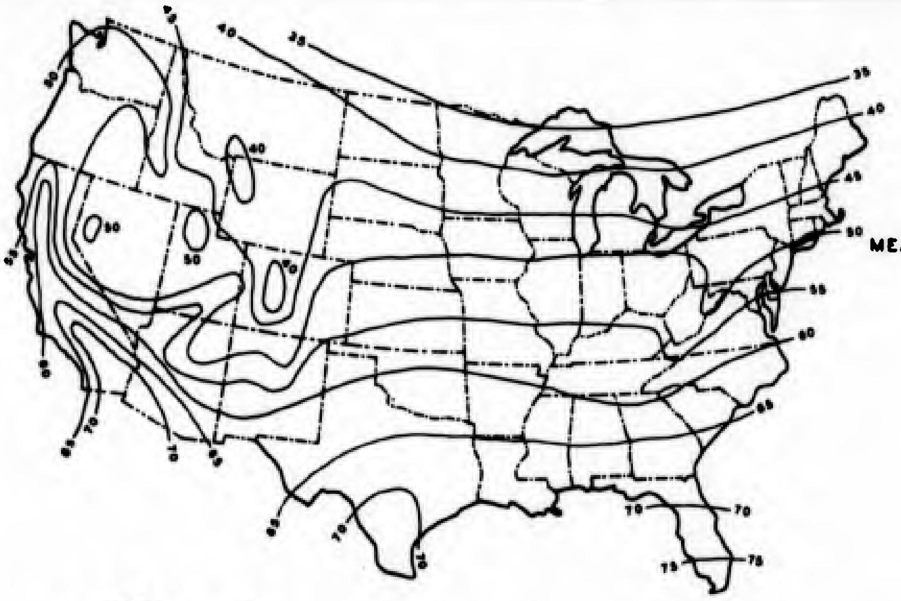
VOLUMETRIC HEAT CAPACITY DETERMINATION

FIG. 2

FROST INVESTIGATION
1945-1946

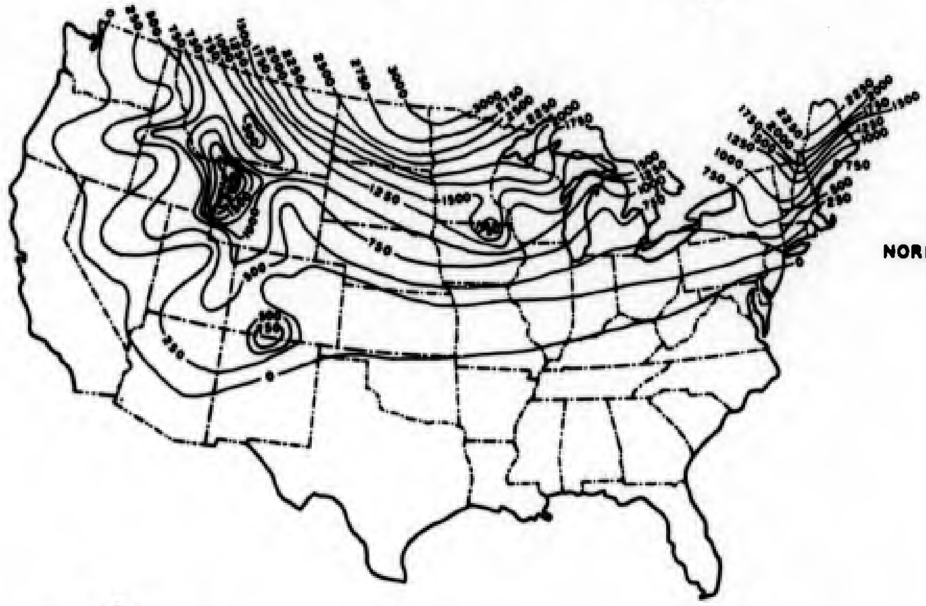
DETERMINATION OF LATENT HEAT OF FUSION AND VOLUMETRIC HEAT CAPACITY

FROST EFFECTS LABORATORY, BOSTON, MASS. JUNE 1946



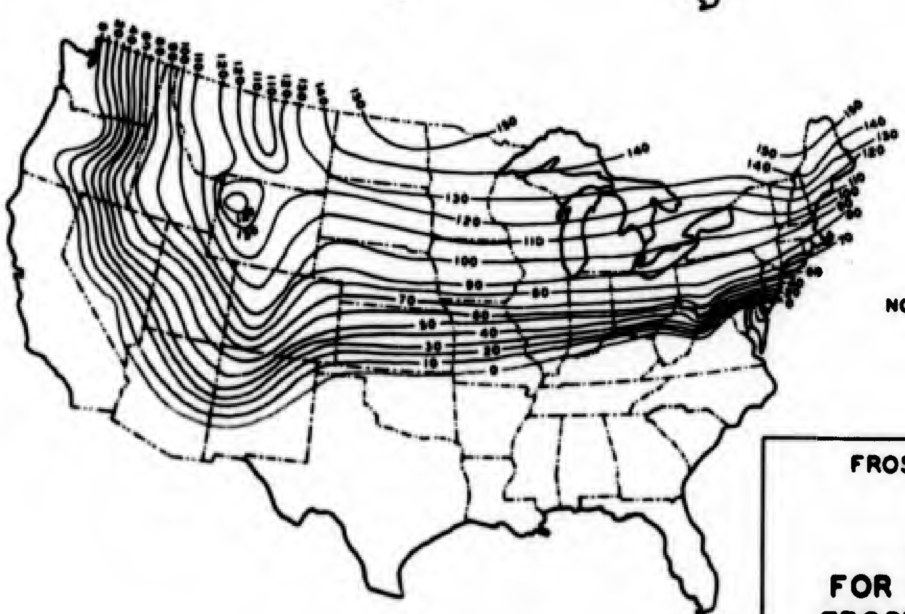
MEAN ANNUAL AIR TEMPERATURE
(DEGREES FAHRENHEIT)

FIG. 1



NORMAL FREEZING INDEX
(DEGREE DAYS)

FIG. 2



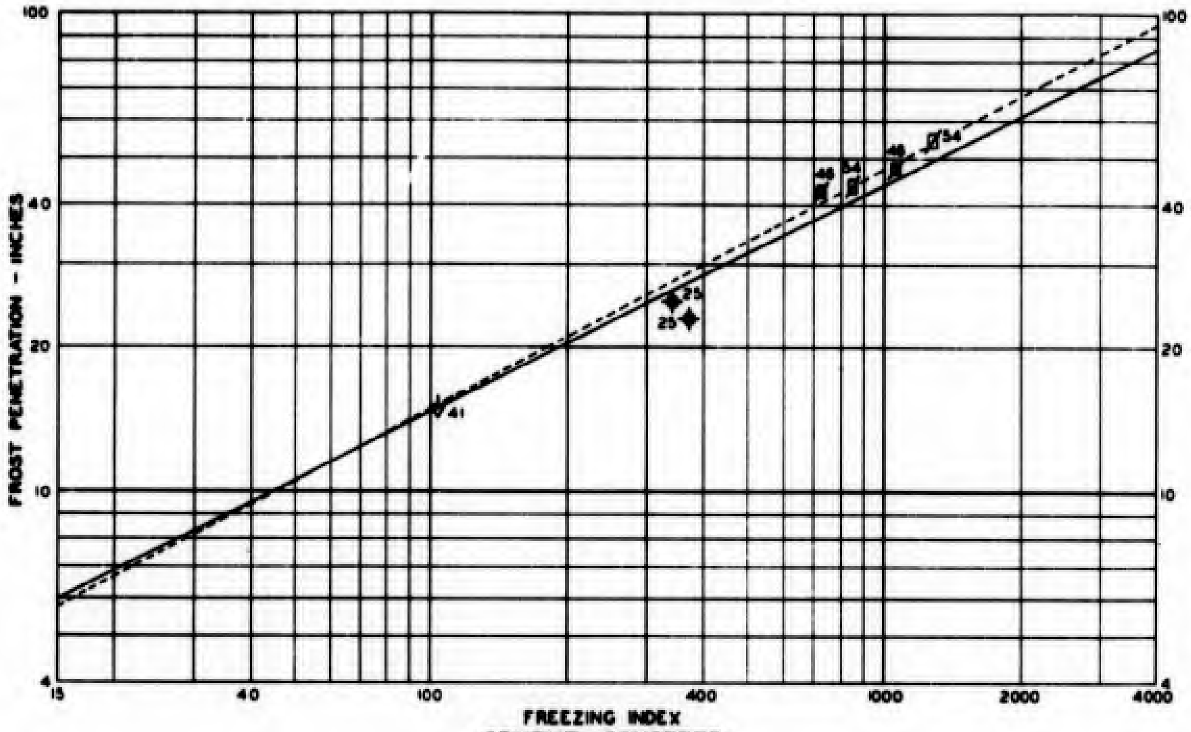
DURATION OF NORMAL FREEZING INDEX
(DAYS)

FIG. 3

FROST INVESTIGATION
1945 - 1946

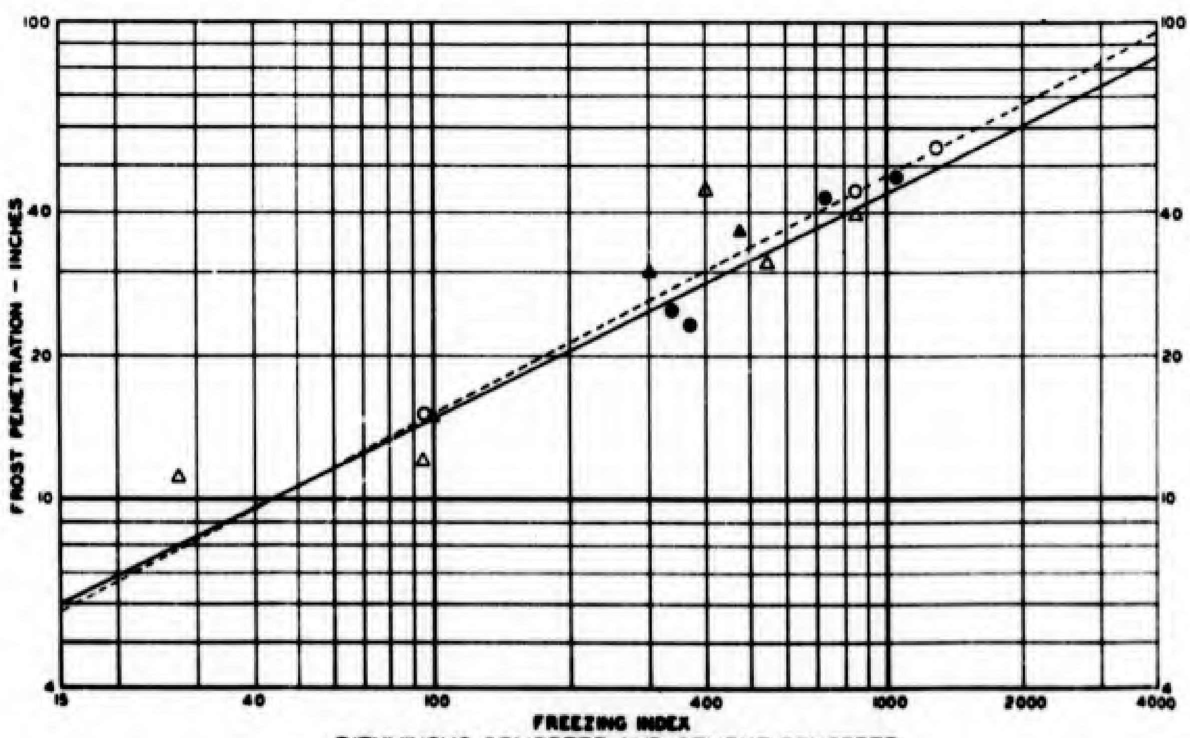
ISOGRAMS FOR PREDICTION OF FROST PENETRATION

JUNE 1946
FROST EFFECTS LABORATORY, BOSTON, MASS



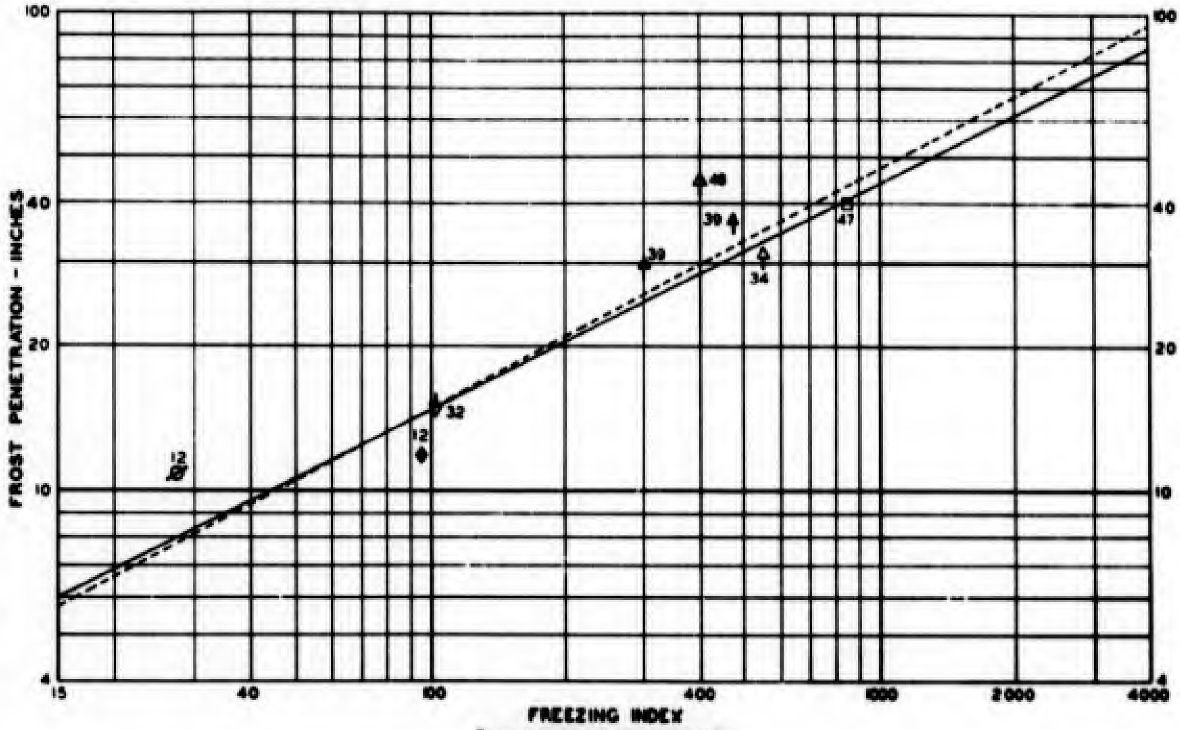
CEMENT CONCRETE

FIG. 1



BITUMINOUS CONCRETE AND CEMENT CONCRETE

FIG. 3



BITUMINOUS CONCRETE
FIG. 2

LEGEND:-

	1944-1945	1945-1946	
FIG. 1 & 2	▽	▼	PRESQUE ISLE
	△	▲	DOW
	□	—	WATERTOWN
	⊠	■	TRUAX
	—	◆	SIOUX FALLS
	—	✦	BEDFORD
	Ø	—	GARDEN CITY
FIG. 3	△	▲	BITUMINOUS CONCRETE
	○	●	CEMENT CONCRETE

—— DESIGN CURVE FROM ENGINEERING MANUAL PART XII CHAPTER 4, JULY 1946

---- CURVE FROM EMPIRICAL FORMULA, $x\,(\text{FEET}) = 0.125\sqrt{F}$

NOTES:-

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

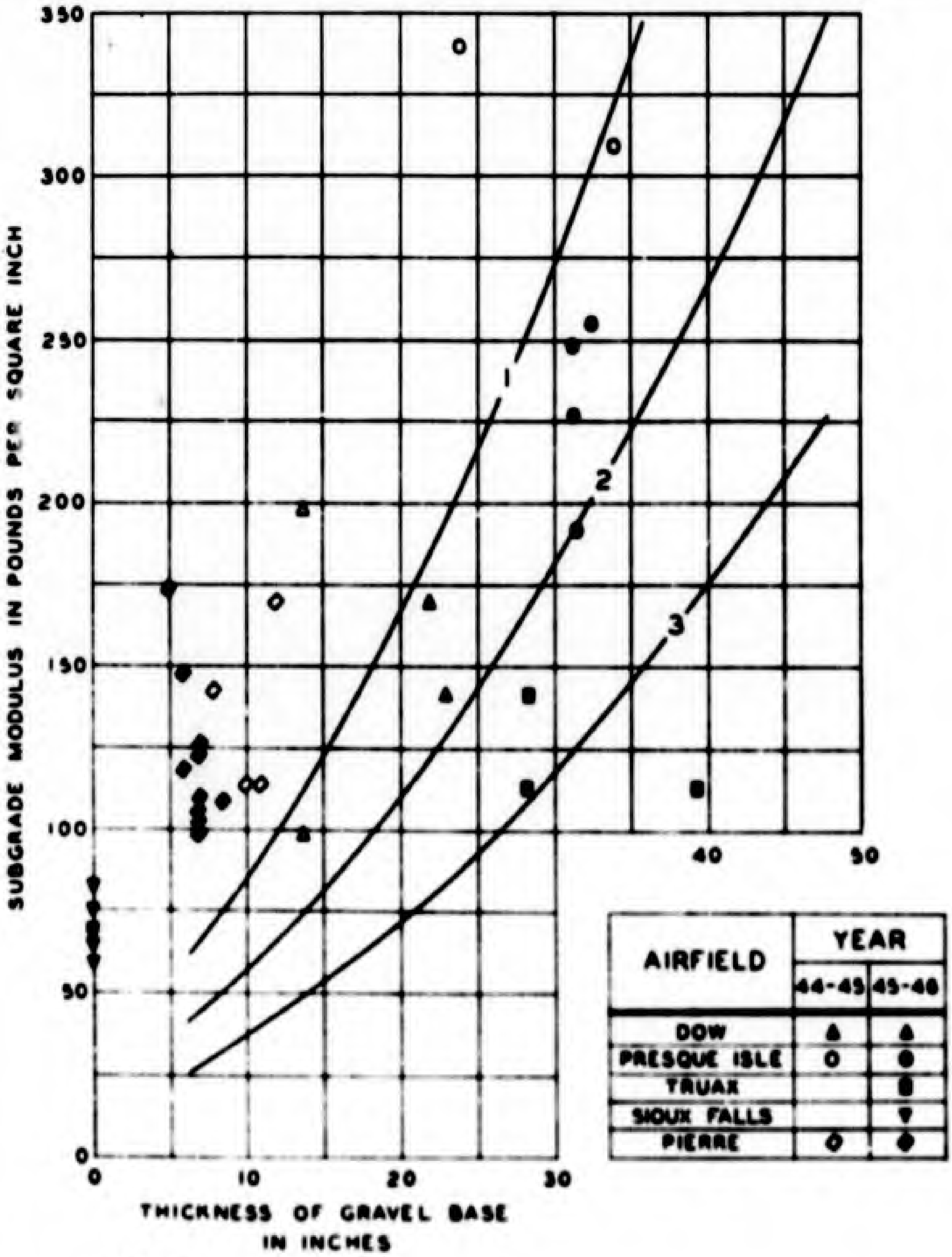
FROST PENETRATION IS IN NON-FROST SUSCEPTIBLE MATERIALS ONLY.

B

FROST INVESTIGATION
1944-1945
&
1945-1946

CORRELATION BETWEEN FROST PENETRATION AND FREEZING INDEX

FROST EFFECTS LABORATORY BOSTON MASS. JUNE 1946



NOTES

1, 2 AND 3 ARE DESIGN CURVES DATED MARCH 1946 FROM ENGINEERING MANUAL PART XII CHAPTER 4

ALL SUBGRADE SOILS ARE FROST SUSCEPTIBLE AND FALL IN GROUP 3

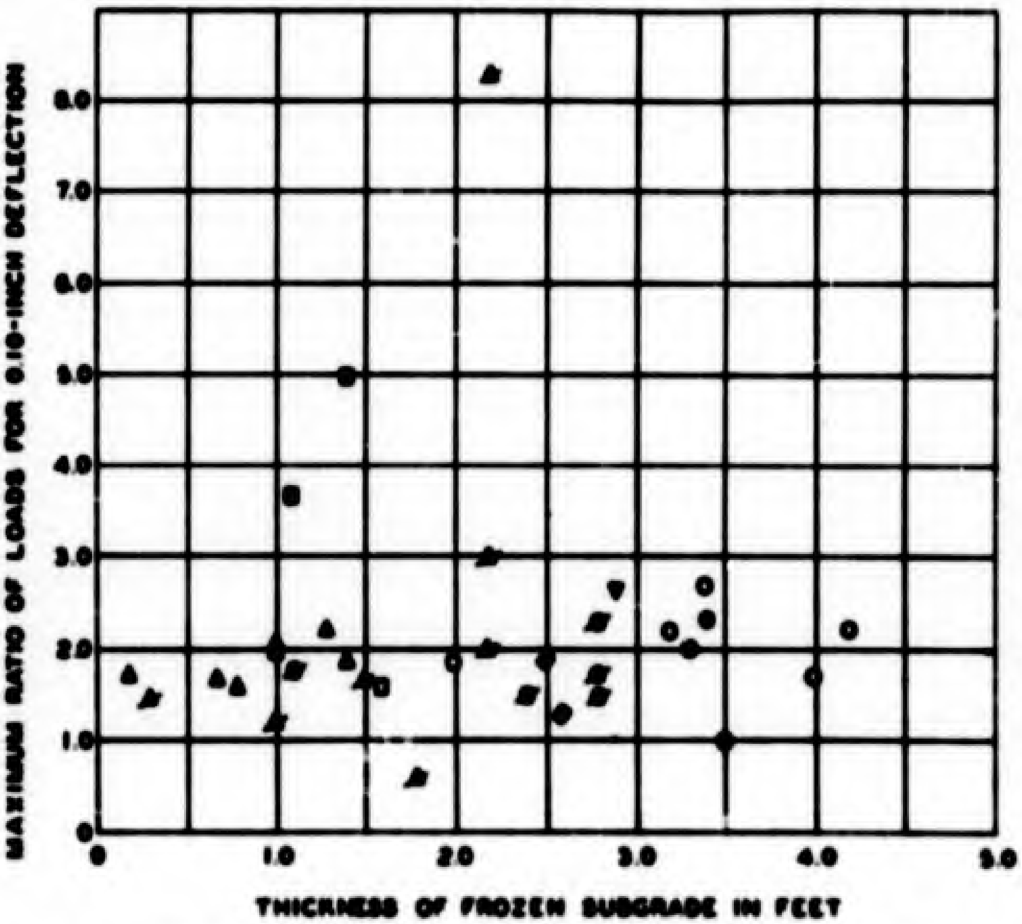
SUBGRADE MODULUS DETERMINED DURING FROST MELTING PERIOD

FROST INVESTIGATION
1945 - 1946

SUBGRADE MODULI AND DESIGN CURVES

RIGID PAVEMENT

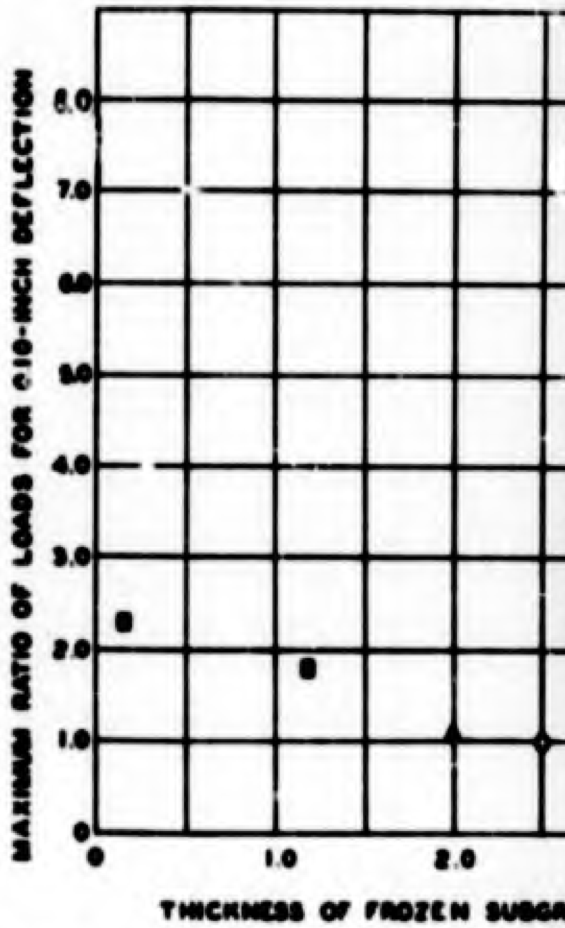
FROST EFFECTS LABORATORY
BOSTON, MASS   JUNE 1946



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

FIG.1

AIRFIELD	YEAR			CLASS OF SUBGRADE SOILS
	43-44	44-45	45-46	
DOW	◭	△	▲	CL
PRESQUE ISLE	◐	○	●	GC
TRUAX		□	■	CL & SF
SIOUX FALLS			▼	CL & CH
PIERRE			◆	CL

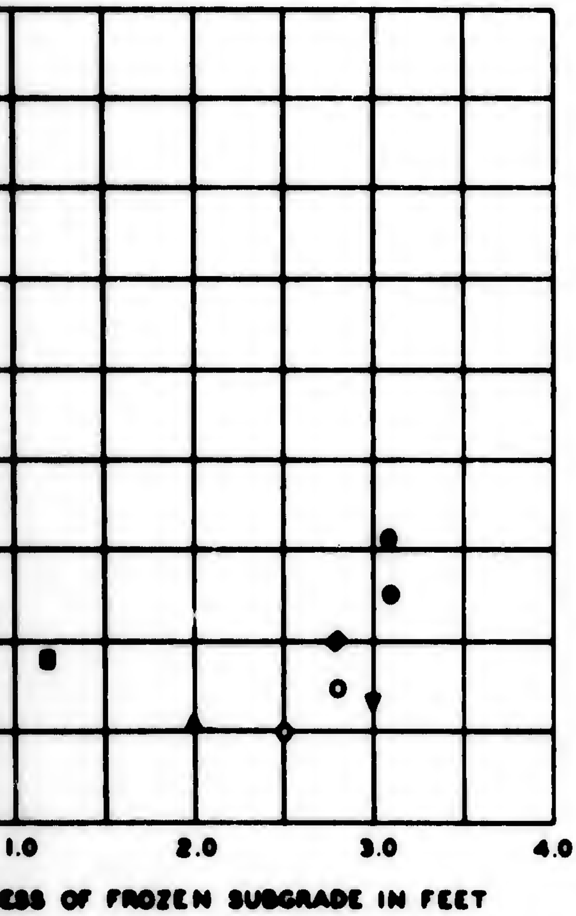


30-INCH PLATE BEARING TESTS (SU ON SOIL UNDER PORTLAND CE

FIG.2

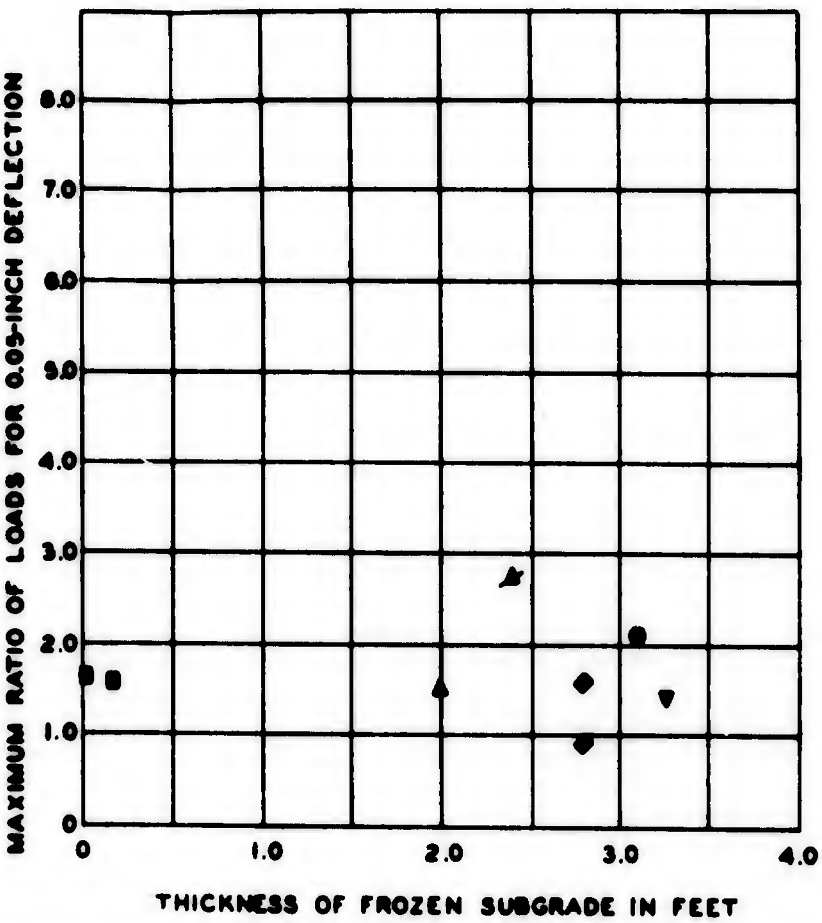
NOTE:-

RATIO = NORMAL PERIOD / FROST MELTING PERIO



...EARING TESTS (SUBGRADE MODULUS)
...ER PORTLAND CEMENT PAVEMENTS.

FIG. 2



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

FIG. 3

NORMAL PERIOD
...FROST MELTING PERIOD

B

FROST INVESTIGATION
1945 - 1946

EFFECT OF THICKNESS OF FROZEN SUBGRADE ON PAVEMENT STRENGTH

FROST EFFECTS LABORATORY
BOSTON, MASS. JUNE 1946

SUPPLEMENT A

MATHEMATICAL STUDIES OF THERMAL PROPERTIES

APPENDIX A MATHEMATICAL STUDIES OF THERMAL PROPERTIES

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^o)	^oF
a	Thermal Diffusivity = k/C	$ft^2/hr.$
B	Amplitude of air temperature change for yearly cycle = 1/2 range	^oF
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	$BTU/(lb)(^oF)$
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	^oF days
H	Total heat given up by soil = Qt	BTU/ft^2
h	Depth below ground surface	ft.
i	Thermal gradient	$^oF/ft$
$\overline{K}$	Constant of integration	
k	Thermal conductivity	$BTU/(ft)(^oF)(hr)$

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	$^oF/ft$
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

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

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

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

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

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

$$\text{Now } \frac{d}{d\beta}\operatorname{erf}\beta = \frac{2}{\sqrt{\pi}}\frac{d}{d\beta}\int_0^\beta e^{-u^2}du = \frac{2}{\sqrt{\pi}}e^{-\beta^2} \quad \ldots\ldots\ldots\ldots [5]$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

At time "t_1"

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

and at time "t_2"

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

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

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

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

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

$$\therefore f(h) = m^2B^2e^{-2mh}[2-2\sin(\omega t_1-mh)\cos(\omega t_1-mh) - 2\sin(\omega t_2-mh)\cos(\omega t_2-mh)] \quad [23]$$

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

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

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

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

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

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",

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

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

For maximum values,

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

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

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

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

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

Example

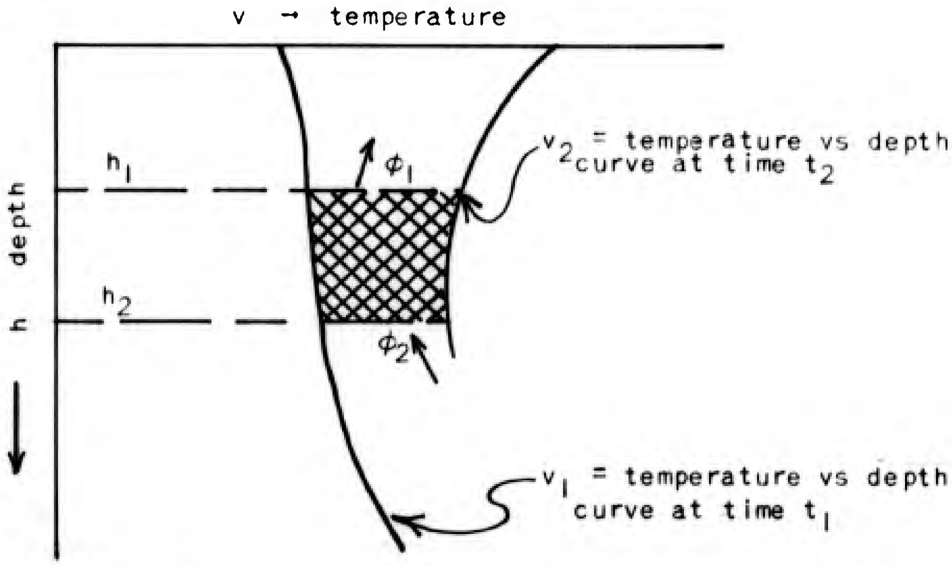
From the curves given in Figure 2, Plate A-1 the following values of "a" are derived

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" ($\Delta t = t_2 - t_1$).

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

= 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".

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

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

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

$$Q = Q_2 - Q_1 = 24k(\phi_2 - \phi_1)(t_2 - t_1) = C \times \text{Area} \quad \ldots\ldots \quad [38]$$

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

In general terms

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

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

where $\frac{"dv"}{dt}$ is the tangent to the time-temperature curve at a given depth and time and $\frac{"di"}{dh}$ 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

Δt = 31 x 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 $\Delta\phi$	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				

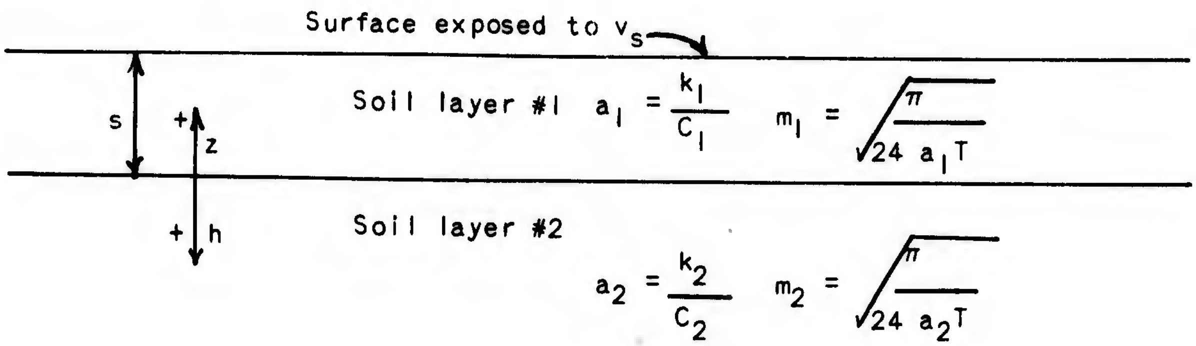
Using equation [40] and values of $\frac{"dv"}{dt}$ obtained from Figure 2, Plate A-1, and values of thermal gradient slope $\frac{"di"}{dh}$ obtained from Figure 3, Plate A-1. Values of $\frac{"dt"}{dh}$ were obtained from tangents drawn to the gradient curves.

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,

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

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

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

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

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

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

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

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

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

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

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

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 ($32^\circ F$) 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 $\sin(\omega t - mx) = 1$

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

Example

Given: $v_o = 42^\circ$; $B = 20^\circ$; $a = 0.03\ ft^2/hr$

Find "x".

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

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

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

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

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

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

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

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

and in layer #2

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

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

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

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

$$dH = L dx \quad \ldots\ldots\ldots\ldots \quad [60]$$

The heat conducted out in time "dt" is

$$dH = 24\ ki\ dt \quad \ldots\ldots\ldots\ldots \quad [61]$$

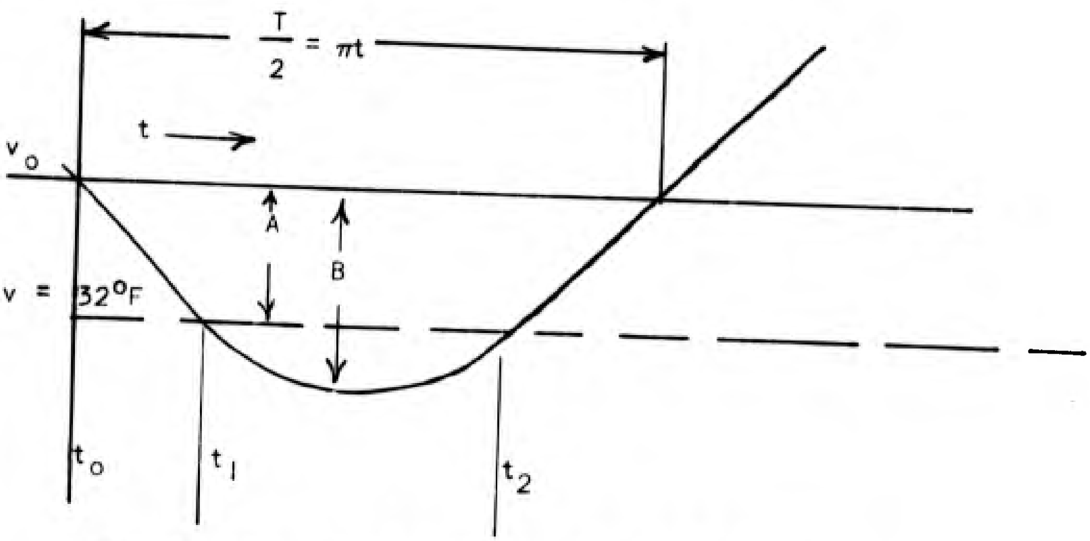
Equating [60] and [61], and substituting [59] for "i"

$$L dx = 24 k i dt = \frac{24k}{x}(B \sin\omega t - A)\ dt \quad \ldots\ldots\ldots \quad [62]$$

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

Integrating

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



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

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

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

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

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

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

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

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

By rewriting equation [63] we have

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

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

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

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.

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

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

Integrating equation [63]

$$\frac{L}{24\,k} \int_0^{x_{max}} x\,dx = \int_{t_1}^{t_2} K(B \sin \omega t - A)\,dt$$

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

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

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

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 $\frac{1}{\omega}$ arc sin $\frac{A}{B}$ for "t_1"

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

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

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

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

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

<u>Example</u>

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

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

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

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

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

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

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

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

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

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

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

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

Integrating

$$\frac{x^2}{2} = \frac{24k}{L}\int_0^t [32-f(t)]dt \quad \ldots\ldots\ldots\ldots \quad [82]$$

Now $\int_0^t 32 - f(t)dt = F$ = freezing index in degree days

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

<u>Example</u>

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

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

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,

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

Hence the rate of upward flow

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

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

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

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

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

Integrating,

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

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

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

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

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

and equation [89] therefore becomes

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

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

Therefore equation [90] becomes

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

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

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

Example

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

Using equation [92]

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

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

Using equation [93]

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

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

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]

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

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

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

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

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

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

Transposing and integrating

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

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

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

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

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

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

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

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

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

<u>Example</u>

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

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

and $dH = Ldx = 24\ kidt = 24k \frac{32 - f(t)}{x} dt$ . . . . [100]

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

Integrating

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

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

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

$$x = \sqrt{\frac{48\ k \int_0^t [32 - f(t)]dt}{L + \frac{3C}{2}\ [32 - f(t)]}} \quad . . . . [106]$$

Now since "v_f" is always below freezing,

$$\int_0^t [32 - f(t)]dt = F$$

Therefore equation [106] can be written

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

Example

Using values from examples for previous Problems

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

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

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

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

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

From equation [62]

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

Now, differentiating equation [108]

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

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

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

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

Combining equations [109] and [111]

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

From equation [108] by differentiation,

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

and

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

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

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

Now from equation [3]

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

Equation [115] becomes

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

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

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

Now from equation [108]

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

Substituting equation [119] in equation [118]

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

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

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

If β is small, then

$$\beta e^{\beta^2} \int_0^{\beta} e^{-u^2} du \approx \beta^2 \quad \ldots\ldots\ldots\ldots \quad [122]$$

Substituting in equation [120]

$$\beta^2 \approx \frac{C(v_p - 32)}{2L} \quad \ldots\ldots\ldots\ldots \quad [123]$$

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

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

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

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

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

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

Then equation [120] becomes

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

and

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

Example

Using data from examples for previous Problems.

$a = 0.03$; $C = 30$; and $L = 2880$. Also assuming $v_p = 42^\circ$

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]

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

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

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

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

$$\frac{C(v_p - 32)}{L \times 2} = \frac{30 \times 10}{2880 \times 2} = 0.0529 = \lambda\beta$$

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]

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

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

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

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

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

or

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

Integrating

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

Now since "v_p" is always below freezing

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

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

and

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

If the surface temperature is expressed by the form

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

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 $G = \frac{C_f B}{2}$

<u>Examples</u>

Using data from examples for preceding Problems

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

$C_u = 32$; $L = 2880$; and $v_p = 22^o$

Using equation [134]

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

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

Using equation [136]

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

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

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

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

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

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

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

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

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

$$= 2505.8 \times 0.0171 \doteq 42.85$$

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

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.

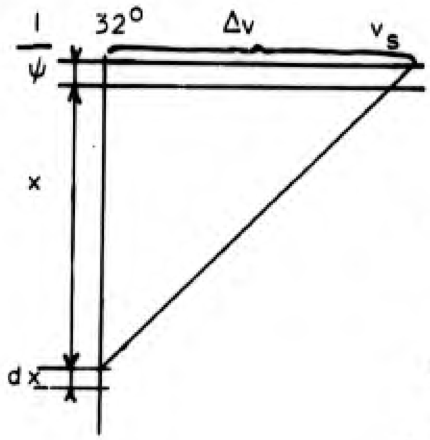
Find the effect of radiation and ground film.

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

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



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

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

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

$\therefore dy = dx$

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

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

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

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

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

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

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

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 $C_f = 30$.

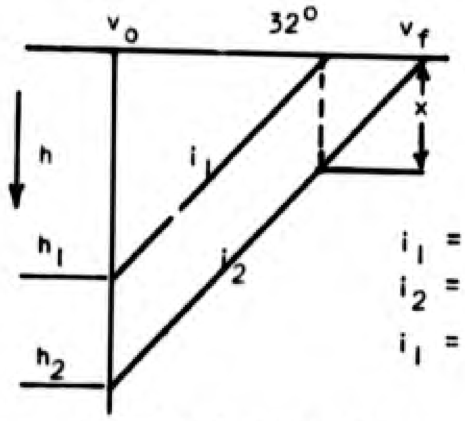
v_s (°F)	Per Cent Error in Omitting $1/\psi$ from Equation [145]											
	E = 6			E = 5			E = 2			E = 1		
	k=0.5	k=1.0	k=1.5	k=0.5	k=1.0	k=1.5	k=0.5	k=1.0	k=1.5	k=0.5	k=1.0	k=1.5
31	3.6	5.1	6.2	4.4	6.1	7.5	10.8	15.2	18.5	21.5	29.4	36.2
27	1.7	2.4	2.8	2.0	2.9	3.4	5.0	7.1	8.5	10.0	14.1	16.7
22	1.2	1.8	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 $H = \int_0^t 24ki\ dt + \bar{K}$ . . . . [146]

when $t = 0$ $H = 0$ $\therefore$ $\bar{K} = 0$ 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

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

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

Substituting equation [150] in equation [148]

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

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

From equation [149]

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

Hence equation [152] becomes

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

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

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

Giver 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

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

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

Solving for x_R

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

Substituting equation [149] for v_f

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

Example

Using same data as for examples for previous Problems

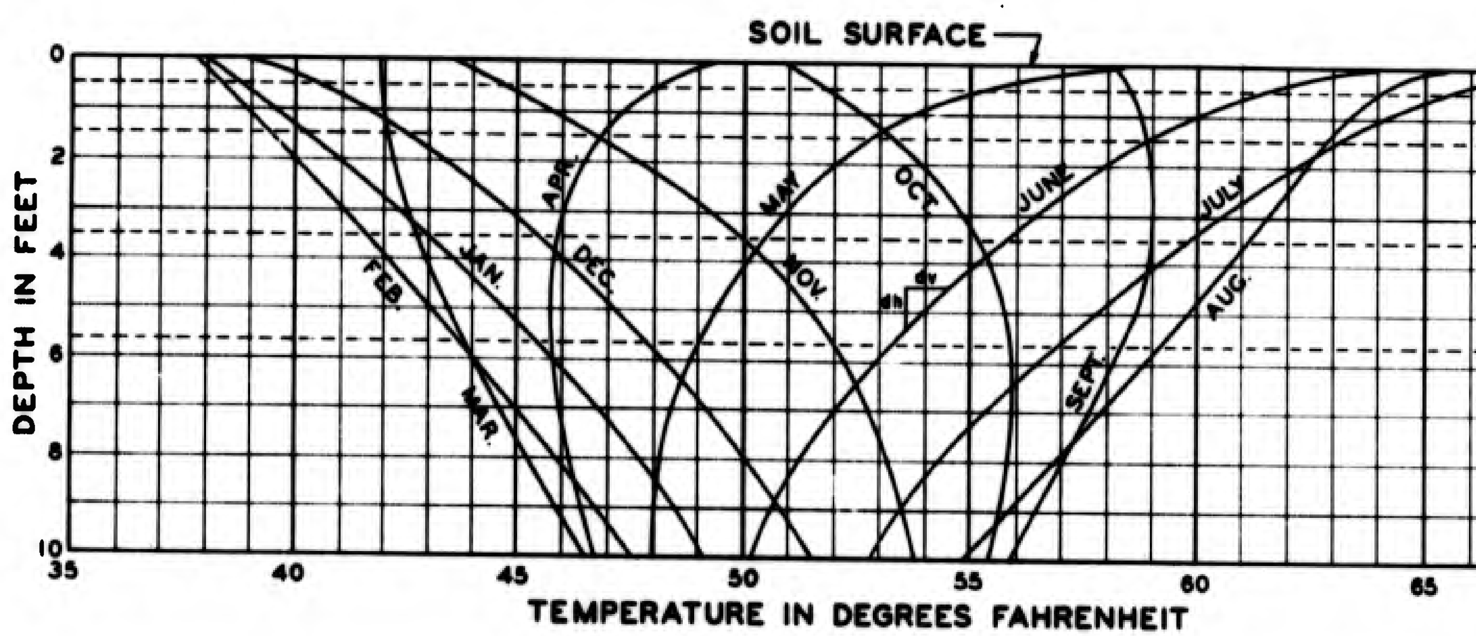
$v_o = 42^o$; $C = 30$; $a = 0.03$ and $L = 2880$; also $d = 1.0$ ft.

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

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

$$= -0.50 + 2.85$$

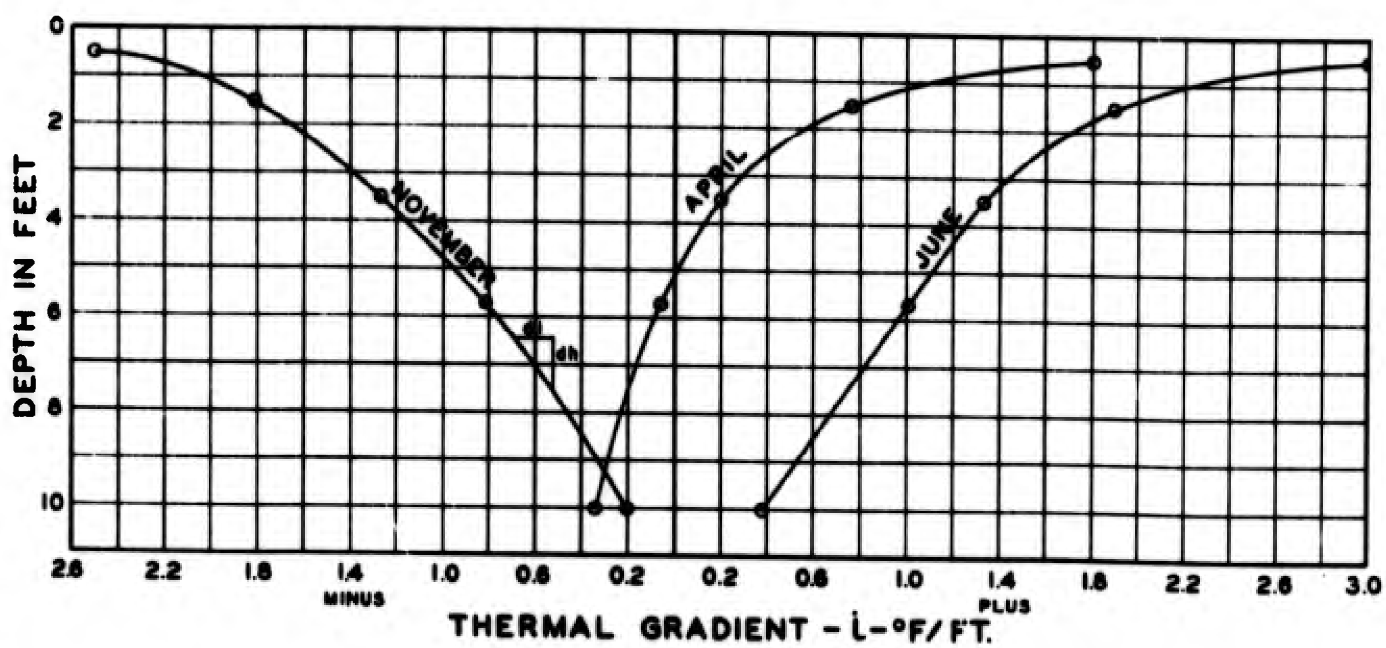
$$= 2.35 \text{ ft.}$$



MONTHLY TEMPERATURE PROFILES FOR A TURFED SOIL

(ADAPTED FROM "RADCLIFFE OBSERVATIONS, RADCLIFFE OBSERVATORY, ENGLAND, 19

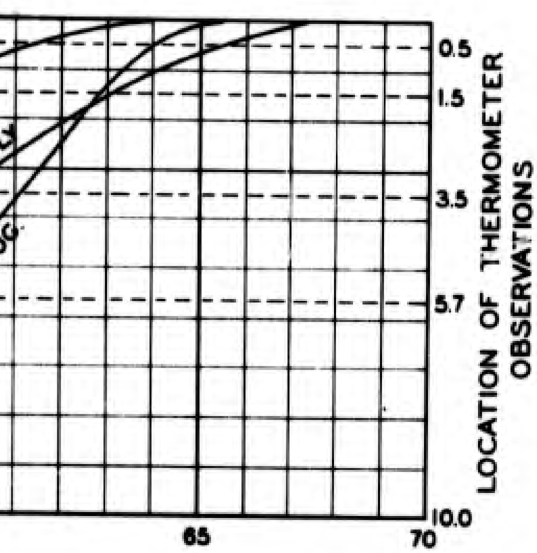
FIG. 1



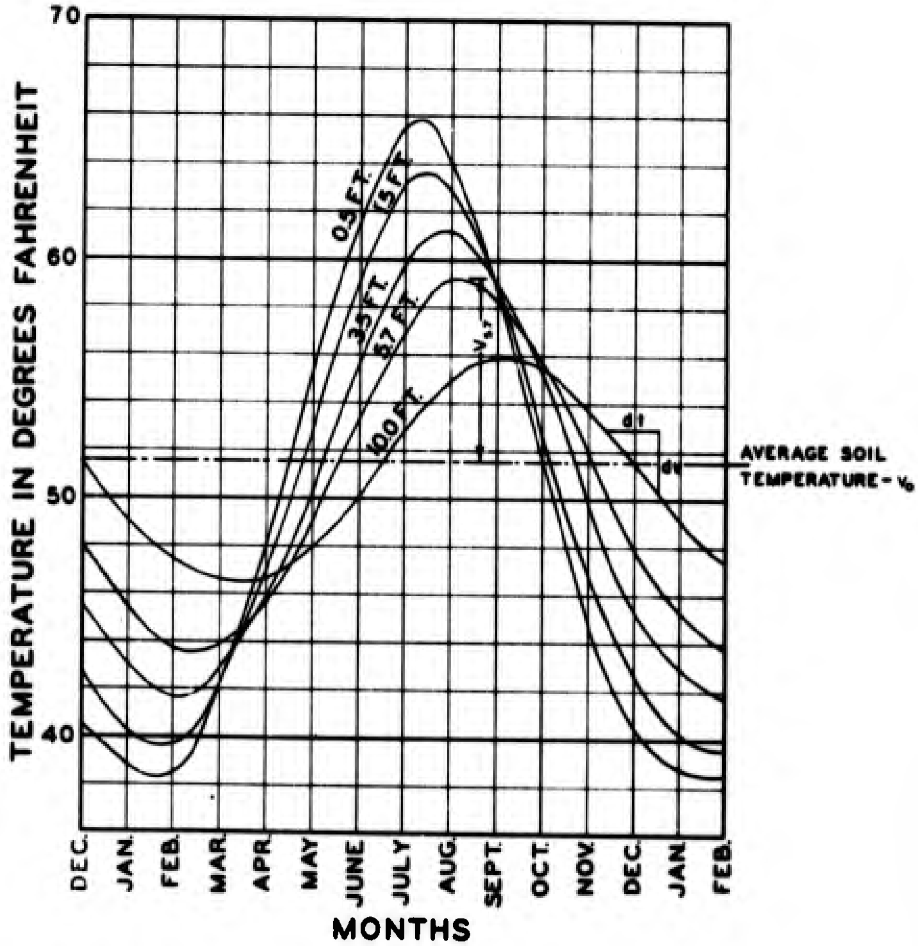
THERMAL GRADIENTS FOR MONTHS OF APRIL, JUNE AND NOVEMBER

FIG. 3

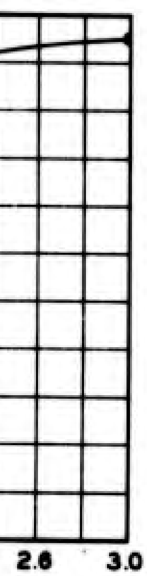
MONTHS



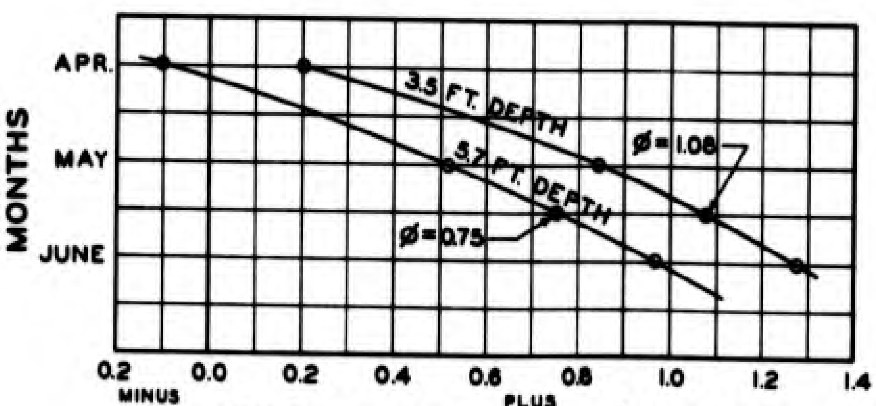
FED SOIL
RY, ENGLAND, 1915")



ANNUAL SOIL TEMPERATURE CURVES
AT DEPTHS OF OBSERVATION
FIG. 2



MBER



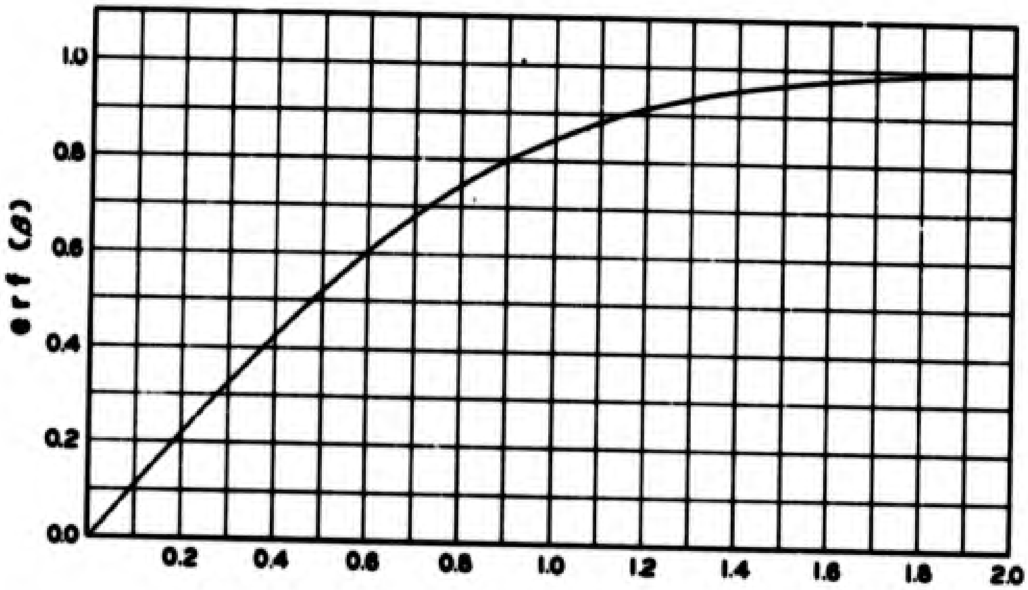
THERMAL GRADIENTS AT 3.5 AND 5.7 FOOT
DEPTHS OF OBSERVATION
FIG. 4

B

FROST INVESTIGATION
1945 - 1946

THERMAL CURVES FOR A TURFED SOIL

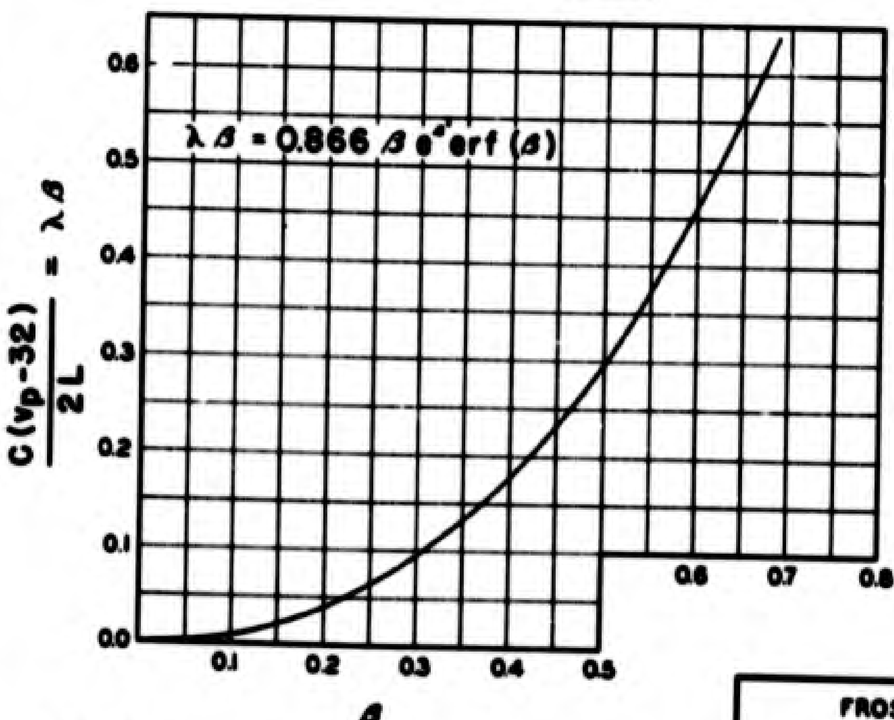
FROST EFFECTS LAB, BOSTON, MASS JUNE 1946



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

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

SUPPLEMENT B

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