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APPROACH ROADS, GREENLAND 1958-59

Robert M. Davis

June 1971

CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
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13. ABSTRACT

Project 1, Approach Roads, Greenland R & D Program, was organized in 1954 to develop methods, techniques and criteria for constructing roads on both glacial ice surfaces and adjacent ice-free terrain. This report covers activities for the years 1958 and 1959, which consisted of construction of additional roads and culverts and an annual assessment of the performance of the various roads and other structures on the ice cap. Special measurements were made of ice surface movement, subsurface temperature and melt-water runoff.

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PREFACE

Project 1, Approach Roads, Greenland Research and Development Program, was organized in 1954 to develop methods, techniques and criteria for constructing roads on both glacial ice surfaces and adjacent ice-free terrain.

In 1954 the project was assigned to the U.S. Army Engineer Research and Development Laboratory (USA ERDL), which requested the U.S. Army Arctic Construction and Frost Effects Laboratory (USA ACFEL) to conduct the program. The first report on the project was prepared by USA ACFEL for USA ERDL.

In 1955 the responsibility of the project was transferred to the U.S. Army Engineer Waterways Experiment Station (USA EWES), which also requested USA ACFEL to conduct the study. The second and third progress reports were prepared by USA ACFEL for USA EWES.

In 1961 the project was assigned to the U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL) and at the same time the functions and personnel of USA ACFEL were transferred to USA CRREL. USA CRREL was responsible for preparing the fourth and fifth reports. This report, the fourth, is the last to be published.

During the years 1954-1961 Mr. H.W. Stevens, USA ACFEL, was assigned as project leader under the direction of Mr K.A. Linell, Chief, USA ACFEL. From 1961 through 1964 Mr. R.M. Davis, Project Leader, USA CRREL, conducted the studies under the general direction of Dr. A. Assur, and later Mr. A.F. Wuori, Chief, Applied Research Branch of the Experimental Engineering Division (Mr. K.A. Linell, Chief).

All technical activities were performed by USA ACFEL and USA EWES personnel. Excellent support was given by military personnel of the U.S. Army Polar Research and Development Center (USA PR&DC) who did the necessary construction and assisted in the field work.

USA EWES was represented by Mr. S.J. Knight and Mr. A.A. Rula of the Army Mobility Research Center. Mr. W.J. Turnbull, Technical Assistant for Soils and Environmental Engineering, and Dr. M.J. Hvorslev, Consultant, Soils Division, of USA EWES provided valuable consulting services, particularly in design of the approach roads. Dr. Keulegan, Consultant, USA EWES, reviewed Appendix C of this report.

Measurements of melt-water flow were made from 9 June-25 August 1958, under the supervision of Mr. C. Brasfield, Hydraulic Technician, USA EWES. He was ably assisted by Messrs. R.M. Davis, A.S. Kormondy, R.T. Milligan, D.C. Boyd, and D. Sanger of USA ACFEL; and SP4 R.J. Fisher, SP4 B.L. Foley, PFC D.L. Garrison, and PFC A.E. Goodhile of USA PR&DC. The author also acknowledges the technical advice and assistance of Dr. Hvorslev and Mr. Rula, USA EWES, and Mr. F.J. Sanger, Special Assistant, USA CRREL.

Mr. Linell, Mr. Sanger and Dr. Hvorslev inspected the 1958 and 1959 field work and made valuable recommendations and suggestions concerning the project. Mr. Stevens and Dr. Hvorslev technically reviewed this report.

Mr. S.D. Wilson, of Shannon and Wilson, Soil Mechanics and Foundations Engineers, Seattle, Washington, prepared Appendix B of this report. Professor R.F. Scott, of the California Institute of Technology, prepared Appendix D.

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CONTENTS

CONTENTS (Cont'd)

ILLUSTRATIONS

CONTENTS (Cont'd)

TABLES

DEFINITIONS

Ablation	The process of removing snow or ice from a glacier or snowfield by melting and evaporation.
Active zone	The top layer of ground subject to annual freezing and thawing.
Average annual temperature	The average of the average daily temperatures for one year.
Average daily temperature	The average of the maximum and minimum temperatures for one day, or the average of several temperature readings taken at equal time intervals during one day, generally hourly.
Berm	A blanket of soil, approximately 1 ft thick, spread over the ice surface and connected to the toe of fill of the road.
Degree-days	The degree-days for any one day equals the difference between the average daily air temperature and 32F. The degree-days are minus when the average daily temperature is below 32F (freezing degree-days) and plus when above (thawing degree-days).
Frost action	A general term for freezing and thawing of moisture in materials and the resultant effects on these materials and on structures of which they are a part or with which they are in contact.
Ice hummock	A mound or hillock caused by an upward pressure within the ice and/or by differential melting.
Ice movement	The motion that exists within the ice of a glacier or ice sheet; also "glacier flow."
Mean annual temperature	The average of the average annual temperatures for several years.
Micrometeorology	The detailed study of the physics of the zone close to and just beneath the earth's surface.
Permafrost	Perennially frozen ground.
Thawing index	The number of degree-days between the lowest and highest points on the cumulative degree-days-time curve for one thaw season. It is used as a measure of the combined duration and magnitude of above-freezing temperatures occurring during any given thawing season. The index determined for air temperatures at 4.5 ft above the ground is commonly designated as the air thawing index, and that determined for temperatures immediately below a surface is known as the surface thawing index.
Thaw season	That period of time during which the average daily temperature is generally above 32F.
Thermal regime	The temperature pattern existing in a body.

APPROACH ROADS, GREENLAND 1958-59

by

Robert M. Davis

INTRODUCTION

Purpose

Project 1, Approach Roads, Department of the Army R&D Program, was begun in 1954 to develop methods, techniques and design criteria for the construction and maintenance of roads on glacial ice and ice-free terrain.

Field investigations were conducted at Camp Tuto, Greenland. The camp was operated by the U.S. Army Polar Research and Development Center (USA PR&DC),* formerly the U.S. Army Engineer Arctic Task Force (USA EATF). Figure 1 shows the location of Camp Tuto at the edge of the Greenland Ice Cap, 14 miles from Thule Air Base. Figure 2 is a detailed map of Camp Tuto and vicinity and shows the locations of all project activities. Figure 2 also shows the location of the edge of the ice cap and other points as of September 1959.

Scope

This report covers the activities of Project 1 for calendar years 1958 and 1959. Since the majority of the work was continuous, reference is frequently made to progress reports for the years 1954, 1955, 1956 and 1957 (USA ACFEL, 1956; USA EWES, 1959, 1963). The majority of the roads on the Tuto Ramp were constructed during 1954, 1955 and 1956. The 1958 and 1959 programs primarily consisted of observing and measuring the performance characteristics of these roads and other structures. Some parts of Project 1 had been completed and new investigations were begun as necessary. Various parts of the investigation required further study so that it was necessary to continue the program for at least one more year. This is one of a series of five reports on the project.

ORGANIZATION AND EQUIPMENT

General

Careful planning in personnel and equipment is necessary for the success of a program in isolated areas such as Camp Tuto. As Project 1 personnel for the 1958-1959 program were not directly responsible for new construction except in an advisory capacity, the number and types of personnel differed from those of the previous years. No new items of equipment were used during the 1958-1959 field seasons.

1958 Personnel

Civilians employed by the U.S. Army Arctic Construction and Frost Effects Laboratory (USA ACFEL)† and the U.S. Army Engineer Waterways Experiment Station (USA EWES) performed all

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* Now U.S. Army Research Support Group (USA RSG).

† USA ACFEL was merged with USA SIPRE in 1961 to form the U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL).

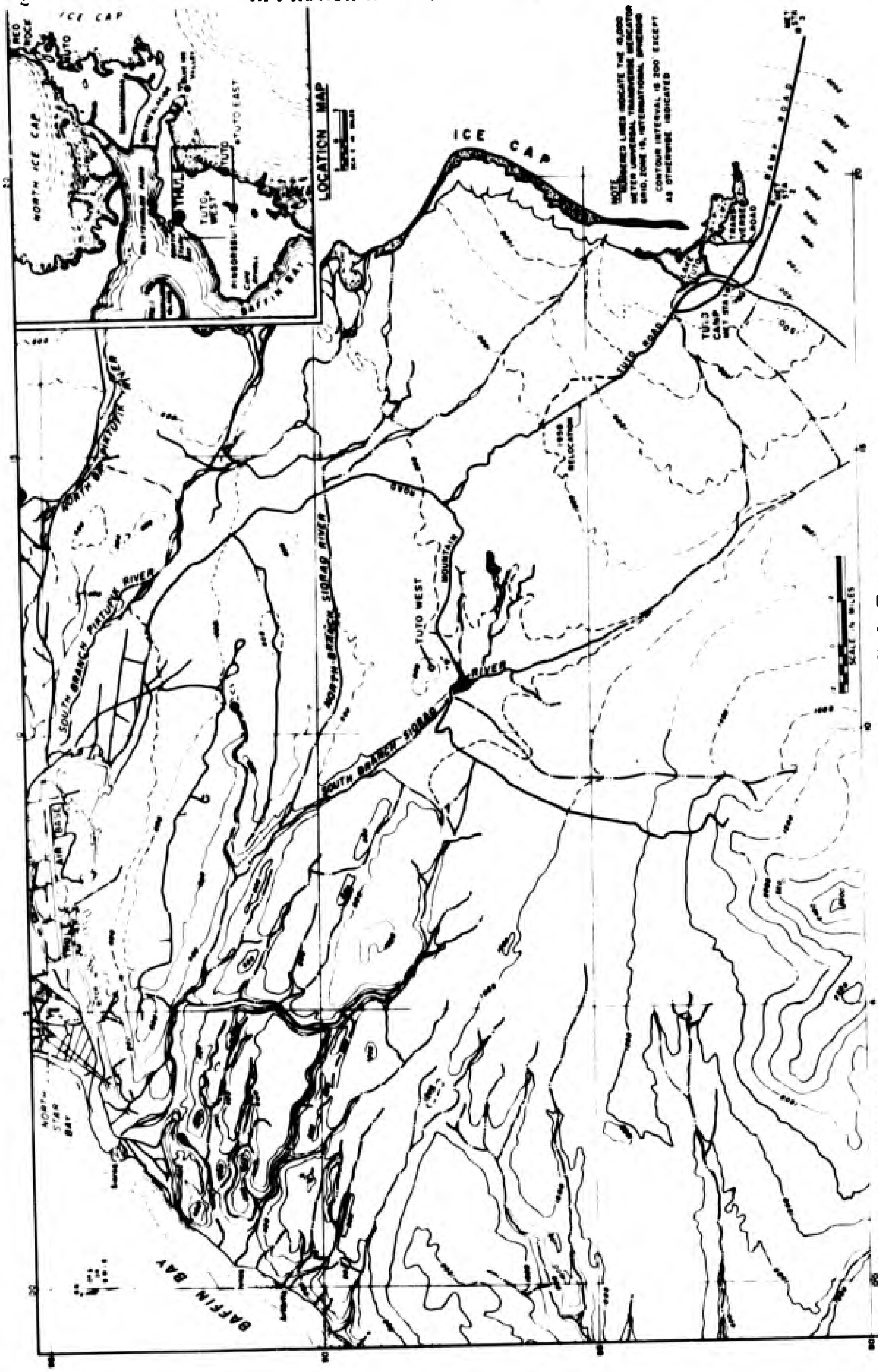

Figure 1. Thule-Tuto area.

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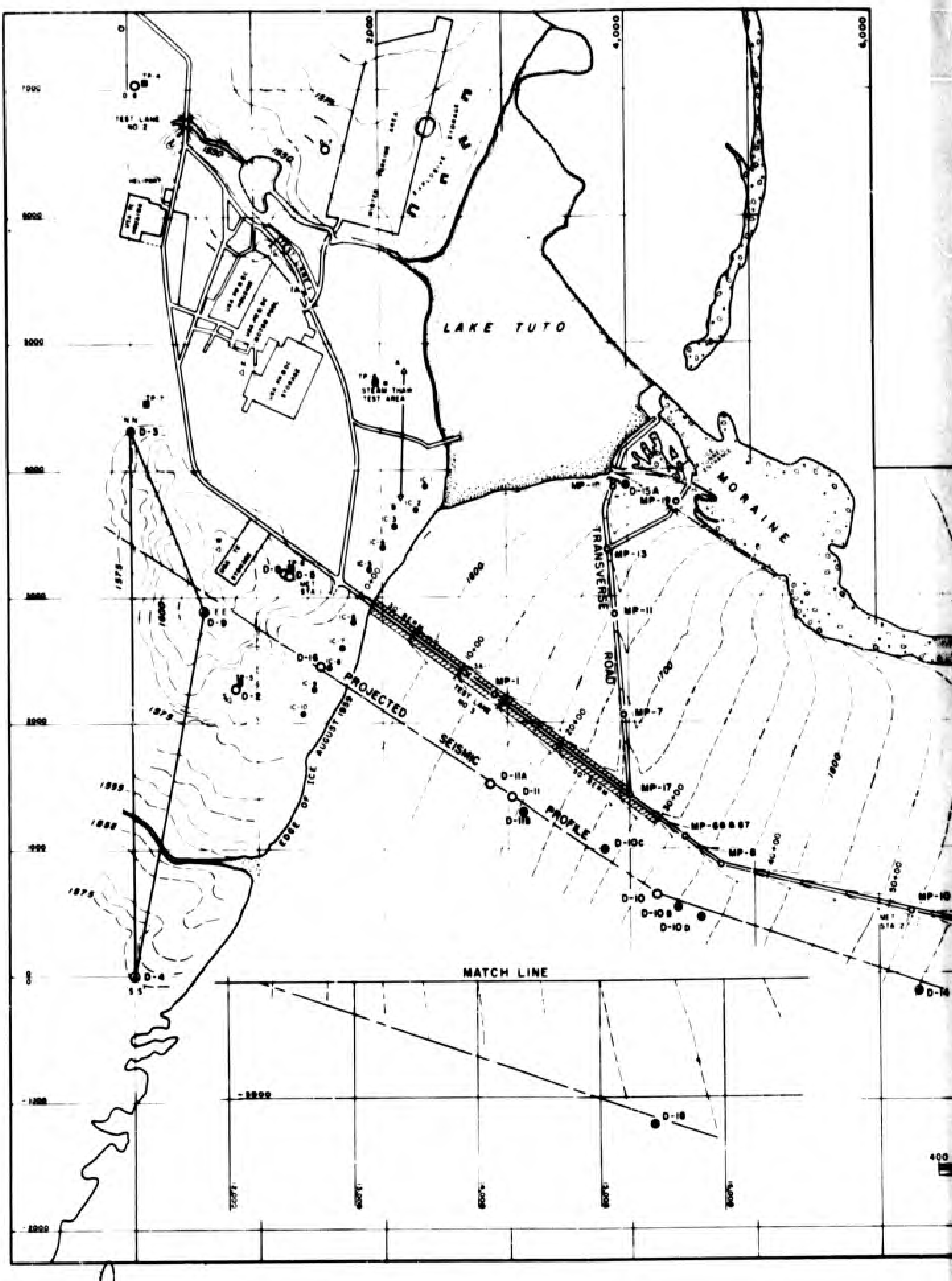
LAKE TUTO
MORAINE
TRANSVERSE ROAD
PROJECTED SEISMIC PROFILE
EDGE OF ICE AUGUST 1959
MATCH LINE
TEST LANE NO 2
TEST LANE NO 3
HELI-PORT
STEAM THAW TEST AREA
D-3
D-4
D-8
D-9
D-2
D-6
D-11
D-11A
D-11B
D-10
D-10B
D-10C
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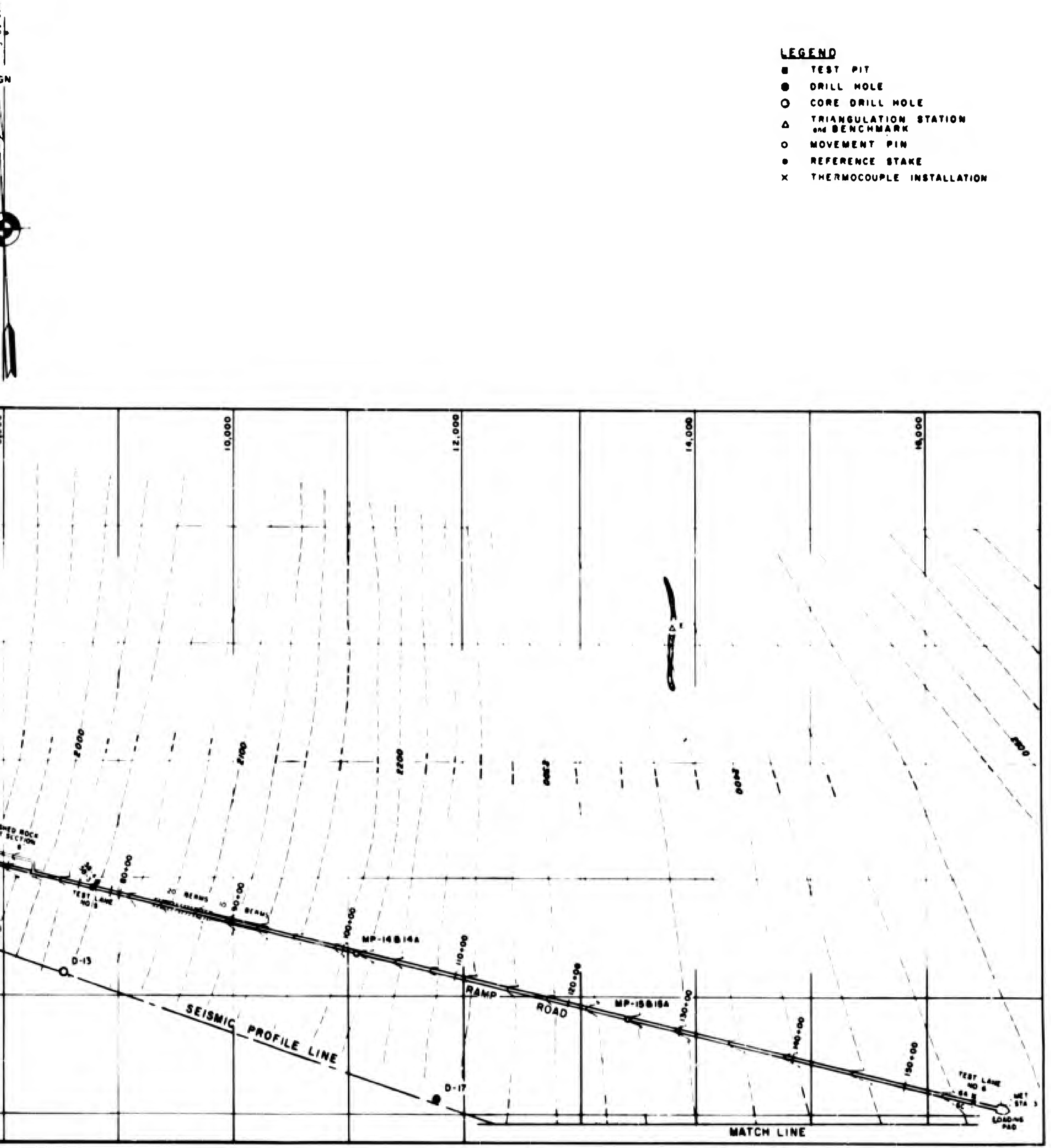

Figure 2. Camp Tuto and Tuto Ramp.

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technical or specialized activities as in the past. All construction and maintenance of roads and equipment were performed by military personnel of the USA PR&DC.

Civilian personnel. The civilian staff of six men were in the field from 1 June to 28 August 1958. In addition to surveying, soil testing, instrumentation reading and other methods of evaluating the performance of the road, they conducted a pilot study of the hydrology of a selected section of the ice cap. They correlated the results of the hydrology survey of the melt water flow with the ablation, air-thawing index and other such factors. They also continued the program of measuring subsurface ice movement with a specially designed inclinometer, which was begun in 1957.

The number and classifications of civilians were well suited for the amount and type of work performed during the field season. A list of civilian members of the project and their classifications is contained in Table AI (App. A).

Military personnel. Since Project 1 was not in charge of construction during 1958, the only military personnel assigned to the project worked directly with the civilian personnel. Some of these men had educational background and technical knowledge equal to those of the civilian staff. A list of the military personnel and their classifications is included in Table AI.

1959 Personnel

Technical and specialized activities were performed by civilians employed by USA ACFEL and USA EWES. Military personnel of USA PR&DC gave support as in the previous years.

As data for the entire season had been measured for the five previous years, it was decided that one set of measurements of the road performance to give an annual value would be sufficient. The data for August 1959 could be correlated with those for August 1958 and provide an annual summary of the surface and subsurface ice movement, ablation and other factors affecting the roads on the ice cap.

Civilian personnel. Three civilians were in the field for the month of August 1959. For this short field season the number of civilians was adequate.

Military personnel. The military personnel assigned to Project 1 by the USA PR&DC were very satisfactory. It was evident that the efficiency of the work was increased by having the same military personnel assigned to the project for more than one season. One of the surveyors in 1959 had been with the project during the preceding two seasons and the other had worked on Project 1 during the field season of 1958.

1958 Equipment

No new equipment was used in 1958, but a further test was made of a trenching machine observed on another project in 1957. The fill was removed from a short section of the Transverse Road and the machine was used to cut a ditch through the ice ridge for installation of a new culvert. The machine was also used to cut holes for the placing of timber piles for the bridge that was constructed in 1958. The instruments used in the hydrology survey were of the same type as used in temperate zones and did not require any adaptation for use on the ice cap. A description of the hydrology instrumentation is contained in Appendix C.

1959 Equipment

During the short period of the 1959 field season, no new items of equipment were used on Project 1.

Summary

1958 program. Since Project 1 was not directly in charge of new construction in 1958, fewer personnel were required than during the previous years.

A ladder trenching machine was useful in cutting trenches on relatively smooth ice. This machine would require extensive modification, however, for use on a rough ice surface. It was also useful in excavating holes in ice for placing piles or timbers to a maximum depth of 8 ft.

1959 program. One set of measurements of the road performance was made in August 1959. Data were available for the entire thaw seasons of the previous five years so that the short-term effect of the various factors on the road perfomance could be analyzed. Starting in 1959, one set of measurements was made during the field season to evaluate the roads annually.

CLIMATE

General

An important factor in the design, construction, and maintenance of a road on glacier ice is the climate of the area. The study of the weather pattern of Camp Tuto and the Tuto Ramp begun in 1956 by the Meteorological Branch of the U.S. Army Signal Corps was continued in 1958 and 1959. The data were reduced and tabulated by the National Weather Records Center, Asheville, North Carolina, which furnished tabulations to the various agencies.

The weather data were used by USA ACFEL in the study of depth and rate of thaw and freeze penetration and as a record of the weather for the field seasons. A graphic summary of the weather data for 1958 and 1959 is contained in Figure A1 to A4 (App. A). Table I gives a comparison of the thaw seasons from 1954 to 1959.

1958 weather

The three stations established in 1956 were operated in 1958. The locations of these stations are shown on Figure 2. The personnel and equipment were satisfactory and a complete set of data for the thaw season was obtained.

The thaw season during 1958 approached an average air-thawing index for the period of record starting with 1954. The average ATI for Station 1 at Camp Tuto is 479; the ATI in 1958 was 494. The same relationship also holds for the other two stations in the area.

The average daily wind speed for the 1958 thawing season was 8.7 mph. The highest daily wind speed was 30 mph. As usual at Camp Tuto, high winds were accompanied by rain, fog and snow.

The snow cover at the beginning of the season was 31.5 in. deep at a point 200 ft south of Ramp Road Station 13+00 on 16 June. By 26 June the snow had melted, exposing the bare ice.

1959 weather

Meteorological Station 2, located beside the Ramp Road, one mile from the edge of the ice cap, was discontinued in 1959. The station on the ice-free land (Station 1) and the station at the end of the Ramp Road (Station 3) furnished data for the entire thaw season.

The 1959 thaw season was very close to that of 1958. The ATI at Camp Tuto was 490 in 1959 and 494 in 1958.

The occurrence of days with average daily wind speed over 15 mph was more frequent in 1959 than in 1958 but the highest daily wind speed was 24 mph. The occurrence of rain, fog and snow was also more frequent, corresponding to the wind pattern.

Table I. Comparison of thaw seasons.

Year	*Start of thaw*	*End of thaw*	*Duration (days)*	*ATI (deg-days F)*	*Avg daily temp (°F)*
Thule Air Base					
1954	29 May	13 Sept	107	779	39.3
1955	4 June	2 Sept	91	688	39.6
1956	15 June	11 Sept	89	747	40.4
1957	11 May	23 Sept	126	1217	41.7
1958	23 May	27 Aug	97	717	39.4
1959	1 June	14 Sept	106	714	38.7
Avg	29 May	10 Sept	103	810	39.8
Station 1 – Camp Tuto					
1954	22 June	28 Aug	68	508	39.5
1955	7 June	23 Aug	78	397	37.1
1956	16 June	19 Aug	65	380	37.8
1957	8 June	31 Aug*	85	606	39.1
1958	7 June	24 Aug	79	494	38.2
1959	1 June	29 Aug	90	490	37.4
Avg	10 June	26 Aug	78	479	38.2
Station 2 – Mile 1†					
1954	28 June	28 Aug	62	258	36.2
1955	17 June	15 Aug	60	108	33.8
1956	20 June	18 Aug	60	238	36.0
1957	8 June	27 Aug	81	427	37.3
1958	7 June	13 Aug	68	248	35.7
Avg	16 June	20 Aug	66	256	35.8
Station 3 – Mile 3					
1956	26 June 28 June	10 July 12 Aug**	30	72	34.4
1957	8 June	19 Aug	73	294	36.0
1958	22 June	11 Aug	51	112	34.2
1959	25 June	4 Aug	38	152	36.0
Avg	20 June	12 Aug	48	158	35.2

* Measurements at Station 1 were discontinued on 31 August 1957. The total ATI is not known.

† Station 2 was not occupied in 1959.

** The 1956 thawing index at Station 3 includes the sum of degree-days of thaw for two periods of 15 days each. The algebraic total of degree-days of thaw, for the entire summer, was minus. The actual average air temperature from 26 June to 12 August was 30.5F.

On 20 May 1959 the first mile of the Tuto Ramp was almost completely bare of snow. The snow cover over the entire ramp was much thinner than in the previous years.

Climate at Camp Tuto

At the end of the 1959 field season, 6 years of weather data were available for Camp Tuto and vicinity. Based on these records, it was possible to outline an "average" thawing season at Camp Tuto and to compare the different thaw seasons and their effects on the road.

Average thawing season. Table I shows that an average thawing season at Camp Tuto would begin on 10 June and last until 26 August for a total of 78 days. The ATI would be 479F with an average daily air temperature of 38.2F. In scheduling operations at this site consideration must be given to the fact that the beginning and duration of the thaw season may vary from the average by several weeks and the ATI by 25%.

Comparison of thaw seasons. The "ATI" is a convenient method for comparing thaw seasons for different years in the same area or for different areas. The ATI is based on the average daily air temperature and the number of days it is above freezing.

Table I shows that the ATI at Station 1, Camp Tuto, varied from 380 in 1956 to 606 in 1957. The figure for 1957 should undoubtedly be higher. Since this station was closed down on 31 August while degree-days were still accumulating the total ATI and the duration of the thaw season are not known.

The effect of a small variation in the average daily temperature and the duration of the season on the ATI can be seen in 1957. At Camp Tuto, with the thaw season only 7 days longer than average and the average daily temperature 0.9F higher, the ATI was 127% of the average. In an area such as the Tuto Ramp this increase in the ATI can be important, as shown on the ice ablation cross sections (Fig. 14) in the section on Performance of Past Construction. These sections indicate that the ablation of the ice beside the road is proportional to the ATI. An exception to this is the 1959 season, during which the combination of a long thawing season (90 days) and a thin snow cover at the beginning of the season resulted in excessive ablation.

The effect of the amount of snow on the surface of the ice at the beginning of the season on the total ablation during the summer is very important. With a heavy snow cover at the beginning of the season part of the available heat is used to melt the snow, while with a thin or non-existent snow cover ablation of the ice begins as soon as the air temperature goes above freezing.

Work days lost due to weather

In 1958 and 1959 the work of Project 1 was limited to observation and measurement of the roads. No records were kept on the number of days of construction work lost since only a small amount of this type of work was done. The accomplishment of surveying activities, such as leveling and triangulation, was difficult to impossible on 14 days during the 1958 field season. Wind, rain, fog, and blowing snow were responsible for the time lost.

During the field season of 1959 (1 month), 4 days were lost by the survey crew. There was no road construction during the 1959 season.

As road construction can continue in all but extreme weather, it is likely that about 7 days would have been lost in both 1958 and 1959. The scheduling of project work in Greenland must be flexible enough to allow for the loss of several days due to weather.

Summary

Six years of weather data were taken at Camp Tuto, and based on the averages of the past years a general prediction of the thaw season could be made. The thaw season should start on 10 June and last until 26 August, for a total thaw season of 78 days. The ATI should be approximately 480. Table I shows that the start and duration of the thaw season can vary by several weeks and the ATI by as much as 25%.

The schedule for a project in Greenland must allow for the loss of a certain number of days due to weather conditions. Construction work can continue in all but the worst weather; usually 6 to 10 days may be lost in a season. The loss of time in other activities, such as surveying, may be twice as much (12 to 20 days) in a season.

NEW CONSTRUCTION

General

The majority of the gravel fill roads on the Tuto Ramp were constructed in 1954, 1955 and 1956. In 1958 the location of the ice tunnel was changed to a higher elevation which required an access road. Project 1 personnel were not directly responsible for the construction but furnished advice and assistance to the U.S. Army Polar Research and Development Center. When the site for the tunnel was selected, several alternate routes were studied. It was decided that a route leading from MP-13 on the Transverse Road (Fig. 2) in a northwest direction to the tunnel site was the most feasible. There was no road construction in 1959.

Road design

A profile of the centerline and cross sections at 100-ft intervals were made at the same time the depth of snow was measured. The snow depth in the area was from 2 to [illegible] ft; it was removed before construction began (Fig. 3) as it had been demonstrated that fill should not be placed on snow over 1 ft deep (USA EWES, 1963). After the snow was removed and immediately before construction was started a second profile was made and the cross sections were repeated.

Based on the performance of the Transverse Road, it was decided that a 3-ft minimum depth of fill was required in this area to prevent ablation of the ice beneath the road. This was composed of 2½ ft of coarse fill with a 6-in. layer of finer surfacing material (Fig. 4). The depth of fill varied with the terrain but was never less than 3 ft. The depth was checked by taking a profile on top of the fill and comparing it with the original profile of the ice surface.

A channel that crossed the centerline at Station 6+35 drained a considerable area of the Tuto Ramp. To carry the volume of water, a large-diameter culvert and a high fill section would be required. It was decided to erect a bridge across the channel.

To maintain the desired grade a cut was required through a small ice ridge on the centerline. Although cuts in ice should be avoided, it would have required a large amount of fill to maintain the grade without a cut section. As the design called for a sidehill cut, there was no danger of the section's being filled with snow.

Bridge design

A bridge span of 24 ft was required for the size of the channel at Station 6+35. Two crib-type abutments supporting three lengths of U.S. Army Treadway prefabricated bridging with a clear span of 24 ft would support all vehicles that would use the bridge. Figure 5 shows the construction details of the bridge and the erosion of the ice beneath the span. Wings were added on each side to prevent slumping of the fill. For the amount of traffic, a one-lane bridge was sufficient.

The design of the new bridge was based on observations of the pile-bent bridge that was constructed in 1956 (USA EWES). A bridge on glacier ice should have as wide a span as possible based on safety requirements, with the stream channel placed in the center of the span. This allows maximum time before erosion undermines the abutments.

Road construction

The road was constructed in the same manner as the previous roads on the Tuto Ramp. The borrow material was scraped up by bulldozers, and stockpiled, and loaded into dump trucks by power shovels. The material was end dumped by the trucks and spread and compacted by bulldozers. The same type of heavy, highly-permeable, base course fill was used as in the earlier construction. The coarse fill was obtained from Borrow Pit "L" (USA EWES, 1963). The material used for surfacing was obtained from Borrow Pit "K" which was also used in 1956 (USA EWES, 1963).

Figure 3. Snow removal along centerline of new Ice Tunnel Road. 5 June 1958.

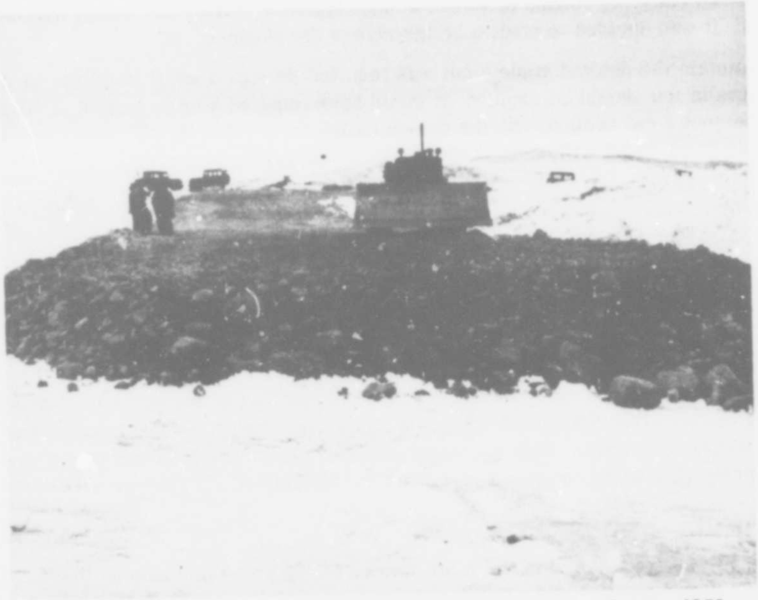
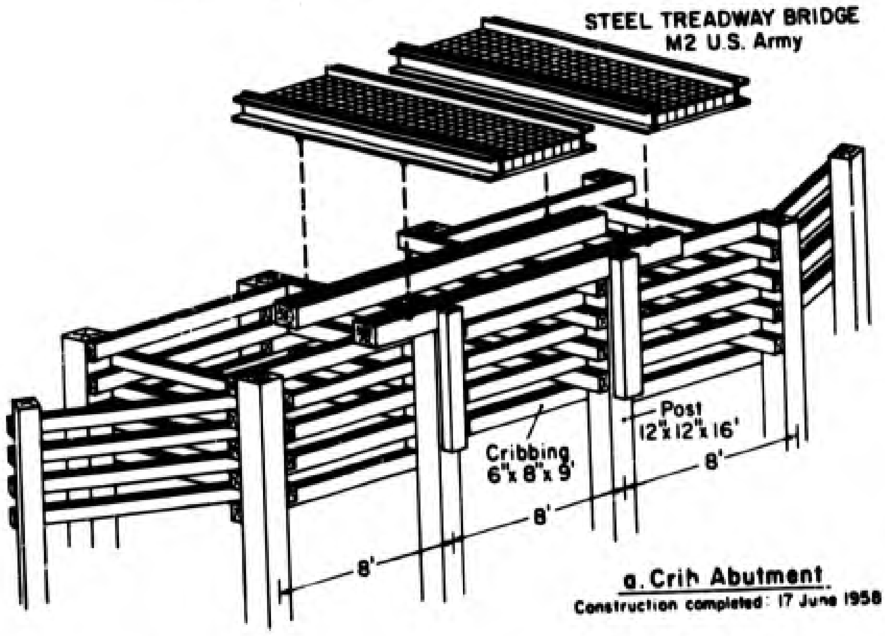
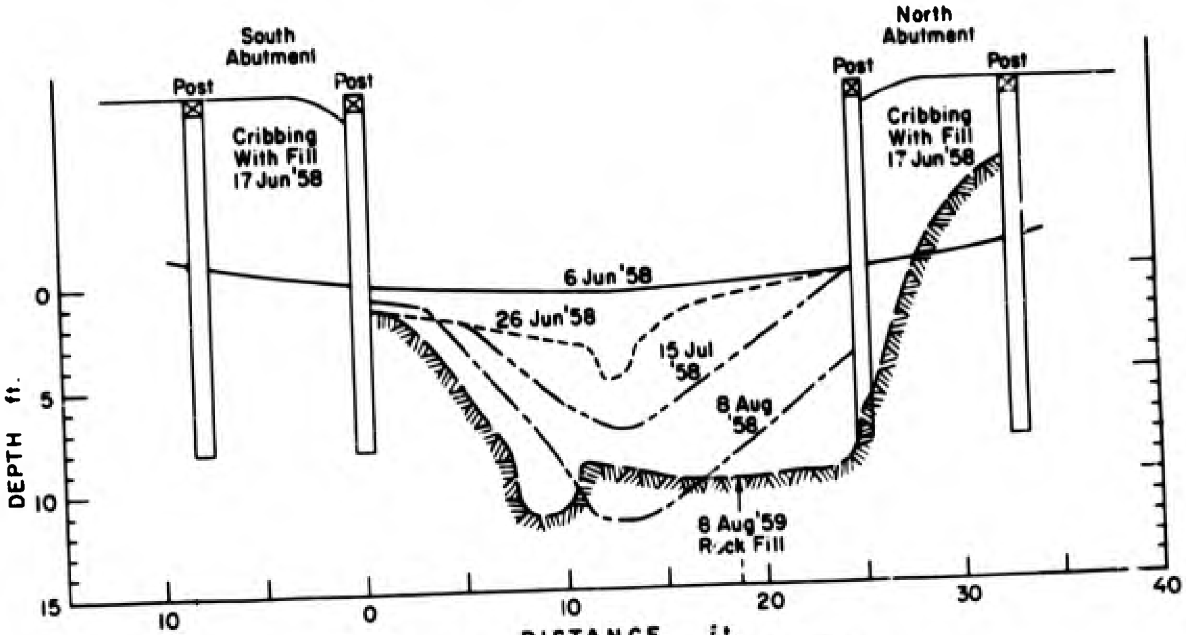


Figure 4. Fill being placed along new Ice Tunnel Road, 7 June 1958.



a. Crib Abutment
Construction completed: 17 June 1958



b. Ice surface profile showing erosion

Figure 5. Crib abutment bridge.

The road was constructed with a cross section of 30 ft and side slopes of 1:1½. This was the same design that had been used in all previous road construction on the ramp. Figure 6 shows that the depth of fill was usually in excess of 3 ft to maintain the desired grade. Turn-arounds were constructed at Stations 6+60 and 7+00 on the north side of the road to aid in road construction. These were not designed to serve as so-called "dikes." In this area, with steep slopes leading in to the road on the south and away from the road on the north, "dikes" would not be effective.

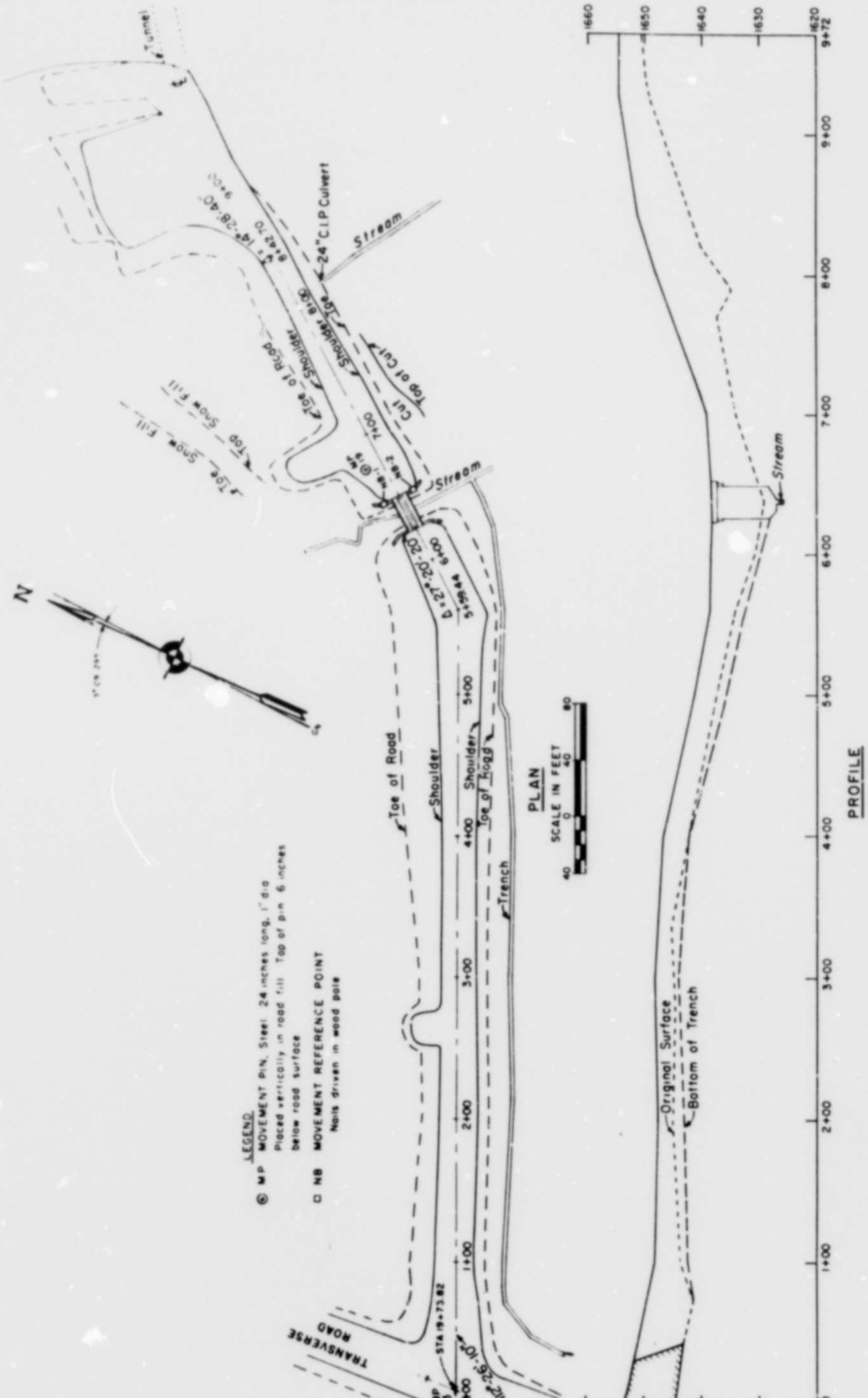


Figure 6. Plan and profile of Tunnel Road.

Figure 7. Construction of timber cribs on new bridge, 14 June 1958.

Exact records were not kept on the amount of yardage, equipment or personnel but observations indicate that the work output was approximately the same as in 1956 (USA EWES, 1963). The same types and numbers of items of equipment, such as trucks and bulldozers, were used. Approximately 5680 yd^3 of material were used to build the road and to build a pad in front of the tunnel entrance.

Bridge construction

Work was started on the bridge at Station 6+35 immediately after road construction began. A ladder-type trencher was used to excavate holes for the placing of the timbers which were used as uprights for the crib. The timbers were placed in the holes and aligned and slush and water were placed around them as backfill. As the work was done in early June, the timbers froze in place in about 24 hr. The timbers were 12 in. × 12 in. × 16 ft and were placed in the ice to a depth of 8 ft. Figure 5 shows that the Treadways were supported by four timbers. The capacity of each abutment was ample to support any vehicle that would use the bridge.

As soon as the piles were frozen in place, cribs composed of 6 in. × 8 in. × 9 ft timbers were nailed in place (Fig. 7). After both cribs were built, the one on the southern end of the bridge was loaded with coarse fill and the Treadways were placed in position. The crib on the northern end of the bridge was filled by end dumping from the bridge and road construction was continued to the tunnel entrance.

The Treadways were placed on the abutments at a spacing of 84 in. from centerline to centerline. This permitted all of the vehicles in use at Camp Tuto to cross the bridge with the exception of the M-29 Weasel.

Cut section construction

A cut was made through a small ice ridge that crossed the centerline of the road approximately at Station 6+90 to 7+60. After the snow was removed by bulldozers, the ice was shattered by a

Figure 8. Cut section on new Ice Tunnel Road, 17 June 1958.

charge of dynamite exploded in a small hole drilled in the ice, and the ice was bulldozed aside. The cut was designed to allow a full depth of fill and still maintain the desired grade (Fig. 8).

Special procedures are necessary in the use of explosives in ice. Only a small number of charges, usually 4 to 8, should be placed at one time, and they should be fired immediately after they are placed. This precaution is necessary because the amount of water present either causes the charges to become damp and not fire or interferes with the electrical connections. Black powder has a better shattering effect than dynamite but is more susceptible to moisture. Experience has also shown that ice should be removed in relatively thin (1- to 2-ft) layers, instead of blasting the entire depth of cut at one time.

Culvert construction

With the failure of all the culverts along the Transverse Road, due to perching, a considerable section of the ramp was drained under the new bridge. In an effort to divert some of the water, a culvert was constructed at Station 14+18 on the Transverse Road. This site was selected because two melt streams intersected at this point and a large amount of melt water would be drained through the road fill.

The culvert, of the cut-and-cover type, was constructed by removing the fill from a section of the Transverse Road and cutting a trench through the ice with the trenching machine (Fig. 9). The trench was covered by 2-in. × 6-in. × 6-ft planks and a layer of 1-in. boards. The fill was replaced and the road opened to traffic. Canvas curtains were hung over each end to shade the ice walls of the trench.

Performance of 1958 construction

Tunnel access road. The failure of all the culverts on the Transverse Road caused a large amount of melt water to flow along the south side of the road, resulting in erosion, slumping and

Figure 9. Ladder-type trenching machine cutting through ice ridge on Transverse Road, 24 June 1958.

abnormal perching. Figure 10 shows a comparison of the cross sections at each station along the road in June 1958 and August 1959. The extremely rapid ablation at Stations 5+00 and 6+00, on the north side, is due to erosion by the melt water. Additional fill was added along the south side of the road in August 1958. The road remained serviceable throughout 1959 without repairs.

Bridge. There was a larger amount of melt water beneath the bridge than expected. Profiles along the centerline of the ice beneath the bridge are shown on Figure 5. Melt-water erosion rapidly undermined the cribs and twice during the 1958 field season additional fill was added to the cribs. At the end of the 1958 season two large culverts composed of oil drums welded end to end were placed in the channel and covered with coarse fill.

In 1959 the culverts beneath the bridge functioned during the beginning of the melt season but by the first week in July the fill was eroded away and the culverts washed down the channel. Fill was added to the cribs three times in 1959 and at the end of the season coarse fill was placed in the channel to the level of the Treadways.

Cut section. No problems resulted from the cut section. The exposed ice along the side melted rapidly; by the end of the 1958 season the ice was level with the road surface and by the end of the 1959 season, it was below the road surface (Fig. 11).

Cut-and-cover culvert. The culvert was finished on 25 July and the largest amount of melt-water flow measured was 18 ft^3/sec on 5 July. Excessive erosion at both ends of the culvert resulted in narrowing of the Transverse Road. As a safety measure, the culvert was filled in and fill placed along both sides of the road. By the time the culvert was filled in the ice on the uphill side had melted below the elevation of the bottom of the trench so that melt water was bypassing the culvert (Fig. 12).

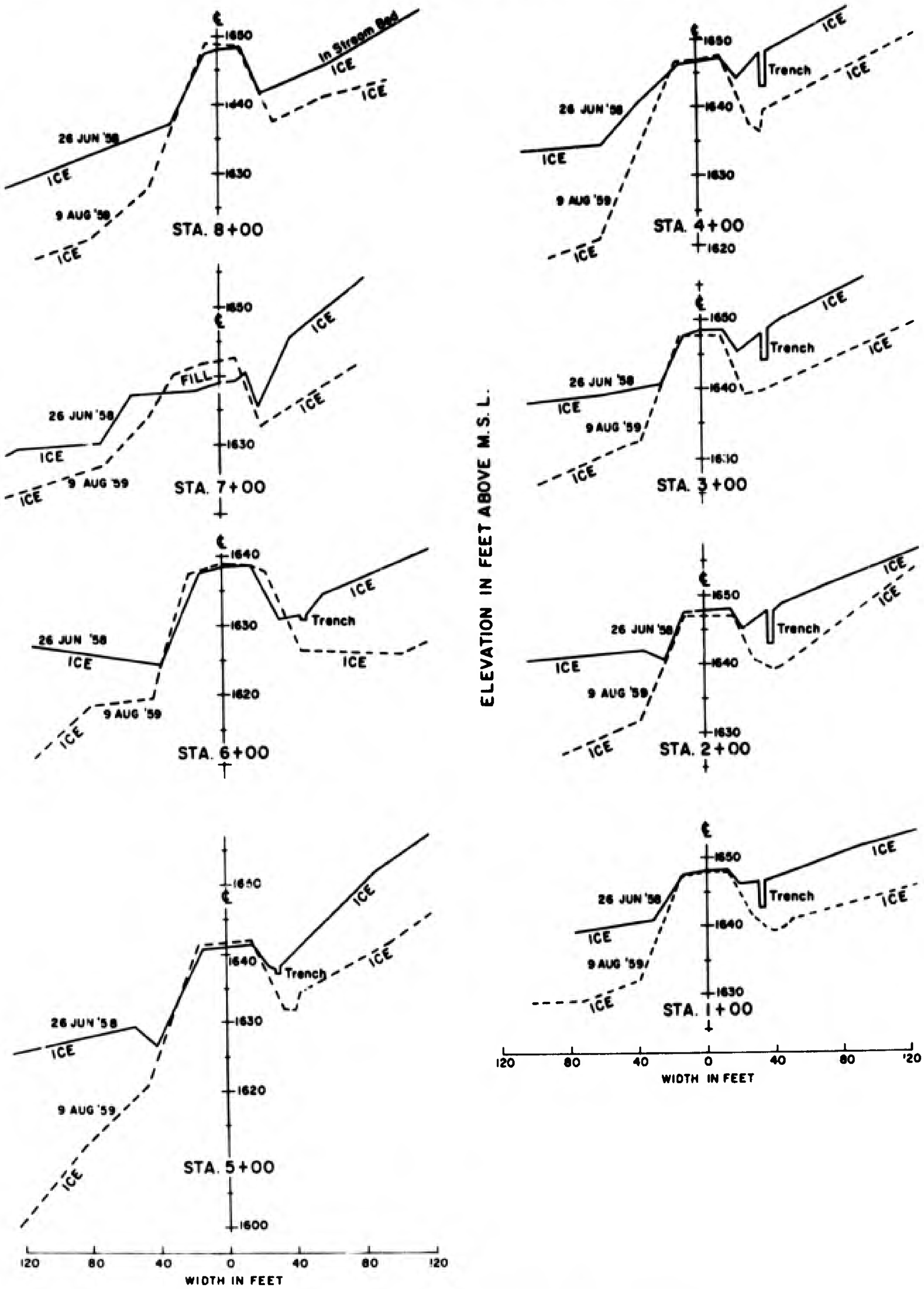


Figure 10. Cross sections of Ice Tunnel Road, 1958 and 1959.

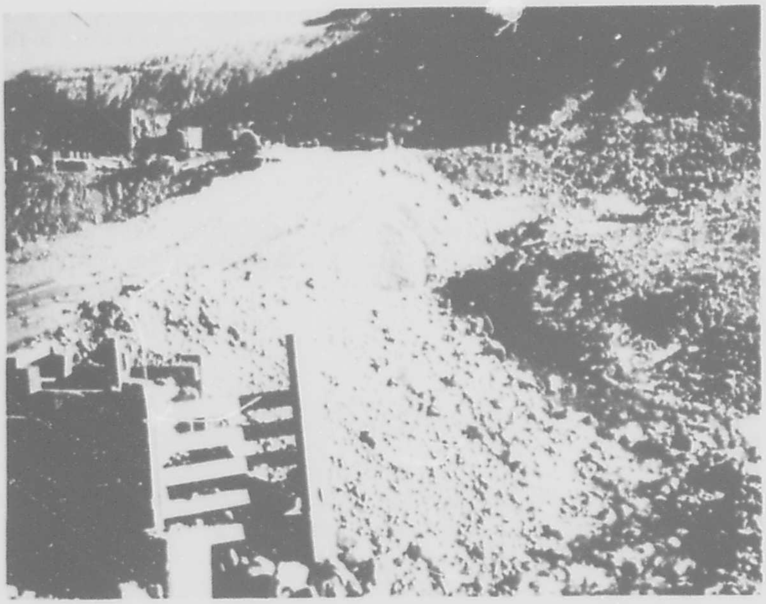


Figure 11. Cut section on Ice Tunnel Road at end of 1959 thaw season, 13 August 1959.

NOT REPRODUCIBLE

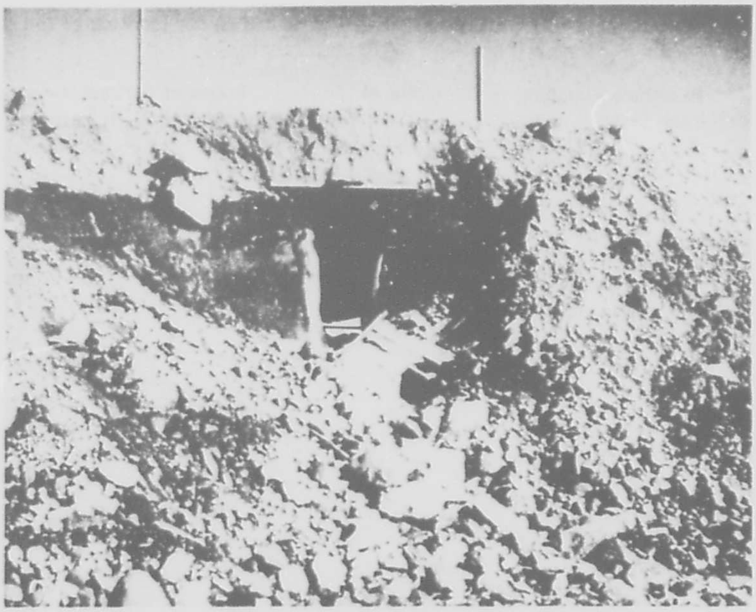


Figure 12. East end of culvert C-12, 24 July 1958.

Summary

1. In 1958 a 900-ft section of gravel fill road was constructed on the ice cap to furnish access to the new location of the ice tunnel. The same design and methods of construction were used as in the previous roads built on the Tuto Ramp.

2. The road design included a crib abutment bridge using U.S. Army Treadway prefabricated bridging and a sidehill cut. This was the only cut section used on any road built on the Tuto Ramp.

3. A cut-and-cover culvert in the Transverse Road worked satisfactorily for part of the season. By the end of the summer, however, the ice had melted below the elevation of the bottom of the trench so that the melt water was bypassing the culvert.

4. All new construction was performing satisfactorily at the end of the 1959 thaw season.

PERFORMANCE OF PAST CONSTRUCTION

General

The gravel fill roads on the Tuto Ramp were constructed in 1954, 1955 and 1956. In 1957 road construction was limited to an experimental section of crushed rock and in 1958 a 900-ft access road was built to the location of the new ice tunnel (see New Construction, p. 7). No new construction was done in 1959. The preceding reports (USA ACFEL, 1956, USA EWES, 1959, 1963) on the project describe the construction details of the various roads and structures on the ramp.

In 1954 the Ramp Road was constructed to a point 4800 ft from the edge of the ice (Fig. 2). In 1955 the road was extended 4900 ft and an experimental section 800 ft long was constructed at an angle to the melt-water flow (Transverse Road). In 1956 the Ramp Road was completed to Mile 3 (Station 159+17) and the Transverse Road was extended to the location of the original ice tunnel (Station 33+75).

In an effort to reduce slumping of the sides of the roads, berms of various widths were placed along the Ramp Road in 1956 and 1957. In 1956 a pile-bent bridge was built across a large melt-water channel that crossed the Transverse Road. An experimental road section consisting of crushed rock placed on the ice in 6- or 12-in. layers was built in 1957.

An experimental road section consisting of crushed rock placed on the ice in 6- or 12-in. layers was built in 1957.

Various types and sizes of culverts were placed in the Transverse Road to determine the most suitable type for use on the ice cap.

Ramp Road

The lower section of the Ramp Road had been in place 5 years and was perched up to 40 ft above the ice (Fig. 13). This resulted in a narrowing of the road surface to such an extent that the road would become dangerous for traffic in a few years. The progressive ablation of the exposed ice and its effect on the road at four points is shown in Figure 14. The ablation of the ice reached a peak at the beginning of the road, decreased toward the end, and varied from the north to the south side. The ablation was increased by dust blown from the surface of the road and by the melt-water streams that usually flow along the toe of the road fill.

The perching and, consequently, the slumping of the fill was increased by an upthrusting of the ice beneath the road at several points. The upthrusting occurred along a band, the center of which crossed the road approximately at Station 33+00. This band resulted in hummocks but as

Figure 13. South side of Ramp Road, Station 4+00, 27 August 1959.

the ablation exceeded the upthrust, this was not apparent except where the ice was insulated by the road fill. Above this area the road surface was gradually lowered by the outward flow of the ice. This resulted in a steepening of the slope from Station 0+00 to approximately Station 33+00 and a flattening of the slope from there to the end of the road. This refers only to the road as the ablation resulted in a steeper slope of the exposed ice from the edge of the glacier to the end of the road.

The road surface was rough and uneven. This was caused, in part, by some melting of the ice beneath the road; e.g. calculations show that in 1957 0.1 to 0.2 ft of ice melted beneath the road fill (USA EWES, 1963). An additional cause was the practice of scraping the road periodically. This removed the fines from the surface and exposed the coarse fill.

Extensive repairs were required to restore the road to its original condition. At the end of the 1959 field season the road had narrowed to 18 ft in some places. A large amount of fill would be needed to rebuild the road to the design width of 30 ft. In addition, the entire road needed resurfacing.

Based on the amount of material required to repair the road it was decided at the end of the 1959 season to abandon the original Ramp Road above the intersection of the Transverse Road and to construct a new road in a different location in 1960. At the end of the 1959 season profiles and cross sections were made in the area south of the present location to select the site for the new road.

Transverse Road

This section of road was constructed to furnish access to the original ice tunnel and to investigate the effect of a gravel fill road at an angle to the drainage pattern. Various sizes and types of culverts were placed in the road fill at the time of construction but due to perching of the road above the ice all became ineffective. Since the road fill serves as a dam, a large

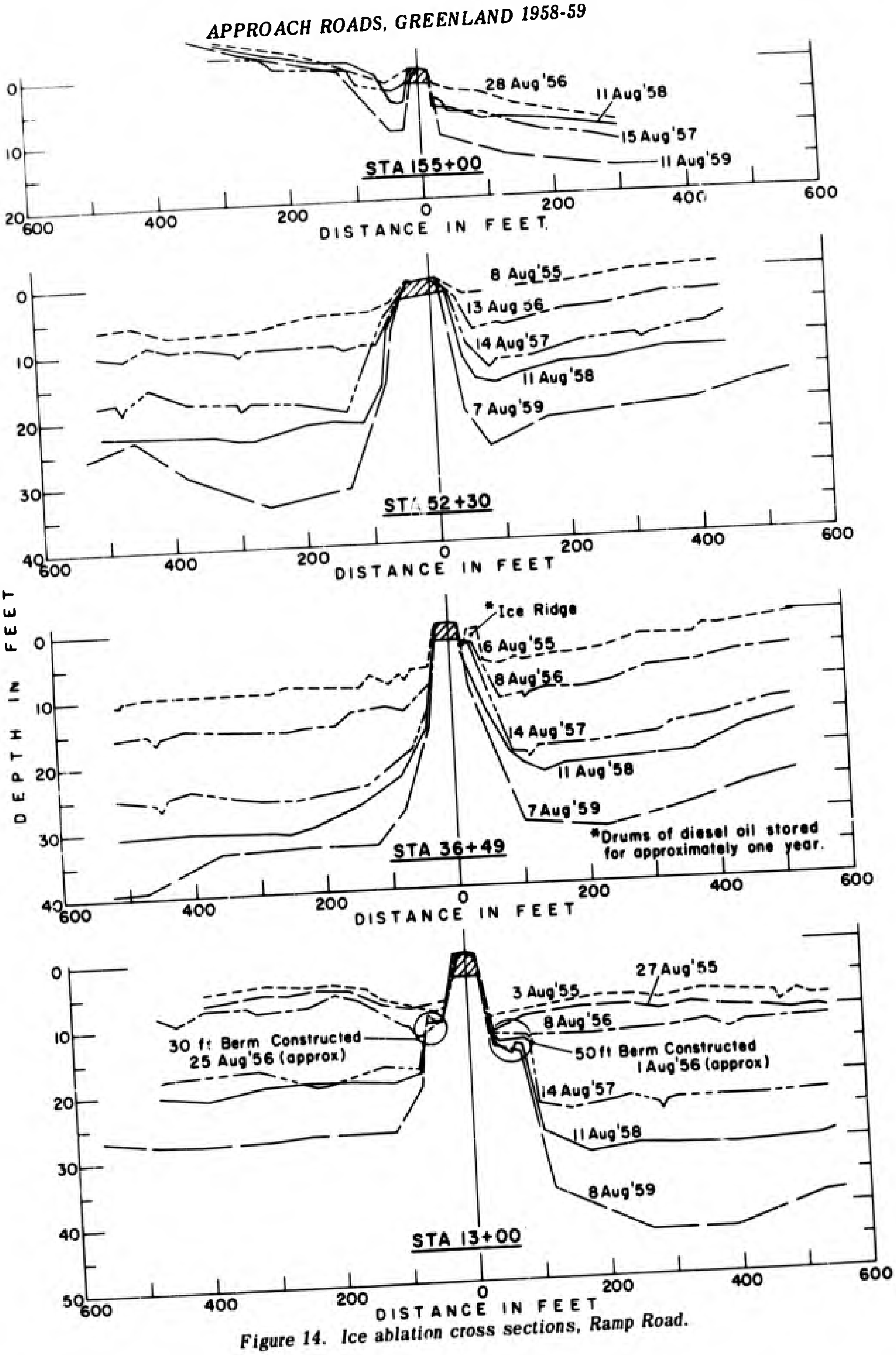


Figure 14. Ice ablation cross sections, Ramp Road.

melt-water channel had formed along the uphill side increasing the perching and the sloughing of the shoulders.

The first 800 ft of the road was built in 1955 and the remainder in 1956. The road had perched about 25 ft above the ice on the west side and up to 15 ft on the east side. At the end of the 1959 season some sections of the road surface had narrowed to 19 ft and large areas needed resurfacing.

When the location of the ice tunnel was changed in 1958, the part of the Transverse Road north of the intersection of the Tunnel Road (Fig. 2) was abandoned. There was no further need for a road to that location and extensive repairs were required in the area of the pile-bent bridge.

Berms

The effect of perching of the road surface above the ice and the falling away of the shoulders has been the major problem of the gravel fill roads on the ice cap. In order to stop or retard the slumping, gravel blankets or berms have been placed on the ice beside the road. Various experimental types have been built in the past (USA EWES, 1959) but the most satisfactory has been a blanket of random mixed fill.

In 1956 berms were constructed along the lower end of the Ramp Road. On the south side, where the rate of ablation was highest, a 50-ft-wide berm was built from the edge of the ice to Station 30+00. On the north side a 30-ft berm was built to the intersection of the Transverse Road. Both berms consisted of approximately 1-ft-thick random mixed fill spread by a self-propelled scraper (USA EWES, 1963). A 1-ft-thick fill was not sufficient to prevent complete melting of the underlying ice but it would retard the ablation. The berms were constructed with different widths to determine the optimum required under the conditions prevailing at the lower end of the ramp. Figure 15 shows that the slumping of the shoulders had been reduced since the berms were built. Measurements show that approximately 2 ft of road width was lost each year due to slumping before the berms were constructed. This has decreased to less than 1 ft/year.

In the 3 years since the berms were built approximately 10 ft had been lost from the edge of the berm on the south side and about 4 ft of ice had melted beneath the fill. On the north side, with less ablation, the edge of the berm had receded about 4 ft and 2 ft of ice had melted beneath the fill.

Two experimental sections of berms were built in 1957 to determine the optimum width at a higher elevation on the ramp. As the rate of ablation decreases with elevation, the width of the berm should be decreased accordingly. It would be wasteful of time and material to construct a berm along the entire road designed for the maximum ablation.

The area of the road between Stations 83+00 and 93+00 was selected for the test. Each section was 500 ft long and was covered by a 1-ft-deep random mixed fill. From Station 83+00 to 88+00 a 20-ft berm was built on each side of the road; and a 10-ft-wide berm was built on each side of the road from Station 88+00 to 93+00. The berms were constructed by end dumping from the side of the road and bulldozing to spread and compact the fill.

Figure 15 shows that the south side of the 10-ft berm had practically disappeared in slightly over 2 years. On the north side, where the ablation at the toe of the fill had been considerably less, the edge had receded approximately 3 ft and about 3 ft of ice had melted beneath the berm.

At Station 85+00 the 20-ft berms were in satisfactory condition. The receding of the edges was minor on both sides but 3 to 4 ft of ice had melted beneath the berms.

Although measurements and observations show that the berms do not completely prevent the shoulders from sloughing, they retard it enough to be of value. On the Tuto Ramp, for a 10-year design life, the berms should be 30 ft wide for the first 1½ miles, taper to 20 ft at 2½ miles and

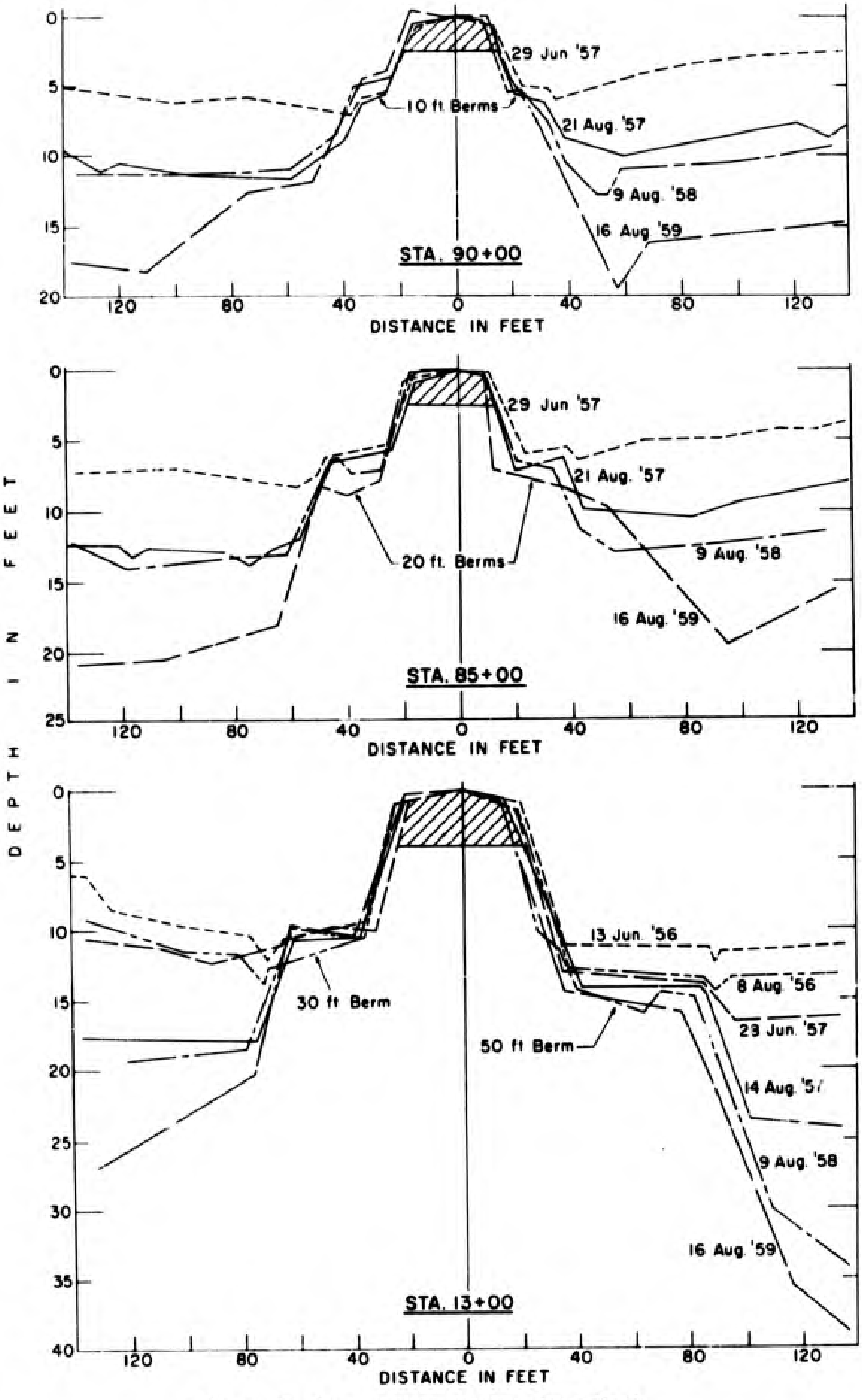


Figure 15. Cross section of berms, Ramp Road.

taper to 10 ft at a point 3 miles from the edge of the ice. The ablation at the end of the Ramp Road (Mile 3) is about 3 ft/yr so a 10-ft berm would be satisfactory.

The value of a berm is demonstrated by the cross section at Station 13+00 on the Ramp Road. This section of the road had been in place for 5 years and there was over 40 ft of ablation on the south side. The width of the road was still sufficient for two-way travel because of the berms placed in 1956.

Berms must not be placed when the road is being built as the fill is in a thawed state and there is some melt of the ice beneath the fill. With a berm of relatively impermeable material the melt water would flow beneath the road, causing erosion of the ice and a rough surface. The melt water must be allowed to drain off the sides of the road. Depending on the amount of ablation in the area, the berms should be placed 1 to 2 yr after the road has been built.

The most satisfactory material for berm construction has been a random mixed fill. The fines form a blanket to protect the underlying ice and the cobbles and boulders prevent the material from being washed away by flowing melt water.

Pile-bent bridge

To investigate the most suitable type of bridge for use on ice and to cross a large melt-water channel on the Transverse Road a pile-bent bridge was built in 1956. The design and construction of the bridge are described in the 1956-1957 Project 1, Approach Roads Report (USA EWES, 1963). The bridge performed satisfactorily for the remainder of the 1956 season and all of the 1957 season. All the material for the ice tunnel was transported across the bridge. Figure 16 shows the plan of the bridge and a profile of the ice beneath the centerline.

When the bridge was built in 1956, the main melt-water channel was at Station 25+70 with a secondary channel at 25+90. In 1957 the main channel moved to Station 25+90 and began to undercut the pile bent at Station 26+00. During the 1958 season the ice was eroded completely from beneath and around this pile bent. This rapid erosion of the ice beneath the bridge was due to the failure of the culverts along the Transverse Road so that a large area of the ramp drained through the channel.

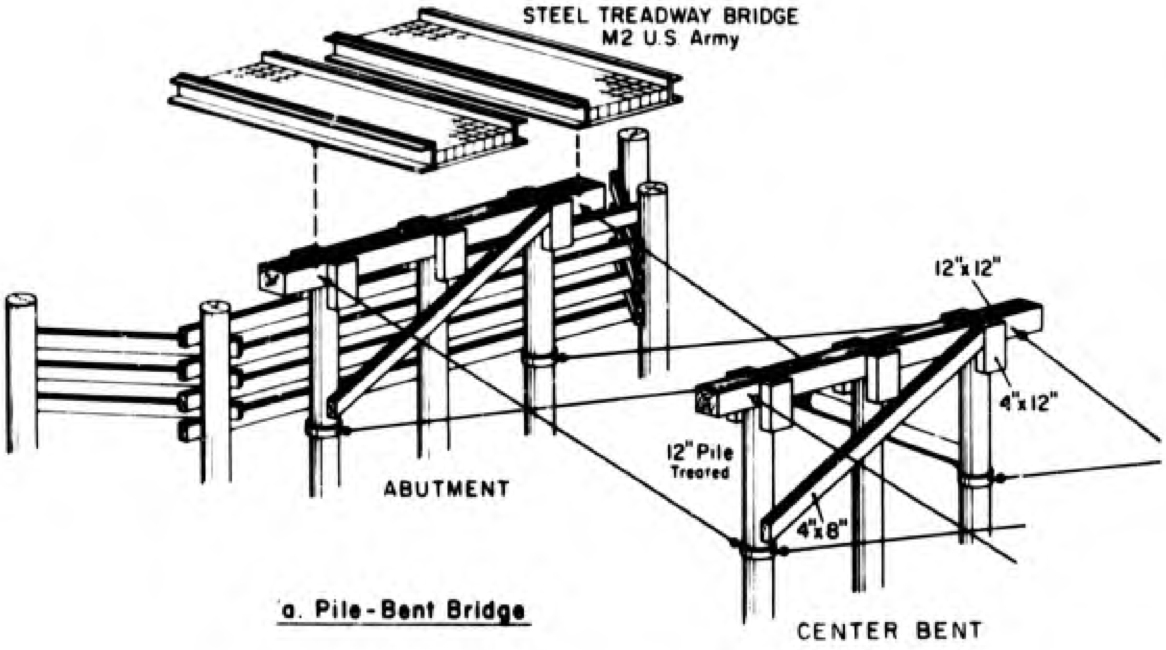
Because of the undercutting of the bent and the relocation of the ice tunnel, access to the area was not required and the bridge was abandoned. The steel U.S. Army Treadways were removed and the reusable material was salvaged. The lifespan of the bridge could have been increased by: 1) placing coarse fill in the channel as was done with the crib abutment bridge (see section on New Construction), or 2) cutting a channel halfway between each timber bent in the spring to divert the water away from the bridge supports.

Crushed rock test section

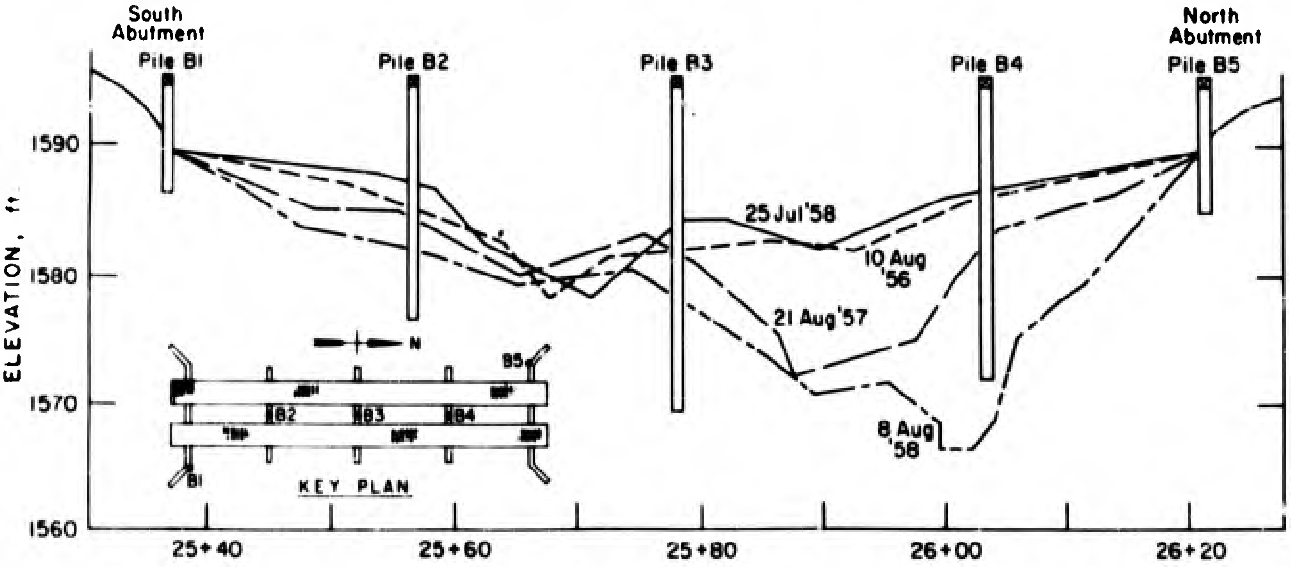
During the construction of the Ramp Road in 1955 a 100-ft section (Station 65+50 to 66+50) was built with a 12-in. layer of crushed rock placed on the ice surface. This section failed and was replaced with the standard road fill. This was not a conclusive test because the section was short, the crushed rock was not of the proper gradation, and it was placed in line with the deeper road fill.

In 1957 a test section was constructed beside the Ramp Road at Station 67+00 to 73+00. This section was divided into two parts, each 285 ft long and 20 ft wide. The ice surface of one part of the test road was covered by a nominal thickness of 6 in. of crushed rock and that of the other by a thickness of 12 in. The construction of the road and materials used are described in a previous report on the project (USA EWES, 1963).

During the 1957 season three accelerated traffic tests were conducted on the test section. Each test represented a month's normal traffic on the Ramp Road. At the end of the season the road surface was perched 6 to 7 ft above the ice but was usable without any maintenance. In 1958



a. Pile-Bent Bridge



b. Ice surface profile showing erosion

Figure 16. Pile-bent bridge.

the road was subjected to about 100 passes of a loaded 10-yd³ dump truck when fill was placed along the Ramp Road. Prior to this a grader was used to level the surface of the road but no additional material was placed. After the road had been used, ruts up to 4 in. deep were observed. In 1959 the road was passable only to small vehicles such as the ¼-ton truck, and at slow speeds. At the end of the season the road surface was perched about 12 to 13 ft above the ice, the shoulders had slumped badly and there were large potholes over the entire length of the road (Fig. 17). The section with the 12-in. thickness was only slightly better than the section with 6 in. of fill. Figure 18 shows the plan, profile and cross sections of the road from the date of construction to

Figure 17. Surface of crushed rock test section after two thaw seasons, 11 August 1959.

the end of the 1959 season. As can be seen, the total ice melt below the 12-in. section was 58% of the melt beneath the 6-in. layer.

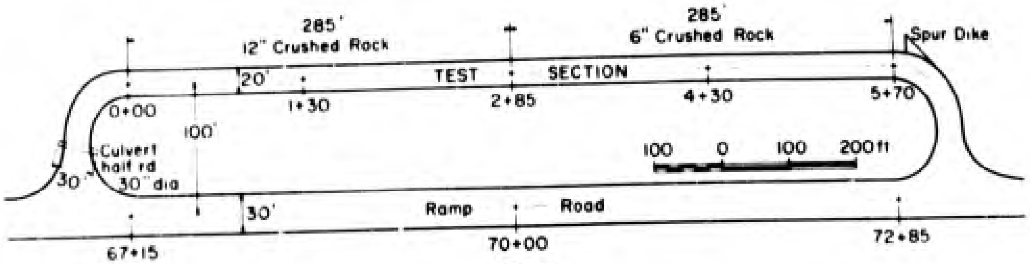
Based on observations and measurements for 2 years it is concluded that a crushed rock road with a thin layer of fill is not satisfactory where there is substantial ablation. A thin fill may be usable in an area where there is no ablation or only a slight amount. In this case, since the road surface was only barely above the surrounding ice, there would probably be a deep snow cover and plowing problems.

The failure of the sections with thin fill layer was attributed to differential melting of the ice beneath the fill. The thickness of the fill was not uniform due to the rough ice surface, and the rate of melting varied with the thickness of fill. Swales, hummocks and ruts developed.

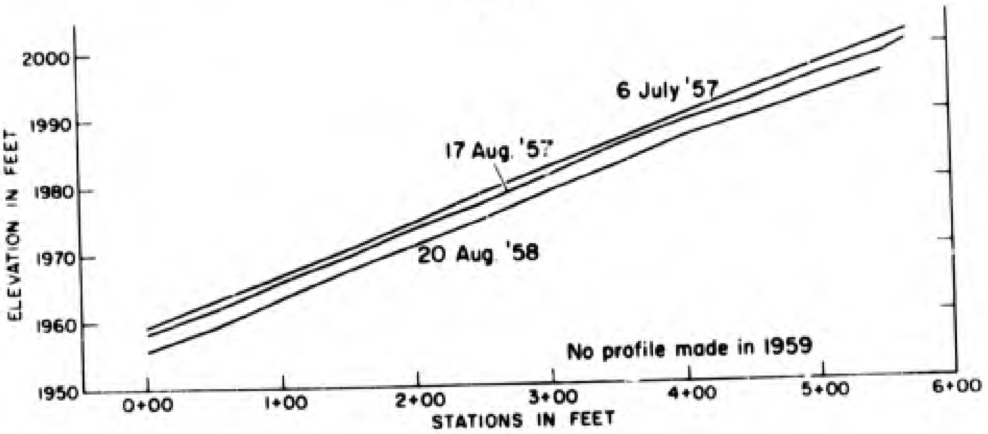
Culverts

The Ramp Road was constructed parallel to the melt-stream pattern so that drainage structures were not required. During the building of the first 800 ft of the Transverse Road in 1955, four types of culverts were incorporated in the road: 1) a 36-in.-diam corrugated iron pipe; 2) a French drain consisting of boulders hand-placed in the channel; 3) oil drums welded end to end; and 4) a 36-in.-diam half-round corrugated iron pipe placed on wood sills. At the end of the 1955 season only the half-round culvert was operating. The other culverts had become perched above the surrounding ice and were bypassed by the melt water.

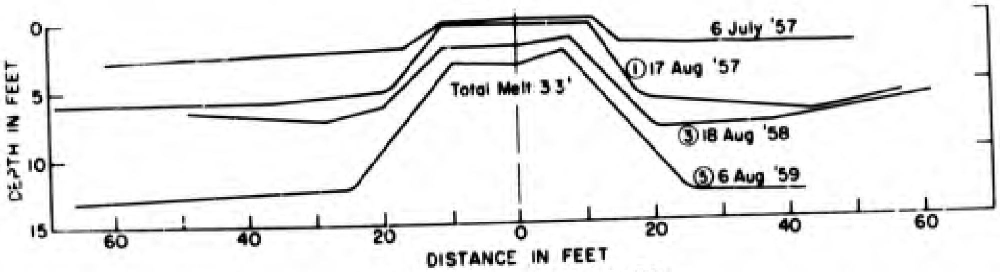
When the road was extended in 1956, seven half-round culverts were placed through the fill. Based on observations of the culverts installed in 1955 this was thought to be the most effective type. In addition, an 18-in.-diam corrugated iron pipe was placed in the fill as an experiment. At the end of the 1956 season only four of the culverts were functioning. By the middle of the 1957 thaw season, the warmest season recorded up to that time, all the culverts were perched above the ice level on either side.



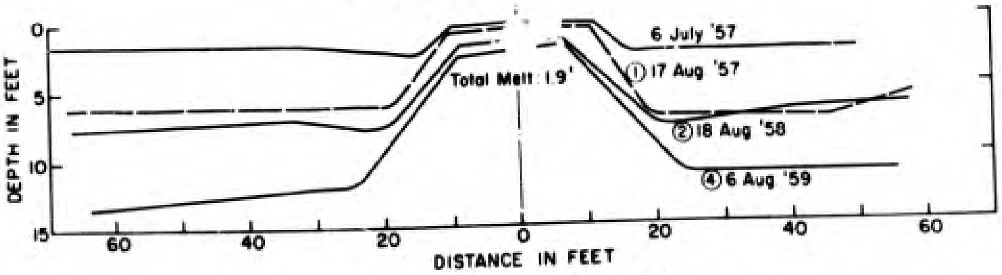
a. Plan



b. Profile



c. Cross Section at Sta. 4+30



d. Cross Section at Sta. 1+30

6 July 1957 to 17 Aug 1957

① Ice melt caused a drop of 0.3 ft

17 Aug 1957 to 18 Aug 1958

Vertical movement of MP 16 was 2.2 ft

② Test Rd. Sta. 1+30 showed drop of 3.2 ft
Difference of 1.0 ft due to melt under road

③ Test Rd. Sta. 4+30 showed drop of 3.8 ft
Difference of 1.6 ft due to melt under road

18 Aug 1958 to 6 Aug 1959

Vertical movement of MP 16 was 2.4 ft

④ Test Rd. Sta. 1+30 showed drop of 3.0 ft
Difference of 0.6 ft due to melt under road

⑤ Test Rd. Sta. 4+30 showed drop of 3.8 ft
Difference of 1.4 ft due to melt under road.

Figure 18. Plan, profile and cross section of crushed rock test section.

The cut-and-cover culvert built in 1958 is described in the section on New Construction. This culvert functioned for only part of the season. Its effective lifespan could have been lengthened by removing the ice sill left at the entrance by the trencher.

Although the half-round culvert has been the most effective type it has not been satisfactory. The principle on which it is based is correct, but its dimensions should be enlarged to those of a small bridge. A fully enclosed culvert will become perched in one or possibly two melt seasons.

In a valley-ridge topography the half-round culvert would have been more effective. Although the culverts were placed in the original stream channels, there was a tendency for the melt water to flow along the east side of the Transverse Road which had a natural slope to the north. In a valley-ridge area the road would serve as a dam and pond the water until it would flow through the culvert. At the same time the water would erode the ice beneath the culvert to the same level as the ice on either side of it.

In an area such as that east of the Transverse Road a system of channels should be cut straight uphill from each culvert with lateral channels to each side. This would intercept the melt water and divert it to the prepared drainage structures. This system was not used because no satisfactory equipment for trenching in rough ice was available. The ladder trenching machine has a high center of gravity and is difficult to use on rough ice.

At present the most feasible drainage structures for use on the ice cap are bridges. Crib abutments and U.S. Army Treadways should be used in their construction. In the spring of each year the Treadways could be lifted by a crane and the snow in the channels removed by a small bulldozer. These bridges should have a clear span of about 20 ft with a channel placed in the middle between the abutments. The number of bridges required should be based on the amount of melt water. On the Transverse Road a short bridge placed about Station 14+00 would have diverted a considerable portion of the melt water from the bridge on the Tunnel Road.

Summary

1. At the end of the 1959 season the Ramp Road was still in usable condition but in some places the width had been reduced to 18 ft. Without extensive repairs requiring large quantities of fill, the life of the road should not be expected to be greater than one or two more seasons.

2. The Transverse Road was in satisfactory condition and could be expected to remain usable for several years without major repairs.

3. The major problem of the gravel roads on the ice cap was the sloughing of the shoulders due to the ablation of the adjacent ice. Over 40 ft of ice had melted at Station 13+00 on the Ramp Road since this section was constructed in 1954.

4. At the present time, the most successful method of preventing sloughing of the road shoulders is to cover the adjacent ice surface with a berm of random mixed fill. The thickness of the berm should be approximately 1 ft and the width should depend on the annual ice ablation.

5. One bent of the pile-bent bridge was undermined when about 21 ft of ice melted below the bridge in slightly over 2 years. With the failure of all the culverts on the Transverse Road a large area of the ice cap was drained through the bridge, resulting in extreme erosion of the ice.

6. A 6- to 12-in. layer of crushed rock placed directly on the ice is not suitable for a road where there is any appreciable ablation. A thin fill section may be feasible where there is no ablation or only a slight amount of it; but since the road would be only barely above the surrounding ice a deep snow cover would inundate the road and present plowing problems.

7. Several types of culverts were incorporated in the road construction on the Tuto Ramp but the most effective was a half-round corrugated iron pipe laid on wood sills. Completely enclosed culverts will become perched above the surrounding ice in one or two thaw seasons.

◆

8. The half-round, although the most effective culvert used, was not satisfactory. The principle is correct; i.e., the bottom of the culvert must be left open so that the ice beneath it can erode to the same level as the ice on either side of it. However, the dimensions were too small. The recommended drainage structures for use on the ice cap are short (approximately 20-ft) bridges spaced along the road as required with a system of channels to direct the melt-water flow to the prepared crossings.

SURFACE AND SUBSURFACE ICE MOVEMENT

General

The program of measuring the surface movement of the ice on the Tuto Ramp that began in 1955 was continued in 1958 and 1959. All measurements were made from the permanent baseline that was installed in 1956.

A study of ice movement below the surface was begun in 1957. This investigation consisted of measuring with an inclinometer the deformation of plastic tubes frozen in the ice to depths of 200 ft. This investigation was continued in 1958 and 1959. The locations of all movement points are shown on Figures 2, 6 and 19.

Surface movement

As part of the overall study of the Tuto Ramp and with particular emphasis on the effect of surface movement on the gravel fill roads the movement of various points in the road fill and the ice had been measured since 1955. The measurements made during 1955 were from a short baseline (2580 ft) with bench marks consisting of large boulders in the area. It was recognized that there would probably be some movement of the boulders due to frost action. In 1956 two permanent bench marks were established and a third bench mark was added in 1957 (USA EWES, 1963). These bench marks are designed to resist any movement from freezing or thawing of the soil.

The movement of the points was measured by precise triangulation with a theodolite. All possible methods were used to achieve maximum accuracy. Each station of the triangle was occupied when possible and all angles were turned six times. The largest error of angle closure was 8 sec before the angles were balanced.

The horizontal movement of the points in the road fill was measured by leveling with the "NN" base point used as a bench mark. Leveling surveys of the three bench marks showed only a small amount of movement well within the limits of instrument error. The level runs on the movement points were kept as accurate as possible by running only short loops.

Some of the points in the road fill had to be replaced due to slumping of the road shoulders. In each case the new point was placed as close to the location of the old point as feasible.

The horizontal movement of all the points and the vertical movement of those in the road fill were measured four times during the 1958 season. An attempt was made to measure the vertical movement of the points on the ice by stadia.

In 1959 only one set of measurements of the movement was made as an annual measurement of the various factors affecting performance of the roads had been judged sufficient. Table II shows that the movement was practically the same as in the preceding years.

Table AIII (App. A) shows all the movements of the various points. Three years of data on the short term movement of the ice are available. The movement for short periods of time was erratic in rate and direction. No data are available during the winter season but measurements made at the end of one thaw season and at the beginning of the following season indicate a reduced rate of movement during the winter.

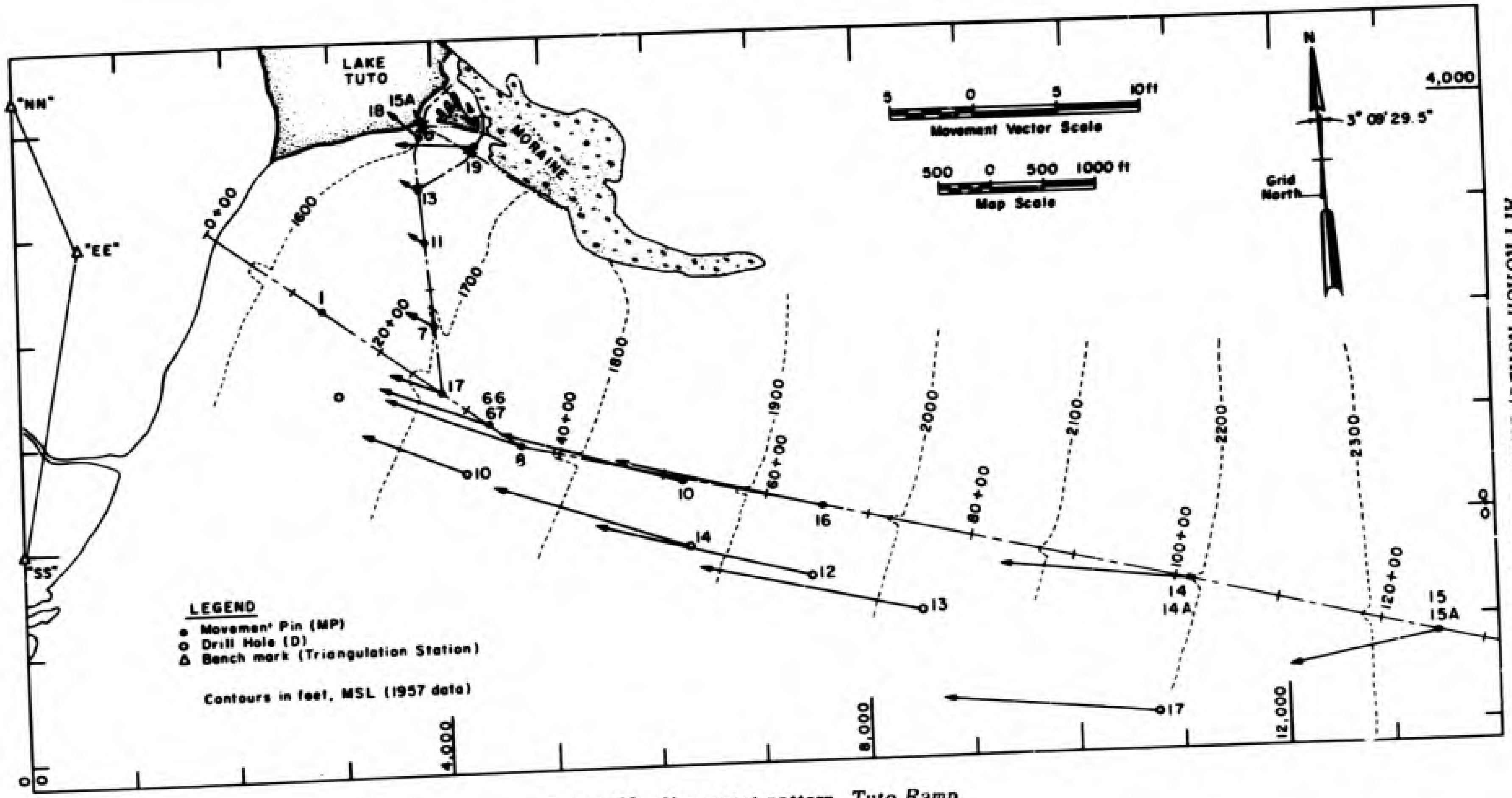


Figure 19. Movement pattern, Tuto Ramp.

Table II. Annual ice movement measurements.

Point	Period	Horizontal		Vertical	
		Ft	Direction	Ft	Direction
		Ramp Road			
MP-1	21 Aug 1956 - 22 Aug 1957	0.19	S34°30'W	0.44	Down
	22 Aug 1957 - 20 Aug 1958	0.20	N63°25'W	0.34	Down
	20 Aug 1958 - 17 Aug 1959	0.17	S80°00'W	0.29	Down
MP-17	22 Aug 1957 - 20 Aug 1958	3.35	N65°50'W	0.72	Up
	20 Aug 1958 - 17 Aug 1959	3.31	N66°30'W	0.56	Up
MP-66	7 July 1956 - 10 July 1957	6.92	N70°00'W	3.11	Up
MP-67	19 Aug 1957 - 21 Aug 1958	6.96	N69°45'W	2.59	Up
	21 Aug 1958 - 17 Aug 1959	6.84	N69°25'W	2.39	Up
MP-8	20 Aug 1956 - 21 Aug 1957	8.71	N74°40'W	1.68	Up
	21 Aug 1957 - 20 Aug 1958	8.53	N72°00'W	1.75	Up
	20 Aug 1958 - 17 Aug 1959	8.48	N60°25'W	1.62	Up
MP-10	20 Aug 1956 - 21 Aug 1957	11.21	N73°30'W	0.67	Up
	21 Aug 1957 - 20 Aug 1958	11.34	N73°35'W	0.93	Up
	20 Aug 1958 - 17 Aug 1959	11.14	N73°30'W	0.90	Up
MP-16	20 Aug 1957 - 20 Aug 1958	12.91	N75°55'W	2.20	Down
	20 Aug 1958 - 17 Aug 1959	12.31	N74°50'W	2.40	Down
MP-14	20 Aug 1956 - 20 Aug 1957	11.17	N86°30'W	1.45	Down
	20 Aug 1957 - 5 Aug 1958	12.01	N82°25'W	1.47	Down
MP-12A	18 Aug 1958 - 17 Aug 1959	11.10	N81°30'W	1.62	Down
MP-15	20 Aug 1956 - 20 Aug 1957	8.35	S73°25'W	1.05	Down
	20 Aug 1957 - 5 Aug 1958	9.52	S81°50'W	1.21	Down
MP-15A	18 Aug 1958 - 17 Aug 1959	8.66	S80°05'W	1.33	Down
		Transverse Road			
MP-7	21 Aug 1956 - 21 Aug 1957	1.85	N63°40'W	0.67	Up
	21 Aug 1957 - 21 Aug 1958	1.92	N61°20'W	0.57	Up
	21 Aug 1958 - 20 Aug 1959	1.93	N57°50'W	0.50	Up
MP-11	21 Aug 1956 - 21 Aug 1957	1.03	N60°10'W	0.09	Up
	21 Aug 1957 - 21 Aug 1958	1.18	N56°45'W	0.06	Up
	21 Aug 1958 - 20 Aug 1959	1.07	N59°10'W	0.06	Up
MP-13	20 Aug 1956 - 22 Aug 1957	0.90	N53°05'W	0.34	Up
	22 Aug 1957 - 18 Aug 1958	0.98	N56°40'W	0.18	Up
	18 Aug 1958 - 19 Aug 1959	1.38	N54°10'W	0.22	Up
MP-18	22 Aug 1957 - 20 Aug 1958	2.42	N50°50'W	0.55	Down
	20 Aug 1958 - 19 Aug 1959	2.52	N46°55'W	0.81	Down
B-1	28 Aug 1956 - 22 Aug 1957	2.26	N70°35'W	NM	
	29 July 1957 - 21 July 1958	3.64	N71°55'W	NM	
B-2	28 Aug 1956 - 22 Aug 1957	2.54	N61°50'W	NM	
	29 July 1957 - 21 July 1958	3.36	N65°10'W	NM	
B-3	28 Aug 1956 - 22 Aug 1957	2.55	N58°50'W	NM	
	29 July 1957 - 21 July 1958	3.15	N61°45'W	NM	
B-4	28 Aug 1956 - 22 Aug 1957	2.45	N54°35'W	NM	
	29 July 1957 - 21 July 1958	2.91	N58°20'W	NM	
B-5	29 July 1957 - 21 July 1958	2.82	N50°00'W	NM	
		Tunnel Road			
MP-19	20 Aug 1958 - 19 Aug 1959	4.55	N84°30'W	NM	
D-11	19 Aug 1957 - 18 Aug 1958	0.96	N18°15'W	NM	
	18 Aug 1958 - 19 Aug 1959	0.49	N66°00'W	NM	
D-10	19 Aug 1957 - 19 Aug 1958	6.48	N70°05'W	NM	
	19 Aug 1958 - 19 Aug 1959	6.76	N68°05'W	NM	

MP Movement pin in road fill.
B Bridge bent
D − Tube in drill hole.
Note: Locations of all points are shown on Figures 2 and 19.

Table II (cont'd).

Point	Period	Horizontal		Vertical	
		Ft	Direction	Ft	Direction
	Tunnel Road (cont'd)				
D-14	21 Aug 1957 - 18 Aug 1958	12.24	N72°05'W	NM	
	18 Aug 1958 - 19 Aug 1959	12.25	N71°10'W	NM	
D-12	20 Aug 1957 - 19 Aug 1958	13.63	N75°10'W	NM	
	19 Aug 1958 - 19 Aug 1959	13.13	N74°40'W	NM	
D-13	18 Aug 1958 - 19 Aug 1959	13.64	N77°10'W	NM	
D-17	19 Aug 1957 - 18 Aug 1958	12.94	N84°40'W	NM	
D-15A	21 Aug 1957 - 21 Aug 1958	1.80	N28°30'W	NM	

D = Tube in drill hole.
Note: Locations of all points are shown on Figures 2 and 19.

Although the movement was erratic for short periods of time, the annual movement was fairly consistent. While the data on the annual movement are consistent, they cannot be extrapolated for shorter periods.

Horizontal movement. Figure 19 shows that the movement of the points reached a maximum rate about 1½ miles from the edge of the ice and decreased in both upslope and downslope directions. Based on all measured data the greatest rate of movement probably occurred in the vicinity of Station 80+00. At MP-1 in the road fill and D-11 in the ice, movement was small, averaging less than 0.2 ft/yr. This confirms the theory that approximately the first 2000 ft of the ramp was a stagnant wedge.

The direction of movement also changed along the ramp. At MP-15 the direction of the ice movement was slightly south of west. The other points on the road and in the ice moved slightly north of west, becoming more northerly near the edge of the ice and along the Transverse Road. As would be expected, the movement was approximately perpendicular to the contour lines.

The movement of the points placed in the ice was of the same order as that of the points in the road fill but the measurements indicate that the points in the ice apparently move at a different rate. The highest rate of movement measured occurred at D-13 in the ice. MP-16, in the road, and D-12, in the ice, were about the same distance from the edge of the ice but the rate of movement was higher at D-12. The same relationship holds for MP-10 and D-11, and D-17 and MP-14. At D-10 the opposite occurred as MP-66 moved slightly faster. It should be emphasized that most of these movements are not based on only 1-yr measurement but show the same relationship for 2 or 3 yr. It is interesting to note that the ice moved at different rates in relatively short distances.

The differential movement of the ice surface had very little effect on the roads on the Tuto Ramp. The alignment of the road changed slightly especially beyond Mile 2. All measurements show that the gravel fill roads were flexible enough to absorb the movement without damage.

Vertical movement. The vertical movement of all points in the road fill had been measured since 1956. As with the horizontal movement, the vertical movement was fairly consistent on an annual basis. The upward movement along the Ramp Road began between MP-1 and MP-17, reached a peak at MP-66 and 67 and changed to a downward movement between MP-10 and MP-16. The movement was downward from MP-16 to the end of the road. Increased perching resulted where the movement was upward.

At MP-66 and 67 the upward movement of the pin in the road fill averaged 2.47 ft/yr for 3 yr. In 10 yr this would amount to 25 ft, which combined with the ablation would result in the road surface being approximately 100 ft above the ice. With the sloughing of the shoulders as a result of the perching, the road would fail before reaching this height, possibly in 2 or 3 years.

The inclinometer tubes installed in the ice were used as triangulation points for the movement survey. Attempts were made to measure the vertical movement of the tubes but the results were not very satisfactory. Precise leveling on the ice is not practical and stadia measurements are not accurate enough. From the rough measurements made, the points in the ice moved vertically about the same amount as the points in the road fill.

Movement of the Tuto Ramp. The trend of the surface movement appears to be toward complete ablation of the stagnant wedge along the edge of the ice and the formation of a cliff by the moving ice from which pieces would break off in the manner of icebergs at the terminal edge of a sea glacier. Such land glaciers may be observed along the present edge of the ice cap, but because of a fortuitous topography of the ground surface, the cliff face has not yet developed at Tuto, and a smooth ramp up the edge of the ice still exists. However, unless the trend is reversed by a change in climate, the smooth ramp will not last for more than another decade or two.

Subsurface movement

The study of the movement of the ice to depths of 200 ft beneath the surface was continued in 1958 and 1959. The program was begun in 1957; the details of the installation of the slope indicator tubes are described in the report for that year (USA EWES, 1963). Appendix B contains two reports on the 1958 and 1959 measurements by Mr. Stanley D. Wilson, Shannon and Wilson, Soil Mechanics and Foundation Engineers, Seattle, Washington. This firm was engaged by USA EWES to furnish the required instrumentation and to analyze the data.

Four sets of measurements were made in 1958 and two in 1959. A full description is contained in Appendix B.

The measurements in 1958 and 1959 confirm the analyses of the movement described in the 1957 report (USA EWES, 1963). At D-12 there was very little differential movement in the top 200 ft of the ice. The entire tube moved in a westerly direction at about the same rate. At D-10 there was an upward thrust of the ice which had elongated the tube several feet since it was installed and the top of the tube moved appreciably faster than the bottom. At D-11 there was very little movement as would be expected in a stagnant zone such as the edge of the Tuto Ramp.

In addition to three 200-ft tubes, eight tubes were installed in the ice to various depths (20 to 40 ft). The results from these were inconclusive so that at the end of the 1957 field season four of the tubes were abandoned; the remaining four were read once in 1958 and then abandoned.

At the end of the 1959 season it was decided to discontinue the measurement of the subsurface movement. In both 1958 and 1959 it was necessary to melt ice from the tubes by the use of hot antifreeze before the readings were made. The tubes were broken below the surface and would probably be completely filled with ice in a few years time. Also, another set of data would add little of value since the annual movement for the 2 yr was consistent. The installations could be used to measure the thermal regime of the ice by means of thermocouples frozen within the tubes and as triangulation points to measure the surface movement.

Summary

1. The surface movement of the points in both the road fill and the ice was measured four times during the 1958 season. All movement was measured from the permanent baseline established in 1956. As data on the short term movement were available for three years, only one set of measurements was made in 1959 to give an annual value.

2. The movement of the points for a short period of time was erratic in both rate and direction but the annual movement was consistent over the period of record. The movement varied from

approximately 13 ft/yr at Ramp Road Station 78+00 to 0.2 ft/yr at Station 13+00. The gravel fill was flexible enough to absorb the movement with no effect except a slight change in alignment.

3. The study of the subsurface movement with a slope indicator that was begun in 1957 was continued in 1958 and 1959. The data for the 3 yr were consistent and as there was subsurface damage to the tubes the program was discontinued at the end of the 1959 season. The data show only 2 in. of differential movement per year in the top 200 ft at D-12, located about 6000 ft from the edge of the ice. At D-10, 3000 ft from the edge of the ice, the top of the tube moved about 10 in./yr in relation to the bottom. At D-11, 1500 ft from the edge of the ice, very little movement occurred, as would be expected in a stagnant zone.

DEPTH OF THAW AND TEMPERATURE MEASUREMENTS

General

One of the major problems of arctic construction is permafrost. The subsidence resulting from the thawing of permafrost containing a considerable amount of ice can be substantial. To determine the effect of road and building construction on the permafrost, the rate and depth of thaw had been measured at Camp Tuto since 1954. In addition to the measurement of the depth of thaw, the thermal regime in the moraine material and the ice had been measured.

Methods of measuring thaw penetration

When possible, the depth of thaw was measured by digging test pits. Where this was not feasible, the depth was measured by the use of thermocouples. Various other devices have been used to measure the depth of thaw (USA EWES, 1963), but so far none has proved completely satisfactory.

Test pits. As part of the micrometeorological studies, the rate of thaw in the natural ground was measured by digging test pits weekly. The pits were dug to the top of the frozen soil and the depths measured with a rule. The main advantage of the test pit method was that soil samples could be collected and tested for moisture content and gradation. The disadvantages were that the pits took considerable time to dig and a new pit had to be dug each time the depth was measured.

Thermocouples. Where thaw pits could not be dug, as in road fills or building foundations, the depth of thaw was measured by the use of thermocouples. The thermocouples were placed in the soil at fixed intervals and the temperature read at the surface. While this method is convenient and in some places the only method available, it has some disadvantages. The freezing point has to be interpolated between two thermocouples 6 or 12 in. apart and it must be assumed that the soil moisture freezes at 32F, although this may not be correct.

Thaw measuring devices. Experiments were conducted on two types of devices to measure the depth of thaw in 1958. The first device consisted of two plastic concentric tubes. The outer tube was placed in the ground and the inner tube was free to be withdrawn. The inner tube was filled with water colored with methylene blue dye. The theory was that the water would be frozen at the same level as the ground. The depth of thaw was measured by withdrawing the inner tube and measuring the distance to the ice from a mark corresponding to the ground surface. When the water froze, the dye was forced out of solution leaving almost clear ice and a sharp dividing line between the frozen and unfrozen water. The device was simple to install and could be read quickly, but the plastic tubes were fragile and at the end of the season the water would freeze from the top down.

The second device was electrical and was used to measure the thaw penetration by the resistance of the soil. A plastic rod with electrodes spaced at 6-in. intervals was placed in the ground. The resistance of the soil to a current passing from one electrode to another was measured. As

Table III. Measured thaw penetrations.

Test pit no.	*Year*	*Depth of thaw (ft)*	*ATI (deg-days F)*	*Remarks*
TP 4	1954	3.5	508	Undisturbed surface, clayey sand, no pronounced pattern
	1955	3.3	397	
	1956	3.6	380	
	1957	3.7	606	
	1958	4.0	494	
TP 6	1954	2.8	508	Undisturbed surface, silty sand, pronounced patterns
	1955	2.9	397	
	1956	3.2	380	
	1957	3.4	606	
	1958	3.3	494	
TP 7	1955	3.25	397	Undisturbed surface, silty sand, pronounced patterns
	1956	3.2	380	
	1957	3.4	606	
	1958	3.75	494	
TP 8	1956	3.6	380	Undisturbed surface, silty sand, pronounced patterns
	1957	3.7	606	
	1958	3.8	494	
1 A	1955	4.25	397	Gravel road fill (2½ ft) on permafrost
	1956	4.6	480	
	1957	4.75	606	
	1958	4.8	494	
	1959	4.8	490	
1 C	1955	4.4	397	Gravel road fill (4½ ft) on permafrost
	1956	4.7	380	
	1957	4.8	606	
	1958	4.5	494	
	1959	5.0	490	
3 A	1955	3.8	-	Gravel road fill (5½ ft) on ice
	1956	4.5	350	
	1957	5.0	580	
	1958	4.5	460	
	1959	4.7	450	
5 B	1956	2.8	150	Gravel road fill (3 ft) on ice
	1957	3.0	350	
	1958	2.9	205	
	1959	2.9	210	

with the thermocouples, the depth of thaw had to be interpolated between two points 6 in. apart. This device usually indicated a shallower depth of thaw than the other methods. Further investigation of a device based on this principle should be made.

Measured depth of thaw

The maximum depth of thaw in the natural ground and the road fill, both on soil and ice, is shown in Table III. Data indicate that there is a tendency for the maximum depth of thaw to increase progressively. In three out of four test pit locations the maximum depth of thaw was deeper in 1958 than in 1957. This occurred with a 1958 air thawing index only 81% of that in 1957. Thaw pits were not dug in 1959 but, where the depth of thaw was measured by thermocouples, there was a slight increase in the depth. This degradation of the permafrost, although a small

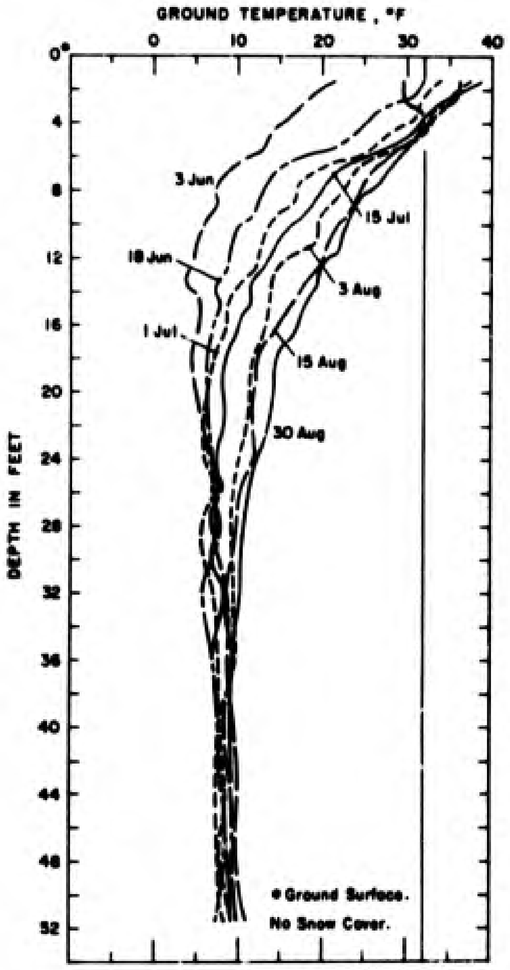


Figure 20. Hole D-5, typical subsurface temperatures, 1958.

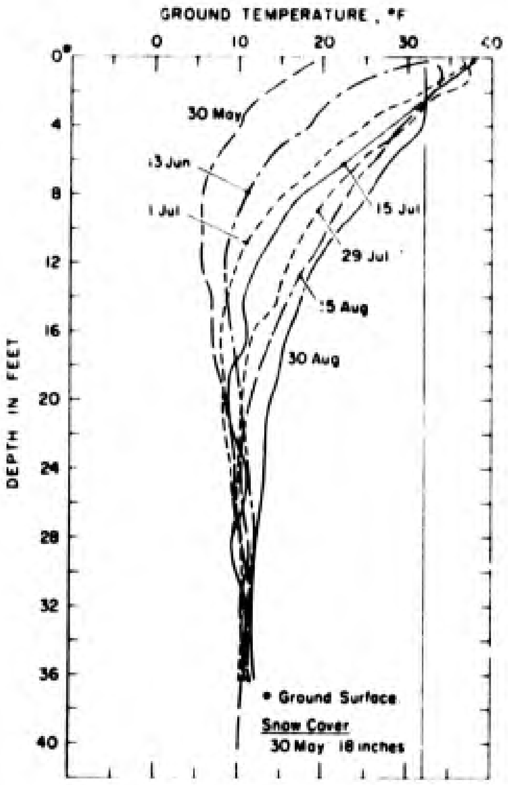


Figure 21. Hole D-6, typical subsurface temperatures, 1958.

amount each year, is continuous. In the active zone with little or no segregation of ice, the heat flow from the surface penetrates to the top of the permafrost and causes a small amount of melting. This thin layer becomes part of the active zone, allowing additional thaw penetration during the following seasons.

Subsurface temperature measurements

To measure the thermal regime below the active zone in the ground and beneath the ice surface, thermocouples were placed to various depths in the vicinity of Camp Tuto.

Temperature pattern in the natural ground. In addition to measurements of the depth of thaw with the relatively short thermocouple strings installed in the natural soil, the temperature pattern was measured to a depth of 50 ft at Meteorological Station 1 and to a depth of 40 ft at Test Pit 6. The locations of these thermocouple strings are shown on Figure 2. The strings were read weekly during the thaw season of 1958 and August 1959. The data obtained indicate that there was a seasonal variation in the thermal regime to a depth of about 40 ft. At this point the temperatures averaged about 10F with only a small variation throughout the season. Figures 20 and 21 are plots of typical subsurface temperatures at Drill Holes D-5 and D-6 for 1958. Data available for August 1959 are similar to those for August 1958.

Temperature patterns in the ice. During the construction of the Ramp Road, thermocouple strings were placed at Test Lanes 3, 5 and 6. Figure 2 shows the locations of these test lanes. Some of the thermocouple strings were placed through the road fill into the ice below the road and others were placed in the ice beside the road. By the start of the 1958 season all of the thermocouples in the ice beside the road were unusable except those at Test Lane 6. To measure the temperature pattern in the ice, a thermocouple string was placed to a depth of 25 ft at Meteorological Station 2 and to a depth of 30 ft at Station 3. The ablation of the ice at these sites constantly changed the position of the thermocouples in relation to the surface; therefore, it was necessary to measure the location of the top thermocouple below the surface each time a set of readings was made. Heat conducted down the thermocouple string melted the ice from around the wire; this resulted in an elongated funnel-shaped hole filled with melt water. Although attempts were made to measure the depth of the water surrounding the wire they were only partly successful. The depth of the top thermocouple embedded in the ice had to be interpolated from the temperatures recorded; this did not give the accuracy desired. The temperature readings from these two installations showed a slightly decreasing temperature with depth.

Twice during the 1958 season the temperature pattern to a depth of about 200 ft was measured in the inclinometer tubes at D-10, D-11 and D-12; in 1959 the temperatures in the tubes at D-10 were measured once. These temperatures were measured by suspending a thermocouple string in the tubes between inclinometer readings. The inclinometer tubes were filled with antifreeze, although the temperatures would not be correct due to convection currents in the antifreeze the gradation of the temperatures would be of value. The results from these measurements show only about a 2F variation in the temperatures to a depth of 200 ft.

Temperature pattern beneath building foundation. In 1958 a hangar was constructed at Camp Tuto. The hangar was built on a 5-ft-thick pad of crushed rock placed on the natural surface of the ground. The crushed rock, with pierced steel planking as a wearing surface, was used as a floor for the hangar. As part of the study of the subsurface temperatures, two strings of thermocouples were placed through the hangar foundation and into the soil beneath it. The thermocouple strings were inserted on 4 August 1959. The fill was thawed when it was laid down, and it remained in a thawed state until 6 September by which time the pad had frozen to the surface of the ground.

Readings were not made during the winter but on 21 May 1959 the entire depth of fill was frozen. On 22 August 1959 the maximum depth of thaw was 3 ft 8 in. Based on these data a 5-ft thickness of crushed rock would be adequate to prevent any degradation of the permafrost. In this area the active zone is approximately 4 ft thick so that the thaw would have to penetrate the 5-ft pad and the 4-ft active zone before any degradation of the permafrost would occur.

Summary

1. Measurements of the depth of thaw in the natural soil were continued in 1958 by the use of thaw pits and in 1959 by the use of thermocouples. Two devices to measure the depth of thaw were tested at Camp Tuto but did not prove satisfactory.

2. There is a tendency for the depth of the active zone to increase progressively despite a decrease in the air thawing index. In three out of four test pits in the Tuto area the depth of thaw was deeper in 1958 than in 1957. This occurred with an air thawing index in 1958 only 81% of that in 1957.

3. In the Tuto area there is a seasonal variation in the thermal regime of the natural soil to a depth of about 40 ft where the temperature remains constant throughout the year. There is also a seasonal variation in the upper part of the ice but the average temperature decreases with depth to the maximum depth of boring in the ice (200 ft). It is not known at what depth the decrease in temperature ceases and changes to a normal temperature gradient.

4. Thermocouples were installed through the foundation of a hangar that was built at Camp Tuto in 1958. Measurements made during the summer of 1959 show that the 3-ft 8-in. maximum depth of thaw did not penetrate the 5-ft crushed rock pad used as a foundation.

HYDROLOGY SURVEY

General

As part of the overall study of the Tuto Ramp and as an aid in the design of culverts and bridges, a pilot hydrology survey was made on a selected area of the Tuto Ramp in 1958. Appendix C covers this survey and Appendix D gives an analysis of the survey.

Test area

The section of the ramp that was bounded on the north by a natural drainage divide, on the south by the Ramp Road and on the west by the Transverse Road was selected for this study. There was no boundary on the east, but based on helicopter flights and ground observation it is doubtful if much melt water entered the area from this direction. As shown on Figure C2, the total drainage from the area could be measured at one or, for part of the season, two points. For this study the section was divided into two areas by a ridge running west from the end of the large moraine formation. The drainage from each area could be measured individually and correlated with the total drainage.

Test procedures

Measurements of the melt-water flow began on 9 June and continued until 25 August 1958. Readings were made several times a day at the main gaging stations. Quantities measured are shown on Table CI. Twice during the season readings were made hourly over a 24-hour period to determine the effect of temperature on the rate of flow.

As shown on Figure C2, an attempt was made to determine the percentage of the total flow deriving from different elevations in area 1. It was impossible to measure all the streams in the area but one network was outlined and measured at Mile 1, Mile 2, and Mile 3. Each station was measured every 2 to 5 days as daily measurements were not necessary. The measurements were complicated by the braided stream pattern and the occasional disappearance of a stream under a layer of snow. The amount measured at each location is shown on Table CII.

Test results

The survey of the melt-water flow covered the entire thaw season as recorded at Meteorological Station 2, located 1 mile from the edge of the ice. The melt-water flow was slight until 22 June, 15 days after the average daily air temperature was above the freezing point. The maximum recorded flow was on 3 August although the thaw season continued until 13 August. The measurements were discontinued on 25 August when the total flow was about 5% of the maximum. This was 12 days after the average daily air temperature was below freezing.

The two 24-hour surveys show that the maximum daily flow occurred during the period 1300 to 1600 and the minimum at about 0600 daily. The afternoon measurements were made during the period of maximum flow and the morning readings were made shortly after the minimum flow. On 3 August the melt-water flow, adjusted in accordance with the 24-hour tests and projected over a 24-hour period, would result in a total discharge of 36,000,000 gal. By way of comparison, the melting of 1 in. of ice over an area of one square mile would result in a total flow of 17,355,000 gal in a 24-hour period. The total flow on 3 August represents the melt of approximately 0.9 in. of ice over the 2.3 square mile test section.

Summary

1. During the field season of 1958 a pilot hydrology study was conducted on a selected section of the Tuto Ramp. This was part of the overall study of the ramp and was intended to aid in the design of bridges and culverts.

2. The maximum measured melt-water flow was 36,000,000 gal over a 24-hour period. This would be the equivalent of the melting of 0.9 in. of ice over the 2.3 square mile test section.

CONCLUSIONS

Organization and equipment

1. The number and classification of personnel must be adjusted to the proposed program. In addition to having the required technical skills personnel should be able to work long hours under severe conditions.

2. Plans and schedules must be carefully prepared but should remain sufficiently flexible to permit changes in the program due to weather or other conditions. The plan of tests should be based on achieving the main objective with several additional tasks to be accomplished if possible.

Climate

1. A complete meteorological program in an arctic area requires highly skilled personnel and complex equipment. The study of the weather at Camp Tuto has been conducted by the Meteorological Branch, U.S. Army Signal Corps, since 1956.

2. An average thaw season at Camp Tuto begins on 10 June and lasts until 26 August for a total thaw season of 78 days. The ATI is approximately 477. The duration of the thaw season can vary by several weeks and the ATI by 25%.

3. The amount of snow cover on the ice at the start of the thaw season is as important in the total ablation as the ATI. With a thin snow cover ablation of the ice begins almost as soon as the air temperature goes above freezing. With a heavy snow cover the ice is protected for part of the season, decreasing the ice ablation.

New construction

1. Under the conditions prevailing on the Tuto Ramp a 3-ft thickness of fill must be considered a minimum. During an abnormally warm summer there is some melting of the ice beneath the fill but this only slightly affects the road.

2. A bridge on the ice cap must have as wide a span as possible based on vehicle safety requirements and type of support. A channel should be placed halfway between the supports to protect them against undercutting as long as possible.

3. Cut sections in ice should be avoided if possible as they become traps for drifting snow. If cuts cannot be avoided they should be of a sidehill design if possible or be designed with extremely flat slopes.

4. A cut-and-cover culvert is a satisfactory design for two or more thaw seasons if it is constructed at the same time as the road. This allows the bottom of the trench to be placed well below the level of the ice on either side. The trench should be carried both upslope and downslope to form a channel to direct the melt-water flow.

Past construction

1. On the sections of the ramp with an average ablation of 7 ft, a road width of 30 ft is satisfactory for a design life of 5 years. At higher elevations the lifespan of the road increases as the ablation decreases.

2. Berms are a convenient method of extending the useful period of a gravel fill road on ice. A berm consisting of a 1-ft thickness of random mixed fill with the width varying with the ablation was satisfactory.

3. The lifespan of a bridge on ice can be lengthened by cutting a channel to direct the water from the supports and by placing coarse fill in the channel at the end of the melt season.

4. A road composed of a thin (6- or 12-in) layer of crushed rock placed directly on the ice is not satisfactory over one or two melt seasons. The depth of fill is not sufficient to protect the ice beneath it from differential melting; this results in a rough uneven surface. This type of road construction can be useful in an area with only a small amount of ablation. But there would be a problem with snow cover as the road surface is only slightly above the ice surface.

Surface and subsurface ice movement

1. The double-tube type base point is satisfactory as a bench mark and triangulation station for a period of at least 3 years.

2. The movements of all the points in the road fill and the ice surface are erratic for short periods but are consistent on an annual basis. The greatest amount of horizontal movement occurs in the area of Station 80+00 and becomes smaller east and west of this point. The rate of movement changes in a relatively short distance.

3. The vertical movement of the points in the road also varies along the ramp. The upward movement begins between MP 1 and MP 17, reaches a peak at MP 66 and changes to a downward movement between MP 10 and MP 16. At MP 66 the upward movement averages 2.47 ft/yr. It is difficult to measure the vertical movement of the points in the ice with the same accuracy as that of the points in the road but the movement is of the same order.

4. The measurements of the subsurface movement of the ice to a depth of 200 ft show that at a distance of 6500 ft from the edge of the ice the differential movement in the top 200 ft is about 2 in./yr. The vertical movement is less than 1 in./yr. At a point 3000 ft from the edge of the glacier there is about 15 in. of movement between the top and the bottom of the tube per year. The differential movement in the top 50 ft of the ice is slight. There is also a vertical movement of about 20 in/yr at this location. At D-11, 1500 ft from the edge, the horizontal and the vertical movements are negligible.

Depth of thaw and temperature measurements

1. A convenient and reliable method of measuring the depth of thaw in the natural soil and beneath building foundations is needed. The present method of measuring the thaw depth in the natural soil by hand-excavated thaw pits requires considerable time and the location has to be changed for each measurement. The advantage is that soil samples can be collected to determine the moisture content and classification of the soil. Thermocouples installed in building foundations to measure the depth of thaw require interpolating the depth of thaw line between two points 6 to 12 in. apart; it must also be assumed that the soil freezes at 32°F.

2. Devices based on the freezing of a liquid in a plastic tube inserted in the ground or on measuring the resistance of the soil to an electrical current do not have sufficient accuracy. Both devices indicate a shallower depth of thaw than is obtained with a thaw pit. The electrical resistance device should be investigated further.

3. There is a progressive increase in the annual depth of thaw. In 1958 three of the four test thaw pits showed a greater depth of thaw while the ATI was only 81% of that in 1957.

4. At Camp Tuto there is a seasonal variation in the thermal regime of the natural soil to a depth of about 40 ft. At this point the temperature remains at +10°F with only a small variation.

5. There are two factors in measuring the subsurface temperature of ice which preclude obtaining satisfactory accuracy. In an area where there is substantial ablation the surface of the ice is constantly changing so that the depth from the surface to the individual thermocouples must be recorded each time a set of readings is made. The thermocouple wires conduct heat, resulting in a funnel shaped hole filled with melt water which must be taken into account.

6. The temperatures measured by suspending a thermocouple string in the inclinometer tubes filled with anti-freeze showed only about 2°F variation to a depth of 200 ft.

7. In the Tuto area a 5-ft pad of crushed rock is sufficient to protect the permafrost beneath a building. The pad beneath a hangar built at Tuto showed a 3 ft 8 in. maximum depth of thaw during the summer of 1959. The thaw would have to penetrate the 5-ft pad and the 4-ft active zone before degradation of the permafrost would occur.

Hydrology survey

1. The instrumentation used in hydrology work in temperate zones is suitable for use on the ice ramp at Camp Tuto.

2. The maximum recorded flow averaged for a 24-hour period was 36,000,000 gal. This is the equivalent of the water produced by the melting of 0.9 in. of ice over the 2.3 square mile test area.

RECOMMENDATIONS

The following recommendations were made following the completion of this study in 1959. USA CRREL Technical Report 133 (June 1967) describes their implementation.

1. It is recommended that the investigation of certain phases of Project 1 be continued for at least one more year. As data are available for the short-term effect of the various factors on the road performance, future measurements and observations should be made on an annual basis. These should include profiles and cross sections of the roads, performance of the berms, ablation of the ice, effect of melt-water flow on the roads and bridges and movement of the various points in the ice and the road fill. Other factors should be measured continuously throughout the thaw season; among these are the depth of thaw and subsurface temperatures which should be measured by the use of thermocouples and the meteorological program.

2. A new section of road south of and parallel to the present Ramp Road should be built starting in 1960. The surface of the present road has become perched above the ice, resulting in sloughing of the shoulders to such an extent that it is doubtful if the road will remain usable for more than one or two years.

Based on observations of the existing roads on the Tuto ramp, the new road should be designed with a 50-ft traveled way. The depth of fill should be about 3.5 ft of coarse fill with a 6-in. layer of surfacing material from the edge of the ice for a distance of 1 mile, a total of 3 ft from 1 to 2 miles and 2 ft from the 2-mile point to the end of the road. This will insulate the ice beneath the road and prevent it from melting under the warmest thaw season yet recorded at Camp Tuto (i.e., 1957).

After one year a berm consisting of 2 ft of random mixed fill should be added on both sides of the road. The width of the berm should be 30 ft for the first 1-½ miles, tapering to 20 ft at the 2-½ mile point and to 10 ft at the 3-mile point.

At the edge of the ice a large culvert consisting of a half-round 48-in. corrugated iron pipe placed on wood sills should be installed. At this location a culvert should be used instead of a bridge, although culverts in the ice have not proved satisfactory, because with heavy traffic the Treadway prefabricated bridge would not be suitable and a drainage structure would be required to drain the melt water accumulating between the two roads. The retreat of the edge of the glacier and the severe ablation in this area will necessitate relocating the culvert periodically.

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APPENDIX A: INVESTIGATIONAL DATA

Table AI. Project personnel, 1958

Position	*Affiliation*	*Date in Field*
Permanent project personnel		
Project engineer (1)	USA ACFEL	29 May 58 - 28 Aug 58
Surveyor (1)	USA ACFEL	18 June 58 - 28 Aug 58
Hydraulic technician	USA EWES	3 June 58 - 28 Aug 58
Engineering aide (3)	USA ACFEL	17 May 58 - 28 Aug 58
Engineering aide (military) (4)	USA PR&DC	17 May 58 - 28 Aug 58
Supervisors and consultants		
Project supervisor	H.W. Stevens, USA ACFEL	17 May 58 - 4 June 58
Field reviewer	F.J. Sanger, USA ACFEL	6 July 58 - 16 July 58
Consultant	Dr. M.J. Hvorslev, USA EWES	4 July 58 - 21 July 58

Table AII. Project personnel, 1959

Position	*Affiliation*	*Date in field*
Permanent project personnel		
Project engineer (1)	USA ACFEL	2 Aug 59 - 2 Sept 59
Engineering aide (2)	USA ACFEL	2 Aug 59 - 2 Sept 59
Engineering aide (military) (4)	USA PR&DC	2 Aug 59 - 2 Sept 59
Supervisors and consultants		
Project supervisor	H.W. Stevens, USA ACFEL	18 Aug 59 - 29 Aug 59
Field reviewer	K.A. Linell, Chief, USA ACFEL	18 Aug 59 - 29 Aug 59
Consultant	Dr. M.J. Hvorslev, USA EWES	18 Aug 59 - 29 Aug 59

APPENDIX A

Table AIII. Ice movement measurements

Locations of all points are shown in Figures 2, 6 and 16.

Point	*Period*	*ft*	*Horizontal Direction*	*ft*	*Vertical Direction*
	Ramp Road				
MP-1	7 July 1956 - 7 Aug 1956	0.02	N63°25'W	0.03*	Down
	7 Aug 1956 - 21 Aug 1956	0.14	N30°10'W	0.01*	Down
	21 Aug 1956 - 13 June 1957	0.12	S65°35'W	0.12	Down
	13 June 1957 - 10 July 1957	0.18	S19°25'W	0.06	Down
	10 July 1957 - 8 Aug 1957	0.19	N18°25'W	0.23	Down
	8 Aug 1957 - 22 Aug 1957	0.12	South	0.06	Down
	22 Aug 1957 - 11 June 1958	0.32	S79°05'W	0.08	Up
	11 June 1958 - 10 July 1958	0.21	N31°10'E	0.21	Down
	10 July 1958 - 6 Aug 1958	0.02	North	0.11	Down
	6 Aug 1958 - 20 Aug 1958	0.05	S21°40'E	0.10	Down
	20 Aug 1958 - 17 Aug 1959	0.17	S80°00'W	0.29	Down
MP-17	8 July 1957 - 8 Aug 1957	0.93	N66°30'W	0.17	Down
	8 Aug 1957 - 22 Aug 1957	0.21	S73°20'W	0.25	Down
	22 Aug 1957 - 11 June 1958	0.32	S79°05'W	0.08	Up
	11 June 1958 - 10 July 1958	0.21	N31°10'E	0.21	Down
	10 July 1958 - 6 Aug 1958	0.02	North	0.11	Down
	6 Aug 1958 - 20 Aug 1958	0.05	S21°40'E	0.10	Down
	20 Aug 1958 - 17 Aug 1959	0.17	S80°00'W	0.29	Down
MP-66	7 July 1956 - 7 Aug 1956	0.56	N53°45'W	0.28	Up
	7 Aug 1956 - 20 Aug 1956	0.42	N75°00'W	0.08*	Up
	20 Aug 1956 - 13 June 1957	5.38	N70°05'W	2.66	Up
	13 June 1957 - 10 July 1957	0.67	N80°15'W	0.24	Up
MP-67	8 Aug 1957 - 19 Aug 1957	0.54	S83°40'W	0.03	Down
	19 Aug 1957 - 18 June 1958	5.67	N72°05'W	2.44	Up
	18 June 1958 - 10 July 1958	0.69	N44°25'W	0.10	Up
	10 July 1958 - 6 Aug 1958	0.39	N62°50'W	0.07	Up
	6 Aug 1958 - 21 Aug 1958	0.30	West	0.02	Down
	21 Aug 1958 - 17 Aug 1959	6.84	N69°25'W	2.39	Up
MP-8	7 July 1956 - 7 Aug 1956	0.63	N66°40'W	0.26*	Up
	7 Aug 1956 - 20 Aug 1956	0.51	N64°25'W	0.06*	Up
	20 Aug 1956 - 28 June 1957	6.68	N72°15'W	1.75	Up
	28 June 1957 - 9 July 1957	1.19	N84°10'W	0.11*	Up
	9 July 1957 - 8 Aug 1957	0.36	N28°00'W	0.14*	Up
	8 Aug 1957 - 21 Aug 1957	0.63	N88°10'W	0.02	Down
	21 Aug 1957 - 20 June 1958	7.19	N71°55'W	1.59	Up
	20 June 1958 - 10 July 1958	0.22	N56°15'W	0.13	Up
	10 July 1958 - 6 Aug 1958	0.87	N72°35'W	0.07	Up
	6 Aug 1958 - 20 Aug 1958	0.27	N85°45'W	0.04	Down
	20 Aug 1958 - 17 Aug 1959	8.38	N60°25'W	1.62	Up
MP-10	24 July 1956 - 7 Aug 1956	0.29	N80°15'W	0.04*	Up
	7 Aug 1956 - 20 Aug 1956	0.58	N81°00'W	0.13	Down
	20 Aug 1956 - 28 June 1957	8.99	N75°00'W	0.80	Up
	28 June 1957 - 9 July 1957	1.00	N78°30'W	0.06*	Up
	9 July 1957 - 8 Aug 1957	0.59	N46°20'W	0.09*	Up
	8 Aug 1957 - 21 Aug 1957	0.72	N88°25'W	0.05	Down
	21 Aug 1957 - 18 June 1958	9.45	N75°15'W	0.80	Up
	18 June 1958 - 8 July 1958	0.68	N58°10'W	0.06	Up
	8 July 1958 - 6 Aug 1958	1.05	N68°50'W	0.11	Up
	6 Aug 1958 - 20 Aug 1958	0.19	N68°45'W	0.04	Down
	20 Aug 1958 - 17 Aug 1959	11.14	N73°20'W	0.90	Up

Table AIII. (Cont'd)

Point	*Period*	*ft*	*Horizontal Direction*	*ft*	*Vertical Direction*
MP-16	15 June 1957 - 8 July 1957	1.15	N85°00'W	0.16*	Down
	8 July 1957 - 8 Aug 1957	0.93	N45°00'W	0.12*	Down
	8 Aug 1957 - 20 Aug 1957	0.47	S77°45'W	0.11*	Down
	20 Aug 1957 - 20 June 1958	10.77	N76°20'W	1.64	Down
	20 June 1958 - 13 July 1958	0.79	N76°50'W	0.27	Down
	13 July 1958 - 6 Aug 1958	1.00	N67°45'W	0.14	Down
	6 Aug 1958 - 20 Aug 1958	0.35	N83°30'W	0.42	Down
	20 Aug 1958 - 17 Aug 1959	12.31	N74°56'W	2.40	Down
MP-14	28 Aug 1956 - 28 June 1957	10.05	N85°50'W	1.14*	Down
	28 June 1957 - 29 July 1957	1.06	N62°30'W	0.14*	Down
	29 July 1957 - 20 Aug 1957	0.56	S19°45'W	0.17	Down
	20 Aug 1957 - 16 June 1958	10.53	N83°40'W	1.58	Down
	16 June 1958 - 22 July 1958	1.19	N34°55'W	0.03	Up
	22 July 1958 - 5 Aug 1958	0.96	S53°25'W	0.03	Down
MP-14A	5 Aug 1958 - 18 Aug 1958	0.62	S86°40'W	0.00	None
	18 Aug 1958 - 17 Aug 1959	11.10	N81°30'W	1.62	Down
MP-15	20 Aug 1956 - 28 June 1957	8.50	S77°10'W	1.20	Down
	28 June 1957 - 24 July 1957	0.55	N56°00'W	0.31	Up
	24 July 1957 - 20 Aug 1957	0.97	S15°30'E	0.16	Down
	20 Aug 1957 - 16 June 1958	9.12	S83°30'W	1.29	Down
	16 June 1958 - 22 July 1958	0.51	N12°25'W	0.15	Up
	22 July 1958 - 5 Aug 1958	0.86	S17°00'W	0.07	Down
MP-15A	5 Aug 1958 - 18 Aug 1958	0.77	S72°45'W	0.01	Down
	18 Aug 1958 - 17 Aug 1959	8.66	S80°05'W	1.33	Down
	Transverse Road				
MP-7	7 July 1956 - 7 Aug 1956	0.18	N16°25'W	0.20	Up
	7 Aug 1956 - 21 Aug 1956	0.21	S76°00'W	0.02*	Up
	21 Aug 1956 - 15 June 1957	1.51	N61°05'W	0.47	Up
	15 June 1957 - 10 July 1957	0.26	N62°30'W	0.00	None
	10 July 1957 - 9 Aug 1957	0.03	West	0.16	Up
	9 Aug 1957 - 21 Aug 1957	0.08	N82°50'W	0.05	Down
	21 Aug 1957 - 20 June 1958	1.80	N61°30'W	0.51	Up
	20 June 1958 - 8 July 1958	0.13	N 8°45'W	0.01	Up
	8 July 1958 - 5 Aug 1958	0.07	S63°25'W	0.09	Up
	5 Aug 1958 - 21 Aug 1958	0.04	S26°35'W	0.04	Down
	21 Aug 1958 - 20 Aug 1959	1.93	N57°50'W	0.50	Up
MP-11	24 July 1956 - 7 Aug 1956	0.18	N 16°25'W	0.20	Up
	7 Aug 1956 - 21 Aug 1956	0.21	S76°00'W	0.02*	Up
	21 Aug 1956 - 15 June 1957	1.51	N61°05'W	0.47	Up
	15 June 1957 - 10 July 1957	0.26	N62°30'W	0.00	None
	10 July 1957 - 9 Aug 1957	0.03	West	0.16	Up
	9 Aug 1957 - 21 Aug 1957	0.08	N82°50'W	0.05	None
	21 Aug 1957 - 20 June 1958	1.80	N61°30'W	0.51	Up
	20 June 1958 - 8 July 1958	0.13	N 8°45'W	0.01	Up
	8 July 1958 - 5 Aug 1958	0.07	S63°25'W	0.09	Up
	5 Aug 1958 - 21 Aug 1958	0.04	S26°35'W	0.04	Down
	21 Aug 1958 - 20 Aug 1959	1.93	N57°50'W	0.50	Up
MP-13	27 July 1956 - 7 Aug 1956	0.05	S83°10'W	0.01*	Up
	7 Aug 1956 - 20 Aug 1956	0.13	N38°40'W	0.01*	Up
	20 Aug 1956 - 15 June 1957	0.90	N44°40'W	0.03*	Up
	15 June 1957 - 10 July 1957	0.18	S66°20'W	0.07*	Up

Table AIII. (Cont'd)

Point	Period	ft	Horizontal Direction	ft	Vertical Direction
	10 July 1957 - 9 Aug 1957	0.07	N26°35'E	0.11*	Up
	9 Aug 1957 - 22 Aug 1957	0.10	S24°00'E	0.02	Up
	22 Aug 1957 - 10 June 1958	1.02	N56°35'W	0.21	Up
	10 June 1958 - 10 July 1958	0.04	S14°00'W	0.04	Down
	10 July 1958 - 7 Aug 1958	0.15	S47°45'W	0.07	Up
	7 Aug 1958 - 18 Aug 1958	0.14	N30°05'W	0.06	Down
	18 Aug 1958 - 19 Aug 1959	1.38	N54°10'W	0.22	Up
MP-18	6 July 1957 - 29 July 1957	0.28	N70°55'W	0.36	Down
	29 July 1957 - 22 Aug 1957	0.26	N17°45'W	0.28	Down
	22 Aug 1957 - 20 June 1958	2.12	N50°00'W	0.45	Down
	20 June 1958 - 21 July 1958	0.29	N53°30'W	0.31	Down
	21 July 1958 - 7 Aug 1958	0.18	N 3°10'W	0.07	Down
	7 Aug 1958 - 20 Aug 1958	0.19	S12°30'W	0.17	Down
	20 Aug 1958 - 19 Aug 1959	2.52	N46°55'W	0.81	Down
B-1	28 Aug 1956 - 6 July 1957	1.85	N66°20'W	NM	
	6 July 1957 - 29 July 1957	0.29	N80°15'W	NM	
	29 July 1957 - 22 Aug 1957	0.16	S75°05'W	NM	
	22 Aug 1957 - 20 June 1958	3.08	N69°10'W	NM	
	20 June 1958 - 21 July 1958	0.44	N80°45'W	NM	
	21 July 1958 - 7 Aug 1958	0.16	N10°35'E	NM	
B-2	28 Aug 1956 - 6 July 1957	2.10	N64°05'W	NM	
	6 July 1957 - 29 July 1957	0.27	N77°00'W	NM	
	29 July 1957 - 22 Aug 1957	0.24	N22°15'W	NM	
	22 Aug 1957 - 20 June 1958	2.86	N67°55'W	NM	
	20 June 1958 - 21 July 1958	0.34	N69°30'W	NM	
	21 July 1958 - 7 Aug 1958	0.18	N 9°30'E	NM	
B-3	28 Aug 1956 - 6 July 1957	2.16	N60°15'W	NM	
	6 July 1957 - 29 July 1957	0.39	N73°25'W	NM	
	29 July 1957 - 22 Aug 1957	0.15	N27°10'E	NM	
	22 Aug 1957 - 20 June 1958	3.22	N68°10'W	NM	
	20 June 1958 - 21 July 1958	0.21	N47°00'W	NM	
	21 July 1958 - 7 Aug 1958	0.14	N 4°05'E	NM	
B-4	28 Aug 1956 - 6 July 1957	2.09	N57°30'W	NM	
	6 July 1957 - 29 July 1957	0.31	N60°55'W	NM	
	29 July 1957 - 22 Aug 1957	0.15	N11°20'E	NM	
	22 Aug 1957 - 20 June 1958	2.53	N60°30'W	NM	
	20 June 1958 - 21 July 1958	0.29	N65°15'W	NM	
	21 July 1958 - 7 Aug 1958	0.17	North	NM	
B-5	6 July 1957 - 29 July 1957	0.29	N71°35'W	NM	
	29 July 1957 - 22 Aug 1957	0.22	N 7°45'E	NM	
	22 Aug 1957 - 20 June 1958	2.42	N53°55'W	NM	
	20 June 1958 - 21 July 1958	0.29	N54°50'W	NM	
	21 July 1958 - 7 Aug 1958	0.20	N14°45'W	NM	
	7 Aug 1958 - 22 Aug 1958	0.08	N23°15'W	NM	
	Tunnel Road				
MP-19	20 June 1958 - 21 July 1958	0.38	N77°50'W	0.05	Up
	21 July 1958 - 7 Aug 1958	0.17	N32°50'W	NM	Up
	7 Aug 1958 - 20 Aug 1958	0.14	S72°50'W	NM	Up
	20 Aug 1958 - 19 Aug 1959	4.55	N82°10'W	0.74	Up
NB-1	20 June 1958 - 21 July 1958	0.38	N71°35'W	NM	Up
	21 July 1958 - 7 Aug 1958	0.14	N30°10'W	NM	Up

Table AIII. (Cont'd)

Point	Period	ft	Horizontal Direction	ft	Vertical Direction
	7 Aug 1958 - 20 Aug 1958	0.20	S49°05'W	NM	Up
NB-2	20 June 1958 - 21 July 1958	0.37	N76°00'W	NM	Up
	21 July 1958 - 7 Aug 1958	0.10	N16°40'W	NM	Up
	7 Aug 1958 - 20 Aug 1958	0.05	N14°05'E	NM	Up
D-11	13 June 1957 - 8 July 1957	0.25	N73°45'W	NM	
	8 July 1957 - 8 Aug 1957	0.57	N61°30'W	NM	
	8 Aug 1957 - 19 Aug 1957	0.61	S19°00'W	NM	
	19 Aug 1957 - 11 June 1958	0.65	N76°35'W	NM	
	11 June 1958 - 8 July 1958	0.59	N42°20'E	NM	
	8 July 1958 - 5 Aug 1958	0.28	N43°35'E	NM	
	5 Aug 1958 - 18 Aug 1958	0.29	N35°15'W	NM	
	18 Aug 1958 - 19 Aug 1959	0.49	N66°00'W	NM	
D-10	13 June 1957 - 8 July 1957	0.79	N87°05'W	NM	
	8 July 1957 - 8 *Aug 1957	0.39	N82°30'W	NM	
	8 Aug 1957 - 19 Aug 1957	0.68	S54°00'W	NM	
	19 Aug 1957 - 12 June 1958	5.32	N65°55'W	NM	
	12 June 1958 - 10 July 1958	0.64	N81°00'W	NM	
	10 July 1958 - 5 Aug 1958	0.37	N64°10'W	NM	
	5 Aug 1958 - 19 Aug 1958	0.35	S50°55'W	NM	
	19 Aug 1958 - 19 Aug 1959	6.76	N68°05'W	NM	
D-14	28 June 1957 - 9 July 1957	1.54	N50°00'W	NM	
	9 July 1957 - 8 Aug 1957	0.57	N60°45'W	NM	
	8 Aug 1957 - 21 Aug 1957	0.99	S00°35'W	NM	
	21 Aug 1957 - 22 June 1958	10.15	N75°55'W	NM	
	22 June 1958 - 7 July 1958	0.59	N69°05'W	NM	
	7 July 1958 - 5 Aug 1958	1.20	N65°35'W	NM	
	5 Aug 1958 - 18 Aug 1958	0.42	S19°20'W	NM	
	18 Aug 1958 - 19 Aug 1959	12.25	N71°10'W	NM	
D-12	28 June 1957 - 9 July 1957	0.91	N86°00'W	NM	
	9 July 1957 - 8 Aug 1957	0.73	N48°50'W	NM	
	8 Aug 1957 - 20 Aug 1957	0.56	S81°45'W	NM	
	20 Aug 1957 - 13 July 1958	11.57	N74°45'W	NM	
	13 July 1958 - 4 Aug 1958	1.70	N72°10'W	NM	
	4 Aug 1958 - 19 Aug 1958	0.42	S76°20'W	NM	
	19 Aug 1958 - 19 Aug 1959	13.13	N74°40'W	NM	
D-13	4 Aug 1958 - 18 Aug 1958	1.08	N85°45'W	NM	
	18 Aug 1958 - 19 Aug 1959	13.64	N77°10'W	NM	
D-17	2 July 1957 - 29 July 1957	0.99	N73°35'W	NM	
	29 July 1957 - 19 Aug 1957	0.23	S15°50'W	NM	
	19 Aug 1957 - 26 June 1958	11.47	N85°45'W	NM	
	26 June 1958 - 10 July 1958	0.85	N50°40'W	NM	
	10 July 1958 - 4 Aug 1958	0.50	S28°35'W	NM	
	4 Aug 1958 - 18 Aug 1958	0.69	N48°30'W	NM	
D-15A	6 July 1957 - 29 July 1957	0.18	N86°40'W	NM	
	29 July 1957 - 21 Aug 1957	0.30	N27°25'E	NM	
	21 Aug 1957 - 22 June 1958	3.35	N45°10'W	NM	
	22 June 1958 - 21 July 1958	0.07	S33°45'W	NM	
	21 July 1958 - 7 Aug 1958	1.80	S66°30'E	NM	
	7 Aug 1958 - 20 Aug 1958	0.12	S70°00'W	NM	

* Interpolated between actual measurements.

MP	Movement pin in road fill.
B	Bridge bent.
D	Tube in drill hole.
NB	Bridge bent.
NM	Not measured.

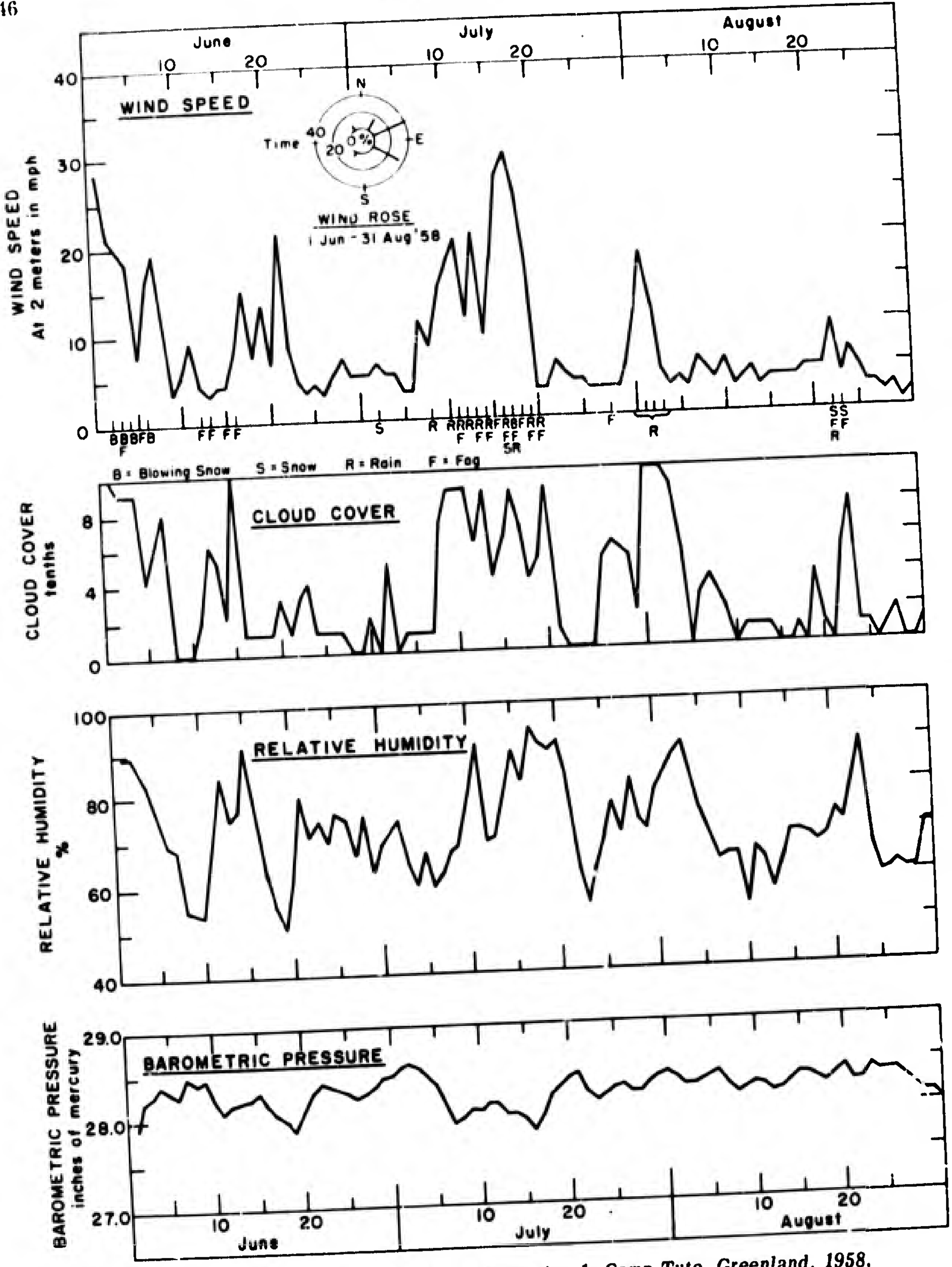
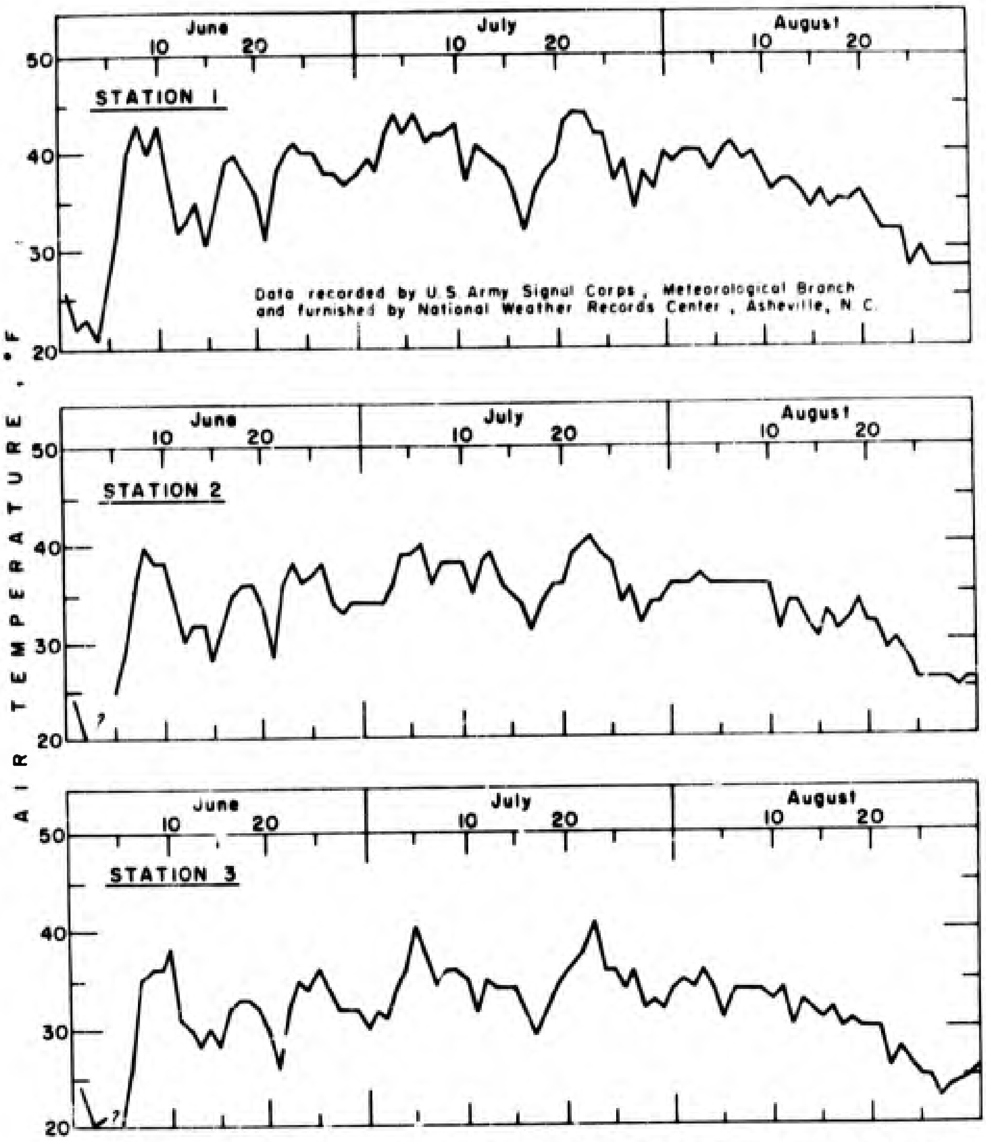


Figure A1. Average daily weather data, Station 1, Camp Tuto, Greenland, 1958.



Data recorded by U.S. Army Signal Corps, Meteorological Branch and furnished by National Weather Records Center, Asheville, N.C.

Figure A2. Average daily air temperature (within standard weather shelter) at Stations 1, 2 and 3, Camp Tuto, Greenland, 1958.

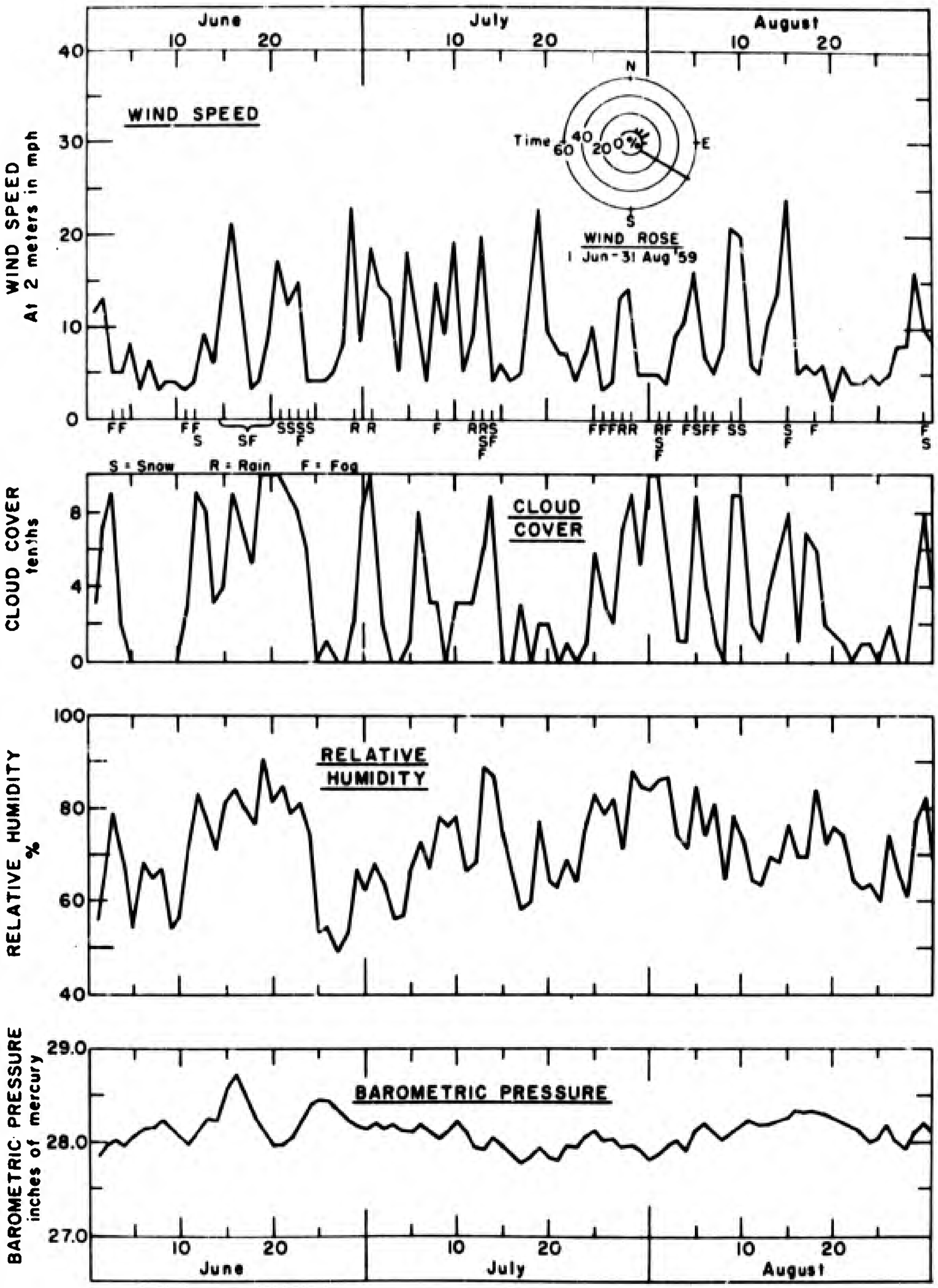
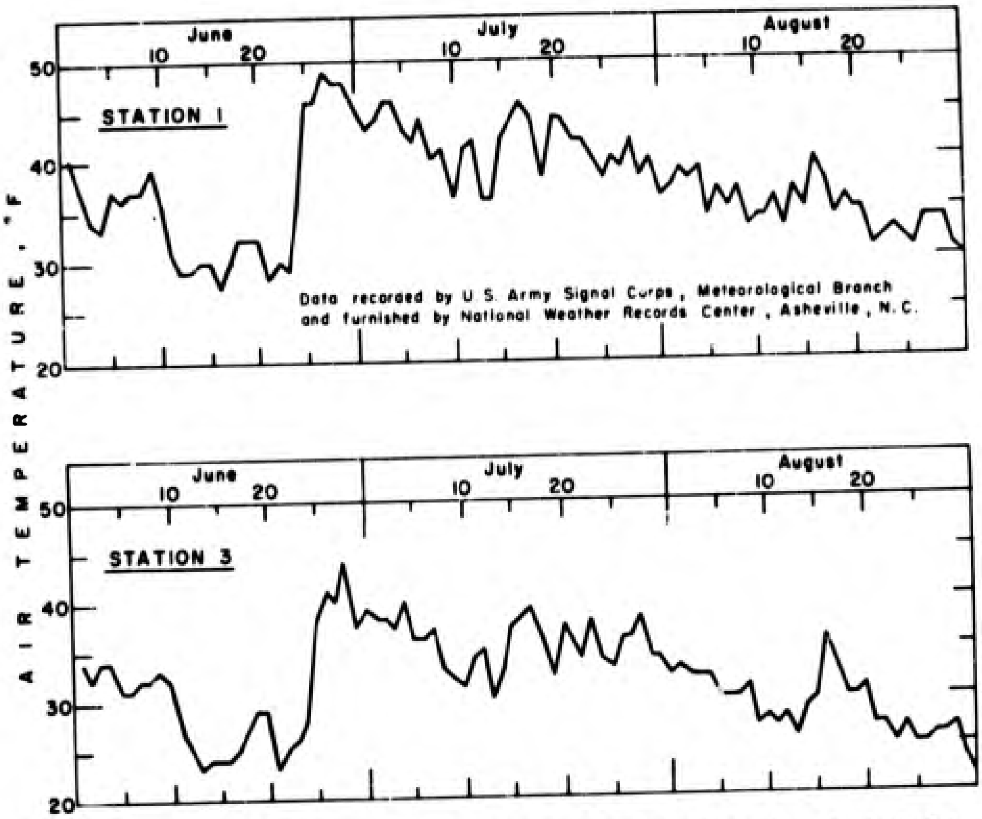


Figure A3. Average daily weather data, Station 1, Camp Tuto, Greenland, 1959.



Data recorded by U.S. Army Signal Corps, Meteorological Branch and furnished by National Weather Records Center, Asheville, N.C.

Figure A4. Average daily air temperature (within standard weather shelter), Stations 1 and 3, Camp Tuto, Greenland, 1959.

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APPENDIX B: TUTO RAMP SLOPE INDICATOR MEASUREMENTS, GREENLAND PROJECT NO. 1

by

Stanley D. Wilson

INTRODUCTION

This appendix is composed of two reports submitted by Mr. Stanley D. Wilson of Shannon and Wilson, Soil Mechanics and Foundation Engineers, Seattle, Washington. The first report, covering measurements of ramp movement made during summer 1958, was submitted on 18 March 1959. It comprises p. 51-64 of this appendix. The second report, covering measurements made in summer 1959, was submitted on 29 February 1960. The text of this report appears on p. 64-66, but the data have been plotted on the figures in the 1958 report (Fig. B1-B17) for easier comparison with the earlier measurements.

1958 MEASUREMENTS*

Introduction

In May 1957, the writer was engaged by USA EWES to assist in obtaining subsurface measurements of the movement of the TUTO Ramp with the Wilson Slope Indicator. Descriptions of the instruments used and the field installation of observation wells, and a detailed analysis of the movements from May through August 1957, were given in a report of 28 February 1958 (USA EWES, 1963)†.

During the summer of 1958, additional measurements were obtained by personnel from USA ACFEL. An analysis of these data follows.

Analysis of slope indicator data

Hole D-10. This hole continued to be the most interesting hole and to yield the most valuable data of all the observation wells installed. Details of the graphical procedure for spiral correction were described in the 1957 report; however, the 1958 data required two additional correction factors. First, the plastic casing had elongated vertically about 20 in. So that the readings would be taken at the same relative place in each section of casing, the readings on the tape were increased by 1%. Second, 22.20 ft were cut from the top of the casing in increments as the ice melted. All data in this report have been corrected to refer to the same position in the casing as in the initial survey. The bottom of the casing, originally 205 ft beneath the ramp surface, in March 1959 was approximately 185 ft beneath the surface, but is still shown on the graphs at 205 ft.

Field measurements were obtained 7 June, 3 July, 30 July and 23 August 1958. The 7 June data were not taken at the correct depths because of the elongation and were somewhat erratic; therefore, they are not included in this report.

Figure B1 gives plots of the computed east-west component dial unit changes between the date of installation (20 May 1957) and 26 August 1957 (taken from Fig. C4, USA EWES, 1963), 3 July 1958, and 23 August 1958.

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* Submitted 18 March 1959.

† Appendix C of this reference describes instrumentation and procedure for conducting this study.

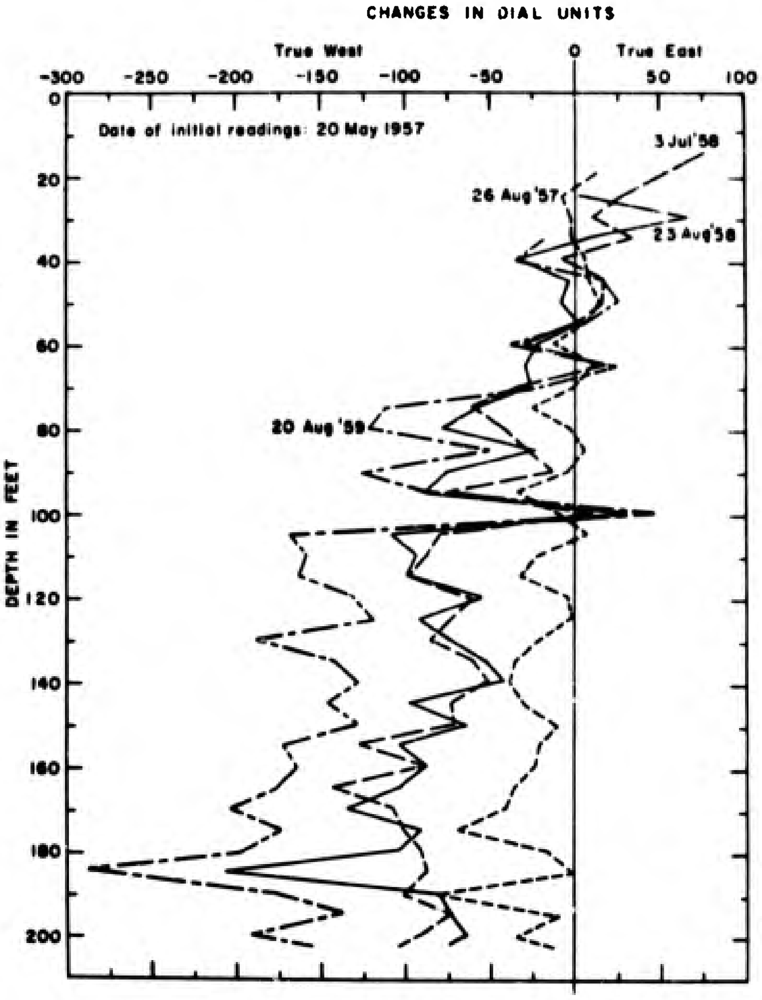


Figure B1. Hole D-10, east-west component of dial changes, 1957, 1958 and 1959.

From Figure B1, it is concluded that 1) The 1958 data show local irregularities of generally the same order of magnitude as that reported at the end of the first season; however, there is little, if any, correlation of such irregularities at equal depths. 2) The data of 3 July and 23 August 1958 are nearly identical; i.e., there was no E-W component of movement during the 1958 summer season.

In an attempt to learn more about the local irregularities, readings were taken in the E-W slots only between depths of 110 and 155 ft, where these slots were closely oriented to the true E-W component. Comparison of the changes from 3 to 30 July with those from 3 July to 23 August 1958 (Fig. B2) shows local irregularities but no overall trend of movement in the E-W direction; this checks the data of Figure B1.

On Figure B3 is plotted the true E-W component of movement from the date of installation to 23 August 1958. The data for 3 July checked those for 23 August 1958 within a fraction of an inch. Shown for comparison are the corresponding data from the 1957 report.

Vertical elongation measurements were continued, but with considerably less precision. Figure B3 also gives plots of the most reliable data that could be computed from the field data; this involved some interpolation of original data, as shown in Table BI.

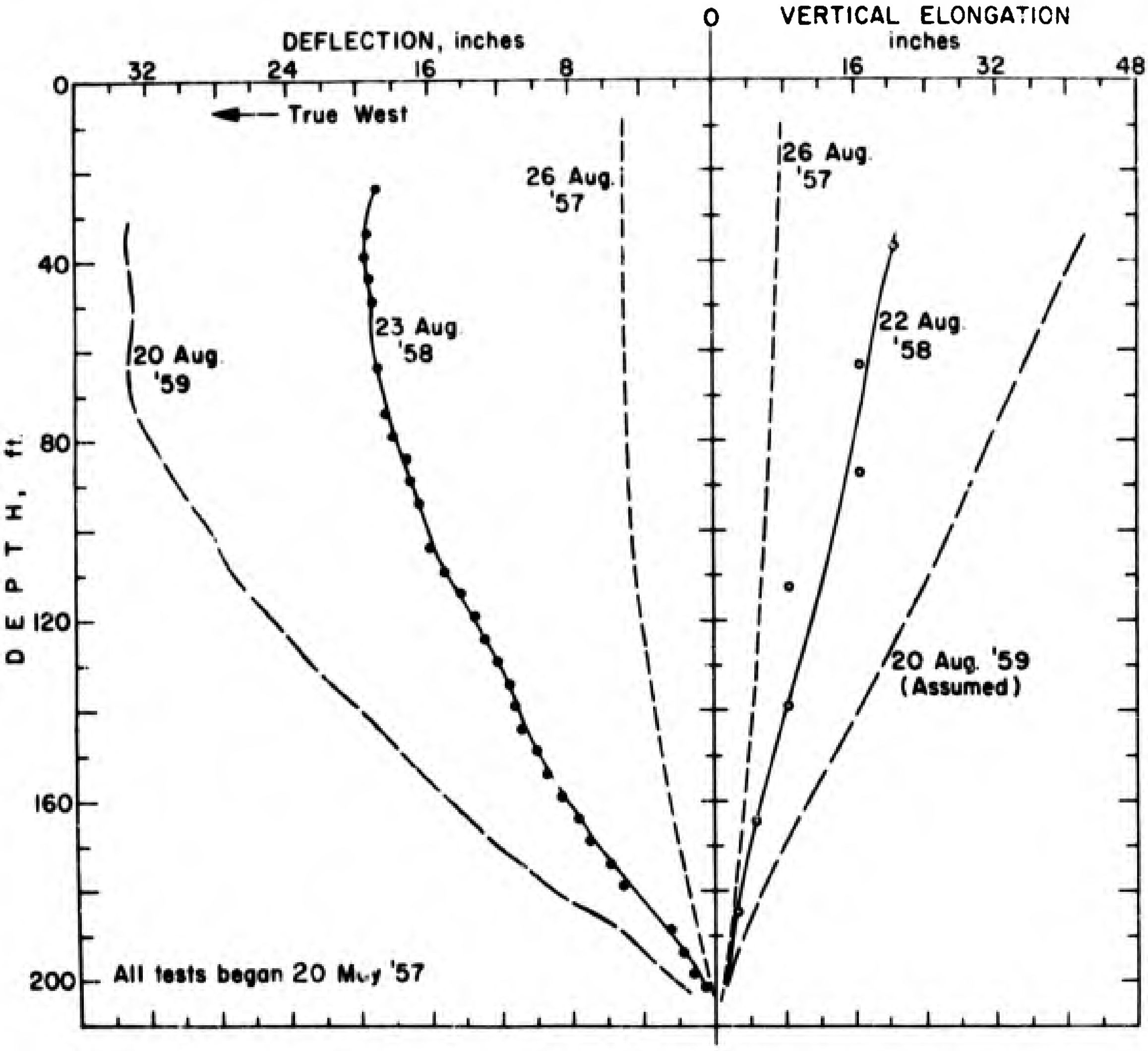


Figure B3. Hole D-10, east-west deflections and vertical elongations, 1957, 1958 and 1959.

In Figure B6 are plotted true displacements (corrected for spiral) of the plastic casing from the initial installation to 3 July, 30 July and 23 August 1958. This plot shows an exceptionally well defined orientation of total movement up to the end of August 1958, oriented N62°W. During the months of July and August, however, the movement of all individual points was actually due north or even a little east of north. Note also that most of this movement developed in July.

In Figure B7 are plotted the true N-S component of dial unit changes for the months of July and August 1958, and the computed displacements. Note the same pattern of local irregularities as reported previously and the change in pattern of displacements for the two periods. Most of the displacement below 100-ft depth occurred in July; that in the upper 100 ft developed in August.

Information as to the magnitude and direction of total movement of the top of the casing is given in an Addendum (p. 62).

Hole D-11. The casing in Hole D-11 was originally installed through the ice cap and into the permafrost to a total depth of 245 ft. The underlying moraine material was encountered at 200 feet. During the freezing it was pinched off at a depth of 97.6 ft. Subsequently, it was found that the slope indicator would not go below 54 ft in the north-south slots. In late July 1958, it was found that the instrument would track properly down to depths of about 84 ft; however, the data obtained are not considered reliable.

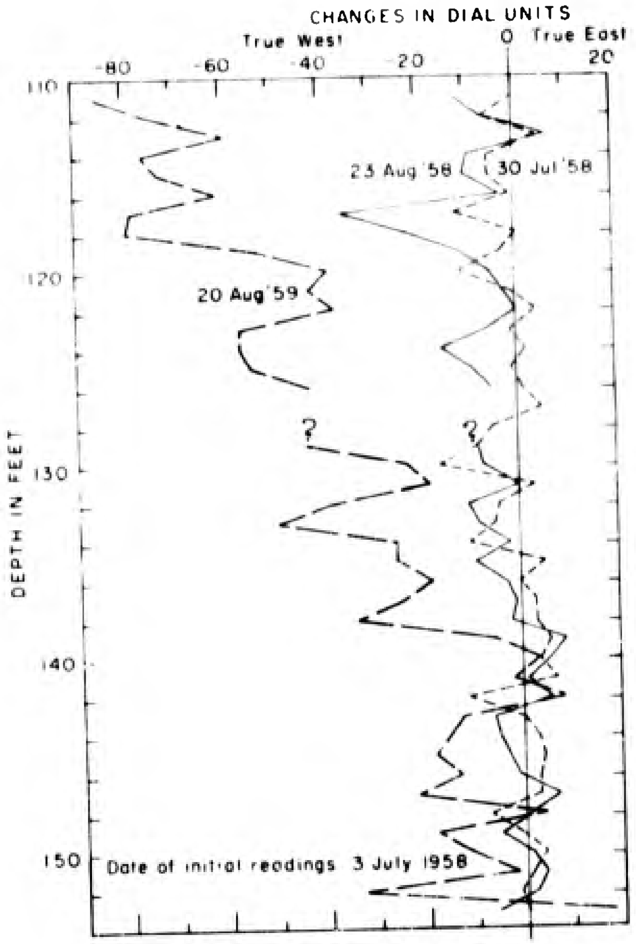


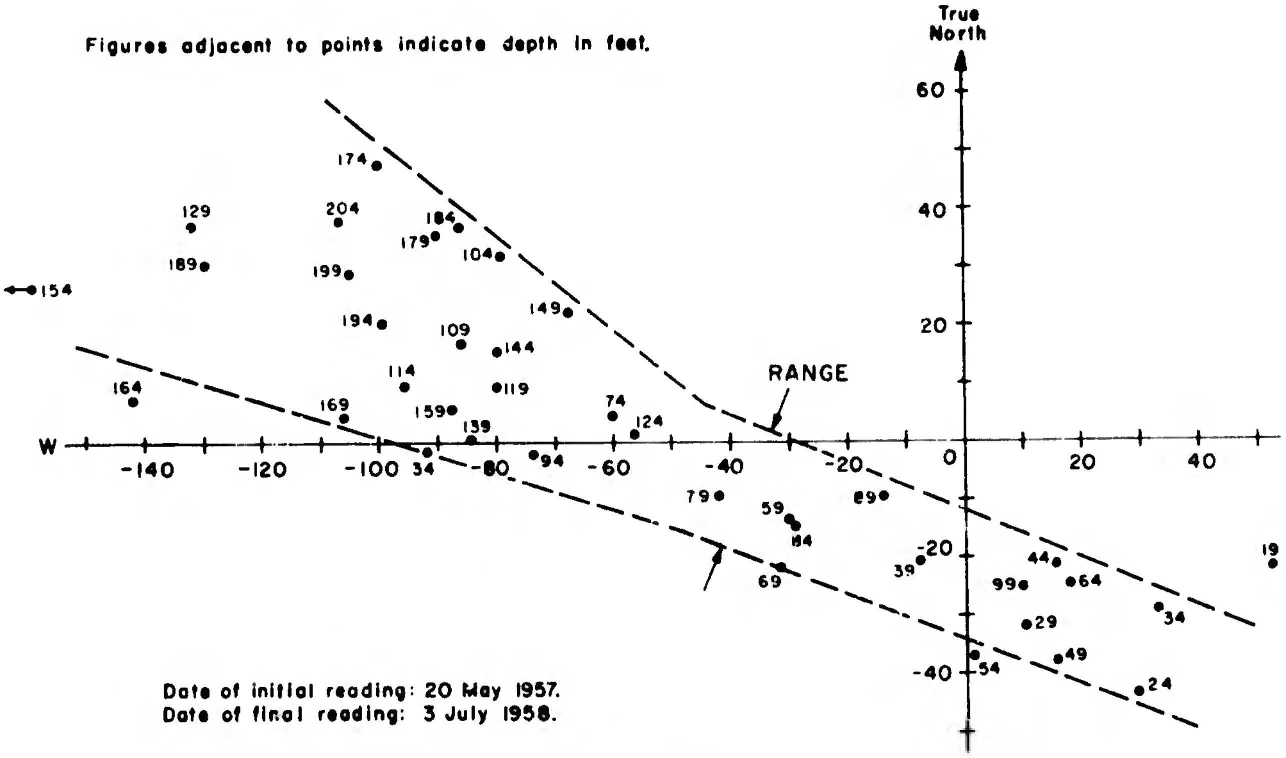
Figure B2. Hole D-10, east-west component of dial changes, 1958 and 1959.

Table BI. Elongation in Hole D-10, measured depths of joints from top of casing

23 May 1957 *(ft)*	*22 Aug 1958* *(ft)*	*Elongation* *(ft)*	*Summation* *(ft)*	*(in.)*
36.82	37.48	+0.66	1.68	20.2
(61.93)	62.87	+0.94	1.40	16.8
87.06	87.99	+0.94	1.40	16.8
(112.11)	113.73	+1.62	0.72	8.6
(137.24)	138.85	+1.61	0.73	8.8
(162.34)	164.27	+1.93	0.41	4.9
(182.43)	184.57	+2.14	(0.20)	2.4
	Bottom		0	

Note: Values in parentheses are interpolated data.

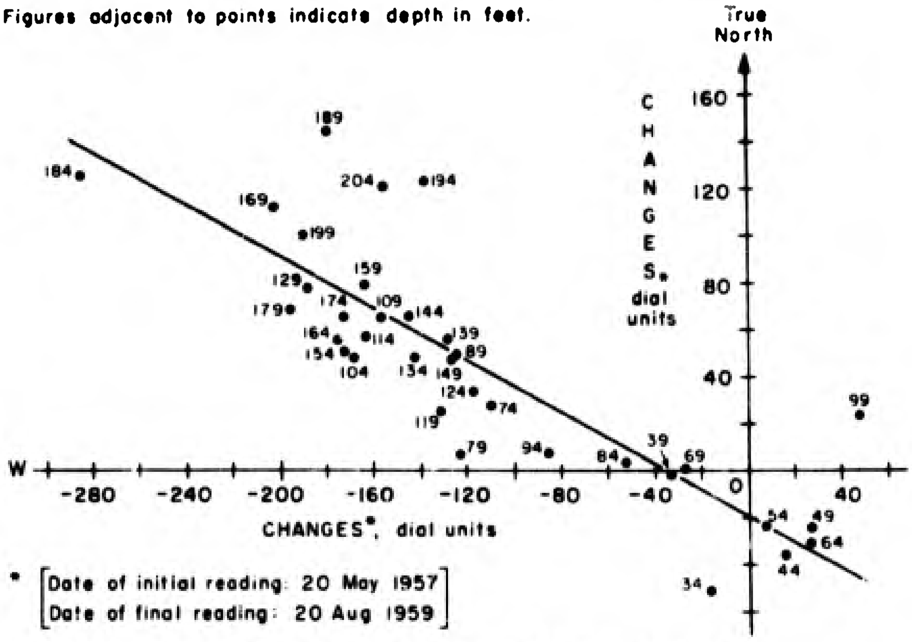
Because of the apparent lack of E-W movement during the 1958 season, considerable effort was made to determine the true magnitude and direction of total movement. The total dial unit changes from 20 May 1957 to 3 July 1958 are plotted in Figure B4a. These data are very consistent with respect to orientation and magnitude of movement. Figure B5 gives plots of total dial changes from the initial date to 23 August 1958 and the measured changes from 3 July to 23 August 1958. Note the rather marked change in orientation that developed during the summer.



Figures adjacent to points indicate depth in feet.

Date of initial reading: 20 May 1957.
Date of final reading: 3 July 1958.

Figure B4a. Hole D-10, dial changes, 1957-1958.



Figures adjacent to points indicate depth in feet.

* [Date of initial reading: 20 May 1957
Date of final reading: 20 Aug 1959]

Figure B4b. Hole D-10, dial changes, 1957-1959.

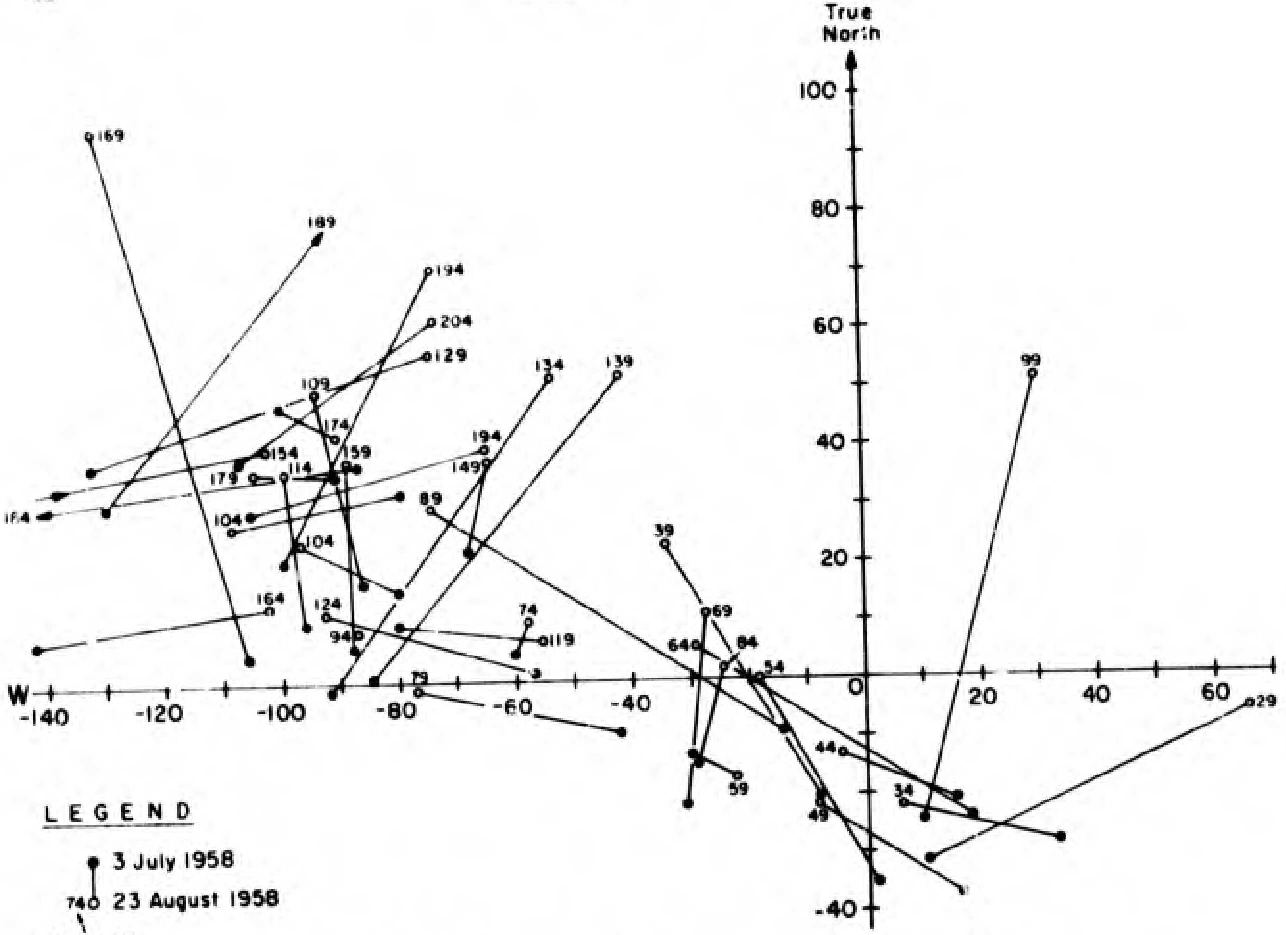


Figure B5. Hole D-10, dial changes, 3 July 1958 to 23 August 1958.

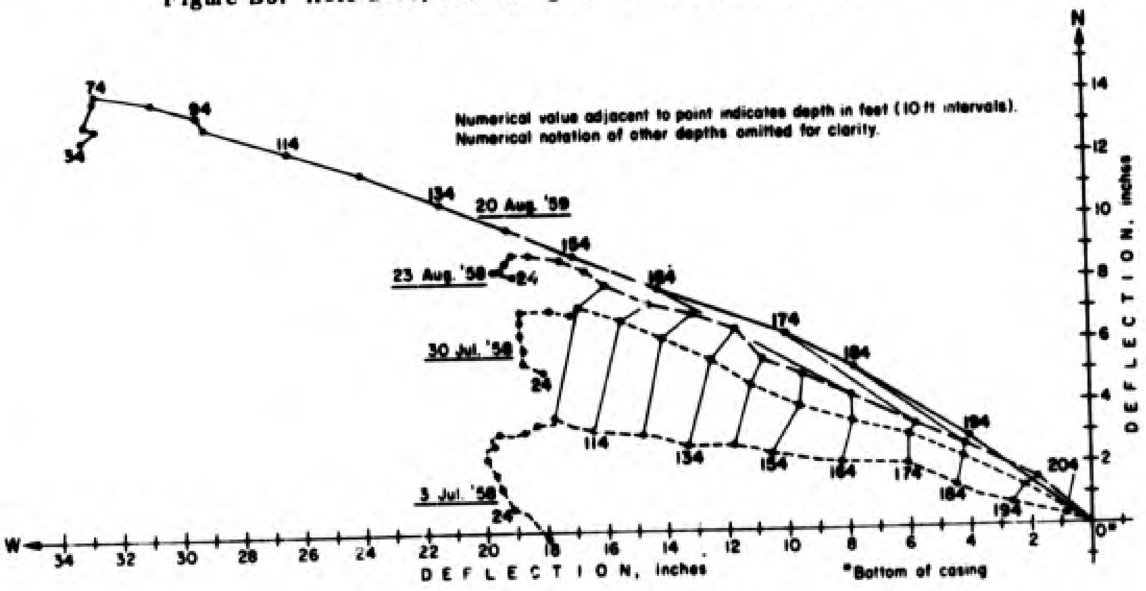


Figure B6. Hole D-10, deflections, 1958 and 1959.

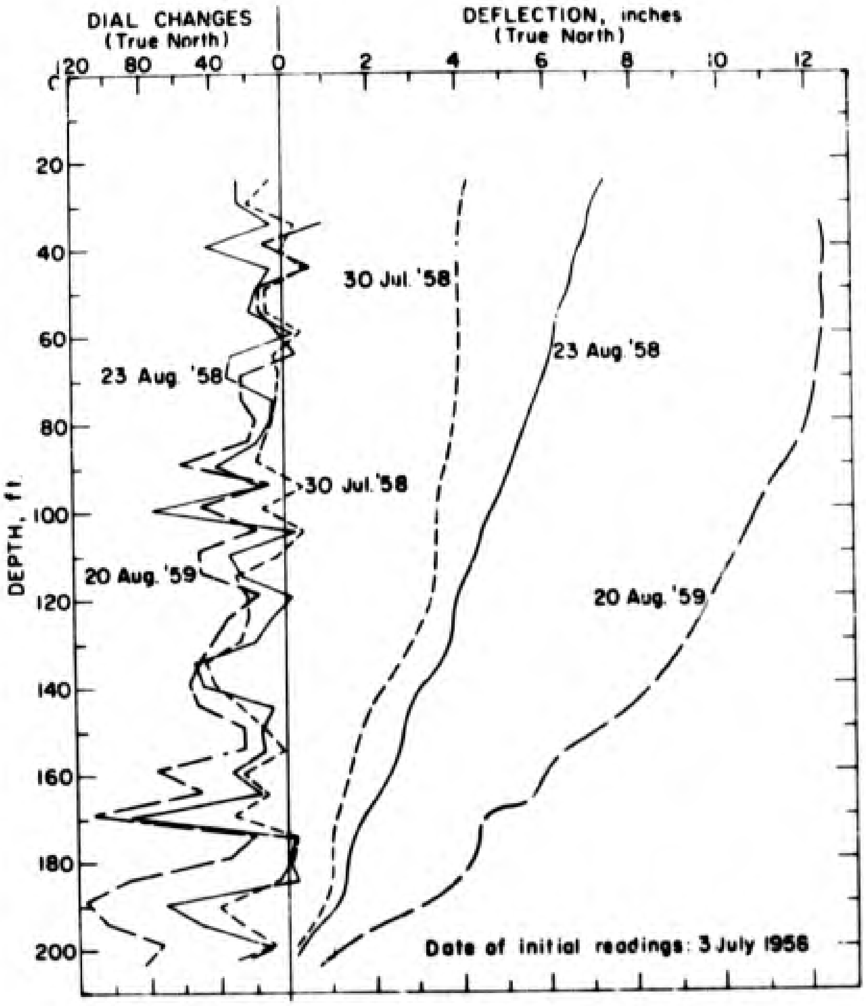


Figure B7. Hole D-10, north-south component of dial changes and deflections, 1958-1959.

In Figure B8 are plotted the corrected total dial changes from the initial date of 14 June 1957 to 29 July 1957 (taken from Fig. 7 of the 1957 report) and from the initial date to 21 August 1958. There appears to be an E-W trend, although the data are rather erratic. Figure B9 shows the E-W component of dial changes and Figure B10 the computed E-W movements. A total westward movement of the upper 55 ft of ice of about 1 in. in 14 months was recorded.

Hole D-12. Figure B11 shows the total two-dimensional dial changes that were recorded between the initial set of 17 June 1957 and 23 August 1957, and the total as of 21 August 1958. Note the random scatter. In Figure B12 are plotted the E-W component of these changes and in Figure B13 the computed movements. The total differential movements from August 1957 to August 1958 certainly do not exceed 1 in., and even this amount may be due to instrument inaccuracies. Elongation measurements in D-12 were inconclusive and are not reported.

Shallow holes. Most of the shallow holes were broken off, bent or otherwise abandoned. Dial change data from Holes D-12B, D-14 and D-15A are shown in Figures B14, B15, and B16. The data are inconclusive.

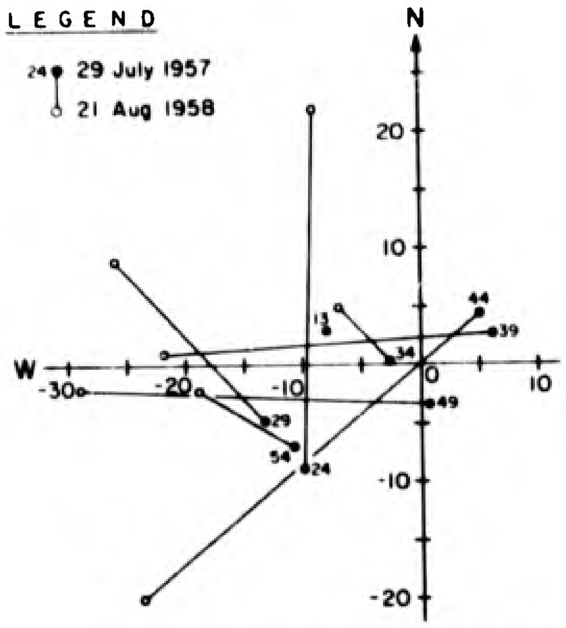
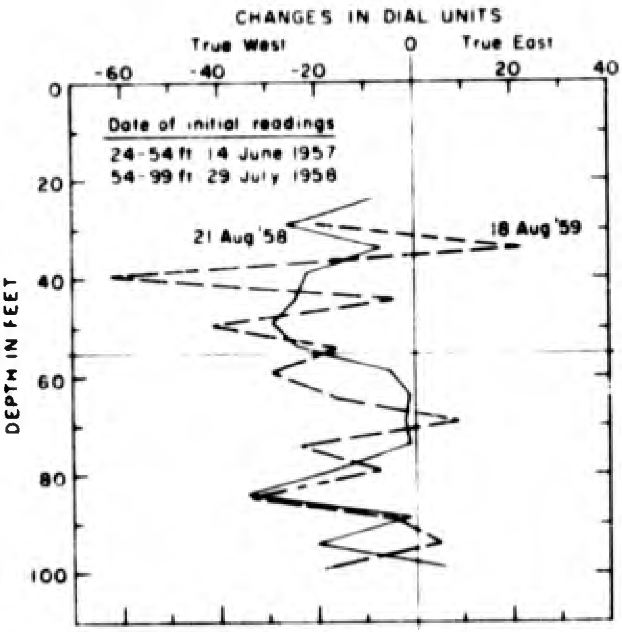


Figure B8. Hole D-11, dial changes, 29 July 1957 and 21 Augus. 1958. Initial reading 14 June 1957.



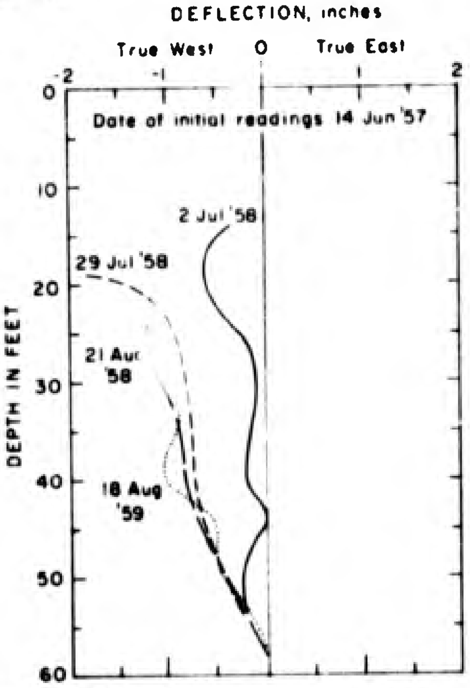


Figure B9. Hole D-11, east-west component of dial changes, 1958 and 1959.

Figure B10. Hole D-11, computed east-west deflections, 1958 and 1959.

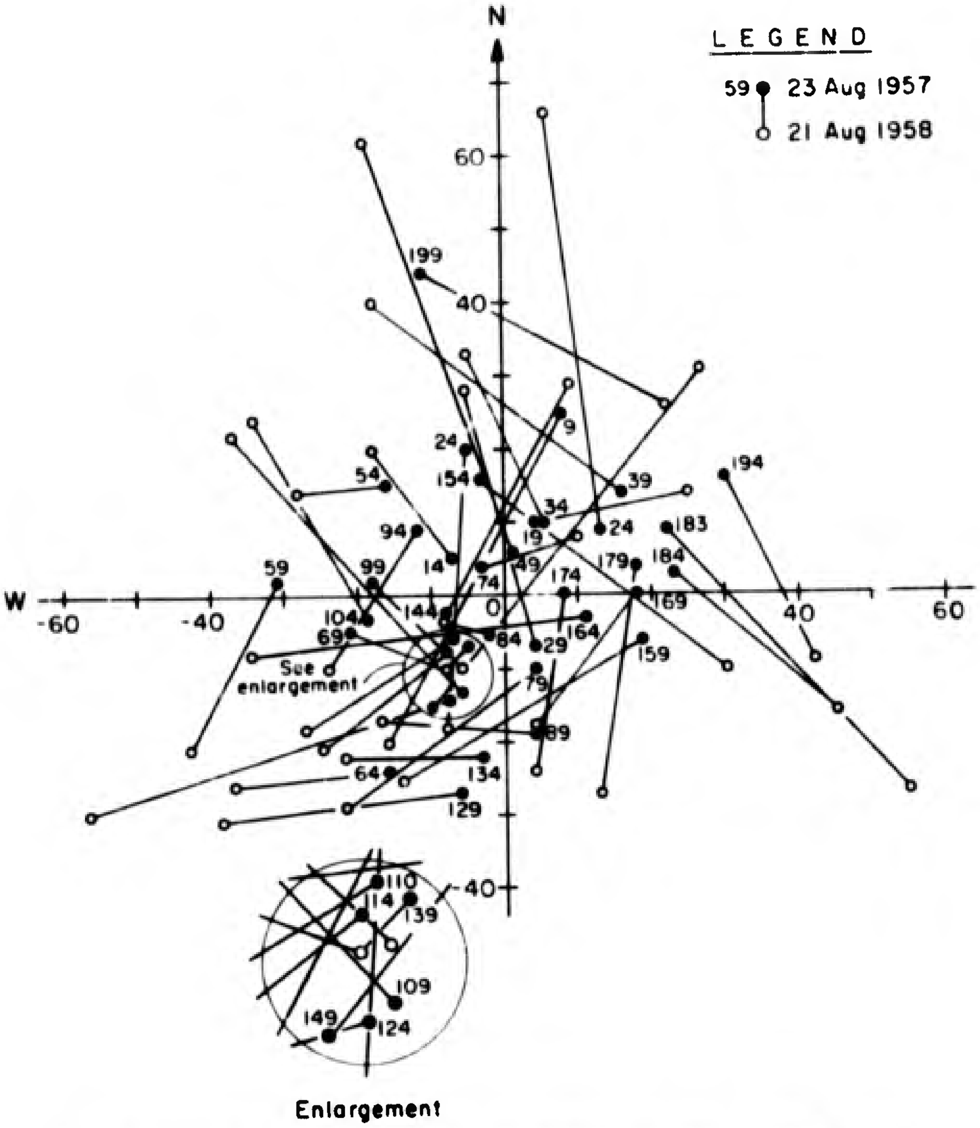


Figure B11. Hole D-12, dial changes, 23 August 1957 and 21 August 1958. Initial reading 17 June 1957.

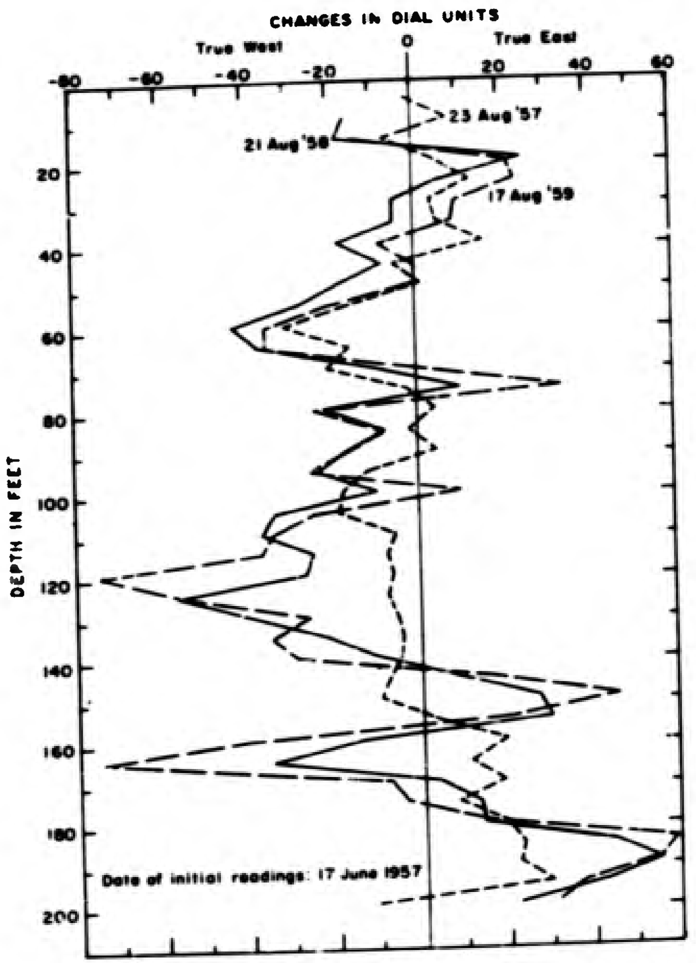


Figure B12. Hole D-12, east-west component of dial changes. 1957, 1958 and 1959.

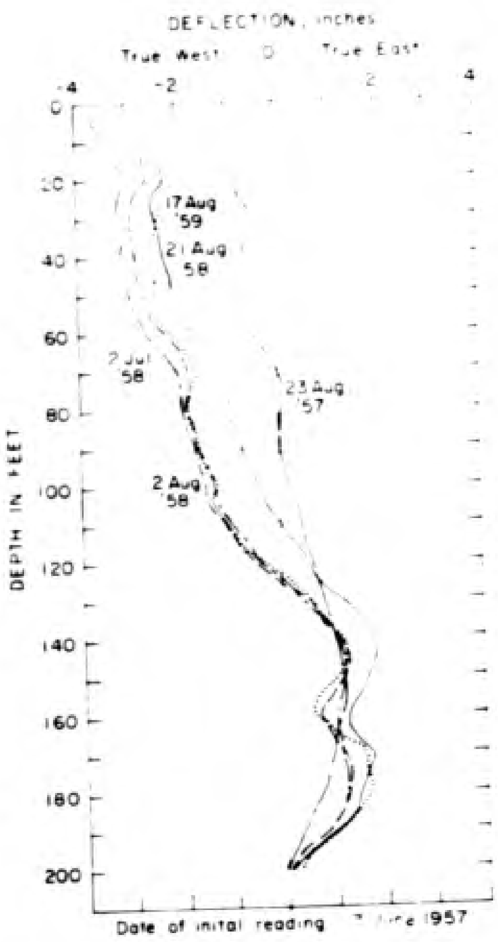


Figure B13. Hole D-12, east-west deflections, 1957, 1958 and 1959.

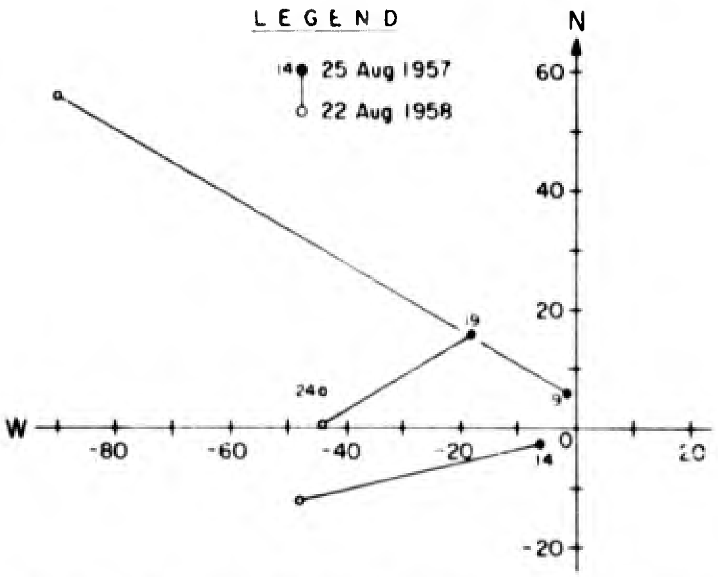


Figure B14. Hole 12-B, dial changes, 25 August 1957 and 22 August 1958.

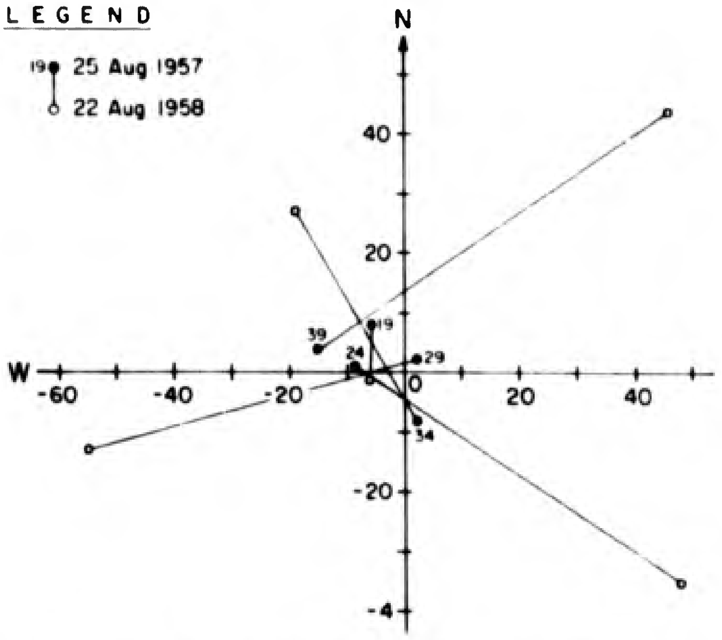


Figure B15. Hole D-14, dial changes, 25 August 1957 and 22 August 1958.

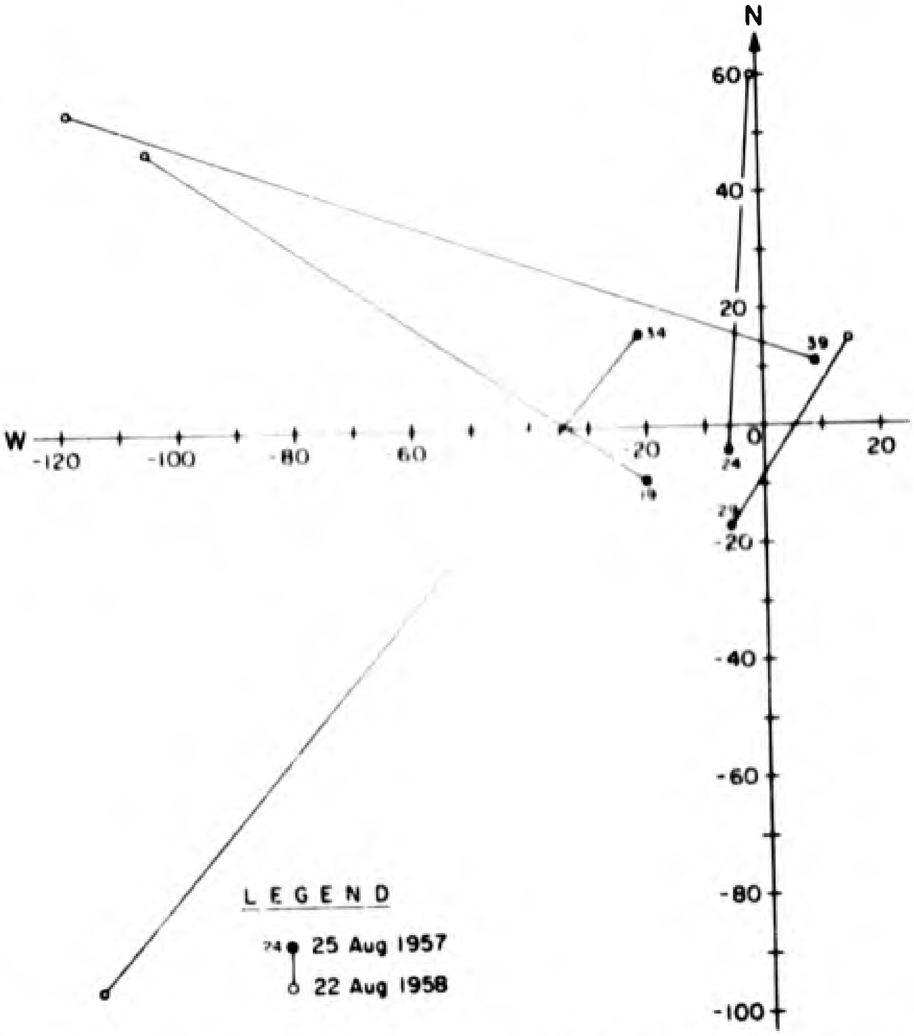


Figure B16. Hole D-15A, dial changes, 25 August 1957 and 22 August 1958.

Discussion of ice movements

The following information on differential movements of the plastic casing has been computed:

	E-W horizontal differential movement in./month			*Vertical elongation in./month*	
	Summer 1957	*Winter 1957-1958*	*Summer 1958*	*Summer 1957*	*Aug 1957-1958*
D-10	1.87	1.25	Zero	2.3	1.3
D-11	Zero	trace	trace		
D-12	Zero	0.1		none	none

From these computations it appears that the rate of both horizontal and vertical movements may be increased during the summer months as compared with the winter months, perhaps by as much as 50%.

APPENDIX B

In general, the 1958 data substantiate fully the general conclusions regarding the nature of the movements as set forth in the 1957 report. One exception to this is the unexplained northward movement of casing in Hole D-10 during July and August 1958. We have reviewed both the field data and our calculations and can find nothing to indicate inaccuracies in the data or error in the calculations. We are not aware of any changes in topography, construction programs, or unusual melt conditions that could explain such a shift in ice motion.

In the 1957 report the scatter of the data was commented upon with the explanation that it could result from instrument inaccuracies, improper freezing of the casing within the borehole, or errors in depth resulting from stretching of the casing. We have reviewed the data quite carefully in this regard and can find no indications of instrument inaccuracies or other errors that could explain this scatter. We conclude that the casing actually deformed in the manner indicated on the plots. We suspect that actual deformation of the ice may develop such that slippage takes place erratically with first one layer deforming, then another, etc. Possibly this is also connected with the erratic surface hummocks.

ADDENDUM

Subsequent to the submittal of the preceding part of Appendix B, information concerning the 1958 surface movements became available. These data help explain the apparent northward component of movement of D-10 during the summer months of 1958. Figure B17 shows the measured surface position of the top of the casing on various dates and the relative position of the plastic casing in early July and late August 1958, taken from Figure B6. Note that the top of the casing has moved nearly due west, whereas the lower position of the casing has moved southwest. Thus, the relative movement of the top with respect to the bottom has been northerly, as shown in Figure B6.

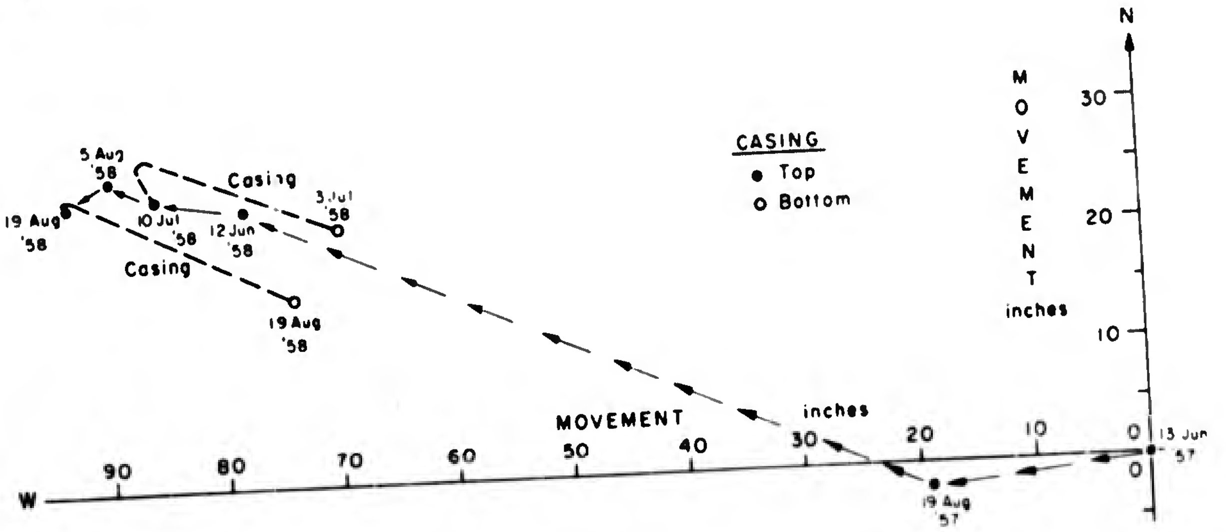


Figure B17. Hole D-10, casing movements, 1957 through 1958.

The surface measurements show that the top of the casing is moving at an average rate of 6.5 ft/year, or 6.5 in./month. Thus, from 20 May 1957 to 19 August 1958, the top would have moved about 97 in. Since the relative movement top to bottom is only 21 in., more than ¾ of the total movement occurs below the bottom of the casing. This checks quite well the findings reported in our 1957 report.

No information is available as to the total vertical movement of the top of the casing.

At D-12, the total movement since the installation amounted to about 15 ft, or twice that of D-10; yet in this period the relative movement of the upper 200 ft of ice could not exceed 2 in.

At D-11, where the total movement was 1 ft/year, the relative movement of the upper 50 ft did not exceed 1 in.

1959 MEASUREMENTS*

During the summer of 1959, additional subsurface measurements were obtained by personnel from USA ACFEL. An analysis of these data follows.

Analysis of slope indicator data

Hole D-10. This continued to be the most interesting hole and to yield the most valuable data of all the observation wells installed. Details of the graphical procedure for spiral correction were described in the 1957 report; however, the 1958 data required two additional correction factors. First, the plastic casing had elongated vertically about 20 in. So that the readings would be taken at the same relative place in each section of casing, the readings on the tape were increased by 1%. Second, 22.20 ft were cut from the top of the casing in increments as the ice melted.

The data of this report were taken after an additional 9.01 ft were cut from the top. During the year the casing stretched an additional 1.8 ft; therefore, all depths were again adjusted in an attempt to take readings at the same position in the casing as in the original survey. The bottom of the casing, originally 205 ft beneath the ramp surface, at the time of this report was about 176 ft beneath the surface, but is still on the graphs at 205 ft. The casing had been broken (probably pulled apart) about 25 ft below the surface. At this depth the tube filled with ice which when melted with hot antifreeze came up around the outside of the tube.

Field measurements were obtained on 14 August and on 20 August 1959. Only the data of the latter date were analyzed since those of the first date were not properly adjusted for depth.

Figure B1 (modified from the 1958 report) gives plots of the computed E-W dial unit changes between the date of installation (20 May 1957) and 26 August 1957, 3 July 1958, 23 August 1958 and 20 August 1959.

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* Submitted 29 February 1960.

All data show local irregularities of generally the same order of magnitude as that reported at the end of the first season. There is little, if, any, correlation of such irregularities at equal depths for the earlier data, but for the 1958-59 period the irregularities appear at identical depths.

In an attempt to learn more about the local irregularities, initial readings were taken in 1958 in the E-W slots between depths of 110 and 155 ft, where these slots were closely oriented to the true E-W component. Comparison of the changes in the summer of 1958 with those during 1959 (Fig. B2) show local irregularities but no consistent pattern. There is also some question as to whether all the data from Figure B2 were obtained at equivalent depths.

In Figure B3 is plotted the true E-W component of movement for the period from the date of installation to 20 August 1959. Shown for comparison are the corresponding data from the 1957 and 1958 reports.

Vertical elongation measurements were attempted without success. However, the total elongation of the casing increased 1.80 ft. Figure B3 indicates the probable shape of this curve, based on earlier data.

In Figure B4b are plotted the total dial changes from 20 May 1957 to 20 August 1959.

In Figure B6 are plotted true displacements (corrected for spiral) of the plastic casing from the initial installation to 3 July, 30 July and 23 August 1958 and 20 August 1959. This plot shows an exceptionally well defined orientation of total movement up to the end of August 1959, oriented approximately N62°W.

In Figure B7 are plotted the true N-S component of dial unit changes and the computed displacements starting with 3 July 1958. Note the same pattern of local irregularities as reported previously.

Information as to the magnitude and direction of total movement of the top of the casing has not been made available.

Hole D-11. The casing in Hole D-11 was originally installed through the ice cap and into the permafrost to a total depth of 245 ft. During the freezing it was pinched off at a depth of 97.6 ft. Subsequently, it was found that the slope indicator would not go below 54 ft in the N-S slots. In late July 1958, it was found that the instrument would track properly down to depths of about 84 ft; however, the data obtained were not considered too reliable. An additional set was obtained on 18 August 1959. Figure B9 shows the E-W component of dial changes and Figure B10 the computed E-W movements. The data are somewhat erratic but indicate a total westerly movement of less than 2 in.

Hole D-12. Figure B12 shows the total E-W component of dial changes in D-12, and Figure B13 shows the computed movements. The total differential movements from August 1958 to August 1959 certainly do not exceed a fraction of an inch.

Elongation measurements in D-12 were inconclusive and are not reported.

Shallow holes. All the shallow holes were abandoned.

Discussion of ice movements

The following information on differential movements of the plastic casing has been computed:

E-W horizontal differential movement, in./month

	Summer 1957	*Winter 1957-1958*	*Summer 1958*	*Winter 1958-1959*
D-10	1.67	1.25	0	1.16
D-11	0	trace	trace	0
D-12	0	0.1		0

Vertical elongation, in./month

	Summer 1957	*Aug 1957-1958*	*Winter 1958-1959*
D-10	2.3	1.3	1.8
D-11			not known
D-12	0	0	0

In general, the 1959 data substantiate fully the general conclusions regarding the nature of the movements set forth in the 1957 and 1958 reports.

In earlier reports the scatter of the data was commented upon with the explanation that it could result from instrument inaccuracies, improper freezing of the casing within the borehole, or errors in depth resulting from stretching of the casing. We have reviewed the data quite carefully in this regard and can find no indications of instrument inaccuracies or other errors that could explain the scatter. We conclude that the casing actually deformed in the manner indicated on the plots. We suspect that actual deformation of the ice may develop such that slippage takes place erratically with first one layer deforming, then another, etc. Possibly this is also connected with the erratic surface hummocks.

APPENDIX C: MELT-WATER GAGING PROGRAM PROJECT NO. 1. APPROACH ROADS - TUTO AREA GREENLAND

SUMMARY

Measurements of melt-water flow from the ice and snow cover were made at various gaging stations in the vicinity of Ramp, Transverse, and Access Roads near Camp Tuto, Greenland, during the summer of 1958. The purpose of these measurements was to determine the amount of melt-water flow in the vicinity of the roads. Measurements were limited chiefly to total runoff from each of two areas, although an effort was made to measure the runoff from secondary melt-water streams immediately to the north of Ramp Road. The maximum total flow from both areas observed was about 120 ft^3/sec and was observed at 1630 on 2 August. Flow was slightly in excess of 100 ft^3/sec on 12 July at 1400 hours. Runoff was affected by temperature, which in turn was affected by cloud cover, wind velocity, and elevation of observation points.

Study area

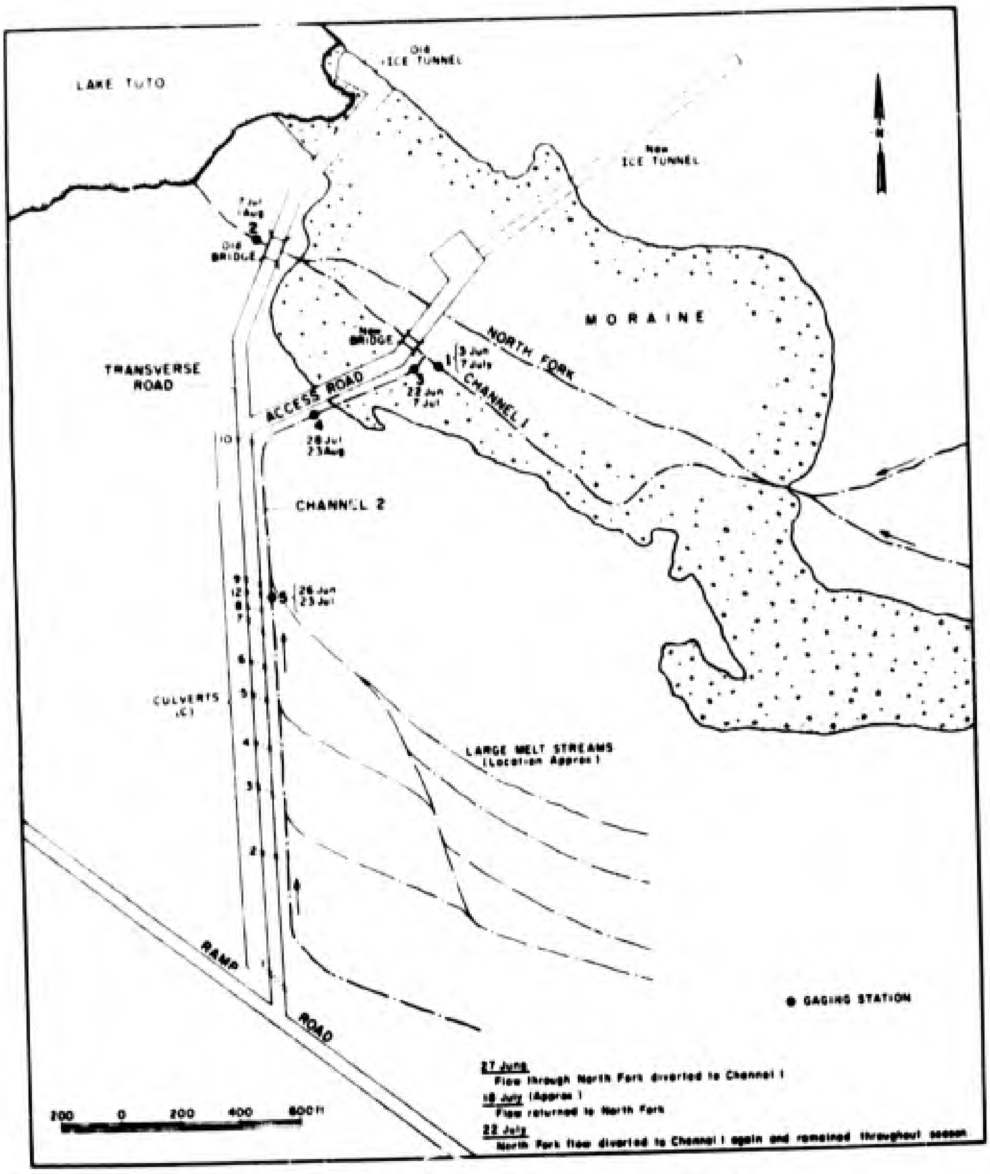
East of Camp Tuto, Greenland, earth-fill approach roads were constructed to the ice cap and to the two ice tunnels. The main road leading to the ice cap was designated Ramp Road and the roads leading to the old and new ice tunnels were designated Transverse and Access Roads, respectively. The location and alignment of the roads are shown on Figures C1 and C2.

The elevation of the ice cap rose rapidly from Transverse and Access Roads eastward; along Transverse and Access Roads the elevation of the ice decreased in a northerly direction. Thus, all melt-water streams that developed flowed westward and thence northerly along Transverse and Access Roads. Culverts in Transverse Road and bridges in both roads leading to the ice tunnels were provided to prevent ponding of flow (Fig. C1).

The problem

During the summer months, the melting of snow and ice to the east and north of the area bounded by the approach roads caused considerable flow along the north side of Ramp Road and along the east side of Transverse and Access Roads. Slopes were steep enough to produce high stream velocities. During the peak of the melt season, sufficient water was discharged to erode large quantities of fill material and cause the roads to become impassable.

The melt water apparently was concentrated in a large stream (channel 1) along the base of the moraine and in a large stream (channel 2) travelling northward along the east side of Transverse and Access Roads. The two melt streams merged immediately upstream from the new bridge on Access Road and passed westward into Lake Tuto through the bridge in Transverse Road. Thus, the melt-water flow was apparently controlled by conditions in two principal drainage areas. Area 1 was approximately 0.7 square miles and was located east of the moraine; drainage was through a depression in the moraine. Area 2 was approximately 1.6 square miles and was bounded by area



27 June
Flow through North Fork diverted to Channel 1
18 July (Approx.)
Flow returned to North Fork
22 July
North Fork flow diverted to Channel 1 again and remained throughout season

Figure C1. Main gaging station locations.

1 on the north, Ramp Road on the south and Access and Transverse Roads on the west. The upper limits of the drainage areas to the east were not defined clearly because of deep slush ice conditions. However, only a small amount of melt water originated farther east than the end of Ramp Road (Mile 3).

The use of culverts through the road fills to divert a portion of the melt water being impounded was unsuccessful. The melting of ice in and around the culverts and the erosion of the adjacent earth fill caused the culverts to become perched and thus inoperative.

Purpose and scope of measurements

To collect hydrological data on the rate and quantity of melt-water flow over representative areas of the Tuto ice cap, a limited gaging program was set up during the summer of 1958. An effort was made to relate the rate and quantity of melt-water flow to meteorological conditions as affected by the time of day or month. Attempts also were made to determine the general orientation of melt channels, the effect of precutting channels, and the degradation of the ice channels, particularly in the vicinity of the bridge locations.

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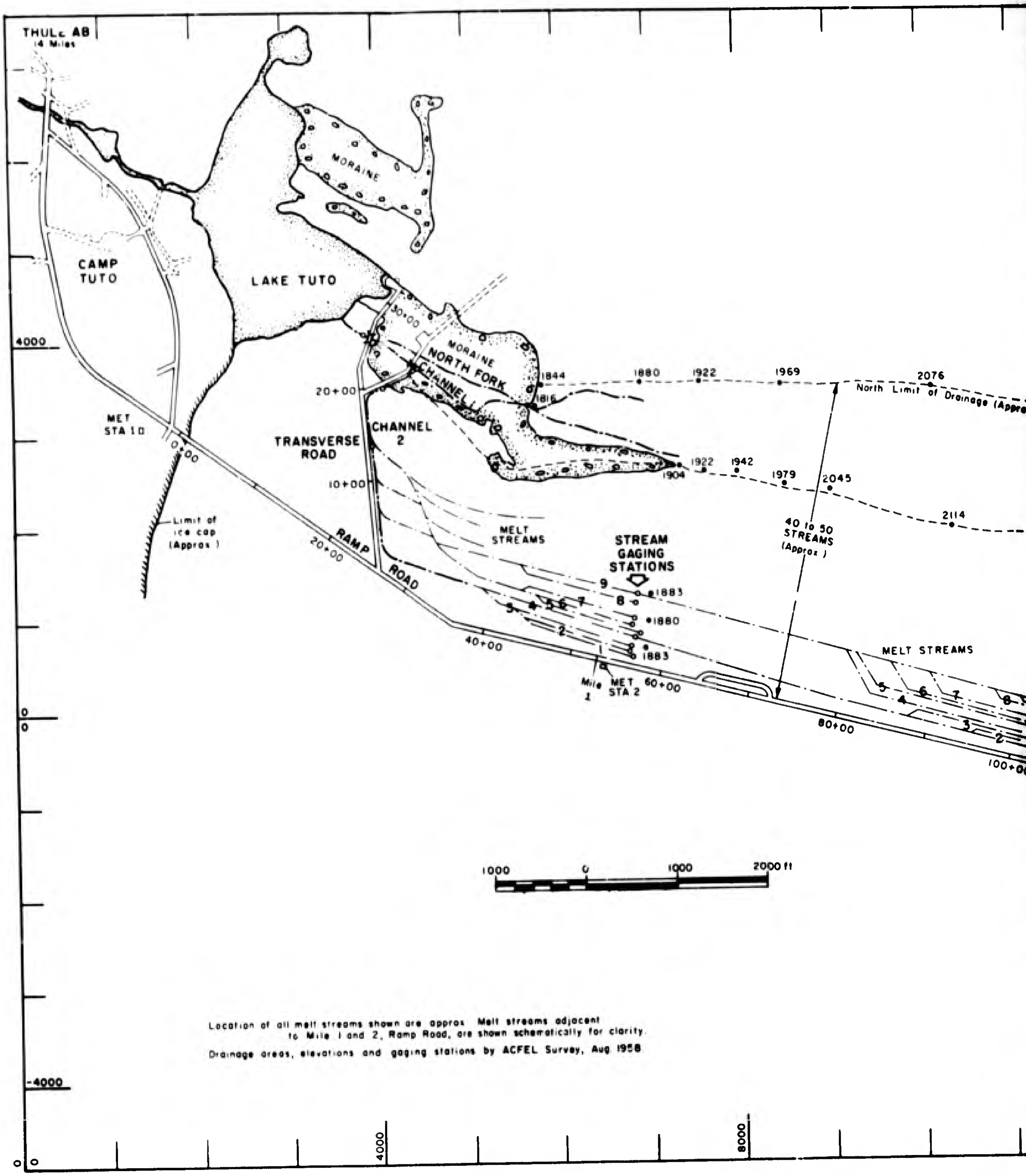

Location of all melt streams shown are approx. Melt streams adjacent to Mile 1 and 2, Ramp Road, are shown schematically for clarity.

Drainage areas, elevations and gaging stations by ACFEL Survey, Aug 1958.

A

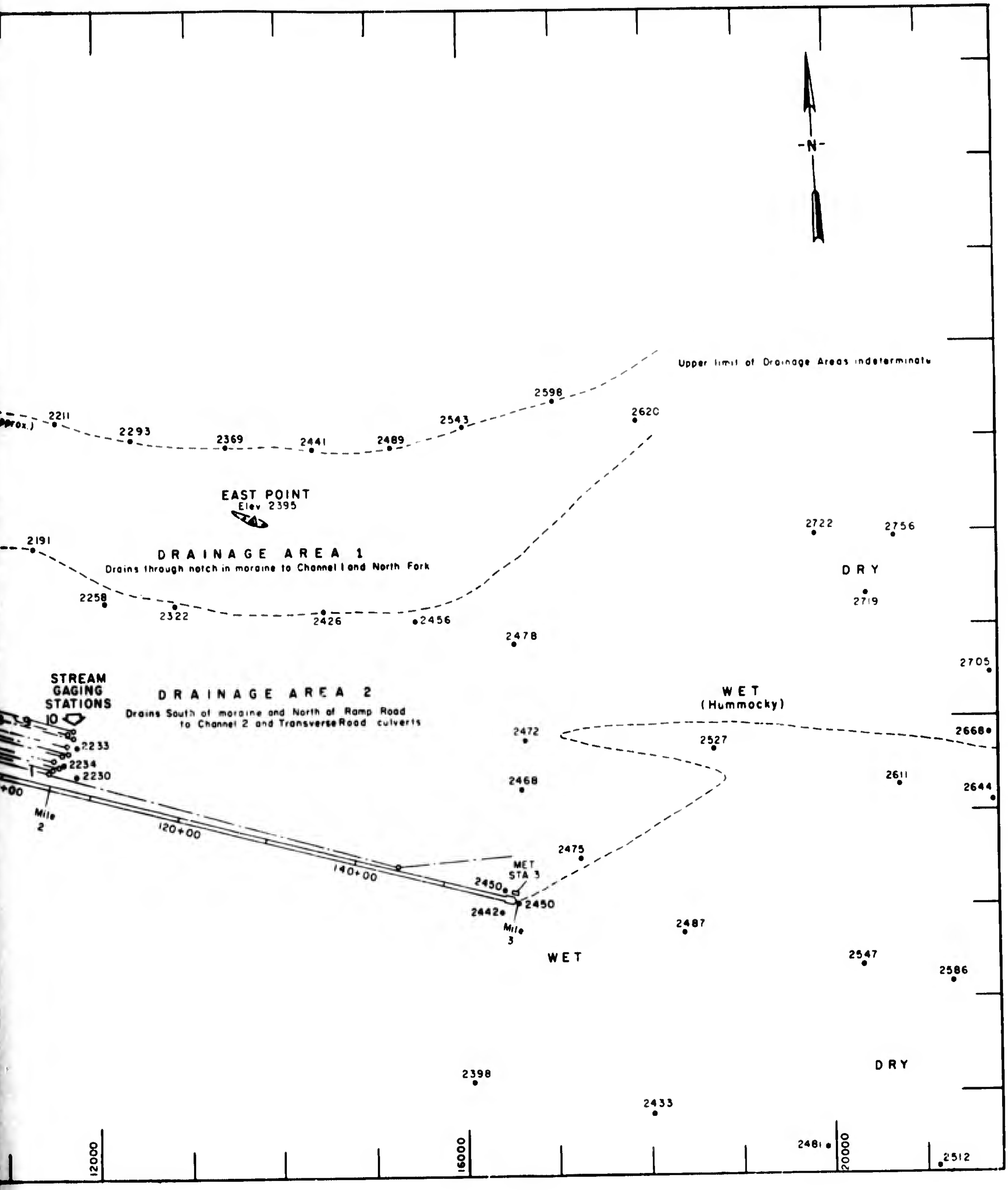

Figure C2. Vicinity of Camp Tuto.

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Test procedures

Gaging stations. Main gaging stations were located at the (old) bridge on Transverse Road, at culvert C12 while it was operational, at the (new) bridge to Access Road, and on channel 2 south of the new bridge. Locations of gaging stations are shown on Figure C1. Measurements were made at various times during the day at each station and on two occasions hourly measurements were made for a 24-hour period at Station no. 4 on channel 2 south of the new bridge. In an effort to determine the runoff for various parts of the drainage area, secondary gaging stations were set up on melt streams located from 50 to 800 ft north of and parallel to Ramp Road; observations were made at Miles 1, 2, and 3.

Gaging methods. The method of discharge determination varied from station to station and depended upon conditions at the gage site. For the most part discharges were based upon velocity measurements at a particular point and the cross-sectional area of the melt stream. Point velocities in the stream were measured by pygmy or standard current meters and/or a pitot tube. Where conditions prevented such methods, average velocities were determined by timing floats or dye slugs over measured distances. Because of steep gradients, corresponding high velocities, and changing configuration of the melt streams, determination of flow by weirs or Parshall flumes was not possible. A salt-dilution method was considered but discarded because of damage to the equipment at the site.

Measurements were made under extreme conditions. The melt streams were constantly changing because of alternating cold and warm periods. When flowing, the streams were extremely turbulent and often contained large quantities of slush or ice fragments, and large rocks and boulders. Flow was particularly turbulent at the new Access Road bridge where flow from channel 2 intersected channel 1 at about right angles. In almost every instance before measurements could be made, the channels had to be cleared of boulders and ice fragments by hand and straightened for improved flow distribution. In certain locations working conditions were hazardous so that a slip or misstep could result in an individual's falling into flow so swift as to render him helpless immediately. Personnel worked in pairs and where necessary were secured by a rope to a stationary object nearby.

Test results

Melt-water flow. Weather conditions were such that it was not possible to begin measurements until 9 June. The first melt flow was noted on 8 June in a cut adjacent to Access Road where snow had been removed during construction operations. Actual measurements were continued at this point until about 22 June because no other melt streams were noted. Discharges were in the range of 0.01 to 0.38 ft^3/sec and were difficult to measure because traffic in the area altered stream conditions. The major portion of the flow came from the face of the moraine and up to 22 June amounted to a maximum of 0.4 ft^3/sec.

The amount of melt flow gradually increased and on 23 June flow through culvert C8 started: flow through culverts C5 and C3 started on 24 June and flow through C12 started on 25 June. Flow through culvert C3 stopped on 25 June, while flow through culverts C8 and C5 ceased on 26 June and 4 July, respectively. On 5 July, flow in channel 1, which appeared to be coming from the snowfield above the moraine, reached a maximum of 6.49 ft^3/sec. Most of the melt water from area 2 passed along Ramp and Transverse Roads and through culvert C12; on 5 July this flow amounted to 17.94 ft^3/sec. Flow entering channel 2, which bypassed the culvert, totaled 1.51 ft^3/sec. Thus, the total melt water from the ice cap amounted to 25.94 ft^3/sec the afternoon of 5 July. Actual daily flows recorded at the various stations are presented in Table C1.

Table CI. Melt-water flow at major gaging stations (ft³/sec).

	June											
	9		10		13		14		15		16	
Gaging station	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
1–Channel 1	0.15e	0.35e		0.24e		0.22e	0.04	0.24	0.01e	0.10e		0.25e
Total flow	0.15	0.35		0.24		0.22	0.04	0.24	0.01	0.10		0.25

	June											
	17		18		19		20		22		23	
Gaging station	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
1–Channel 1		0.38	0.15	0.29	0.12	0.39	0.11	0.24		0.38	0.23	0.63
3–Channel 2										0.38	0.52	0.60
5–Culvert C-8												0.10e
Total flow		0.38	0.15	0.29	0.12	0.39	0.11	0.24		0.76	0.75	1.33

	June											
	24		25		26		27		28		30	
Gaging station	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
1–Channel 1	1.61	1.14	0.87	1.23	0.88	1.24	1.12	3.93	1.51		0.95	
3–Channel 2	0.66	0.89	1.10	1.02	1.33	1.19	1.19	1.49	1.57		1.77	
5–Culvert C-12			0.00	0.50e		0.47	0.90	1.37		0.88		1.63
5–Culvert C-8	0.10e	0.10e	0.10e	0.05e								
5–Culvert C-5	1.00e	2.00e	3.04	1.31	2.77	1.69	2.04	3.10		2.72	2.62	
5–Culvert C-3	0.10e	0.10e										
Total flow	3.47	4.23	5.11	4.11		4.59	5.25	9.89				

	July											
	1		2		3		4		5		7	
Gaging station	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
1–Channel 1	0.87	1.62		1.46	1.35	3.13	1.96	6.06	4.37	6.49	6.35	
2–Channel 1												28.03
3–Channel 2	1.49	1.53		1.92	2.07	2.98	1.33	1.53	1.02	1.51	0.41	
5–Culvert C-12	1.05	1.65	1.33		6.23	8.99	8.30	12.51	10.89	17.94	16.42	15.03
5–Culvert C-5	2.43		3.16		3.00e	0.00						
Total flow	5.84				12.65	15.10	11.59	20.10	16.28	25.94	23.18	43.06

	July											
	8		9		10		12		14		15	
Gaging station	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
2–Channel 1	24.48	40.93		43.94		49.62		98.56	65.75	50.00e	80.00e	
5–Culvert C-12	11.71	10.67		6.31		8.50	4.13	4.00e	0.00	4.00e	2.60	
Total flow	36.19	51.60		50.25		58.12		102.56	65.75	54.00	82.60	

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e Estimated

Table CI (Cont'd).

	July											
	16		17		18		19		21		22	
Gaging station	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
2–Channel 1	45.00e			15.00e	40.00e	60.00e	37.53	75.00e	63.67	90.00e	54.24	
5–Culvert C-12	1.00e		0.00	0.00	2.50e	3.00e		4.003	2.00e		1.00e	
Total flow	46.00			15.00	42.50	63.00		79.00	65.67		55.24	

	July											
	23		24		25		26		28		29	
Gaging station	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
2–Channel 1	53.76	71.19	40.80		48.48	74.76	35.16	67.43	31.35	40.00e	20.00e	
4–Channel 2									19.58	22.83	12.81	30.82
5–Culvert C-12	0.00	0.50e	0.00									
Total flow	53.76	71.69	40.80		48.48	74.76	35.16	67.43	31.35	40.00	20.00	46.2c

	July				August							
	30		31		1		2		4		5	
Gaging station	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
2–Channel 1	18.32	45.00e	36.05		59.55							
4–Channel 2	12.23	24.65	26.48	38.29	37.41	66.16	55.64	79.94	36.98	59.46	10.72	35.07
Total flow	18.32	45.00	36.05	42.4c	59.55	99.0c	83.4c	119.8c	55.5c	89.1c	16.1c	52.6c

	August											
	6		7		8		9		11		12	
Gaging station	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
4–Channel 2	8.96	33.15	20.78	49.43	11.21	32.14	10.62	30.71	10.87	18.32	7.29	21.30
Total flow	13.4c	49.7c	31.2c	74.1c	16.8c	48.2c	16.0c	46.0c	16.3c	27.5c	10.9c	31.9c

	August											
	13		14		15		16		18		19	
Gaging station	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
4–Channel 2	7.85	17.05	6.32	17.00	5.33	14.82	5.50	15.02	4.74	10.31	4.61	8.08
Total flow	11.8c	25.5c	9.5c	25.5c	8.0c	22.2c	8.3c	22.5c	7.1c	15.5c	6.9c	12.0c

	August									
	20		21		22		23		25	
Gaging station	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
4–Channel 2	4.51	10.71	4.28	9.26	3.17	4.04	1.55	3.79		1.50e
Total flow	6.8c	16.1c	6.4c	13.8c	4.8c	6.1c	2.3c	5.7c		2.3c

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e Estimated

c Based on per cent (150%) of flow in channel 2

Flow from North Fork (Fig. C1) bypassed Gaging Station 1 until 27 June when it was diverted to channel 1 above the new bridge; on 18 July it returned to its former channel alignment. All flow was recorded, however, in that measurements were started at Station 2 on 7 July. Flow from North Fork was again diverted to channel 1 on 22 July and continued to flow through channel 1 for the rest of the season.

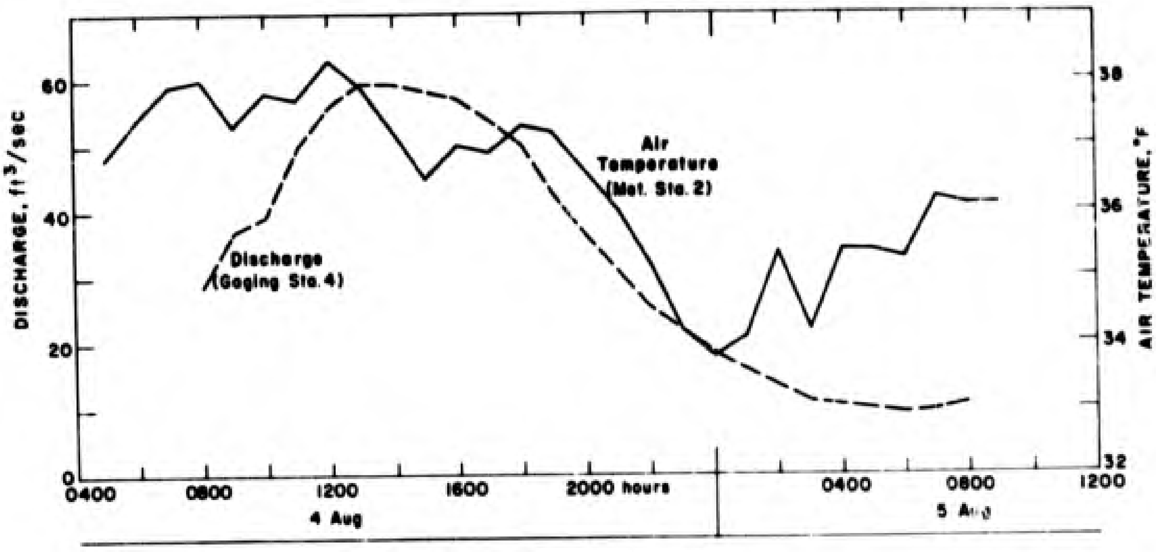
From 9-19 July the weather was generally bad, with low temperatures, rain, sleet, snow and winds up to 60 knots. Field operations were completely halted on several days. The second highest recorded runoff for the season was made at 1400 hours on 12 July. The total flow at Gaging Station 2 and culvert C12 was slightly in excess of 100 ft^3/sec. On 13 July, over a distance of 3200 ft north of the Ramp Road, there were 44 melt-water streams varying from small to medium large. Culvert C12 functioned satisfactorily and passed 18 ft^3/sec. This discharge steadily decreased from 5 July to a small trickle on 23 July because the culvert invert was too high compared with the bed of the melt channel. By 19 July, the total flow from the ice cap had decreased to 75 ft^3/sec at the old bridge and 4 ft^3/sec through culvert C12.

A helicopter flight over the drainage area on 19 July showed that all melt streams were apparently originating within the limits of areas 1 and 2. Considerable effort was made to number and gage the melt streams immediately north of the Ramp Road. Gaging stations were established at Miles 1 and 2. However, the melt streams were so sinuous and intermingling that accurate determination of discharge was almost impossible. Often the melt streams would flow for several hundred yards, disappear beneath the snow and reappear as 3 or 4 interconnected streams. Drifting snow sometimes obliterated the smaller channels. Slush conditions in the area above a 2200-ft elevation (about Mile 2) were unusually severe. The depth in some instances exceeded 5 ft and the average depth was estimated to be 3 ft. A large amount of water was stored in the slush; when it was released by the formation of melt-water channels, discharges downstream increased appreciably within a short time. Near the end of July, 9 streams were observed within 500-800 ft of the Ramp Road at Mile 1. There were 10 streams at Mile 2 and one small stream at Mile 3. Figure C2 gives an approximate location of the melt stream and Table CII presents the discharges recorded.

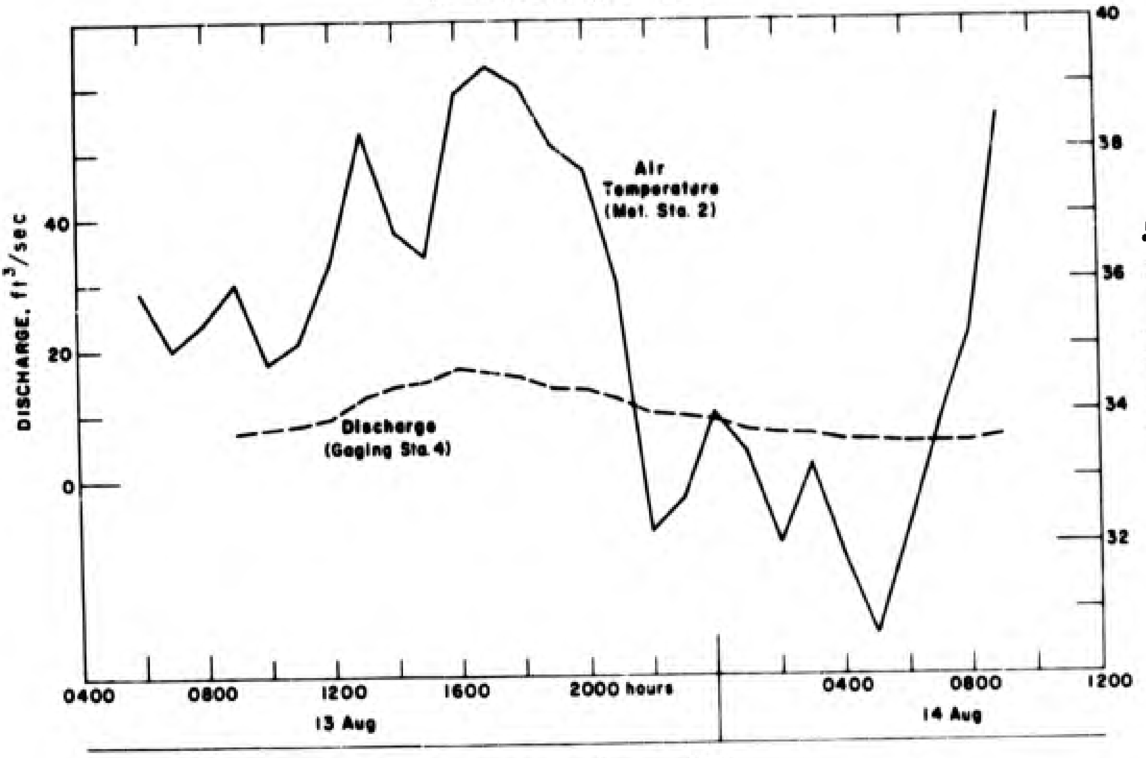
On 26 July culvert C12 was filled with earth to prevent further ice ablation which was endangering the road fill. On 1 August it became impossible to measure flow at the old bridge site (Station 2) because of extremely high velocities and the passage of rock and ice fragments with discharge flow. Subsequent measurements were made in channel 2 and the total combined flow of channels 1 and 2 was computed on a percentage basis. Previous observations indicated that flow in channel 1 was about 35 to 40% of the total flow or total flow was about 150% of the flow in channel 2. On the afternoon of 2 August a flow of 79.94 ft^3/sec was measured in channel 2. Application of the above percentage factor indicates a total runoff from the ice cap of about 120 ft^3/sec; this was the peak flow recorded during the summer. Estimates of total combined flow from channels 1 and 2 after 1 August were obtained in the same manner.

Final discharge measurements were made on 25 August 1958. Maximum flow at the channel 2 gaging station was only 1.5 ft^3/sec; this represents the total runoff from area 2. Total runoff from area 1 would be about 0.8 ft^3/sec or the total runoff of both areas on 25 August was only about 2.3 ft^3/sec.

Effect of temperature variation. To study the effect of temperature variation a discharge was continuously recorded in channel 2 from 0800 hours on 4 August until 0800 hours on 5 August. Temperatures recorded at Meteorological Station 2 (Mile 1) were used for plotting purposes. During this period the weather was clear with little wind. Data obtained (Fig. C3) indicate that the maximum temperature recorded was 38.3 F on 4 August and the maximum flow was 59.5 ft^3/sec. Minimum temperature and flow recorded during this period were 33.8 F and 9.5 ft^3/sec, respectively. Flow did not increase until about 6 hours after the temperature started to rise. Average



a. 4 and 5 August 1958.



b. 13 and 14 August 1958.

Figure C3. Discharge and air temperature comparison, 24-hour period, channel 2, Gaging Station 4.

flow for the 24-hour period was 33 ft³/sec; this would result in a total runoff from area 2 (1.6 square miles) of 2,860,000 ft³. Similar data were recorded on 13-14 August (Fig. C3). Although the temperature ranged from a maximum of 39.3 F to a minimum of 30.6 F, flow ranged from 17 ft³/sec to 5.5 ft³/sec. Average flow for the period 13-14 August was 10 ft³/sec or a total runoff of 867,000 ft³.

Stream flow profiles. On 9 August and 22 August profile data were recorded for a distance 80 ft upstream from the recording station on channel 2. Maximum flows on the two dates were 30.7 ft³/sec and 4.0 ft³/sec, respectively, and occurred in the afternoon. The depth of flow in each instance was from 0.75 ft to 1 ft although the width of the channel was 10 ft for a flow of

Table CII. Melt-water flow in secondary streams (ft³/sec).
Mile stations refer to miles along Tuto Ramp Road (see Fig. C2).
Streams 1, 2, and 3 at Mile 2 combine to form Stream 4 at Mile 1.
Streams 4-10, inclusive, at Mile 2 combine to form Stream 9 at Mile 1.
All other streams at Mile 1 originate between Mile 1 and Mile 2.
e indicates flow was estimated.

	July 1958					
Gaging station	*18*	*21*	*23*	*25*	*28*	*30*
Mile 3:						
Stream 1	0.50e			0.01e		
Mile 2:						
Stream 1	3.50e		8.82	6.68	4.67	3.37
Stream 2	0.00		0.29	0.12	0.11	0.13
Stream 3	0.00		1.01	0.80	0.32	0.32
Stream 4	0.00		0.04e	0.01e	0.08	0.07
Stream 5	0.00		1.50e	0.62	0.41	0.53
Stream 6	0.00		0.04e	0.01e	0.01e	0.00
Stream 7	0.00		0.08e	0.60	0.05e	0.08
Stream 8	0.00		0.85	0.08e	0.01e	0.00
Stream 9	0.00		0.80	0.77	0.40e	0.51
Stream 10	0.00		0.13	0.08e	0.10e	0.10
Total for Streams 1-3	3.50		10.12	7.60	5.10	3.82
Total for Streams 4-10	0.00		3.44	2.17	1.06	1.29
Total flow at Mile 2	3.50		13.56	9.77	6.16	5.11
Mile 1:						
Stream 1	0.00	0.00	0.01e	0.11	0.01e	0.01e
Stream 2	0.02e	0.10e	0.24	0.22	0.19	0.18
Stream 3	0.01e	0.44	0.21	0.22	0.20e	0.18
Stream 4	7.50	9.24	12.44	7.35	6.02	6.21
Stream 5	0.03e	0.40e	0.33	0.50	0.30	0.24
Stream 6	0.00	0.20e	0.09	0.30	0.10e	0.12
Stream 7	0.00	0.00	0.10	0.10	0.05e	0.08
Stream 8	0.01e	0.10e	0.12	0.08	0.05e	0.08
Stream 9	0.30e	3.70	8.01	3.97	1.42	1.62
Total flow at Mile 1	7.87	14.18	21.55	12.85	8.34	8.72
Culvert C-12	3.00e	2.00e	0.50e	Flow ceased		
Channel 2					22.83	24.65
Channel 1	60.00e	90.00e	71.19	74.76	40.00e	45.00e
Grand total	63.00	92.00	71.69	74.76	40.00	45.00

Table CII (Cont'd).

Gaging station	*August 1958* *1*	*6*	*8*	*11*	*13*	*16*	*20*	*22*
Mile 3:								
Stream 1		0.60e	0.37	0.10e		0.00	0.00	0.00
Mile 2:								
Stream 1	3.60	5.55	3.68	2.66	1.80	1.50	1.00e	0.30e
Stream 2	0.32	0.12	0.12	0.05	0.02e	0.01e	0.00	0.00
Stream 3	0.89	0.77	0.63	0.32	0.02e	0.01e	0.00	0.00
Stream 4	0.10	0.01e	0.01e	0.01e	0.00	0.00	0.00	0.00
Stream 5	0.87	0.42	0.29	0.10	0.02e	0.01e	0.00	0.00
Stream 6	0.06	0.01e	0.01e	0.00	0.00	0.00	0.00	0.00
Stream 7	0.12	0.10	0.04e	0.01e	0.00	0.00	0.00	0.00
Stream 8	0.01e	0.04e	0.01e	0.01e	0.00	0.00	0.00	0.00
Stream 9	1.41	0.94	0.97	0.75	0.45	0.20e	0.10e	0.01e
Stream 10	1.28	0.35	0.29	0.20	0.03e	0.02e	0.00	0.00
Total for Streams 1-3	4.81	6.44	4.43	3.03	1.84	1.52	1.00	0.30
Total for Streams 4-10	3.85	1.87	1.62	1.08	0.50	0.23	0.10	0.01
Total flow at Mile 2	8.66	8.31	6.05	4.11	2.34	1.75	1.10	0.31
Mile 1:								
Stream 1	0.01e	0.01e	0.01e	0.02	0.02	0.01e	0.01e	0.01e
Stream 2	0.20	0.25	0.14	0.20	0.18	0.10e	0.01e	0.01e
Stream 3	0.35	0.25	0.22	0.24	0.18	0.10e	0.01e	0.01e
Stream 4	8.36	9.24	6.56	4.20	3.60	3.00	1.50e	1.50e
Stream 5	1.00	0.41	0.30	0.30	0.25	0.10e	0.00	0.00
Stream 6	0.27	0.11	0.10	0.01e	0.00	0.00	0.00	0.00
Stream 7	0.15	0.04e	0.09e	0.01e	0.00	0.00	0.00	0.00
Stream 8	0.15	0.04	0.06e	0.00	0.00	0.00	0.00	0.00
Stream 9	4.00	2.68	2.64	1.42	0.82	0.78	0.20e	0.01e
Total flow at Mile 1	14.49	13.03	10.12	6.40	5.05	4.09	1.73	0.54
Culvert C-12 Channel 2 Channel 1	66.16	33.15	32.14	18.32	17.05	15.02	10.71	4.04

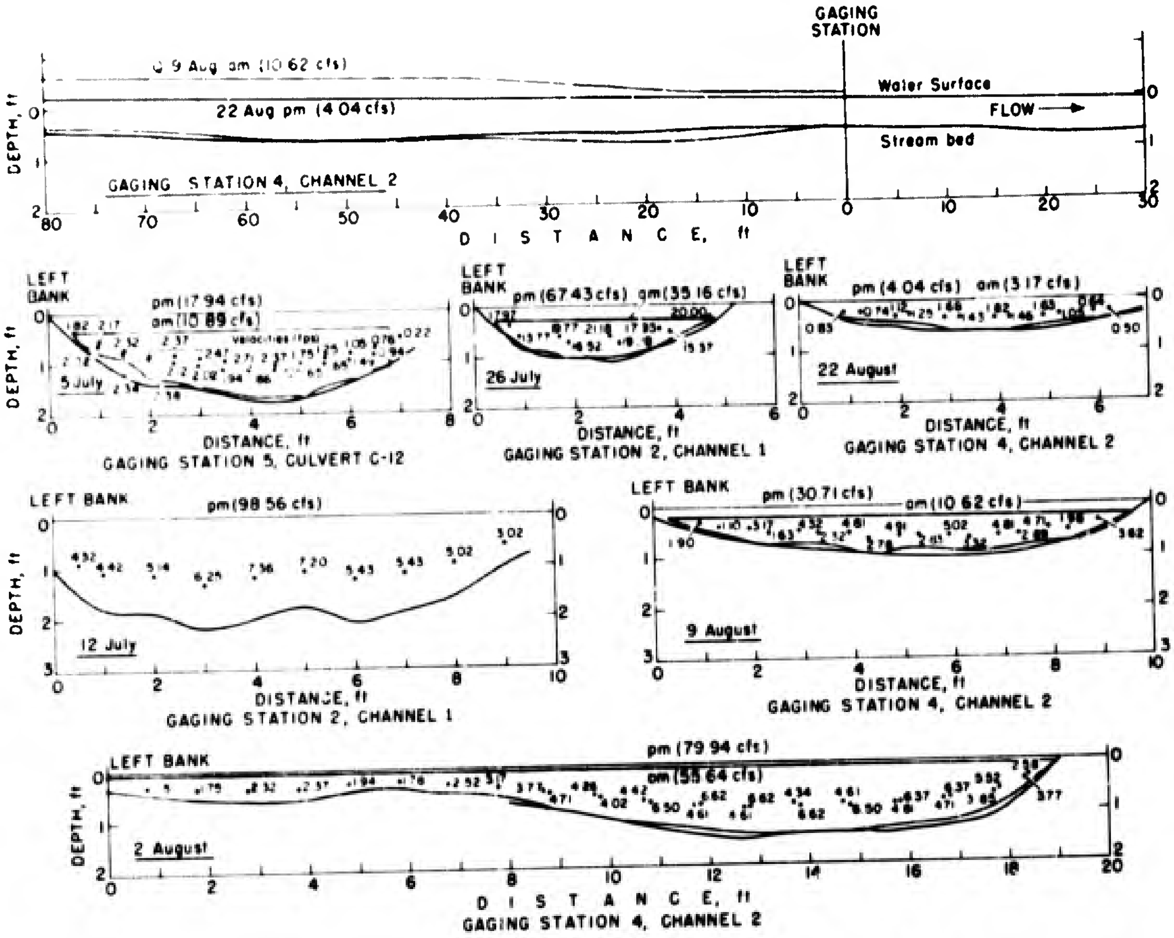


Figure C4. Typical cross sections and profiles at gaging stations.
a.m. = gray; p.m. = black

30.7 ft³/sec as compared with a width of 7 ft for a flow of 4.0 ft³/sec (Fig. C4). The overall drop in water surface over the distance of 80 ft was 0.5 ft for the larger discharge and only 0.2 ft for the lower flow. Other typical cross sections at various gaging stations are also shown on Figure C4.

Degradation of ice channels. Measurements of ice degradation at the two bridge sites were made by personnel of USA ACFEL. Precise measurements were difficult because of the high velocity of the flow.

Discussion of results

The data presented in tabular form in Tables CI and CII and described in the previous paragraphs should provide some basic information on the amount and distribution of melt water from the Greenland Ice Cap in the Camp Tuto area. A more comprehensive correlation of runoff data with the meteorological data may provide some additional information. A cursory review indicates that air temperatures at Meteorological Station 3 were generally 2 to 3F lower than at Station 2, whereas temperatures at Station 1 were generally 2 to 3F higher. Thus, a temperature gradient that would cause the amount of melt water to vary per unit of area was present. Also the temperature was dependent upon the wind velocity; the higher the wind velocity, the lower the temperature.

However, snow at the same temperature melts more readily when the wind is blowing because of mixing of the cool air at the interface and the air contained in the upper layer of the snowpack. The effect of wind, however, may be negligible over bare ice. Personnel experienced in conditions at the Camp Tuto site agreed that melt-water flow during the summer of 1958 was much less than during the previous two summers.

Figure C5 gives a plot of total melt-water flow from drainage areas 1 and 2. Discharges in the afternoon generally were greater than in the morning. Considerable effort was made, without success, to correlate the discharge information with the maximum observed daily temperature, the average daily temperature and the net radiation exchange observed at Meteorological Station 2. Only a few degrees range in temperature apparently was sufficient to make an appreciable change in melt-water flow. Best correlation was obtained by development of an accumulative heat index from the observed average daily air temperatures at Meteorological Station 2. This heat index was based on the difference in mean daily air temperatures (average of maximum and minimum temperatures). The index was positive when the mean daily temperature was greater than 32F and negative when the mean daily temperature was less than 32F; e.g., a mean daily temperature of 34F represents a +2F index. The steeper the slope of the plot shown on Figure C6, the more rapid the warming trend. Comparison of Figures C5 and C6 reveals that generally the greatest melt-water flows occurred at the time the accumulative heat index was increasing the fastest.

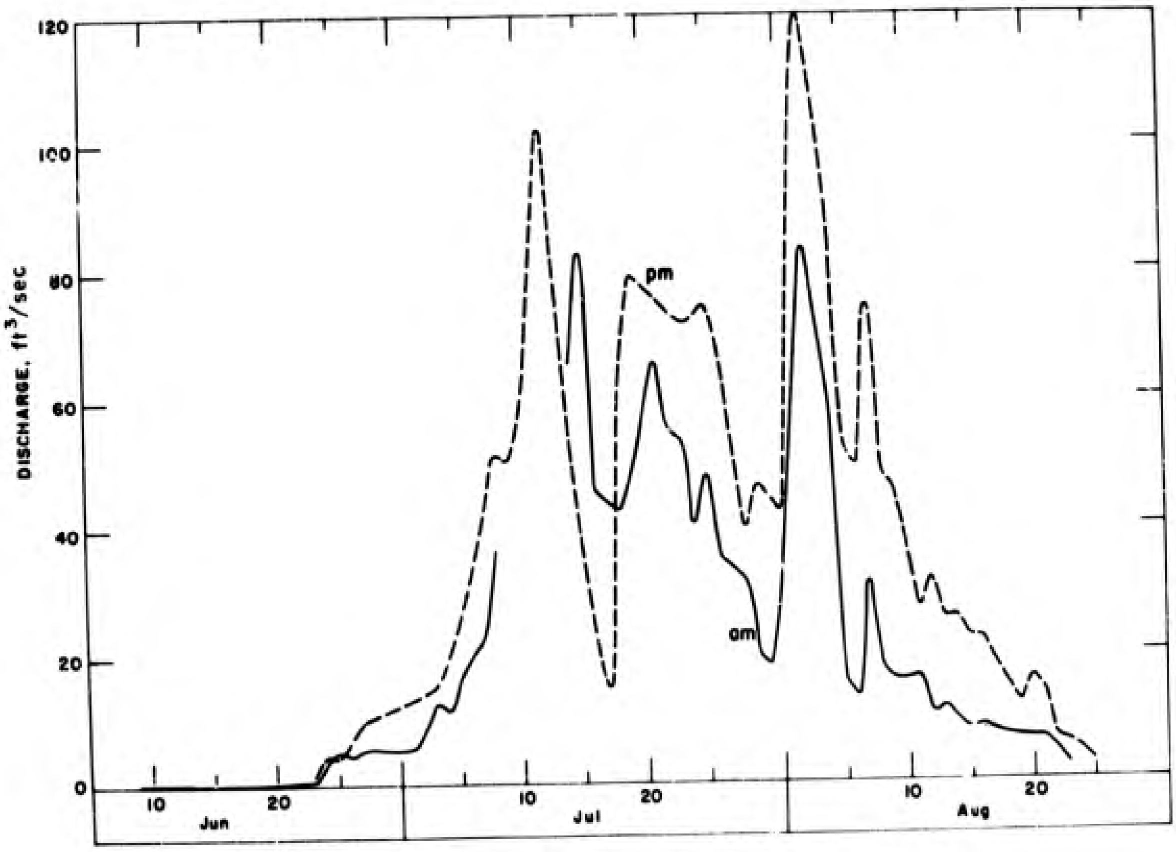


Figure C5. Total melt-water flow, drainage areas 1 and 2, 1958.

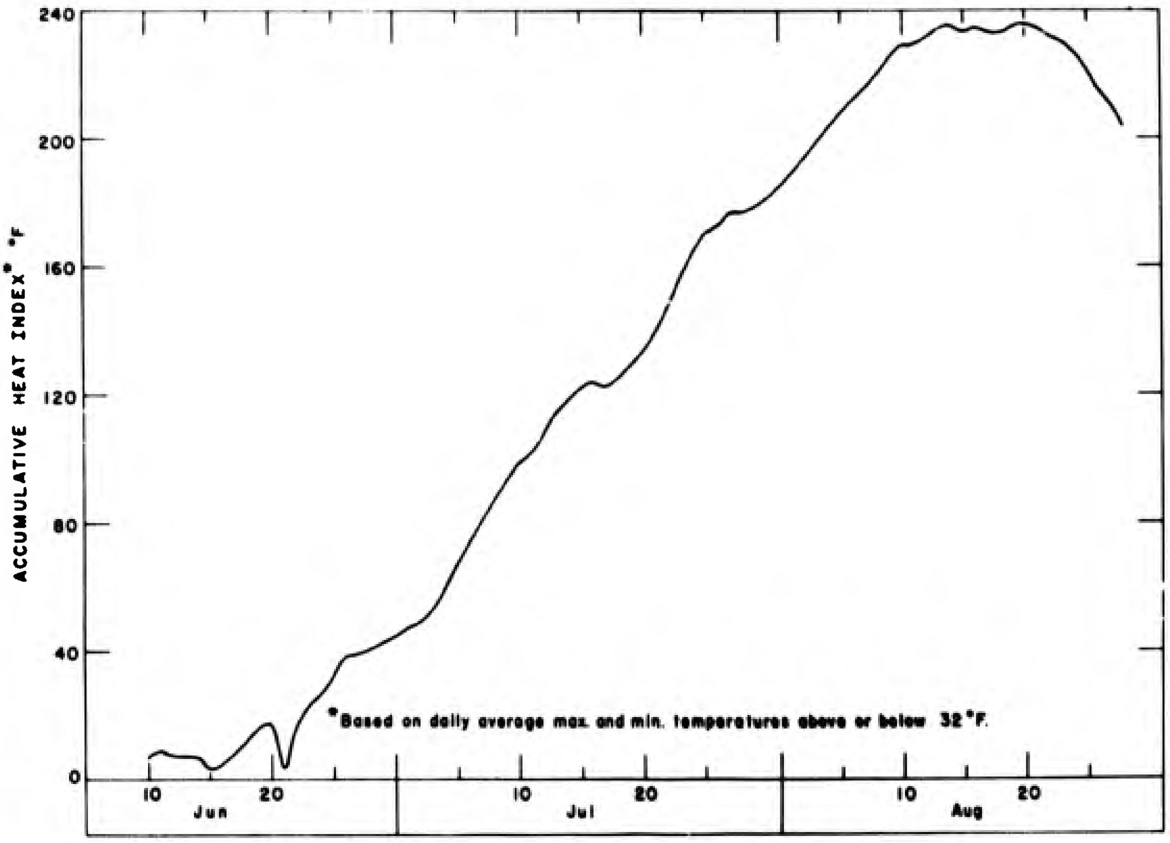


Figure C6. Accumulative heat index, Meteorological Station 2.
9 June-25 Aug 1958

Analysis of the data from the secondary gaging stations shown in Table CII is extremely difficult. Consideration of total flow indicates only roughly an increase in flow of about 50% at Mile 1 over that observed at Mile 2. This 50% increase would be the result of the melt flow originating between Mile 1 and Mile 2. An effort to delineate the amount of runoff per acre was abandoned when it was realized that the area immediately to the north of Ramp Road was not typical of area 2. Dust from Ramp Road settling over the immediate area accelerated the melting action. Thus, the melt-water data shown in Table CII would exceed the flow to be expected per unit area in locations not contaminated by dust.

Recommendations

To provide better information on melt-water flow from the ice ramp in the vicinity of Camp Tuto, the following procedures are suggested:

1. Guide channels should be excavated before melt water begins to flow. Once the melt water starts, the channels would become enlarged through erosion; this in turn would tend to concentrate the flow in the location desired. Secondary guide channels should be aligned generally with Ramp Road, with a few larger transverse channels to intersect the flow from the secondary channels.

2. A snow depth and density map over the area should be prepared to permit an estimate of the melt-water potential of the snowpack.

3. Additional personnel should be provided to permit more complete measurements.

4. Controlled aerial photographs of the drainage area should be made daily (weather permitting) at the height of the melt season to trace more accurately all melt streams.

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APPENDIX D: ANALYSIS OF MICROMETEOROLOGICAL DATA OBTAINED AT CAMP TUTO, GREENLAND: MELT-WATER QUANTITIES*

by

Ronald F. Scott†

INTRODUCTION

In 1954 the U.S. Army Corps of Engineers established Camp Tuto at the edge of the Greenland Ice Cap as a supply and equipment base for military operations and as a site for basic and applied research in arctic regions. The ground around the base is perennially frozen but thaws a few feet down from the surface in the summer. The soil is well graded, with a rocky, gravelly surface on which polygons can be distinguished in certain areas.

The edge of the ice cap is east of the camp; here the ice cap begins at ground surface and slopes upward to the east at about 6% gradient. Prevailing winds, generally katabatic, blow from the east down the ice cap.

As part of an arctic construction research program, USA ACFEL,aided by personnel and equipment of the U.S. Army Signal Corps Electronics Proving Ground, Fort Huachuca, in 1956 began to make extensive micrometeorological measurements. The analysis of the first season's data indicated the necessity for improved instrumentation, which was subsequently supplied.

At Camp Tuto in 1957 and 1958 measurements were made at three stations representing three terrain types and included: 1) continuous observations of temperature, wind, humidity, air pressure, radiation, etc., generally several levels above the surface, but also in the upper atmosphere; 2) observations of ground temperatures and, where appropriate, moisture content of the soil at several depths; and 3) standard first-order weather station observations.

The data were reduced and tabulated at the National Weather Records Center, Asheville, North Carolina, and were furnished to the author by the Corps of Engineers for analysis. The results of the analysis were reported to USA ACFEL (Scott, 1959). The analyses included comparisons of short-and long-wave radiational amounts, with theoretical values for clear and cloudy days; and calculation of ground surface, snow and ice albedos and their time variations. The heat flow to the air by convection was calculated by several methods, evaporation heat flow amounts were discussed, and analyses of soil and ice temperature profiles were made to determine the daily heat budget components.

In this paper, the micrometeorological data obtained in 1958 were used to calculate the heat quantity available for melting the snow or ice at the ice cap stations. The amount of melt water obtained for a given drainage area of the ice cap for these computations was then compared with the measured quantity of runoff. Close correlation exists between the computed and measured total quantities, and an added storage delay time calculation improves the day-to-day comparison and gives information on the water permeability of the snow.

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STUDY AREA

The topography of the ice cap in the vicinity of Camp Tuto is appropriate for a melt-water study. The area studied (see Fig. C1 and C2) is bounded as follows: to the west by Transverse Road, through culverts in which the flow passes and is gaged; to the north, by a natural watershed on the sloping ice surface; to the east, by the upper limits of drainage, supplying, by their elevation, little or no drainage to the area; and to the south, by the main Ramp Road. In the width of the area occur 40 or 50 melt water streams flowing from east to west. The ice surface slopes upward to the east from the Transverse Road at about a 3 or 4% gradient.

Along the main Ramp Road were situated the three meteorological stations: Station 1 on the natural soil a few hundred feet west of the edge of the ice cap; Station 2 approximately 1 mile up Ramp Road; and Station 3 at Mile 3 on Ramp Road. These stations supplied the necessary micrometeorological data from which the melt-water quantities were computed. All the flow from the study area, as far as could be determined, passed through the stream gaging stations set up on the melt-water streams where they passed under Transverse Road. The total drainage area consisted of about 2.3 square miles.

MELT-WATER COMPUTATIONS

To compute the quantity of melt taking place on the ice cap near Camp Tuto it was necessary to establish the heat budget of the ice surface at Meteorological Stations 2 and 3.

The measurements of incoming and reflected short- and long-wave radiation made at these stations gave information on the primary sources of heat supplied to the surface. Some of this heat helped to melt the ice and some to warm up the underlying ice layers. Some heat was rempved from the surface by evaporation and by sensible heat transfer into the air. Since the amount of heat used to melt the ice was not known, it was estimated by evaluating the other heat flows. Insufficient information was available in 1957 to make calculations based on an entire summer's conditions; therefore, the calculations were applied only to the data obtained in 1958.

First, the amount of heat supplied to warm the underlying ice layers was evaluated from information obtained from a thermocouple string installed in the ice near Meteorological Station 2 at the beginning of June 1958. Although errors were apparently present, it was possible by inspection to estimate and plot temperature profiles in the ice at various dates. Areas between successive temperature profiles were obtained from the plots and multiplied by the specific heat of ice (assumed to be 0.45 cal/cm^3 C). By this calculation, values of heat flow for various periods were evaluated. These results were combined to give estimates of values of heat flow into the ice for the entire summer. Such a value of specific heat of ice may not apply to the ice at all depths since there is generally a change of density with depth. However, the ice at Meteorological Stations 2 and 3 was old and might be considered relatively stable with depth with respect to specific heat.

The amount of heat flow was 5 to 10% of the net radiation at the surface. Table DI gives the estimates resulting from this calculation for both stations using the thermocouple data obtained at Station 3:

Table DI. Estimates of heat flow to ice

Period	*Meteorological Station 2* *cal/cm^2 day*	*Meteorological Station 3* *cal/cm^2 day*
Before 19 May	0	0
19 May - 4 June	5	5
5 June - 20 June	10	10
21 June - 4 July	18	15
5 July - 19 July	13	10
20 July - 4 Aug	8	8
5 Aug - 20 Aug	3	5
After 20 Aug	0	0

These calculations are quite crude because of the uncertain nature of the thermocouple data. However, as the relative magnitude of the heat to ice is so small, it is unlikely to influence the results except at the beginning and end of the melt period.

Next, the amount of heat flow to the air was calculated. Not enough time and information were available to make daily estimates at Stations 2 and 3 during 1958. However, heat flows to the air were calculated at Station 2 for clear and completely cloudy days and at Station 3 for clear days only. These calculations gave some idea of the order of magnitude of heat flow to the air on days that might be considered to represent the extremes of flow. Heat flows to the air were computed using air velocity and temperature profiles by methods given by Scott (1957) and Halstead (Lettau and Davidson, 1957). The difference between the results obtained by these methods was small except for heat flows to the air greater than 250 cal/cm^2 day (not encountered over ice surface). A method suggested by Budyko (1956) gave obviously too small values under all conditions.

The quantity of heat flowing to the air at either Station 2 or 3 was extremely small compared with that occurring at Station 1. This may be because the temperature of the surface of the ice never rises above 32 F so that the temperature gradients between the surface and air flowing over it are very small. Generally there are indications that heat flows to and from the air take place during the summer, but an average heat flow to the air of about 10 cal/cm^2 day occurred at Station 2 on clear days while at Station 3 about 12 cal/cm^2 day was lost to the air. These may be compared with values of 100 to 200 cal/cm^2 day at Station 1. From the limited amount of data for Station 2 on cloudy days, apparently slightly more heat was lost to air under this condition. This is believed to be an anomalous result but since there is no other information available to check it it must be accepted provisionally. Apparently about 20 cal/cm^2 day on the average flowed into the air from Station 2 on cloudy days.

From this information, estimates of the heat flow into the air at Stations 2 and 3 for the summer of 1958 were made. On clear days the heat flow into the air was considered to average 10 cal/cm^2 day; on cloudy days, 20 cal/cm^2 day; on all other days, 15 cal/cm^2 day. No variation of these quantities was made to account for the different times of year as the indications were not clear enough that there was a variation. At Station 3, because of the lack of data, an average value of heat flow to air of 10 cal/cm^2 day was assumed for all days during the summer. Once again the relatively small magnitude of flow into the air compared with the net radiational heat quantity at the surface made the difference of a few calories relatively unimportant.

Then the heat budget at the ice surface at Stations 2 and 3 was calculated. Heat is supplied to the surface in the amount of the net radiation at the surface. Heat is subtracted from this amount to warm the underlying ice and to supply heat to the air passing over the surface. Therefore, for

10-day periods during 1958 the totals of net radiation were obtained and from them the ten-day totals of heat flows to the ice and to the air were subtracted. The remainder was considered to be the heat flow that results in melting the ice at the surface. This value was summed cumulatively for the ten-day periods and converted to a water equivalent by a conversion factor, the latent heat of water (80 cal/cm³). Thus, an estimate of the cumulative total depth of water melted at each of the stations could be obtained. This represented the total ice melt in the summer when converted by a factor relating the amount of water to the equivalent volume of ice. The amount of water could finally be used to estimate the runoff in any period.

In this way the plots shown on Figure D1 were made. These plots show the height of water in centimeters obtained as a result of the melting of the ice cap near Stations 1, 2 and 3; the calculations described so far give the curves marked "No evaporation." No humidity gradients were measured at the stations; therefore, it was not possible to compute directly the amount of heat flow to evaporation. If some heat were used up in evaporating water at the ice surface, it might not go to melting ice. Consequently, the consideration of evaporation would result in smaller estimates of the amount of ice melt than would be obtained by neglecting evaporation.

If it is assumed that the amount of heat flow to evaporation roughly equals the amount of heat flow to the air, some estimate of the amount of melt that would take place if evaporation were considered can be made. This seems to be a not unreasonable estimate considering the results of other investigations and the data from Station 1. But this view is somewhat doubtful as the difference between a relatively dry ground surface and a wet ice surface is not adequately considered. The method, however, is thought to give a reasonable idea of the amount of heat flow to evaporation; it is unlikely to be substantially greater than this amount. The curves on Figure D1, therefore, can be amended by this assumption. Curves marked "evaporation" incorporating this assumption are shown. Between the two curves a line representing a probable variation of cumulative melt with time is drawn. On summer nights, when the amount of incoming radiation is very small, some condensation of the surface takes place, offsetting the amount of evaporation during the day.

The data from Meteorological Station 1 and estimates of the albedo of the ice near the limit of the ice cap permitted calculations to be made, giving the curve of cumulative melt near Station 1.

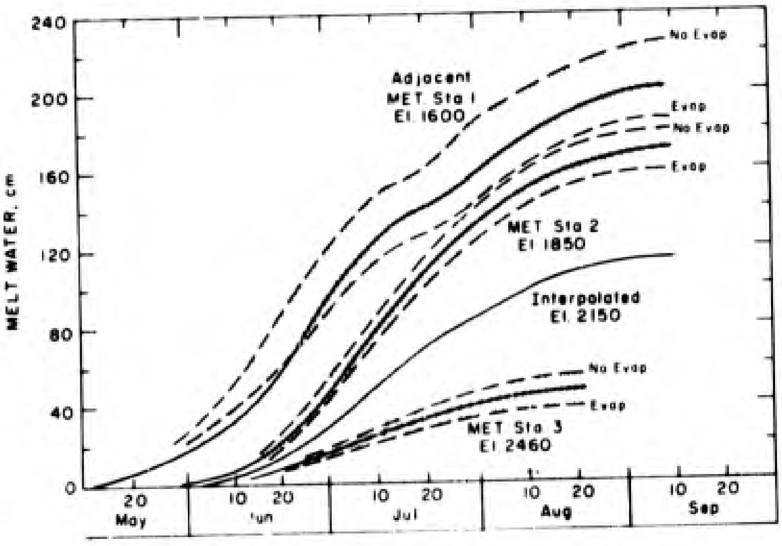

Figure D1. Computed melt water, 1958.

From the information on Figure D1 and Figure C2, the amount of water runoff due to melt in any period during the summer could be calculated. To calculate melt-water amounts, the area was arbitrarily subdivided into three sections bounded internally by the 2000- and 2300-ft contours and externally on the east by the 2600-ft contour, and on the west by Transverse Road. The calculated melt at Station 3 was considered to represent the average for the most easterly section and that at Station 2 the average for the most westerly section. The center area, bounded by the 2000- and 2300-ft contours, was assigned interpolated melt amounts based on the interpolated curve for elevation 2150 (Fig. D1) derived from the other three curves on the basis of altitude. The area of the drainage zone was multiplied by the average amount of melt for the period. Table DII gives the values obtained.

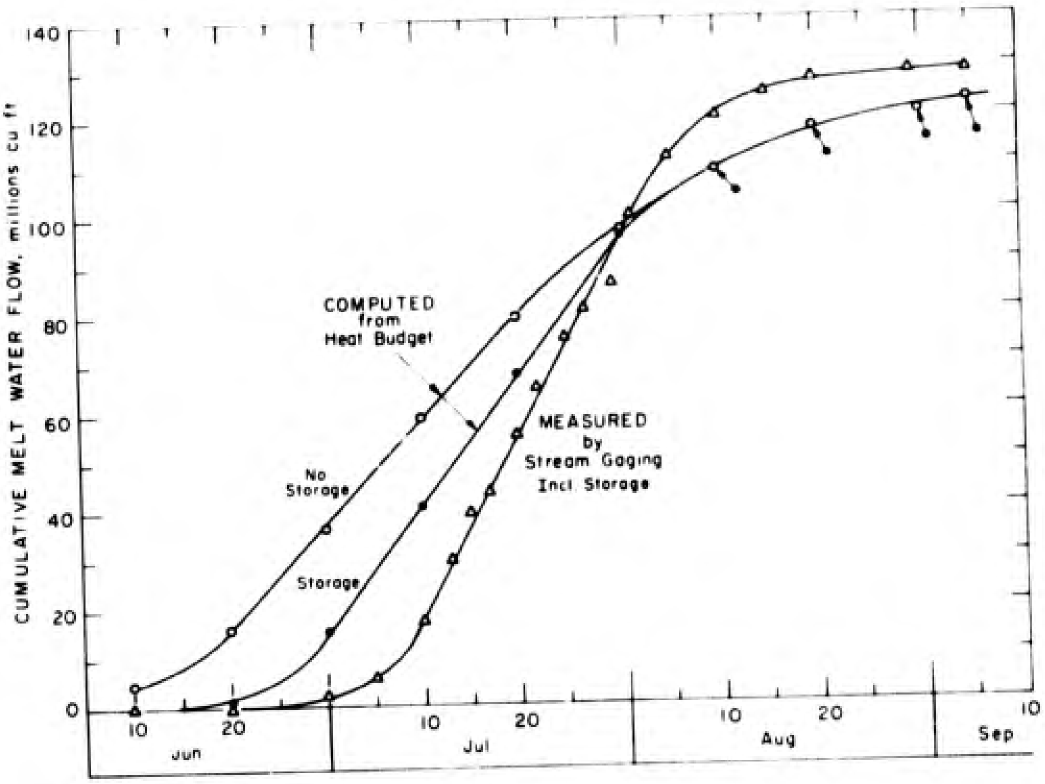

Figure D2. Comparison of measured and computed melt-water flow, 1958.

Table DII. Computed melt-water runoff, 1958

	Millions ft³	
Date	*Total in Period*	*Cumulative*
20 May	2.1	0
31 May	2.8	2.1
10 June	11.3	4.9
20 June	20.2	16.2
30 June	22.4	36.4
10 July	20.3	58.8
20 July	17.8	79.1
31 July	12.2	96.9
10 Aug	8.1	109.1
20 Aug	3.0	117.2
31 Aug	2.1	120.2
10 Sept		122.3

◆

These figures represent the estimated amounts of flow based on available heat for melting the snow and ice. The major part of these estimated flows would have passed through Transverse Road and under the bridges so that measurements made in these places could be used to check with the calculated amounts. It is considered that substantial amounts of melt water are not derived from elevations greater than 2600 ft. Any refreezing of melt water that might have taken place at night at the beginning and end of the recorded period was not taken into account. The cumulative total flow is plotted on Figure D2.

MELT-WATER MEASUREMENTS

In 1958 personnel of USA EWES established gaging stations on various melt-water streams in the study area, including stations at sites on Transverse Road. Since the majority of the melt water from the local drainage area passed these locations, the gaged melt-water quantity could be compared with the amount computed in Table DII. Readings were made on most days in 1958 under arduous conditions, in the morning and in the afternoon, when the peak flow usually occurred. These data were supplied for this study by USA EWES and were used to compute first average daily flows, then a cumulative melt-water flow curve for the summer. This curve is also plotted on Figure D2. Although a good deal of subjective judgment was involved in the estimation of the average daily flows from the twice-daily readings, the results have been plotted as obtained without adjustment.

Figure D2 shows that the computed and measured total summer melt-water flows compare well but that there is considerable difference between the progress of the two cumulative curves with time. This difference is primarily due to the neglect of the delay in the computed runoff caused by the storage of the melted water in the snowpack. No computation of this delay was made originally because it was thought that it should await a comparison of computed and measured total quantities of melt. Because of the good correspondence between the two, a storage-delay calculation was subsequently made; this is presented in the following section.

MELT-WATER STORAGE MODEL AND DELAYED RUNOFF CALCULATION

Each year the melt water in the latter part of the season ran down the bare ice surface forming well defined streams. When melt ceased and the fall and winter snows occurred, the streams were covered over but remained the potential paths of melt-water flow beginning in the following thaw season. As shown in Figure C2, there were 40 to 50 such streams across the 3000- to 4000-ft width of the drainage area studied; therefore, each stream on the average drained an area about 80 ft wide.

At the beginning of the thaw season, snow covered the ice surface to a depth of 3-4 ft, which varied considerably from place to place in depressions and drifting areas. Figure D3a shows a typical cross section of the ice cap taken along a contour line, including two drainage channels, when the snow surface temperature just reached the melting point at the beginning of summer. The underlying snow and ice were below freezing at this time.

The melted snow at the surface first trickles down into the underlying snow and refreezes, raising the snow temperature to the melting point by the released latent heat as it does so. For snow at Camp Tuto, the first 2 or 3 cm of melt water is absorbed in this way; this is a negligible amount in comparison with the yearly total. The next quantities of melt water coat the surface of snow grains and are held in capillaries in the snow in the form of hygroscopic and capillary water which is not available for runoff until the snow structure melts. Snow can hold about 3 to 4% by

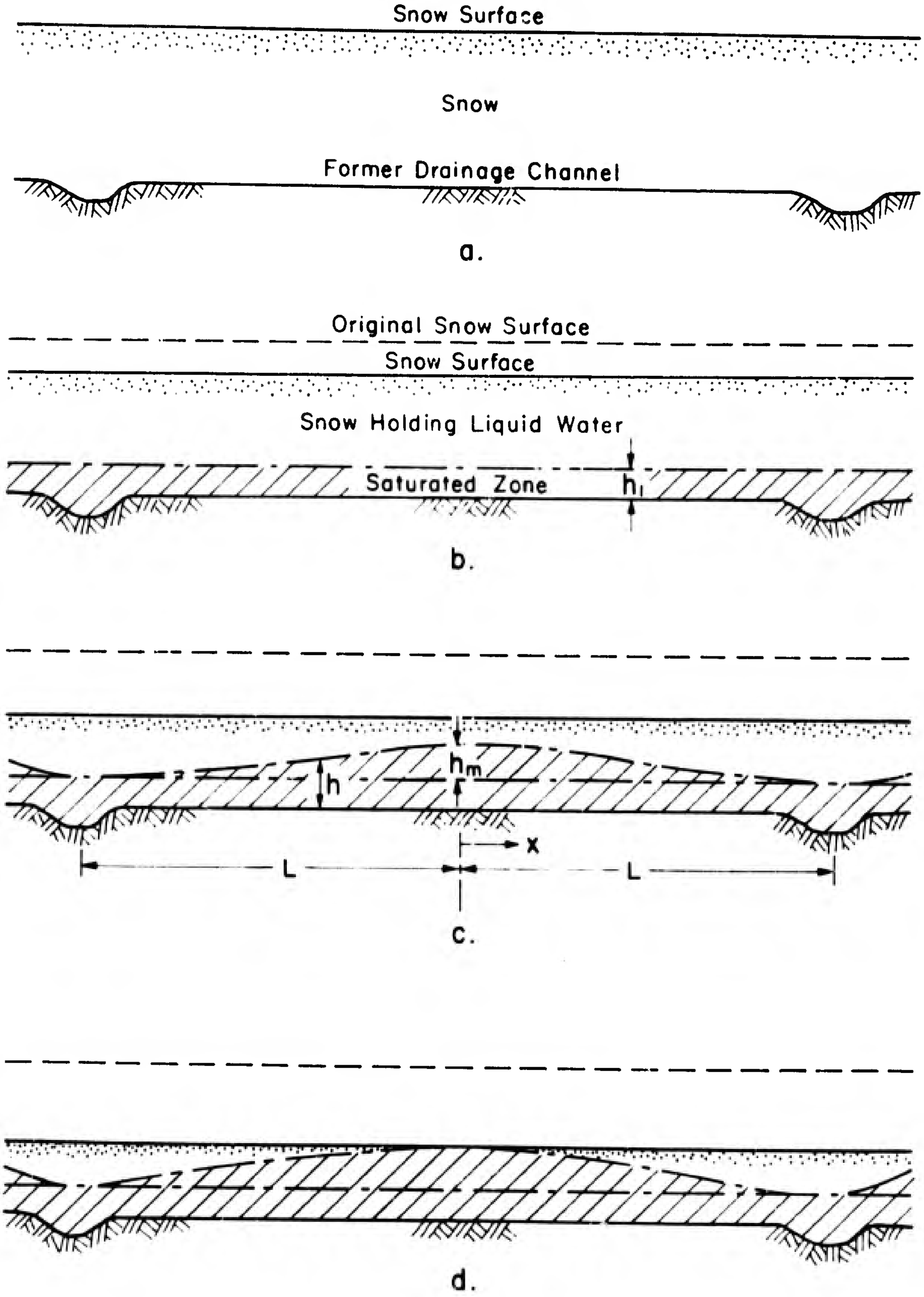

Figure D3. Melting of snow surface and drainage.

weight of water this way and, in the vicinity of Camp Tuto, about 2 cm more of melt is absorbed in the snow. When the liquid water-holding capacity of the snow is reached, further melt water trickles down through the snow, arriving at the ice surface where it is considered to build up a layer of saturated (or nearly saturated) snow; i.e., a large proportion of the snow voids are filled with water.

It is postulated that the saturated zone increases in depth up to a point at which runoff begins in the old melt-water channels under the snow surface. At this stage the snow profile is as shown in Figure 3b with the overall snow depth decreased by approximately twice the depth of melt water produced, the upper zone holding its limit of liquid water, and the lower zone saturated to a depth h_1 with water. It is difficult to estimate what depth h_1 will be, but it obviously corresponds to the time at which substantial runoff begins; this can be obtained from the readings of measured flows. Apparently this occurs approximately when about 10 cm of melt water has been produced. With deductions for the quantities of water used to heat the snow, and held hygroscopically and in the capillaries, it appears that h_1 will be about 0.5 to 0.6 ft in snow whose porosity n is about 40 to 50% (ratio of volume of voids to total volume).

Subsequently, it may be assumed that the depth h_1 is maintained in the region of the melt-water channels and that the upper surface of the saturated zone (the water table in the snow) increases in height, becoming convex upwards, so that drainage takes place to channels at each side, from the reservoir of water in the snow. If melting takes place at a uniform rate from the upper snow surface, the water table rise represents a transient flow condition in the snow as water is added from above and is removed along the sides.

This condition is represented in Figure D3c and is a case of transient flow in an unconfined aquifer. As such the horizontal hydraulic conductance of the flow zone may be represented by kh at any point where k is the hydraulic conductivity of the snow and h is the total depth of the saturated zone measured from the ice surface. To solve the problem, it is necessary to assume an average value of h to obtain an average or mean conductance. It is usually assumed in such cases that the average under the boundary conditions of:

$$h = h_1 \qquad t < 0$$

$$h = h_1 \qquad t > 0,\ x = L$$

$$h = h_1 \qquad t > 0,\ x = -L$$

can be written

$$D = h_1 + h_m/2 \tag{D1}$$

where h_m is the height of the water table above the initial height h_1 at the center point $x = 0$, if the origin of the coordinates is taken as shown on Figure D3c. Based on this, the transient flow equation can be written (Werner, 1957):

$$\frac{\partial^2 h^2}{\partial x^2} = \frac{1}{a}\frac{\partial h^2}{\partial t} - \frac{2p}{k} \quad . \tag{D2}$$

where a is a hydraulic diffusivity defined by the equation

$$a = \frac{kD}{n} \tag{D3}$$

and where p is the rate of flow into the water saturated zone from above (the melting rate) in feet per hour per unit area.

The solution to eq D2 is (Werner, 1957):

$$h^2 = h_1^2 + \frac{npL^2}{k} \left\{ 1 - \left(\frac{x}{L}\right)^2 - \frac{32}{\pi^3} \sum_{r=0}^{\infty} \frac{(-1)^r}{(2r+1)^3} \right.$$

$$\left. \cos\left[\frac{(2r+1)\pi}{2}\left(\frac{x}{L}\right)\right] \exp - \frac{(2r+1)^2\pi^2}{4} \frac{at}{L^2} \right\} \qquad \text{(D4)}$$

where t is time.

This equation is similar to the solution for temperature as a function of distance and time in an infinite flat slab whose faces are maintained at a constant temperature, in which heat is generated at a constant rate per unit of volume. As such, numerical dimensionless values of

$$\frac{(h^2 - h_1^2)k}{npL^2} \quad \text{vs} \quad \frac{at}{L^2}$$

are plotted in Carslaw and Jaeger (1959). In particular, it is necessary to calculate the center height h_m as a function of time. This is obtained by placing $x = 0$ in eq D4; this results in

$$\frac{[(h_1 + h_m)^2 - h_1^2]\,k}{npL^2} = \left[1 - \frac{32}{\pi^3} \sum_{r=0}^{\infty} \frac{(-1)^r}{(2r+1)^3} \exp - \frac{(2r+1)^2\pi^2}{4} \frac{\partial t}{L^2}\right]. \qquad \text{(D5)}$$

Values of h_m can be obtained as a function of time from the left-hand side of eq D5 and the results in Carslaw and Jaeger.

It is necessary to compute h_m and the diminution in depth of the snow cover simultaneously since at some time the snow surface meets the rising water table. Thereafter, melting of the snow surface releases not only the melted snow, but the water filling the pores, since the structural skeleton of the snow retains the pore water until the skeleton melts. From this time until all snow is melted down to the ice surface, runoff will be computed to be twice the values for the corresponding period in Table DII. In this table, 1 cm melt water implies a decrease of about 2 cm in the snow surface height; this will release 2 cm of water, 1 cm of newly melted snow and 1 cm of stored water. This situation is illustrated in Figure D3d. Although there will still be some delay in runoff, it is considered that this time the melt water channels will be open and the delay small. Therefore, the runoff is calculated by doubling the runoff values in Table DII for the appropriate time interval.

For the period between the time the water table reaches the height h_1 and the time it coincides with the snow surface, the runoff must be computed by calculating the drainage from each zone into the two side channels. Differentiating eq D4 with respect to x will give on the left-hand side $2h\,(dh/dx)$. To obtain the hydraulic gradient at the channel, it is necessary to substitute $x = L$ into the right-hand side. Multiplying both sides by the hydraulic permeability of the snow then gives the flow rate into both channels from a snow layer as shown in Figure D3.

$$q = 2kh_1\left(\frac{dh}{dx}\right)_{x=L} = 2\,npL\left[\frac{8}{\pi^2} \sum_{r=0}^{\infty} \frac{(-1)^r}{(2r+1)^2} \exp - \frac{(2r+1)^2\pi^2}{4} \frac{\partial t}{L^2}{}^{-1}\right]. \qquad \text{(D6)}$$

To obtain the cumulative flow up to time t, this expression must be integrated with respect to time as follows:

$$\frac{Q\,a}{2\,npL^3} = \frac{1}{3} - \frac{a\,t}{L^2} - \frac{32}{\pi^4} \sum_{r=0}^{\infty} \frac{(-1)^r}{(2r+1)^4} \exp - \frac{(2r+1)^2\,\pi^2}{4} \frac{a\,t}{L^2} \qquad \text{(D7)}$$

in which Q is in cubic feet per foot of cross section if all units are chosen in feet and hours.

The right-hand side of eq D7 has been evaluated and the function $Q\,a/2\,n\,p\,L^3$ has been plotted versus $a\,t/L^2$ on Figure D4.

To compute runoff with the included delay according to this model, the study area was subdivided into three sections as before. In each section no drainage was assumed to occur until 10 cm of melt water had occurred. For the succeeding period, the rate of surface melting p was assumed uniform by drawing a straight line through the appropriate depth of melt curve (Fig. D1) and the cumulative melt-water quantity Q per foot of surface (parallel to melt flow) for the melt stream was calculated from Figure D4. For this purpose D was estimated (and checked from the calculations) to be 0.8 - 0.9 ft and the hydraulic permeability of the snow was assumed to be approximately that of a medium-to-coarse sand, or 1 ft/hr. L was assumed to be 40 ft. At the same time, the calculated height of the water table in the snow was checked against the falling snow surface. When they coincided, the method of computing runoff due to melted and stored water quantities was used. Then the quantities from each subdivision were added together for each time period to obtain the calculated curve shown in Figure D2. The original "instantaneous" flow curve was improved considerably by this method.

Obviously with so many arbitrarily estimated factors, it would be difficult to achieve an exact correspondence between computed and measured quantities. In particular, the value of hydraulic permeability estimated for the snow is only the roughest of guesses, based merely on remembered snow characteristics. If it were reduced from the value of 1 ft/hr to 0.2 or 0.3 ft/hr the correlation of the data would be much improved.

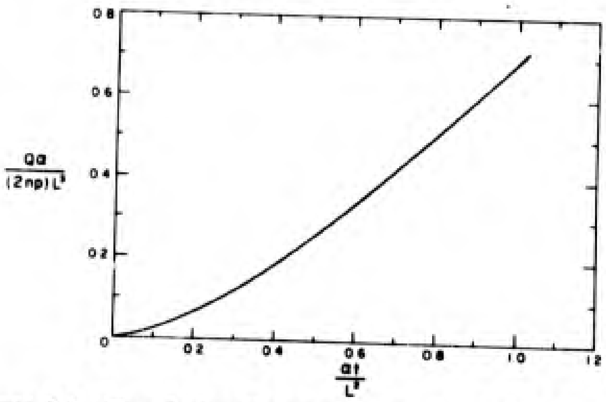

Figure D4. Cumulative flow versus time including storage.