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DITCH BLASTED IN ICE—ALASKA HIGHWAY

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The reports of research published in this magazine are necessarily qualified by the conditions of the tests from which the data are obtained. Whenever it is deemed possible to do so, generalizations are drawn from the results of the tests; and, unless this is done, the conclusions formulated must be considered as specifically pertinent only to described conditions.

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ICE FORMATION ON THE ALASKA HIGHWAY[1]

Reported by WILLIAM L. EAGER and WILLIAM T. PRYOR, Highway Engineers, Public Roads Administration

THE ALASKA HIGHWAY extends from Dawson Creek, B. C., to Fairbanks, Alaska, a total length of 1,520 miles. Twelve hundred and twenty miles of the main highway is in Canada and 300 miles is in Alaska. Elevations range from 1,000 feet above sea level at the Muskwa River near Fort Nelson to 4,251 feet at the summit, 90 miles west of Fort Nelson. Most of the highway lies between elevations of 2,000 and 3,000 feet. A map and profile of the highway are shown on page 69. It extends from about latitude 56° to 64°, and from about longitude 120° to 146°. The area traversed is hilly or mountainous and for the most part is thickly timbered but the trees are generally too small to be of commercial value.

The highway was built during the period from March 1942 to November 1943. In 1942 seven regiments of U. S. Army Engineers, and 47 civilian contractors employing about 7,500 men working under the direction of the Public Roads Administration pushed through a pioneer road. Streams were bridged with temporary timber trestles not expected to withstand the spring break-up. The engineer troops were withdrawn from the highway before the beginning of the 1943 construction season with the exception of two companies that remained until July. Most of the permanent bridges required and an all-season gravel road suitable for heavy trucking were constructed during 1943 by 81 contractors employing about 14,000 civilian workers. These forces were directed by the Public Roads Administration.

REGION OF THE HIGHWAY HAS A SEVERE WINTER CLIMATE

The climate of the region traversed by the highway is classed as the subarctic and is characterized by relatively short and wet summers and long, cold, and dry winters. Spring and fall are short, inconspicuous seasons. Table I gives a comparison of the climate along the highway with other better-known places.

Figure 1 shows normal mean monthly temperatures along the route of the highway based on records of 5 years or more and compares these data with that for the past two winters. It will be noted that the maximum mean temperature variations occurred during the winter months. This condition seems to be typical for subarctic climates. Temperatures are apt to fluctuate widely during the same winter and from one winter to the next.

The few hours of sunlight in winter during which radiant heat is received and the long days in summer account for the wide spread in mean temperature. About midway of the highway between Watson Lake and Whitehorse, at latitude 60°, the sun is above the horizon for approximately 6 hours daily in midwinter and has an altitude of only about 7°. The highway receives practically no direct sunlight at that time. In midsummer the sun is visible for 19 hours and twilight extends through the night from April 23 to August 22.

[1] Prepared for the 1944 annual meeting of the Highway Research Board.

TABLE I.—*Climatological data* [1]

Place	Temperatures			Mean annual precipitation (water)
	Mean annual	Maximum	Minimum	
Along the Alaska Highway:	*°F.*	*°F.*	*°F.*	*Inches*
Fairbanks, Alaska	26	99	−66	11.8
Tanacross, Alaska			−76	
Whitehorse, Y. T.	27	84	−69	11.4
Fort Nelson, B. C.	30	98	−54	13.9
Fort St. John, B. C.	35	105	−65	15.7
Off the highway:				
Yellowstone Park, Wyo.	39	97	−66	20.4
Bismarck, N. Dak.	40	114	−45	16.3
New York City, N. Y.	52	102	−14	43.0
Denver, Colo.	50	105	−29	14.1
Los Angeles, Calif.	62	109	28	15.2
Miami, Fla.	74	96	27	55.7

[1] From the Statistical Abstract of the Bureau of the Census and from data obtained from offices of the U. S. Weather Bureau and the Canadian Department of Transport.

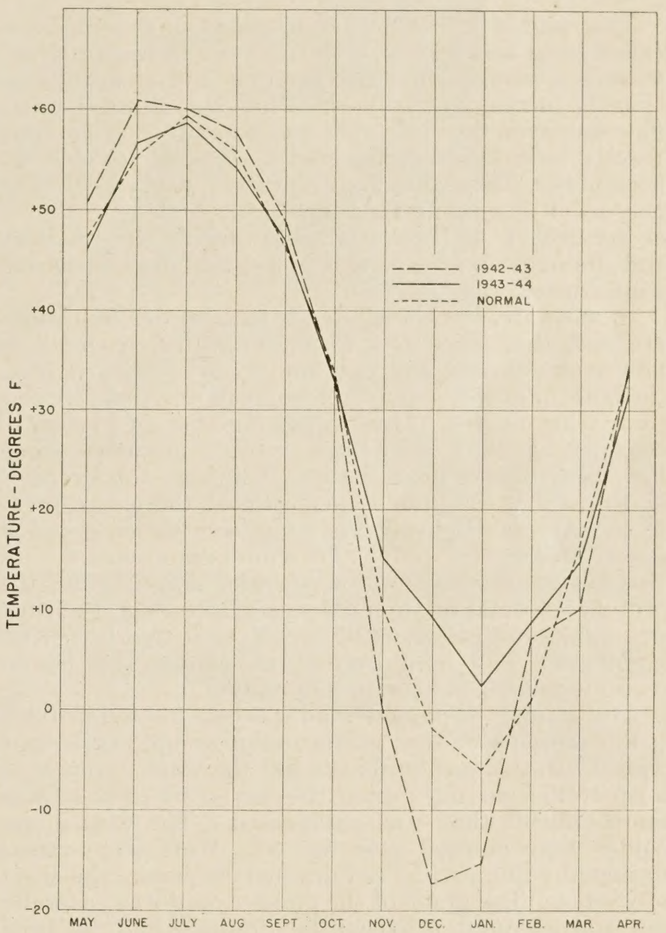


FIGURE 1.—MEAN MONTHLY TEMPERATURES ON THE ALASKA HIGHWAY BASED ON RECORDS AT FORT ST. JOHN, FORT NELSON, WATSON LAKE, WHITEHORSE, NORTHWAY, TANACROSS, BIG DELTA, AND FAIRBANKS.

About 60 percent of the precipitation in the areas traversed by the highway normally occurs from May through September. As these months are relatively cooler than they are at more southerly latitudes, the evaporation is less and the growth of vegetation is much more profuse than might be expected from the annual precipitation figures.

FORMATION OF ICE A SERIOUS OBSTACLE ON PIONEER ROAD

The type of ice formation described in this report is called icing and may be defined as the formation of ice in such a manner that its thickness and area are continually increased. It occurs when thin films of water flow out over the surface of the ground, snow, or previously formed ice during periods of subfreezing temperatures. These thin films of water quickly freeze and may result in a rapid build-up of ice. Unless prevented or controlled, ice formation may engulf the roadway and drainage structures and prevent or impede normal winter use of the highway.

In most areas of the United States, winter conditions are such that if ice does form, the water continues to flow under the ice and any additional freezing is from the bottom of this ice cover downward and little trouble from icing results. However, icing that builds up to considerable thickness is not entirely unknown along highways in the United States. Climatic, topographic, and drainage conditions along almost the entire route of the Alaska Highway are conducive to icing and it constitutes a major problem in winter maintenance. In this region the engineer must take into account the probable formation and effects of icing in locating, designing, and constructing highways if they are to be maintained and used during the winter and winter maintenance costs kept to a minimum.

At the time the pioneer road was constructed in 1942, it was anticipated that ice formation would cause some winter maintenance problems but the work required to keep traffic moving during the winter of 1942–43 was more difficult than was anticipated. The winter was colder than normal (see fig. 1). Wet, seepy areas drained by ditches had not drained out before the onset of winter. The grade of the pioneer road was generally low and adequate provision for drainage had not been made. Adequate equipment for the control of icing was not available.

Ice filled the ditches and culverts and formed on the road surface to considerable depth at many places. Crossings of the larger rivers of glacial origin such as the Donjek, White, and Robertson were practically impassable at times.

Some observations of ice conditions were undertaken the first winter both by the Army and by the Public Roads Administration. Major B. F. Hake of the Northwest Service Command reported on the icing conditions between Whitehorse and Big Delta. W. A. Keranen and R. J. Greisiger of the Public Roads Administration reported on conditions from Lower Post to the White River and in Alaska.

In constructing the final highway in the summer of 1943, 467 miles was relocated away from the pioneer road and 970 miles either coincided exactly or was placed approximately on the location of the pioneer road. In making relocations and in improving sections of the pioneer road to satisfactory standards, advantage was taken of the knowledge gained the previous winter about icing.

CAUSES OF ICING AND METHODS OF CONTROL STUDIED

The highway was relocated around a number of places where icing occurred; at places it was so constructed as to minimize the effect of ice formation, and at other locations water flow likely to cause icing was diverted away from the roadway.

After completion of the highway in October 1943, the U. S. Engineer Department assumed responsibility for maintenance. Most of the highway was maintained under contracts entered into with construction contractors. Advantage was taken of the experience in ice control gained the previous winter and the crews were much more adequately equipped and organized. This, combined with a milder winter and the greatly improved highway, resulted in keeping the roadway ice free and in excellent condition throughout the winter of 1943–44. The cover page shows a location where icing was kept under control by blasting to keep a ditch open.

Since icing had been such a serious problem during the winter of 1942–43, it was desired to make a more thorough study of the matter during the winter of 1943–44. In accordance with a request from Thomas H. MacDonald, Commissioner of the Public Roads Administration, the Division Engineer of the U. S. Engineer Department, Brigadier General L. D. Worsham, granted permission for the Public Roads Administration to carry on icing studies during the winter of 1943–44 as a research project. The information obtained in this study was made available to the maintenance forces on the highway, and the engineers assigned to this work served as consultants with the objective of improving the icing prevention and control methods used.

Preliminary icing investigations and studies were made during the summer and fall of 1943 under the direction of S. E. Horner, geologist of the Public Roads Administration. Studies during the 1943–44 winter were carried on by the writers of this report with the assistance of R. J. Greisiger, highway engineer, whose experience along the Alaska Highway the previous winter proved of great value.

The studies were carried out with the intention of obtaining information for use in maintaining the Alaska Highway and in construction and maintaining other roads where similar conditions exist.

PHENOMENA OF ICING DISCUSSED

When thin films of water are exposed to very low temperatures such as are common along the Alaska Highway in the winter, a very rapid build-up of ice may occur. Generally speaking, icing cannot be prevented entirely by any method that is reasonable in cost but under certain conditions it may be controlled so as not to interfere with the use of the highway. It is important to know what causes the water to emerge on the surface in thin films, since once it emerges icing will result if the temperatures is low enough. In the area of the Alaska Highway the temperatures are generally below freezing throughout the winter and the surface insulation in the form of snowfall is generally light. Ice forms on the surface of water in normal drainage channels and the water continues to freeze downward from the surface, inward from the sides of the channel, and even occasionally upward from below. Ice may so constrict a channel that the water is forced by hydrostatic pressure to break out on the surface.

Icing on the Pioneer Road in Winter of 1942–43: A, On Branch Road to Haines Near Its Junction With the Alaska Highway; B, Along the Kluane River, Several Feet of Ice Has Formed on the Road. Note the Barrels for Burning Oil; C, Thawing a Culvert in Early Spring.

Icing can occur only when the latent heat contained in water is transferred to some colder medium. There are three methods of heat transfer—radiation, convection, and conduction—and all of them are important in icing.

Radiation.—Solar radiation—past or present—is the source of practically all our heat and energy. Terrestrial radiation from the earth outwards into space maintains the heat balance so that the earth as a whole remains at a livable temperature. During winter in the higher latitudes, the receipt of solar radiation is greatly decreased while the loss of heat from the earth by terrestrial radiation goes on practically unabated. This process cools the surface of the earth and therefore the air which is in contact with it. Precipitation occurs in the form of snow rather than rain. A snow covering on the ground further cools the air since snow is both a good reflector and a good radiator. It does, however, serve to conserve the heat in the underlying earth or water as it is a good insulator. Thus the air temperature in winter in the higher latitudes is apt to be very low and any flow of water exposed to air may quickly freeze. The rate of change in air temperature throughout the year follows closely that of receipt of solar energy. Figure 2 shows the variation in radiation received and the variation in mean monthly temperatures at Fairbanks, Alaska.

Convection.—Convection currents in water or in the air account for a large part of the transfer of heat involved in freezing water to ice. The warmer air or water tends to rise since it is less dense while the colder particles settle. However, in the case of air an additional complication enters since air expands as it rises and this expansion tends to cool the air. Thus the air over most of the world is in continual motion, particularly during the warmer seasons of the year. In arctic or subarctic regions the cooling of the air next to the earth's surface (as described under radiation) tends to establish an equilibrium and the lowest temperatures are found in the valleys or on the plains.

In pure water the maximum density occurs at a temperature of 39.2° F. so that as the surface of a body of water becomes cooler, by losing heat by radiation and conduction, the cooler water becomes denser and therefore sinks and is replaced at the surface by warmer, less dense water. This process continues until the entire body of water reaches a temperature of 39.2° F. As cooling progresses beyond this point the colder water is less dense and remains on top, eventually reaching a temperature of 32°. It remains at this temperature

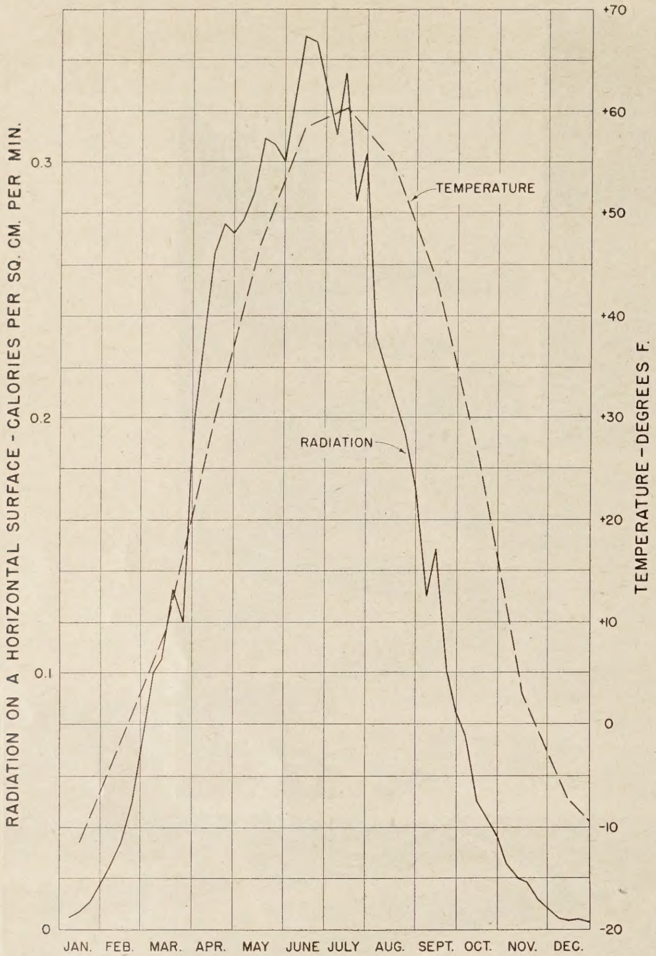


Figure 2.—Total Solar and Sky Radiation and Mean Temperature, by Months, at Fairbanks, Alaska.

until it has lost its latent heat and turns into ice which thereafter grows by freezing downward. The ice covering may then have a temperature differential varying between 32° on its lower surface and whatever the air temperature is on its top surface.

In swift, turbulent streams the normal action described above is prevented. Rapid mixing of the water takes place with the result that the entire flow will at all times be at approximately the same temperature. The temperature remains at approximately 32° F., until the water all freezes to ice or until a surface cover of ice forms. In swift streams this action is conducive to the formation of anchor and frazil ice.

Conduction.—Conduction is the transfer of heat by vibration of the molecules of the substance through which the heat is being transferred. In the action of icing conduction is an important means of heat transfer through all solid substances and the rates at which it is transferred are more readily determined than the rate by which it is transferred by convection through liquids or gases.

Water in contact with colder solid substances loses heat largely by conduction to these substances. The heat contained in water may be transferred by conduction and convection through and from the water to the substances with which it is in contact such as ice, snow, air, ground, and vegetation. Once the heat contained in the water (at least 80 calories of heat per gram must be removed before water turns to ice) reaches the surface it may be lost directly by radiation into space or it may warm air and be distributed elsewhere by convection currents. The rate of heat transfer by conduction increases with increase in the temperature differential between the air and the water with which it is in contact. Water cannot ordinarily exist as such at a temperature lower than 32° F., but the substances in contact with the water may be at temperatures as low as that of the air. On the Alaska Highway temperatures as low as −76° F. have been recorded.

Ordinarily the coldest medium with which water will come in contact is the air and that air is cold principally because it has been in contact with the surface of the earth or substances or objects on the surface of the earth which have lost heat by radiation into space. Air itself has no great capacity for storing heat and it is a poor conductor but conduction to very cold air and convection currents will remove large amounts of heat from a water surface. Since a water surface radiates heat nearly like a black body, much heat may be lost directly by radiation into space if the sky is clear and the air has a low moisture content. Radiation back from the sky is largely controlled by the moisture content of the atmosphere.

Ultimately the heat lost by water when it freezes is lost to the air by conduction or radiation or is radiated into space. This heat loss may be directly from the water or it may be through intermediate substances in contact with the water. These substances generally act to retard the loss of heat from the water. The thicker the covering of ice on a lake or stream the greater the insulating effect and the slower the rate of freezing. Snow has an insulating effect 4 to 20 times that of ice depending upon its degree of compaction. The ice over a body of water provides a support for a snow layer so that under normal conditions the depth of ice covering tends to become stabilized. This is fortunate else many streams and lakes would freeze solidly to the bottom resulting in the destruction of much animal life.

SNOW ONE OF THE BEST INSULATORS

Reference to typical conductivity constants indicates that heat is transferred by conduction through water about 20 times faster than through air, and through ice about 4 times faster than through water. The rate of conduction through ice is slightly faster than through earthy materials such as moist soil and the earth's crust and from 4 to 20 times faster than through snow, depending upon the age and compaction of the snow. The rate of conduction through water or air is not highly important, since convection in these materials will affect a much greater transfer of heat than will conduction alone.

It is apparent that if icing is to be prevented or retarded, the loss of heat—by any method—must be prevented or retarded or the lost heat replaced from some other source. Of the materials readily available in an icing area, snow is one of the best insulators. This explains why icing is not a serious problem in areas of heavy snowfall, even with very low temperatures. While ice is not a particularly good insulator it does prevent direct radiation of heat from underlying water and serves as a support for subsequent snow cover—either naturally or artificially placed. The vegetation which grows so profusely in the region of the Alaska Highway has excellent insulating properties and should not be disturbed any more than necessary if icing in a watercourse is to be minimized. At some places, it may be desired to cause icing, so that water will freeze before it reaches the vicinity of the highway. At such places conditions which would naturally insulate the water must be altered.

OCCURRENCE AND DEVELOPMENT OF ICING DESCRIBED

As the winter progresses there is freezing at the sources of flowing water. Frequently this results in a decrease of channel flow after the surface has been frozen over. Air spaces will then occur between the surface of the water and the ice and the loss of heat is apt to be materially decreased since confined air is an excellent insulator. This action occurs in both large and small channels.

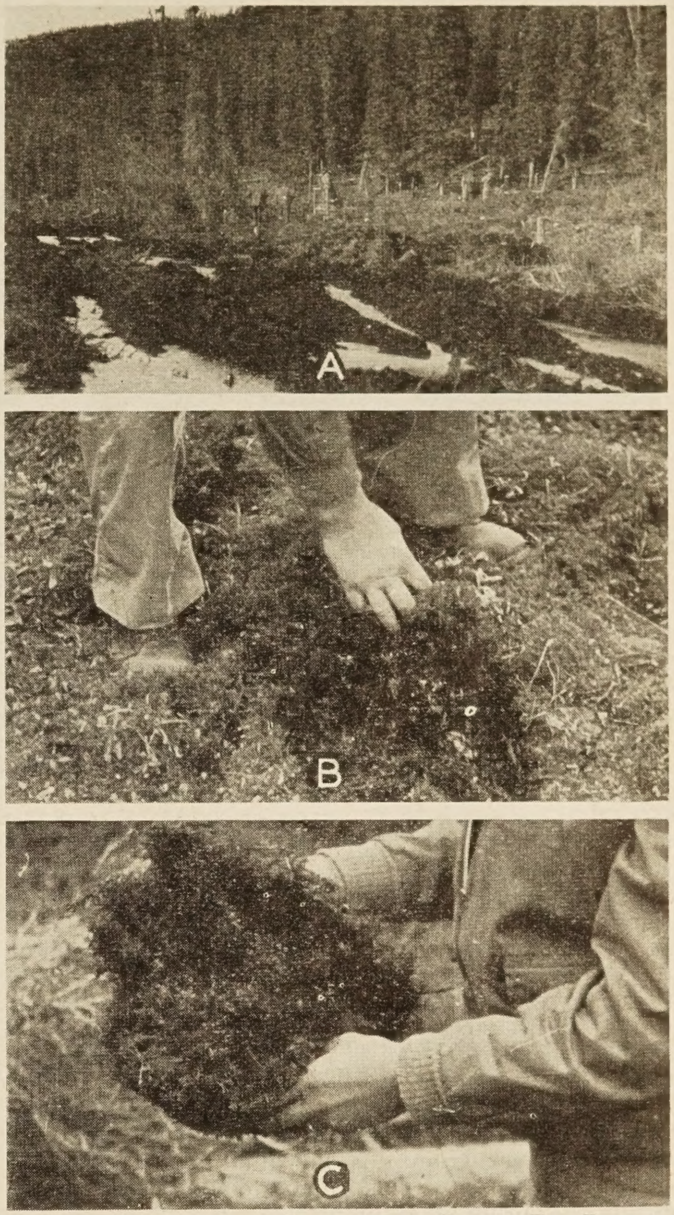
Moss, vegetal debris, and down timber over an area will act as insulators. It is difficult to say what the relative insulating values of these materials are, but undoubtedly the materials are effective, particularly when supporting a fluffy covering of snow. Moss, low bushes, and grasses, when densely matted, make such a good insulating combination that a thickness of 12 to 18 inches will preserve underlying permafrost during the summer and will prevent water from freezing near the roots of the vegetation during the winter. Just how this water is prevented from freezing with frozen material both above and below is something not explained, yet this condition was frequently observed along the Alaska Highway. Water that continues to seep or flow from such areas is responsible for a large part of the icing along the highway. It may be possible that organic decay in the mass of dead roots and vegetation generates enough heat to keep the water from freezing.

The water flow which eventually emerges on the surface and results in icing on or near the highway, may come from any one or all of three sources: (1) Surface water flowing in rivers, creeks, and small streams, the source or sources of each being at a considerable distance from the icing; (2) spring water from fissures and porous strata flowing to the surface at a definite place on or near the highway, and; (3) percolating water or seepage from muskeg swamps, talus slopes, alluvial fans, seams between strata of ledge rock, and sloping ground with a heavy vegetal cover.

The term "seepage" is used here in a limited sense to describe water surfacing on or near the highway that does not have a single discernible surfacing place. The term "muskeg swamp," as used in the region of the Alaska Highway, refers to any basin which does not readily drain and which is filled with saturated muck, fine silty soil, decayed vegetation, and has a heavy ground cover of moss, grasses, and low-growing bushes. There are frequently scattered growths of stunted trees on these areas. These swamps frequently occur on hillsides between ridges, where, in spite of the slope, the muck and vegetation retain a high concentration of water. Frequently, the subsoil in these swamps is permanently frozen.

ICING PROBLEMS AT RIVER CROSSINGS SOLVED

During the winter of 1942–43 the most serious icing conditions, from the standpoint of travel, developed at some of the rivers and larger streams which were crossed at low level on temporary timber trestles. It was evident at this time that the permanent bridges should be placed above any possible ice formation, and

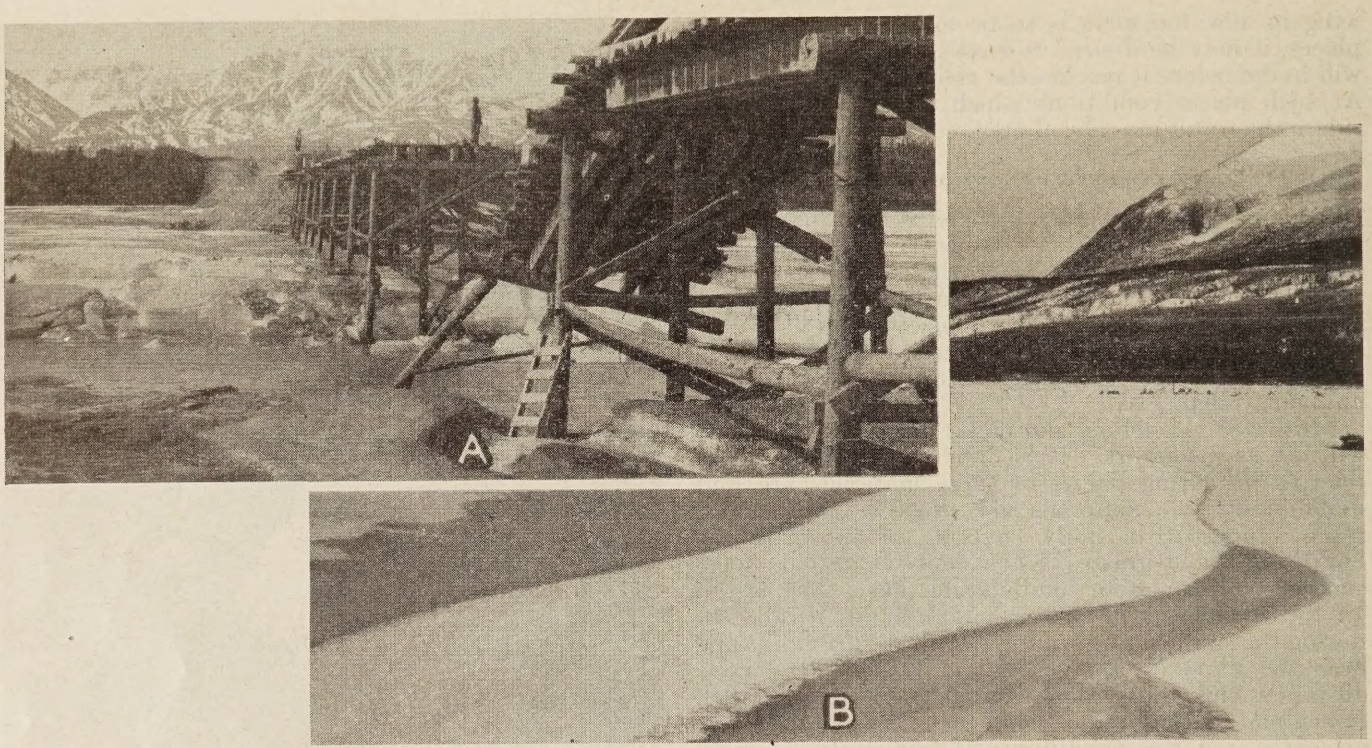


A, Natural Conditions Conducive to Icing. The Picture Was Taken in October 1942 as Winter Began. B and C, Ground Cover of Moss and Vegetal Debris That Prevents Evaporation in Summer and Freezing in Winter.

the designs for the permanent structures were prepared accordingly.

During the 1943–44 winter, after the permanent crossings had been constructed, no trouble was experienced at any of these locations. Ice in such rivers as the Donjek and the Robertson developed to about the same level as the winter before. At the Donjek, one of the few large streams where timber trestles remained in use, ice formed to within 1 foot of the bottom of the stringers. The original crossing here had been replaced by a series of timber trestles, at somewhat higher level, separated by gravel fills. At the Robertson, which was crossed all winter on a temporary trestle, ice did not form high enough to approach the road level. Floating ice in the spring knocked out several bents.

Icing on the larger streams has been successfully coped with by placing the superstructures above the level of



A, Floating Ice Took Out Two Bents of Temporary Trestle Across the Robertson River. Ice Resting on Gravel Beds Has Formed to a Considerable Height Above the Summer Stream Level. B, Ice Blister in the Donjek River Caused by Hydrostatic Pressure in the Constricted Channel. Water Has Emerged and Will Soon Freeze.

all possible ice formation, and by making the substructures substantial enough to withstand the effects of floating ice during the spring break-up. In streams like the Robertson and Johnson Rivers, ice builds up in successive layers as a result of overflow and freezing on top of previously formed ice. The ice layer is so thick that it rests on the stream bed rather than floats on the water. Consequently most of it melts in place the next spring and summer and is not carried downstream in blocks. Natives say that the ice "rots out." In other streams with broad surfaces, like the Peace, Sikanni Chief, Muskwa, and Liard Rivers, thick ice forms by downward freezing but does not build up greatly on the surface first frozen. This ice goes out in a wild charge during the spring break-up.

The remainder of this article is devoted almost entirely to icings caused by seepage water or flowing streams not more than a few feet wide, although there is occasional reference to the action in larger streams.

ICINGS CLASSIFIED

Icings along the Alaska Highway may be divided into two classes.

Natural Icings.—These would develop normally regardless of road construction. They occur as follows:

(1) In glacial rivers and creeks and in streams on alluvial fans, where the nature of the channel is such that little protection from freezing is afforded the flow. Relatively steep gradients are a factor, since channels under the ice become constricted by continued freezing, and water is subjected to considerable hydrostatic head, often breaking through the ice cover and spreading out on the surface. Icing is always worse in a wide, shallow, gravelly channel with a steep gradient than in a deep, narrow, low-velocity stream having a heavy overhanging growth of vegetation along the banks.

(2) Where seepage and subsurface water flows from springs that reach the surface near the base of a hill or mountainside. Wherever water emerges in small quantity it is sure to freeze. The additional exposure at the roadway with the resulting greater depth of frost penetration may be a factor in forcing the flow to the surface. However, it has been noted that ice frequently forms where water emerges at locations remote from any influence of the highway construction.

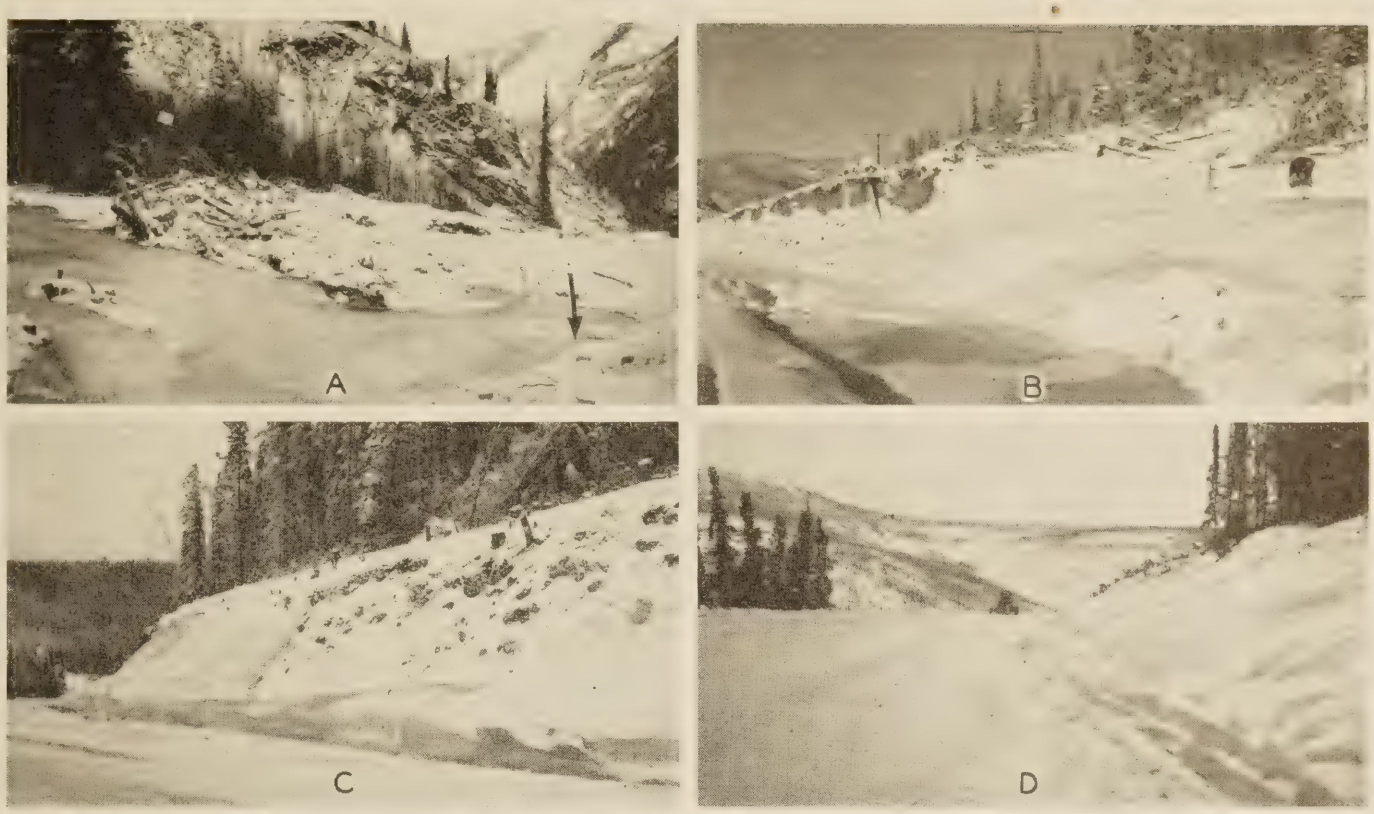
(3) At light surface flows down steep watercourses. Here the flow is spread out thinly to give maximum exposure to the atmosphere and loss of heat by radiation.

Artificial Icings.—These are caused or promoted by the road construction. They occur as follows:

(1) At seeps and springs intercepted by highway excavation. Springs are more apt to be found at considerable depths and therefore are likely to continue active all winter. Seepage flows most often appear in the lower part of or immediately under a heavy vegetal ground cover. With prolonged periods of cold weather and only a light snow cover, these seepage flows may freeze up before they reach the roadway and become inactive.

(2) At crossings of small streams where the additional exposure created by the construction promotes the formation of ice. These are narrow, deep, low-velocity streams with heavy vegetation on banks which normally do not ice—at least not at the point crossed by the highway.

Icing may be started by freezing in a culvert or under bridges or at a disruption or obstruction of the normal drainage channel. Since the culverts and bridges are invariably placed under or in fill materials of high heat conductivity, and snow covering on the road surface is removed by maintenance forces, the opportunity for heat loss is greater than in the original channel. The



A, Ice Formation Where a Small Stream Enters a Culvert. The Arrow Indicates the Entrance to the Culvert. B, Typical Icing in a Waterway and Roadside Ditch. C, Ice Formed in the Ditch and on the Back Slope. D, Ice Had Begun to Encroach on the Roadway When It Was Loosened and Bladed Across the Road.

normal, protected channels are necessarily disturbed within the limits of the construction operations and may even be unnecessarily obliterated or obstructed in these operations.

(3) At highway fills where subsurface flows are forced to the surface by a damming action. This may result from additional compaction but more often removal of protective cover in construction and maintenance of the highway permits frost to penetrate much more readily and thus create a "frost dam." Considerable icing occurred where very light fills were placed.

The mass which forms in icing action has the appearance of a heavy viscous liquid in motion. The formation of ice in relation to the supporting earth is much the same as that of a lava flow, although the methods of formation are entirely dissimilar. Small obstructions or restrictions in the channel cause the ice to dam up in its downstream progress.

CONDITIONS UNDER WHICH MAJOR ICINGS OCCUR ANALYZED

In the study of icing conditions along the Alaska Highway during the winter of 1943–44 the highway was divided into two sections, since one man could not travel and inspect icings on the entire highway with sufficient frequency, even though the highway could be traveled without difficulty throughout the winter. One section extended 913 miles from Dawson Creek to Whitehorse. The other section included the 509 miles to Big Delta, approximately 100 miles from Fairbanks.

At 92 places between Dawson Creek and Whitehorse the icing was active enough to constitute a considerable maintenance problem and was classified as major. There were 34 such places between Whitehorse and Big Delta. In addition, there were 57 places between Dawson Creek and Whitehorse and 38 between Whitehorse and Big Delta where minor icing activity occurred. Observations of all these icing points were made on various inspection trips during the winter. Information on icing activity and maintenance methods used were obtained by discussion with the maintenance men and from written reports prepared by them and by officials. In the spring after the snow and ice had largely disappeared a close inspection was made of the drainage conditions and other features at each of the major icing points.

Practically none of the icings observed could be attributed wholly to a single circumstance or condition. More than half occurred where natural conditions would have produced some icing had they been left undisturbed but the amount of icing was greatly increased as a result of disturbance in construction of the highway.

There follows a summation of the data concerning conditions at places where major icings occurred. Following this presentation the effect of the conditions will be discussed.

Natural and Artificial Conditions.—At 65 percent of the icings the natural slope of the drainage channel was conducive to icing and 49 percent of the icings formed where subsurface flow emerged naturally near the foot of a hill or mountain. Increased exposure of water to freezing by removal of ground cover or alteration of channels in construction of the highway contributed to over 90 percent of the icings.

The original, natural drainage channels at the roadway were classified as follows: 13 percent good, 37 percent fair, 31 percent poor, and 19 percent were not classified. Of the constructed drainage channels at the roadway, 2 percent were classed as good, 27 percent fair, 46 percent poor, and 25 percent were not classified.

Source of Water.—Flow of water to points of icing sometimes came from more than one source. Percentages of icings by water sources were as follows:

	Percent
Creek	6
Small stream or branch	54
Spring	14
Seepage	44

Road Location.—Terms descriptive of road location are applicable at points of icing as follows. At some locations two terms are applicable.

	Percent
Across flats and at a considerable distance from a hill or mountainside	21
Rolling, irregular grade	34
Sidehill cut and fill	30
At or near foot of hill or mountainside	33
Miscellaneous	27

The cross slopes at the major icing locations are grouped as follows:

	Percent
Nearly flat	20
Light, up to 15 degrees	45
Heavy, over 15 degrees	35

Subgrade Soil.—Considering the length of the entire highway, 43 percent was located on soils classed as better than A–3–4. These better subgrades were mainly A–2, A–2–3, A–2–4, A–2–7, A–2–3–4, rock and gravel. The subgrades worse than A–3–4, found on 57 percent of the highway, were classified as A–4–7, A–5–7, A–7, A–4–6, A–2–4–6, A–4, A–6–7, A–8, and A–4–6–7.

The distribution of points of icing as to character of soil was as follows. A few places had two types of soil and were placed in two classifications.

	Percent
Sand, sand and gravel, rock	45
Silt with some sand or gravel	23
Silt with little or no sand or gravel	9
Clay with some sand or gravel	11
Clay with little or no sand or gravel	9
Silt and organic soil, A–5, A–8	11

Type of Culvert.—On the entire highway 66 percent of the culverts were made of wood and 34 percent were metal. The points of icing were distributed as follows:

	Percent
Wood culvert	46
Metal culvert	40
Both wood and metal culverts	13
No culvert	1

Ground Cover.—Practically the entire region of the Alaska Highway below the timber line is covered with a thick mat of moss and vegetal debris. With regard to thickness of ground cover the points of icing were distributed as follows:

	Percent
Heavy, over 12 inches	72
Medium, 6 to 12 inches	25
Light, 6 inches or less	2
None	1

Months of Icing Activity.—During the winter of 1943–44 major icings were active as follows:

	Percent
November	31
December	62
January	76
February	75
March	54

SEEPAGE AND SMALL STREAMS CAUSE MOST ICINGS

Icing occurs in a natural channel when it is wide and shallow, has little protection by vegetal growth, and a fairly steep gradient or a sudden change in gradient. Near the foots of hills and mountains subsurface flows tend to be forced to the surface and icings are likely to occur at such places.

At practically every icing the greater exposure resulting from construction of the highway has been a factor. Greater exposure cannot be avoided but can be compensated for to a certain extent by improvement of the natural drainage channels. Methods will be discussed later in this report. In making most roadway cuts it is impossible to avoid altering the natural drainage channels and intercepting new ones. However, many of the natural drainage channels were obstructed by debris pushed aside in clearing the roadway or with excavated material. Some drainage structures were so located as to disturb the continuity of the natural drainage course.

On the whole it must be expected that numerous locations naturally subject to icing or which will be made subject to icing by construction of the road will be found. If winter maintenance is to be kept within reasonable bounds some compensation must be made in the design of the roadway and drainage channels.

Streams from about 1 to 4 feet wide and from 3 to 12 inches deep and seeps are the principal sources of water causing major icing. In most cases the small streams originate in springs or seep from muskeg areas or from under a heavy mat of ground cover. Seepage most often emerged near the tops of cut slopes. A heavy protective layer of moss and vegetal debris and sometimes snow prevented the water from freezing before reaching the highway.

The seepage, in addition to supplying water that froze on emerging on or near the highway, produced conditions that afforded a considerable degree of protection of the water until it reached the highway. Trees and other vegetation grow more densely in the presence of an ample water supply and these produced a thick ground cover. This cover not only protected the water from freezing in winter but in summer it prevented lowering of the level of permafrost.

The data on road location and on cross slope at icings indicate that there is less of a tendency toward icing where the highway is located on relatively flat ground. Conversely, a fairly steep watercourse gradient is conducive to icing.

Observations on the direction of exposure of icings indicated a definite tendency for icings to be more active on southerly slopes. Apparently the additional heat from the sun keeps some small water flows active yet this heat is not sufficient to prevent icing where the flow is exposed to cold air at the roadway. The direction of exposure is not important at midwinter since practically none of the highway is exposed to direct rays of the sun at that time.

The data on type of subgrade soil indicate a tendency for ice to form where the subgrade material is of the more porous or granular type. Obviously such soil is better able to carry subsurface water and is most commonly deposited along stream courses.

It has been suggested that wooden culverts, because of their better insulating properties, might have less tendency than metal to cause freezing in the winter. The observations made do not indicate that either material is superior to the other in this respect.

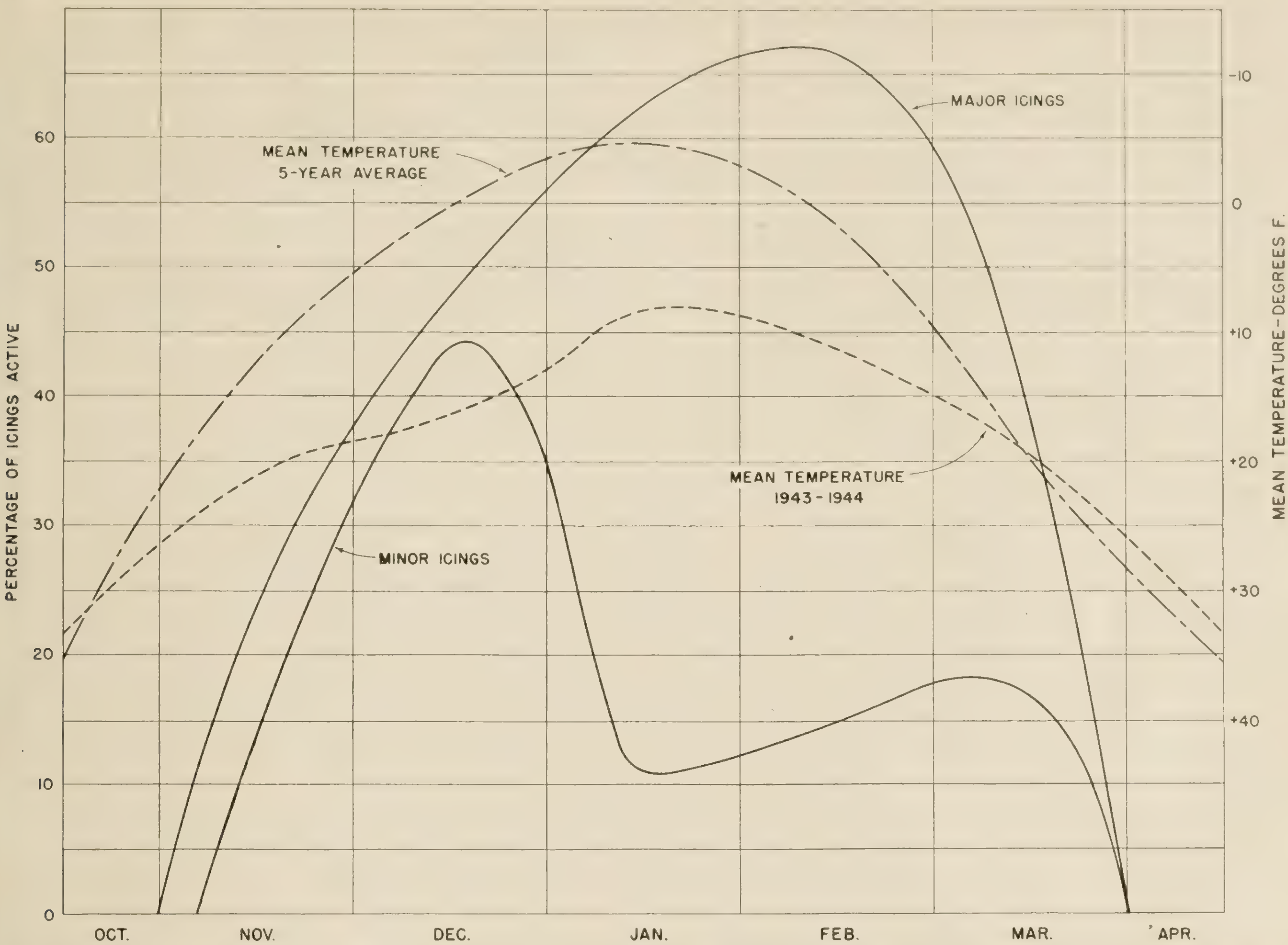


FIGURE 3.—PERCENTAGE OF ICINGS BETWEEN PROCHNIAK CREEK AND WHITEHORSE ACTIVE, BY MONTHS. ALL DATA ARE FOR THE WINTER OF 1943–44 WITH THE EXCEPTION INDICATED. THE CURVE MEAN TEMPERATURE, 5-YEAR AVERAGE, IS BASED ON RECORDS AT WHITEHORSE, WATSON LAKE, FORT NELSON, AND FORT ST. JOHN FOR A PERIOD OF 5 YEARS OR MORE. TEMPERATURE DATA FOR 1943–44 ARE BASED ON RECORDS AT SIX STATIONS BETWEEN PROCHNIAK CREEK AND WHITEHORSE.

PERMAFROST A FACTOR IN PROMOTING ICING

Permafrost is permanently frozen ground, or ground in which the temperature remains below freezing throughout the year. If the ground contains enough moisture, the soil particles will be bound together in a hard, impermeable mass. If little moisture is present, the materials may be loose even though the temperature remains below freezing. Along the Alaska Highway all permafrost observed had a high ice content. The upper level of frozen material commonly varies somewhat with seasonal changes in temperature and may, in the winter, meet the lower level of surface freezing. Very little permafrost occurs south of the upper crossing of the Liard River at mile 642, apparently because the average temperatures are higher at the lower latitudes. From observations along the route of the highway it appears that the mean annual temperature must generally not exceed 28° F. if permafrost is to be maintained.

Table 2 shows the occurrence of permafrost and of icing activity on the 437-mile section of highway south of Whitehorse to Prochniak Creek. The greatest amount of permafrost was encountered between Nisutlin Bay and Teslin River. This table indicates a decided tendency for icing to occur on areas of permafrost.

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TABLE 2.—*Occurrence of permafrost and of icing on 437-mile section of highway south of Whitehorse*

Highway section	Length	Over permafrost					
		Highway		Major icing		Minor icing	
	Miles	*Miles*	*Percent*	*Number*	*Percent*	*Number*	*Percent*
Prochniak Creek to Lower Crossing	16.4	0	0	0	0	0	0
Lower Crossing to Upper Crossing	146.2	.5	.3	0	0	1	7
Upper Crossing to Nisutlin Bay	160.9	7.0	4.4	1	4	3	6
Nisutlin Bay to Teslin River	33.1	9.0	27.2	9	64	3	30
Teslin River to Whitehorse	80.3	2.0	2.5	0	0	0	0
Total	436.9	18.5	4.2	10	17	7	8.5

From Whitehorse to Big Delta 28 percent of the road was constructed over ground classed as permanently frozen at the time of construction. Sixty-eight percent of all the major icings in this section occurred on these areas. Permafrost appears to be a factor in promoting icing activity. It is evident that permafrost layers hold the water near the surface where it can readily freeze instead of allowing it to soak away to protected depths.

ICE DAM FORMED OVER PERMAFROST CAUSES TROUBLE

An interesting icing condition occurred on a 3-mile section of the road west of Tanacross in Alaska. Here,

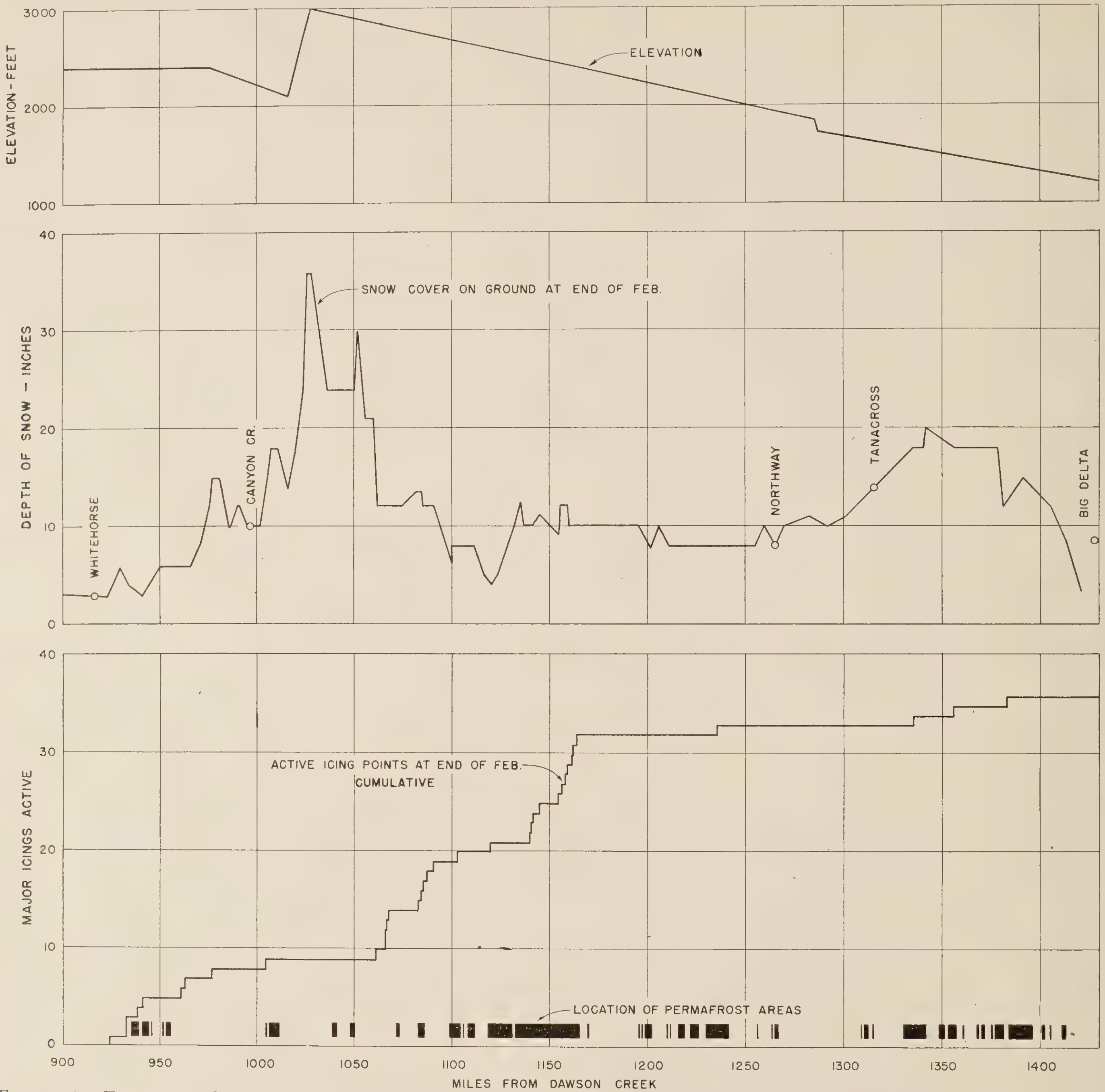


Figure 4.—Elevation, Snow Cover, Active Icing Points, and Permafrost Between Whitehorse and Big Delta. All Data Are for 1943–44.

the roadway crosses several miles of a rather flat, swampy ground. There is a slight slope to the ground in a direction at right angle to the highway and some water normally seeps down slope through the grass roots and in the porous layer of decayed vegetation immediately underneath. The swamp is crossed on a gravel fill about 3 feet deep and there are numerous cross culverts. The vegetation is underlain everywhere at a depth of a foot or so with permanently frozen ground.

During the winter of 1943–44 a solidly frozen dam of material developed at the highway, extending from the roadway surface down to the permafrost layer below. This sealed the normal seepage channels and left the cross culverts as the only passageway for the flow. Since these culverts were in a relatively exposed location they quickly froze, and flooding developed over the swamp area upward from the highway. This flooded area then froze over, the ice forming around the vegetation. Continued flow of water under the impermeable cover of ice developed hydrostatic pressure which lifted the entire mass—grass, bushes, small trees, roots, and ice cover—as much as several feet. This action did not take place uniformly over the entire area but produced a series of small hummocks. Trees growing on these hummocks were shifted from a vertical position, resulting in what is called by the Russians a "drunken forest."

Water flow from ruptured places in the ice cover caused additional flooding and icing and, for a time,

Figure 5.—Elevation, Temperature, Snow Depth, and Icing Locations Between Dawson Creek and Whitehorse, Winter of 1943–44.

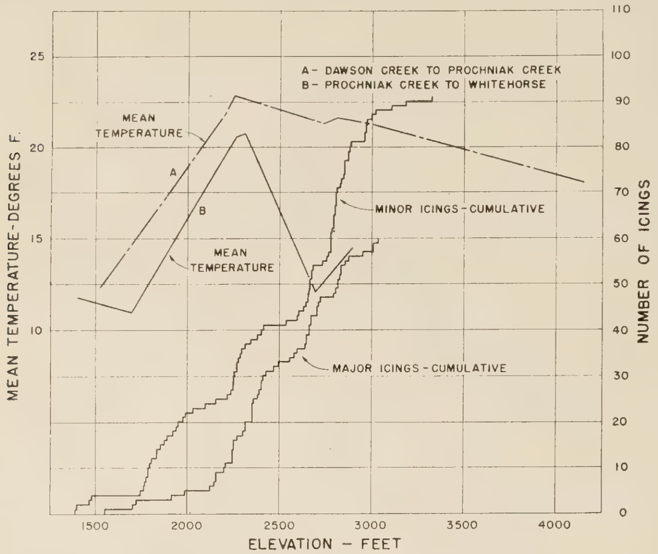


Figure 6.—Effect of Elevation on Mean Temperature and Icings From Dawson Creek to Whitehorse From November Through March 1943–44.

threatened to invade the road surface. However, this was prevented by throwing up dikes of snow and brush and opening the culverts.

ICING MOST ACTIVE IN JANUARY AND FEBRUARY

Formation of ice was most active in January and February. Figure 1 shows that the minimum mean temperature was reached in January, but there was little recession in icing activity until about a month after the mean minimum temperatures had been passed.

Figure 3 presents data on icings between Prochniak Creek and Whitehorse. It indicates that the major icings in this section continued to increase for about a month after the mean minimum temperature had been passed, but a considerable portion of the minor icings became inactive about 2 months after the onset of the icing season.

DEEP SNOW PREVENTS ICING

Figure 4 shows the number of icing points active at the end of February and the estimated depth of snow cover along the section of highway from Whitehorse to Big Delta. Between Whitehorse and mile 1,163 icings occurred at fairly regular intervals wherever the depth of snow cover was less than 15 inches but did not occur when the snow cover exceeded this amount. There were other factors—topography, type of drainage, temperatures, etc.—which prevented icings at all but four points west of mile 1,163. The area traversed between mile 1,115 and 1,163 is one which might be expected to have heavy icing normally. Several heavy icings on this section were reported the previous winter by Major Hake, but the deep snow cover during the winter of 1943–44 apparently prevented recurrence of the icing.

Figure 5 shows the approximate elevation, mean temperature, observed depth of snow, and cumulative totals of active icings for the section from Dawson Creek

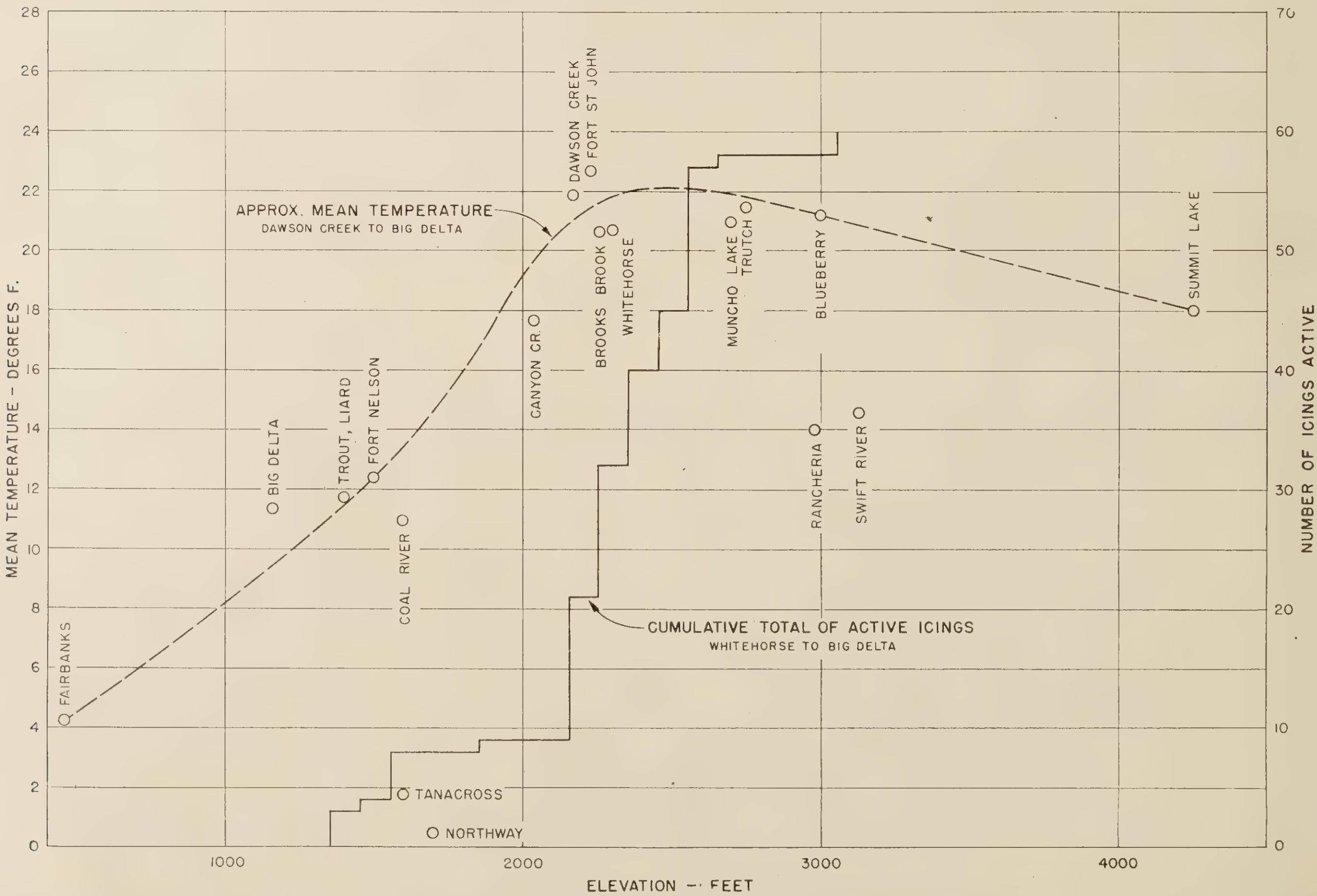


Figure 7.—Effect of Elevation on Mean Temperature and on Icings Between Whitehorse and Big Delta, November Through March 1943–44.

A, At This Location Near the Alaska Border the Natural Conditions are Conducive to Icing; B, Deep Snows in the Region Near Kluane Lake Prevented Serious Icing.

to Whitehorse. The observed depth of snow and totals of active icings are for the same period of time in early March when the snow had reached its maximum depth. There appears to be little connection between the elevation and the depth of snow cover, but it will be noted that west of Fort Nelson, the frequency of icing increases as the highway passes over a divide or range of mountains. This is probably largely due to the more adverse drainage conditions from an icing standpoint that occur in such locations.

ELEVATION AFFECTS BOTH THE TEMPERATURE AND EXTENT OF ICING

In figure 6 elevation above sea level is compared with icing location and mean temperature for the Dawson Creek to Whitehorse section. Figure 7 shows similar data for the Whitehorse to Big Delta section. Two conditions are apparent from these figures.

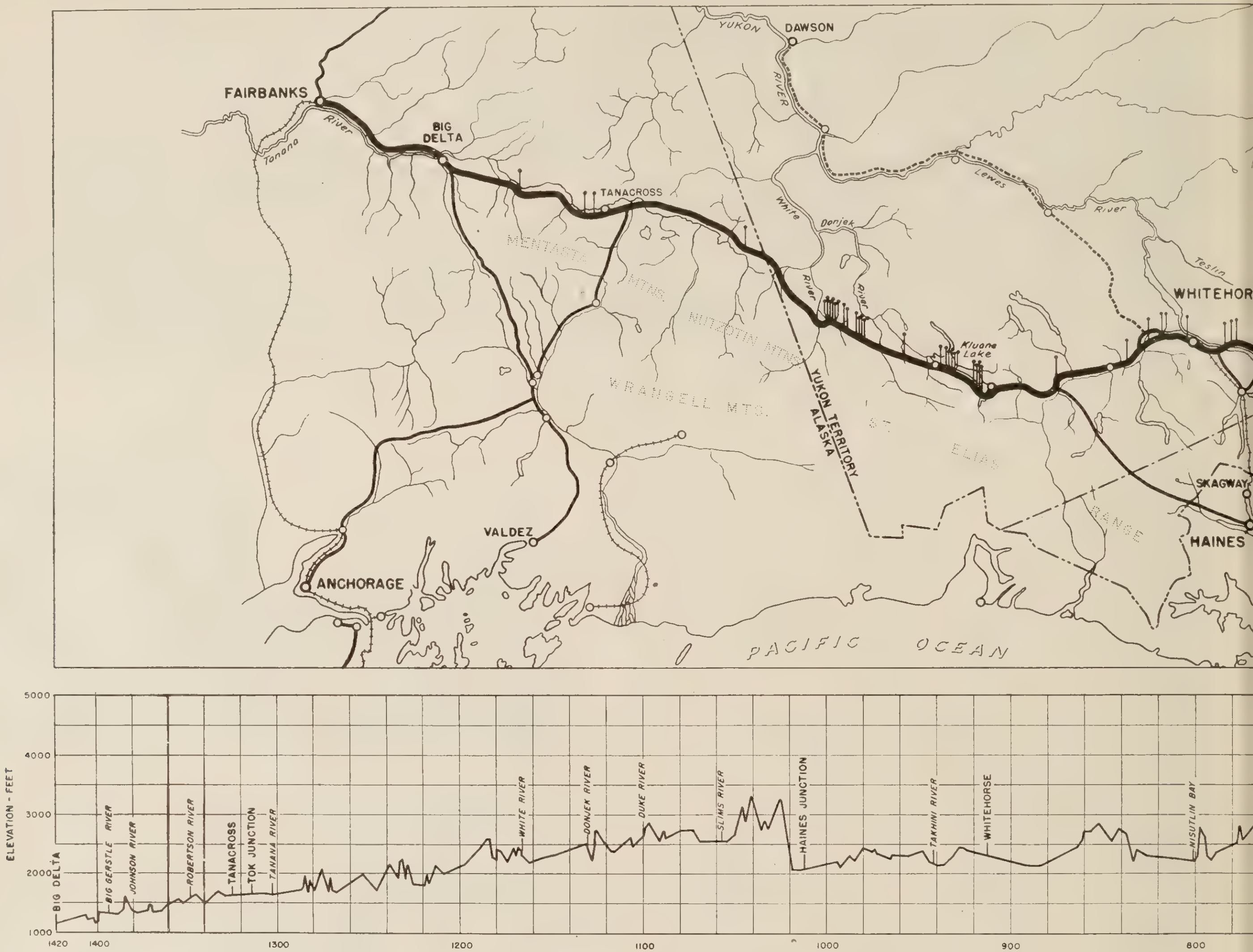
(1) The maximum mean winter temperatures during the winter of 1943–44 occurred at elevations of about 2,300 feet. Mean temperatures were appreciably lower at elevations both above and below this level.

(2) The greatest frequency of active icing was at elevations above 2,100 feet.

The first condition is probably associated with the commonly observed "temperature inversion" in subarctic and polar regions. By means of sounding balloons it has been noted that the temperature during the winter in subarctic regions frequently increases from the ground upwards to some certain elevation above the ground surface, from which point on the temperature again decreases. Over relatively flat ground a stable condition results from this phenomenon which is caused by loss of heat from the snow-covered surface by radiation. In mountainous country the cold air resulting from contact with the cold snow surface being heavier tends to flow to the lowest possible elevations and is replaced at the higher elevations by warmer air. Also, cold polar masses of air commonly move southward and because of their greater density, tend to remain at the lowest possible elevations.

Figure 7 shows the mean winter temperatures at all of the stations reporting weather between Dawson Creek and Fairbanks. Mean temperature at all of the stations except Rancheria, Swift River, Tanacross, and Northway fall quite close to a well-defined curve. These four stations are in river valleys between mountains where the cold masses of air tend to remain, reducing the mean winter temperature.

A, Permafrost Exposed by Grading in Alaska. B, West of Tanacross Where a "Frost Dam" Formed at the Roadway. Hydrostatic Pressure Has Tipped the Trees From Vertical Position. Note the Water on the Surface. C, At the Same Location as B. Hydrostatic Pressure Has Raised the Thick Vegetal Cover at the Right About 6 Feet.



Map and Profile of Alaska Highway. Loc

It may be noted in figures 5 and 7 that the stations below an elevation of 2,100 feet are not in any particular locality or latitude but are scattered over much of the length of the highway.

That the greatest frequency of active icing was found at elevations above 2,100 feet may be explained by the following conditions:

(1) At the higher elevations the topography is more rugged and the water flows intercepted by the highway, although smaller, are more numerous.

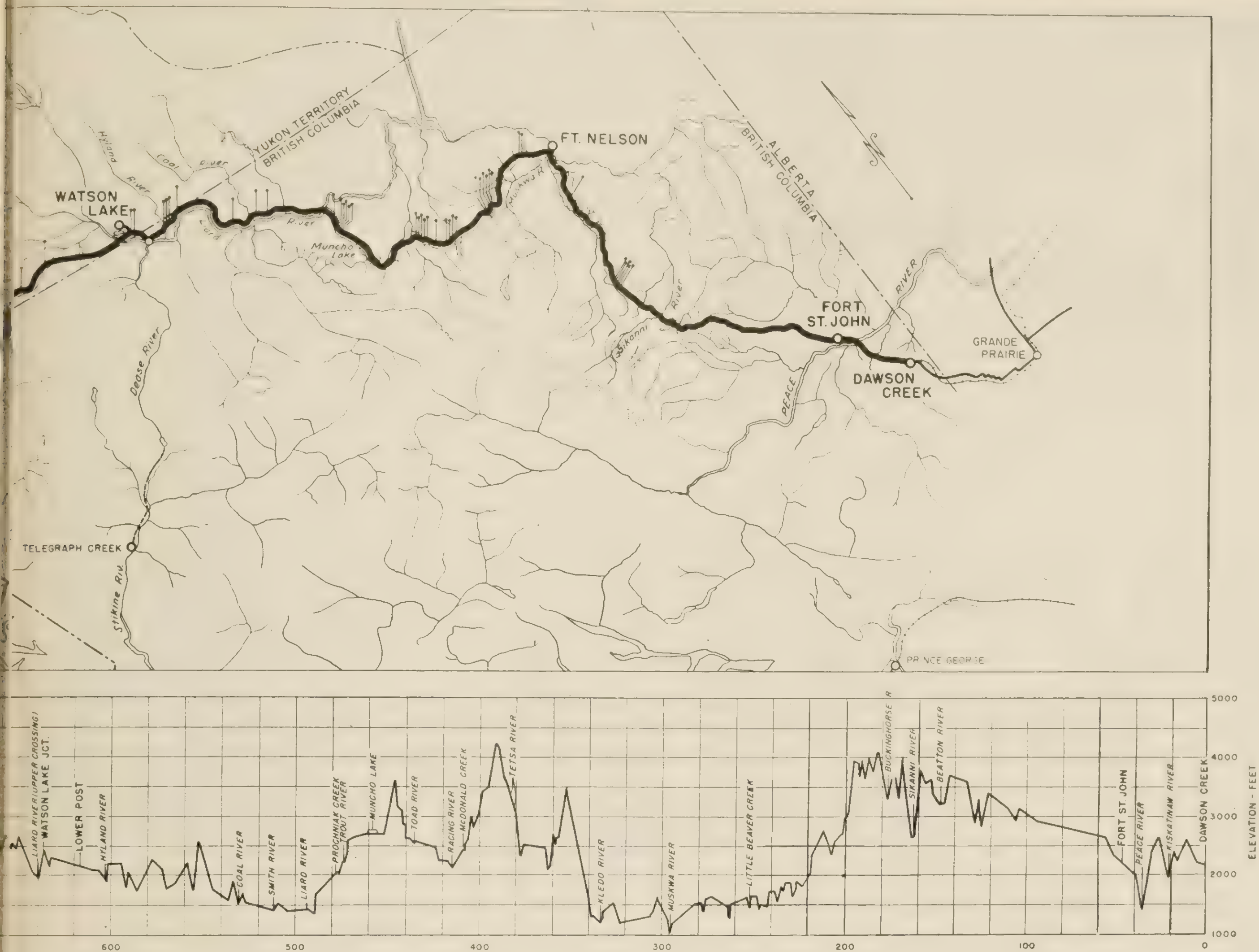
(2) Water flows having steep gradients are more subject to icing and at the higher elevations the watercourses are naturally steeper.

(3) Temperatures during the winter, while averaging higher than at the lower elevations, are apt to fluctuate more widely.

That the greatest frequency of active icing occurred at elevations above 2,100 feet while the lowest mean temperatures were found below that elevation is not in agreement with the general observation that icing activity varies inversely with temperature, the period of greatest icing activity lagging somewhat behind the lowest mean temperatures. It is possible to rationalize these two conditions by considering that icing, to a very large extent, depends upon the flow of water and also upon the temperature. Other things being equal, for maximum icing there must be a maximum flow of water coupled with low temperature. However, when the temperature consistently remains very low, the flow of water is inevitably decreased which in turn decreases the icing. This decrease in flow is bound to lag considerably behind decrease in temperature whereas an increase in icing activity takes place immediately after the temperature drops.

VARIOUS METHODS USED TO PREVENT OR ALLEVIATE ICING

It is impracticable to prevent icing entirely, but there are steps that may be taken in locating, designing, and constructing a highway to reduce or even eliminate the necessity for control of the icing during the winter. Certain locations are most apt to be subject to icing and these locations should be avoided if possible. Generally it will be impossible to avoid all such locations and where they cannot be avoided certain procedures should be adopted to reduce the winter maintenance. This work can be done during initial construction but may also be done by maintenance forces after the location of the most active icing points has been determined by experience. Only a careful study at each icing point will indicate the best methods to use. Records of past



...s Indicated by Lines Erected Along Route.

activity at any particular location will help to determine how much preventive work is justified.

Procedures in use on the Alaska Highway or suggested by observations on the highway are:

1. Improvement of drainage channels and structures.
2. Installation of numerous and large drainage structures.
3. Raising the roadway grade.
4. Construction of dikes to confine the flow within certain channels.
5. Construction of subsurface drains.
6. Construction of basins for formation and storage of ice, either at the roadway or some distance upstream.
7. Construction of diversion dikes and ditches.
8. Stripping areas across watercourses and seepage areas to induce icing when winter starts.
9. Construction of dikes to act as storage dams for ice formation.

It has been observed that improvement of drainage channels and structures and raising the grade are always good practices in combating icing. A fundamental rule to follow in constructing drainage ditches for ice control is to make them as deep and as narrow as conditions permit. This will often necessitate placing a culvert well down in the original ground. There should be no break in the channel grade line at the drainage structure. An overflow culvert at higher elevation may be necessary for use if the lower culvert becomes blocked by ice or debris.

Two important advantages are gained in having the drainage trenches as deep and as narrow as possible. Water flowing in the trench receives considerable protection from the close, high banks and vegetation growing on them. Space is provided for a considerable depth of ice formation under which flow channels may be opened later with a steam jet. Considerable protection is thus afforded the water flow by the covering of ice, air space which may occur between the water and the ice, and any snow cover which may fall or be placed on the ice covering. The protection resulting from this combination of conditions was often so effective that the water flow continued under the surface for as much as a month without further attention and in some cases there was a complete cure for the rest of the winter. Ice itself is a relatively poor insulator but it does prevent the loss of heat from underlying water by direct radiation into the atmosphere. Air confined by ice and loose snow supported by it are very effective insulators.

Culverts for cross drainage should be placed at frequent intervals along sections subject to icing, since icing may divert the flow from its normal courses.

Outlet of a Culvert That Is Completely Filled With Ice.

They should be at least double the size necessary to take care of the normal run-off in order to allow for the reduction in effective size by icing. At least part of the culverts should be placed well down in the original ground so that the water flow may be carried in relatively deep and narrow trenches within the limits of construction without a break in the continuity of the gradient.

DIKES AND SUBDRAINS DISCUSSED

A high grade line is often the surest way of avoiding trouble. To be effective there must be high ground along the center line on either side of the point of icing and to be economical the high grade line must be required for only a short distance. When the roadway grade is raised after original construction it will usually be necessary to extend drainage structures. The cost and practical difficulties in the way of such extension will usually determine the feasibility of a higher fill.

Ice forming on the upstream side of the roadway fill constitutes a problem only if it gets high enough to invade the road surface or if a passageway is not opened through this ice to and through the drainage structure in time to take care of the spring run-off. Along the Alaska Highway the spring thaw comes in April—one of the driest months of the year. The run-off is almost entirely from melting snow and ice and is relatively slow. It is necessary to have only a small passageway started under or in the ice. The flow itself will enlarge the passageway as required.

In a wide stream bed with shallow flow—which is the type most subject to icing—the formation of ice is apt to divert the flow of water in new directions. This flow with its resulting ice formation may then reach the highway at locations where no drainage structures, channels, or provision for ice storage or ice control have been provided. At such places, dikes can be effectively used to direct the flow within certain channels. Usually it is best to construct the dikes in the fall before freeze-up but after the water flow has subsided to winter normal.

Dikes can be thrown up in a short time with a bulldozer, but are apt to be washed out by the next summer's high water, and may need to be replaced each fall. A more permanent dike can be constructed by riprapping the face of the dike. The channel provided should be as wide as possible to give space for the formation and storage of a large volume of ice before the dike is overtopped. A relatively deep and narrow channel may be constructed within the diked area to direct the flow to the drainage structure until ice begins to cover the entire diked area.

Springs or seeps in cut banks often can be effectively intercepted by porous subdrains if permafrost does not exist. The drain must be below the depth of frost penetration. Five or six feet will ordinarily be adequate in the region of the Alaska Highway. The drain must have an outlet in a protected area. Protection can be afforded by covering with moss and vegetative material common in wet areas along the Alaska Highway and may be further increased by snow thrown off the roadway in maintenance operations. An exposed subdrain outlet will quickly freeze and the water flow may be forced to seek a new outlet in or above the highway. Subdrainage, if successful, offers a permanent cure of icing but requires careful study for adaption to a particular location.

Icing basins immediately upstream from the roadway serve somewhat the same purpose as a high grade line. If the flow is small or active for only a short time during the winter, it may be possible to provide a basin that will hold all of the ice forming during the winter.

In some places, it may be possible to construct dikes to divert the water to some new channel or to an area where the formation of ice will not affect the roadway. This was done at two places in the Rocky Mountain region west of Fort Nelson during construction of the highway in 1943. In both cases the flow was effectively diverted to strike a main stream channel without crossing the highway and icing on the highway was entirely eliminated.

INDUCED ICING EFFECTIVE IN CERTAIN LOCATIONS

Under certain conditions icing may be induced at some point up hill from the roadway by exposure that causes some or all of the water flow to freeze at that point and correspondingly reduces the icing at the roadway. Icing is usually induced by stripping or compacting the vegetation and snow cover so that the insulation normally provided is largely destroyed. The ground itself may readily freeze upon exposure forming a "frost dam" and forcing an underground flow or seepage to the surface where it will form into ice. For such a method to be effective in preventing the formation of ice at the roadway the following conditions must exist:

(1) The flow of water must be near the surface.

(2) The flow of water must be light or the space available for ice storage must be large. A flow of 6.9 gallons per minute will cover an acre of ground with 1 foot of ice in a month's time.

(3) Conditions must be such that the flow will not merely be diverted around the initial ice formation and strike the highway at a new place to cause icing there.

(4) Snow cover at the induced-icing area must be removed or compacted whenever the accumulation prevents freezing.

An induced-icing area can be effectively combined with dikes and ditches to accomplish the following results:

Ditches can be constructed to drain wet areas during the summer and fall and thus decrease the flow of water

A, Icing Started at Roadway Early in the Winter. Stripping an Area Across the Watercourse at This Point Induced Icing and Protected the Roadway for the Remainder of the Winter. B, An Induced-Icing Area Made With a Bulldozer. C, A Building Placed Over the Culvert Inlet to Increase Heating Efficiency. D, Storage of Ice and Water at an Induced-Icing Area.

during the winter. The ditches should be made narrow and deep to carry winter flow with a minimum of freezing.

Material excavated from the ditches can be used to form a dike behind which the ice can be stored, thus increasing the ice storage area.

The ditches and dikes can be so arranged as to insure that such water as does not freeze at the induced-icing area will reach the roadway at a point where it can be effectively handled.

Frost will readily penetrate the area exposed by the ditch and dike construction, creating a "frost dam" and causing subsurface water flows to emerge and freeze.

An area on which icing is to be induced need not be level. Thin films of water upon freezing will form masses of ice with a surface conforming to that of the area over which the flow occurs. The ice formed has the appearance of a heavy, viscous liquid in motion. A dam or dike to hold ice need not be watertight; brush or similar obstructions will effectively restrain the flow to form ice. While ice will form to follow the slope of the ground in the direction of normal flow, it will fan out laterally to an elevation about equal to or in some cases greater than the elevation of the ice surface at the middle of the watercourse.

Icing induced away from the highway must generally be watched and controlled or its effectiveness will soon be lost. If a "frost dam" completely seals off the subsurface flow further trouble is prevented. This occurred at several places along the Alaska Highway.

Many of the preventive or alleviative measures adopted resulted in the formation of large masses of ice upstream from the highway. Some may wonder whether the large volumes of ice constituted a hazard at the time of the spring thaw. Actually, the masses of ice melted slowly and did not cause any difficulty.

CONTROL MAINTENANCE NECESSARY IN ADDITION TO PREVENTIVE MEASURES

Where all reasonable ice-preventive measures have been taken in the location, design, construction, and summer maintenance of the highway it may still happen that, as the winter progresses, ice may threaten to invade the road surface. Some method of direct control must then be applied. The primary purpose will be to keep ice from forming on the road surface where it would interfere with the normal use of the highway. Three general methods were followed in control of the icing on the Alaska Highway during the winter of 1943–44:

(1) Heating the flowing water by artificial means to prevent its freezing. This was done in locations near the highway.

(2) Periodic removal of the ice formed, usually by mechanical means, but sometimes by melting the ice using artificial heat.

(3) Carrying the flow in channels in the ice. These channels required periodic maintenance, the amount depending upon the degree of protection given them.

On induced-icing areas some control maintenance is necessary. Snow must be removed or compacted from time to time and the dikes raised or new ones constructed. Maintenance of induced-icing areas is to cause ice to form rather than prevent its formation.

The methods used on the Alaska Highway during the winter of 1943–44 were selected largely by superintendents and maintenance men. Various ideas were developed and an opportunity afforded to study and compare them. The control methods used are described in more detail in the following paragraphs.

FREEZING PREVENTED BY HEATING

Heating can effectively prevent the formation of ice at the roadway by warming the flow of water. All heating methods are expensive as equipment must be obtained and its use requires frequent attention as well as considerable fuel. With the heating equipment originally available on the Alaska Highway it was found difficult to concentrate the heat where it would be most effective and most of it was dissipated into the atmosphere. To concentrate the heat in the water where it would be most effective, the Army maintenance organization designed and built an oil burner shown in the accompanying illustration. Oil is fed from the tank on top of the heater through a small tube which passes through a larger draft tube nearly to the bottom of the oil drum where combustion takes place.

Since icing inside of culverts was one of the chief difficulties, methods intended to prevent freezing there were devised. Wood and oil fires were kept burning in open-end oil drums standing in the water at the inlet end of culverts. While most of the heat developed by these fires was lost to the atmosphere, some of it did warm the flow of water, usually enough to prevent icing in the culvert. Heaters were also placed at the outlet ends to prevent icing there and consequent blocking of the culvert. To give greater heating efficiency small houses were frequently built around the stoves at the ends of the culverts. The oil stoves burned from 10 to 20 gallons of fuel oil per day under extreme conditions. In some cases small oil-burning flares were placed inside of the culverts. The heat thus generated was more efficiently used, particularly when the ends of the pipe were almost entirely covered to prevent loss of heat to the outside atmosphere. This type of heater consumed only 3 to 4 gallons of fuel oil per day.

In many place the heating devices were spaced at intervals along trenches cut in the ice. The heat developed at each unit was sufficient to keep the water flowing to the next fire and so on until it passed through the drainage structure and beyond the roadway. Thus a number of heating units might be set up both upstream and down from the roadway to control one icing. In periods of extreme cold, fires were required at intervals of about 50 feet along any open trench where it was desired to maintain the water flow.

Under the most adverse temperature conditions, icing will occur in spite of all such heating methods. At an icing location the points where water emerges may shift frequently and with each change the entire heating set-up must be changed. This is a troublesome and expensive task and a frequent check of each heating set-up is required.

Advantages of this method of icing control are: The necessary equipment is simple and may be readily made or repaired with the facilities available at each maintenance camp; skilled operators are not required; and control of icing does not depend upon the continued operation of any one unit of equipment. The disadvantages are: The method is expensive both in fuel and labor, it is inefficient, and in periods of extreme low temperature does not prevent icing.

ICE REMOVED WITH TRACTOR RIPPERS AND GRADERS

At some places the ice was removed periodically with tractor rippers, blade graders, and motor patrols; by blasting; and by thawing with large oil-burning torches or wood fires. Where these methods were used no attempt was made to control the formation of ice. It was merely removed whenever the formation began to encroach upon the road surface. No advantage was taken of the natural laws governing the formation of ice.

Tractor rippers, blade graders, and motor patrols were used regularly to remove ice on only two sections. One was the Steamboat Mountain section west of Fort Nelson and the other was a 2-mile section with rock hillsides between Fort St. John and Fort Nelson. On this last section blasting was also done to break up the ice along the inside road ditch. On both sections the roadway was constructed as a cut and fill on a fairly steep hillside and with a relatively narrow ditch on the inside. Ice formed on the back slopes and in the roadside ditches from seepage and spring water. As the winter advanced, the flow of water gradually spread out in both directions from the original source by contour spreading along the back slopes so that eventually the ice formed on the back slopes and in the ditches for considerable distances along the highway.

Whenever formation of ice on the roadway impended, the ice was broken out along the ditch line by a tractor-drawn one-tooth ripper and bladed across the roadway and over the shoulder with a tractor-drawn grader or motor patrol. It was necessary to repeat this operation every day or two during the colder part of the winter. Even then removal did not quite keep up with the ice formation but a travelable surface was maintained. Actually the highway surface was gradually built up and widened with broken ice fragments cemented together with ice films. This material was not slippery, however, and caused no difficulty as long as it remained frozen. It seems quite possible that such an accumulation of ice might create a hazardous condition at the time of the spring thaw but no particular difficulty was reported on either of the sections where the method was used.

While this system is less efficient and more costly than other methods, there are occasions when it must be resorted to. If icing occurs continuously on a section quite close to camp and is rather slow in forming so that it can be easily controlled by the occasional removal of ice, and if there is other work in the area to justify the maintenance of heavy equipment, then such procedure may be justified.

There is little to recommend the method for general use. A large crawler tractor is the only machine with enough power and traction to pull or push the equipment necessary to break up the ice. Such a unit is expensive to operate, particularly under such extreme weather conditions. If the ice formations are spread out over a considerable length of highway, much time will be lost in traveling from one to another or else several complete outfits must be maintained. Unless

A, Thawing a Channel With a "Flame Thrower" and Inverted Halves of Oil Drums; B, Oil-Burning Torch Used Inside Culverts; C, Oil-Burning Heater; D, Opening a Trench With a Steam Jet, Steam Generator is Mounted on Truck; E, Channel Kept Open by Wood Fires in Oil Drums; F, Placing Tar Paper Over a Trench in the Ice; and G, Oil Fires in Drums.

The Steam Generator in Action.

the tractor is placed in a heated garage at night or operated 24 hours a day, it may be difficult to start it and considerable time may be lost. Ice forms in many places inaccessible to heavy equipment. In culverts and inlet and outlet ditches it must be removed by other means, so that other equipment must be available.

BLASTING OF ICE HAS DISADVANTAGES

Blasting was resorted to in certain areas to loosen ice in roadside ditches. Ice broken by blasting is not entirely removed from its original position and hand or machine work may be necessary to supplement the blasting. As the ditches again fill with ice the blasting operation must be repeated. At some places the ice broken by blasting was not removed from the ditch and later was covered with snow plowed from the roadway surface. This appeared to be good practice as the small amount of seepage water readily percolated between the broken fragments of ice and was prevented from freezing by the insulating covering of snow.

The blasting method is probably not as expensive as the tractor-ripper, blade-grader, and motor-patrol method and may be used in places inaccessible to heavy equipment. It should not be used to open culverts or in the vicinity of telephone lines, camps, or other facilities. After a few unfortunate experiences with broken telephone wires blasting as a method of ice control was largely discontinued along the Alaska Highway. Blasting is sometimes effective in starting induced icing or in opening subsurface channels for the passage of seepage water.

NARROW CHANNELS THAWED WITH STEAM GENERATOR GIVE EFFECTIVE CONTROL

Occasionally results similar to those with the tractor-ripper and blasting methods were obtained by actual thawing of the ice. This method is expensive and has little to recommend it. Heat is supplied either by oil-burning torches or by wood fires. The flame thrown by torches was usually confined under half sections of oil drums or culvert pipe for more efficient heat direction against the ice to be thawed. While the large oil-burning torch or "flame thrower" as it was called thaws the ice quite rapidly, it requires about 6 gallons of oil per hour. It cannot safely be used in wooden drainage structures and its general use is not recommended.

Carrying water in either protected or open channels made with portable steam generators such as were made available along the highway during the latter part of the winter was found to be a useful method. Other methods were also used to construct open channels in the ice. The steam jet is well adapted to cutting a confined channel so that a minimum of water surface will be exposed to the atmosphere. Flow in the channels may be facilitated by supplemental heating, as previously described, or the channels may be reopened at intervals as the icing development necessitates.

This method, combined with channel protection appeared to offer the greatest possibilities of control of icing, after it actually begins, of any method observed along the highway. Full advantage may be taken of the insulating properties of ice, snow, and air. The ice must first be allowed to form to a depth of 2 feet or more to provide a medium through which drainage channels may be cut. This ice will insulate the flow, and will support further insulation such as paper, boards, brush, or snow falling directly on the covering or thrown off the road surface by maintenance forces. If conditions are such that the required depth of ice cannot be permitted to form without danger of icing on the road surface, then much more frequent attention will be required. Grade raises, icing basins, and deep and narrow drainage trenches permit the formation of ice to such depth that effective channels may be opened through or under the ice by a steam jet.

If a steam jet is used for cutting passageways under the ice, it is best to start operations at the culvert or drainage structure outlet. As a channel is formed under the ice in the drainage structure, the water from the condensed steam and melted ice, will enlarge the opening already formed and will also, in most cases, find an outlet for itself under the vegetation and snow downstream. It is good practice to leave this downstream cover undisturbed, and allow the outflow of water to form its own subsurface drainageway.

After an opening has been made under the ice in the drainage structure, a channel can be formed under the ice from the culvert inlet to the apparent source of the flow. This can be done by pushing the steam jet down through the ice at intervals of about 3 feet. It may take some probing with the steam jet to locate the source of the water but when this is done a considerable volume of water is likely to be released and further icing activity stopped for some time. At a number of places the method was so successful as to give a complete cure for the rest of the winter.

Trenches jetted with steam are definitely better than those made by other methods. Blasting forms wide, irregular trenches that refill rapidly. Trenches may be cut by hand but the method is slow and it is difficult to cut to the required depth. However, the Alaska Road Commission controls icing on some of its roads entirely by hand trenching.

The equipment most used for steam jet operation was a quick-acting oil-burning steam generator, which was usually mounted in an enclosed truck. The factory price of a unit was about $3,200. The generators were very effective, producing a large volume of steam within a very short time and were readily moved from one icing location to another.

The apparatus was somewhat complicated and required careful operation for continued trouble-free use. Apparently it has been designed primarily for stationary use as it was susceptible to damage by rapid movement over rough surfaces.

A number of these units were placed on the highway. Control methods developed with their use proved so

(Continued on p. 82)

AN EMPIRICAL METHOD OF INTERPRETATION OF EARTH RESISTIVITY MEASUREMENTS[1]

BY THE DIVISION OF PHYSICAL RESEARCH, PUBLIC ROADS ADMINISTRATION

Reported by R. WOODWARD MOORE, Associate Civil Engineer

MANY PAPERS have discussed the interpretation of data obtained from earth resistivity tests when using the four-terminal method of electrode spacing developed by Wenner (*9*).[2] Most of these have dealt with theoretical analyses for two-layer and three-layer formations. In some instances, sets of reference curves have been presented for use in analyzing field data to determine the depth to the first and possibly the second horizon below the earth's surface. Although practically all of these theoretical methods of analysis have appeared to have particular merit and, in some cases, have been successfully used in practice, they have been found to be of little value in those cases where the local conditions surrounding the test failed to conform to those assumed in the theory.

In certain fields, particularly in civil engineering, relatively shallow explorations are often required and geophysical methods of test must compete with the direct methods of exploration ordinarily used. Only when it can be demonstrated that geophysical methods of test can materially reduce the time and cost of a given exploration project will the civil engineer abandon direct methods in their favor.

Empirical methods of analyzing earth resistivity data have been used in many instances in the past. Such methods have been used for a number of years by the Public Roads Administration in research on application of the resistivity test in the field of highway construction. Prior to 1940 the empirical relation proposed by Gish and Rooney (*2*) was generally used in the study of field data. In this method of analysis, the apparent resistivities measured for a succession of gradually increased electrode spacings are plotted as ordinates and the corresponding electrode spacings as abscissas. There appears to exist an empirical relation that the "effective depth" of current flow approximates the value of the electrode spacing used. If, within this "effective depth", an underlying formation with a specific resistance materially different from that of the surface layer is encountered an inflection will presumably be found in the apparent resistivity-electrode spacing curve.

Gish and Rooney found that where such an inflection appeared the value of the electrode spacing at the point of inflection could be interpreted as the approximate thickness of the surface layer. Where a low resistivity material is underlain by one of a higher resistivity a U-shaped curve is often obtained and in such cases the electrode spacing for the low point of the curve is usually assumed to indicate the depth to the underlying material.

[1] Paper presented at the February 1944 meeting of the American Institute of Mining and Metallurgical Engineers and published by them as Technical Publication 1743.
[2] Italic numbers in parentheses refer to the bibliography at the end of this article.

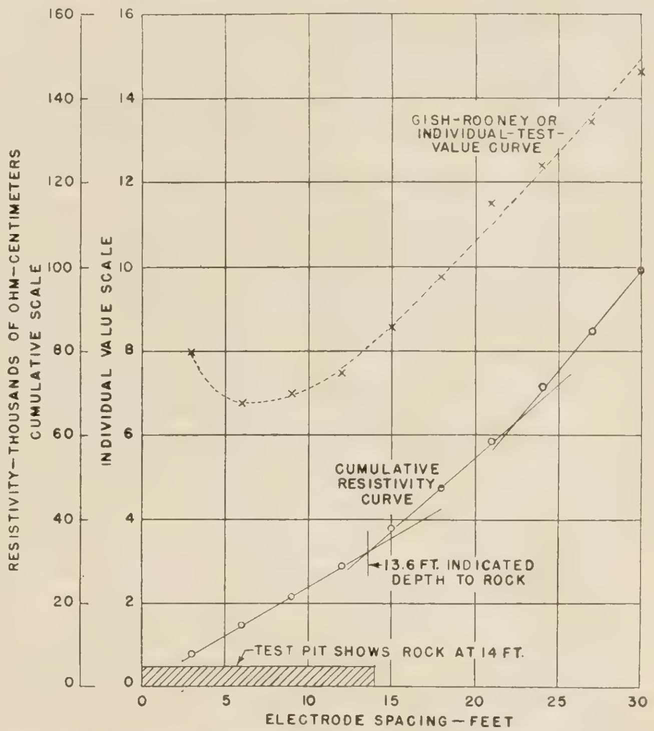


FIGURE 1.—TYPICAL RESISTIVITY DATA AND METHOD OF ANALYSIS USING THE CUMULATIVE RESISTIVITY CURVE.

TABLE 1.—*Data on resistivity and electrode spacing used in plotting figure 1. Data obtained where a test pit showed 14 feet of clay overlying hard rock*

Electrode spacing	Apparent resistivity	Cumulative resistivity
Feet	*Ohm-centimeters*	*Ohm-centimeters*
3	8, 000	8, 000
6	6, 800	14, 800
9	7, 050	21, 850
12	7, 510	29, 360
15	8, 600	37, 960
18	9, 800	47, 760
21	11, 550	59, 310
24	12, 430	71, 740
27	13, 500	85, 240
30	14, 650	99, 890

Often in shallow work abrupt breaks in the apparent resistivity-electrode spacing curves have been found which, when interpreted in this manner, give a reasonably accurate indication of the position of the interface between the surface materials and the underlying material in simple two-layer formations. There are other instances, however, in which resistivity depth tests in two-layer or multilayer formations yield resistivity-electrode spacing curves that are smoothly rounded

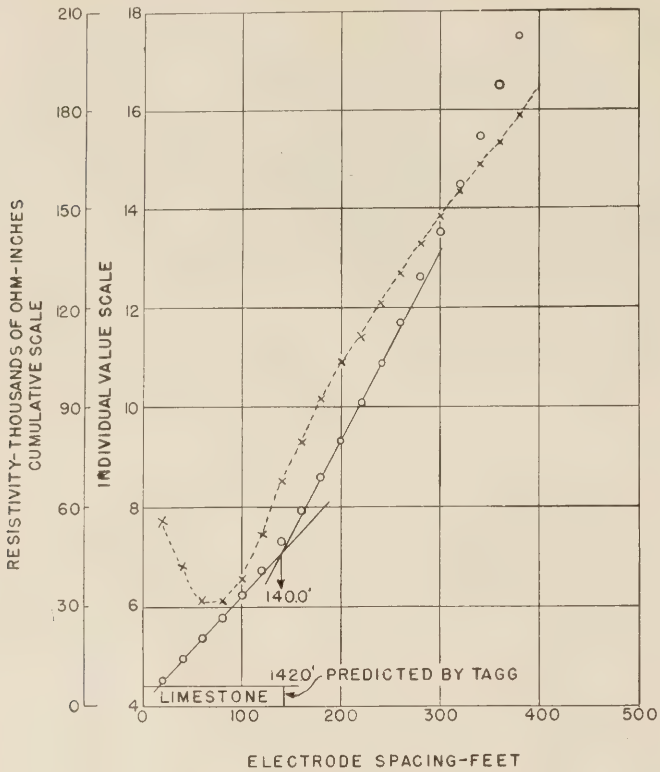


FIGURE 2.—REPRODUCTION OF CURVE FOR "STATION A" FROM MEASUREMENTS BY G. F. TAGG.

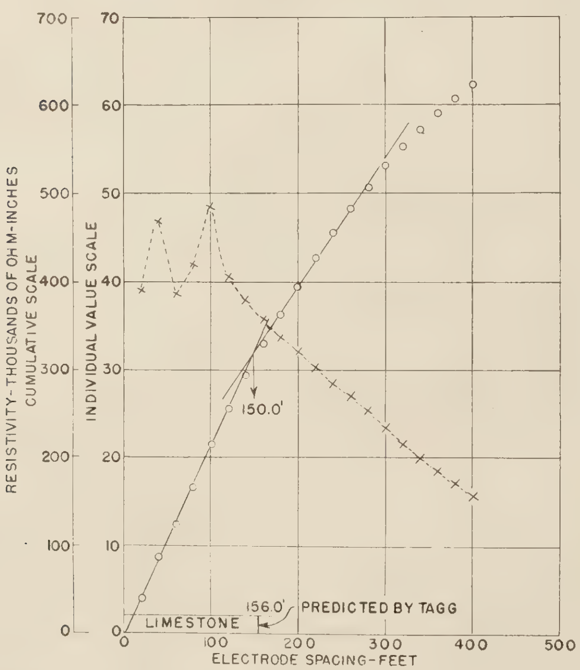


FIGURE 3.—REPRODUCTION OF CURVE FOR "STATION B" FROM MEASUREMENTS BY G. F. TAGG.

without marked inflections or other indication of the position of the various strata. No satisfactory empirical method of analysis of such curves is available and such theoretical methods as have been proposed are both uncertain and time consuming.

There follows a discussion of an empirical method of analysis developed in the resistivity research of the Public Roads Administration. When applied to test

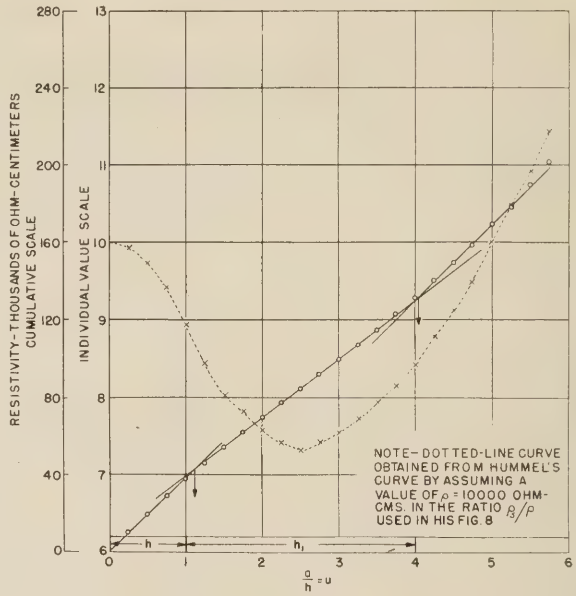


FIGURE 4.—HUMMEL'S CURVE OF APPARENT RESISTIVITY FOR CASE OF $H_1=3H$ AND RATIO ρ_0: ρ: ρ_1: $\rho_2=\infty$: 1: 0.5: ∞.

data of the type described above from various sources and over a wide range of field conditions, it seems to offer definitely better correlations than other methods.

PROPOSED METHOD OF ANALYSIS DESCRIBED

In the proposed method of analysis the data are obtained in the field using the Wenner four-electrode configuration, and a conventional Gish-Rooney or apparent resistivity-electrode spacing curve is prepared. The Gish-Rooney curve is used for whatever indication it may give of subsurface conditions at the point of test. The data for the curve are replotted on the same sheet in the form of a cumulative resistivity-electrode spacing curve. By reason of a greatly reduced ordinate scale and the effect of successive summations of individual resistivity values this plotting of the data tends to minimize the effect of a single resistivity value and thus eliminate purely local effects caused by surface anomalies or any peculiarity of a particular setting of the electrodes.

In obtaining the field data for plotting in this manner an initial electrode spacing of some convenient value, say 3 feet for shallow work, is chosen arbitrarily and the electrode spacing is then increased regularly by increments of 3 feet for each successive determination. The initial value of apparent resistivity is plotted as the initial ordinate of the cumulative curve. Each subsequent value of apparent resistivity is added to the sum of all preceding resistivity values and each total thus obtained is plotted as the ordinate of another point for the cumulative curve. Use of regularly increased electrode spacings, for example, 3 feet, 6 feet, and 9 feet, may suggest that approximately a straight line with a given slope should be obtained so long as the "effective depth" of current flow remains primarily within the surface layer and this layer consists of a relatively homogeneous material. In practice, however, where the surface material is relatively shallow and the soil layer is not perfectly homogeneous, the plotted data frequently will take the form of a generally smooth line with gentle curvature rather than a straight line. Probably this is due to a gradual change of resistivity with depth and with soil variation.

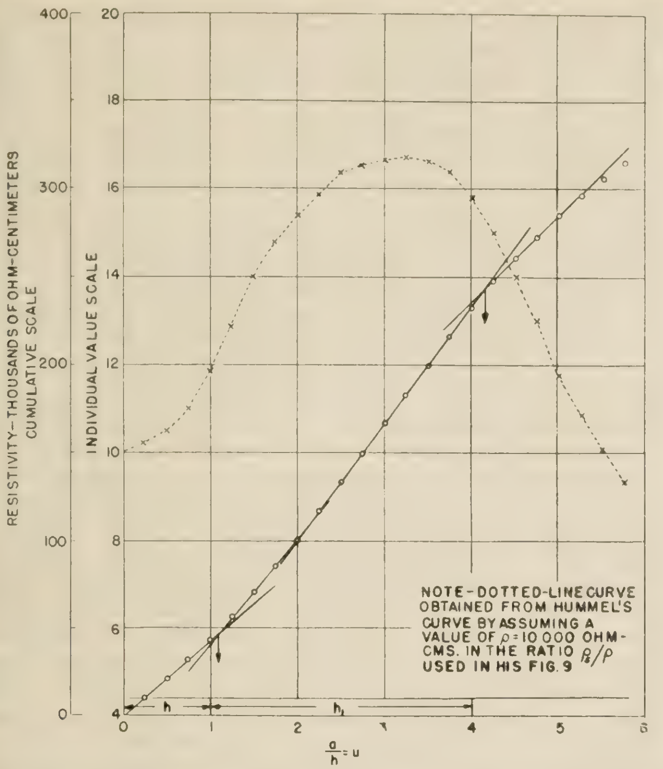


FIGURE 5.—HUMMEL'S CURVE OF APPARENT RESISTIVITY FOR CASE OF $H_1 = 3H$ AND RATIO $\rho_0 : \rho : \rho_1 : \rho_2 = \infty : 1 : 3 : 0$.

It has been found that as the electrode spacing approaches and passes a value corresponding approximately to the depth of the surface layer the plotted cumulative curve usually tends to change direction, the new slope depending upon the relative resistivities of the two layers of material. From the electrical principles involved this slope should increase if the lower formation possesses a higher resistivity than the surface layer and conversely should decrease if the underlying formation is the more conductive. It has been found that lines drawn tangent to the cumulative curve and intersecting in the region where the change in slope occurs give a good approximation of the depth to the interface between the two materials if the point of intersection of the tangents is projected to the horizontal or dimensional axis.

Figure 1 illustrates the method applied to a typical case. The data used in plotting the curves are given in table 1. The values of electrode spacing and of apparent resistivity in columns 1 and 2, respectively, were obtained in field tests in the vicinity of Washington, D. C., where there existed a simple two-layer formation consisting of clay underlain by rock.

In figure 1 the Gish-Rooney or individual-test-value curve is shown by crosses connected by a dotted-line curve and the cumulative resistivity curve by plotted circles. For clarity the curve connecting the circles has been omitted. This same method of presenting the data is employed in each of the subsequent figures and for simplicity the identification of the curves is not repeated.

Referring to figure 1, the presence of the rock formation of high resistance at the relatively shallow depth of 14 feet affects strongly the measured apparent resistivity beyond an electrode spacing of about 10 feet and for this reason the plotted values of cumulative resistivity continue to show a rather marked degree of curvature beyond what might be termed the "critical point" on the curve. The trend of the Gish-Rooney or individual-test-value curve is used to indicate the probable "critical point" which on this curve appears to be at an electrode spacing of 10 or 12 feet. Guided by the indications of this curve and such related data as may be available from test pits or drill holes in the general area, the additional tangent intersections beyond the "critical point" may or may not be disregarded.

Admittedly, this procedure is empirical in every sense, but the results obtained in the analysis of data from many tests under various field conditions have been encouraging. In addition to the use of this method in the analysis of data obtained in field tests of the Public Roads Administration, the literature has been reviewed and resistivity curves presented by various authors have been replotted and analyzed by the method wherever the necessary depth data were given. The results obtained appear to substantiate the conclusions reached in analyzing the test data of the Public Roads Administration.

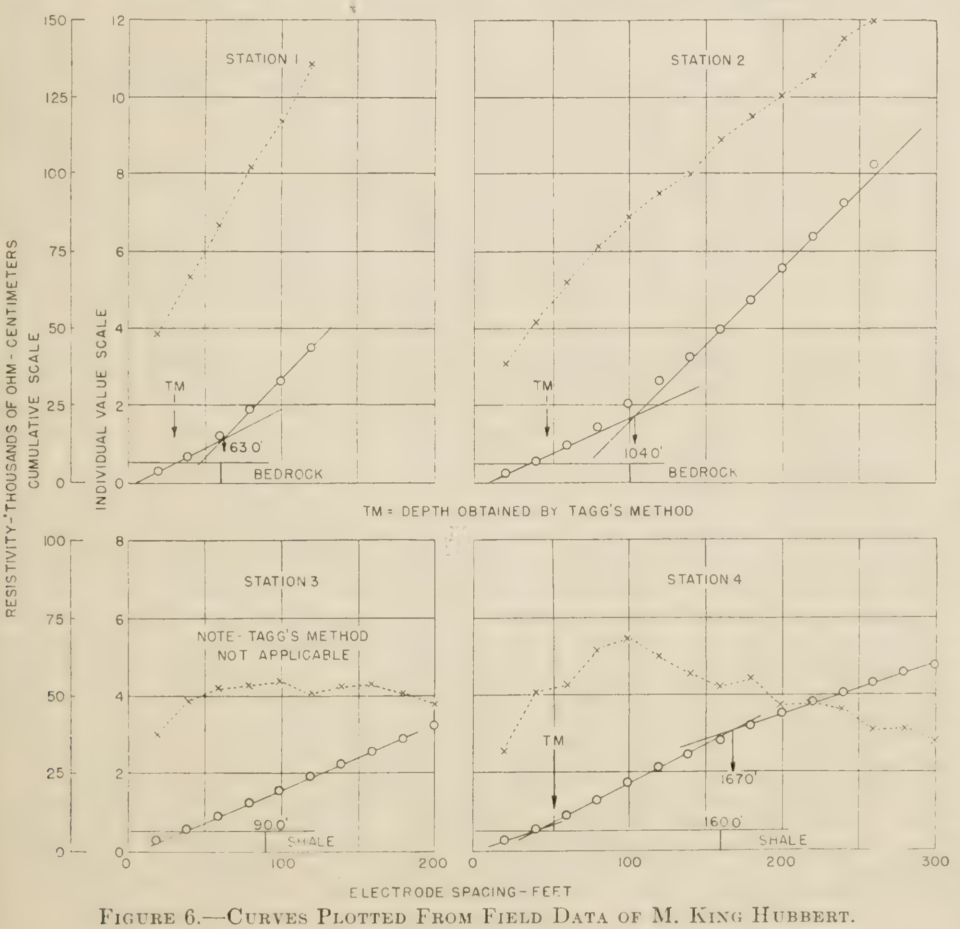


FIGURE 6.—CURVES PLOTTED FROM FIELD DATA OF M. KING HUBBERT.

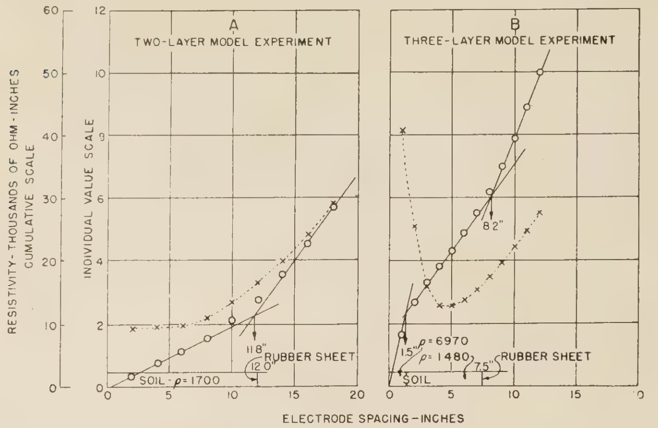


FIGURE 7.—CUMULATIVE RESISTIVITY CURVE METHOD OF ANALYSIS APPLIED TO LABORATORY DATA OBTAINED BY R. J. WATSON.

CUMULATIVE CURVE METHOD APPLIED TO DATA REPORTED BY VARIOUS INVESTIGATORS

Figure 2 shows Tagg's (*7*) classical curve for his "Station A," representing typical field data to which he applied his method of analysis, together with the points that result when the data are replotted in the manner previously described. Figure 3 shows a similar treatment of Tagg's "Station B." The cumulative values in figures 2 and 3 indicate depths that closely approximate those obtained by Tagg with a rather laborious method of analysis. In connection with these curves and others that are to be presented, it should be pointed out that frequently it is rather difficult to read accurately values of coordinates from the necessarily small figures found in the published papers when taking data for replotting.

Figures 4 and 5 show data from Hummel's (*4*) curves of apparent resistivity for two theoretical cases [3] in which two surface layers of differing resistivity and thickness are underlain by, in one case, a layer having infinitely high resistivity and, in the other case, a layer having infinitely high conductivity. The ordinate v of Hummel's figures is given as the ratio ρ_s/ρ in which ρ is the true resistivity of the upper layer of the ground and ρ_s is the average or apparent resistivity resulting from the influence of the underlying layers on the values of resistivity as measured at the ground surface. In plotting the dotted-line curves in figures 4 and 5 a value of 10,000 ohm-centimeters was assumed for ρ and applied to the ratios ρ_s/ρ taken from Hummel's curves. This resulted in conventional apparent resistivity-electrode spacing curves from which the data for plotting the cumulative curves were obtained. The positions of the interfaces as determined from the cumulative curve appear to agree with those assumed in the theoretical treatment rather closely despite the fact that a three-layer condition was involved in both instances.

The curves shown in figure 6 were plotted from data which were presented in a paper by Hubbert (*3*). The data for his stations 1, 2, and 4 when plotted using the cumulative values of resistivity give depth indications that check the known conditions reasonably well. As stated by Hubbert, Tagg's method of analysis, although giving good intersection zones for groups of curves plotted for each of his stations 1, 2, and 4, gives depth indications that are in error by 50, 54, and 70 percent, respectively. The individual-test-value or Gish-Rooney curves for these stations were of little value in determining the depths of interfaces. The data for sta-

[3] Hummel's figures 8 and 9.

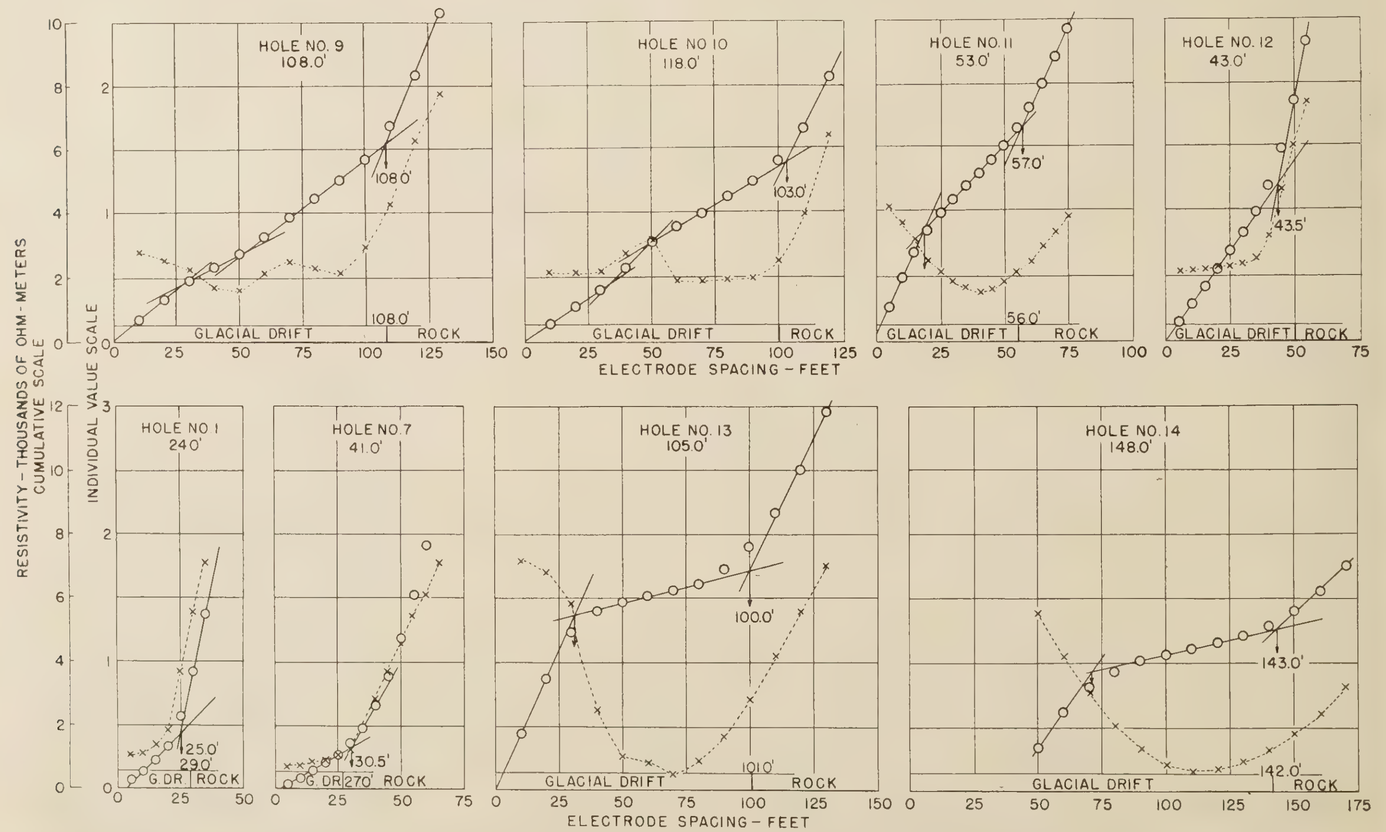


FIGURE 8.—REPRODUCTION OF CURVES PUBLISHED BY I. B. CROSBY AND E. G. LEONARDON. THE DEPTH AS ESTIMATED BY ORIGINAL INVESTIGATORS IS GIVEN AT THE TOP OF EACH DIAGRAM.

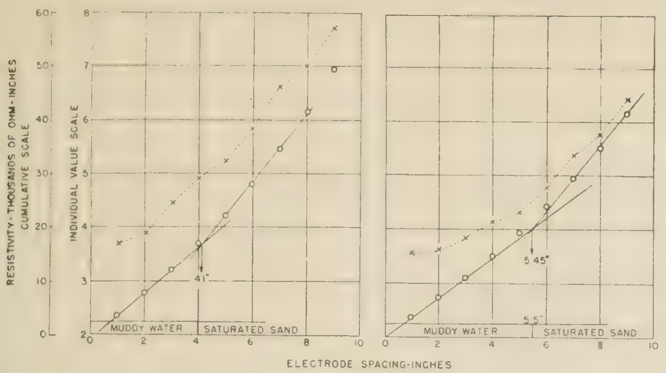


FIGURE 9.—CUMULATIVE RESISTIVITY CURVE METHOD OF ANALYSIS APPLIED TO DATA OBTAINED IN EXPERIMENTS ON MODELS BY T. A. MANHART.

tion 3 apparently cannot be interpreted by any known method.

Figure 7 shows data from a paper by Watson (*8*) in which curves obtained from experiments on models are described. He made experiments in which a carefully prepared sandy shale was screened and mixed with different percentages of moisture to form surface layers having different resistivities. A rubber sheet was placed under the surface layer to simulate a bottom layer having infinite resistivity. Both cumulative curves indicate rather accurately the location of the buried rubber sheet as well as the interface between layers of soil of different resistivity.

Figure 8 contains reproductions of several curves published by Crosby and Leonardon (*1*). The depth to rock as predicted by Crosby and Leonardon is noted near the top of each graph while that estimated by the author is shown on the cumulative curve. The actual depth as obtained by drilling is shown along the lower edge. With three exceptions, the cumulative curve method of analysis checked the actual conditions beneath the surface within about 3 percent. The average error for all curves was 5.8 percent.

No data were included in Crosby and Leonardon's paper relative to variations in the surface layer of material classed as glacial till. It is possible that the presence of a water table is responsible for the breaks in some of the cumulative resistivity curves at depths less than those given for the rock surface.

Curves from a paper by Manhart (*5*) are reproduced in figure 9. In this paper the author reports on experiments in which he made numerous tests on materials placed in a tank under laboratory controlled conditions. The two curves were obtained when using a surface layer of muddy water which was underlain by saturated sand. The smooth curves of apparent resistivity obtained by Manhart lend themselves well to a solution by the method of analysis proposed in this paper. Of the many curves presented by Manhart 13 were analyzed by the proposed method. Four curves represented 2 layers of material and 9 represented 3 layers. A total of 22 depth determinations were made. In only two or three cases were the conditions indicated by the analysis materially different from those established in the laboratory.

In figure 10 a curve given by Roman (*6*) has been replotted as a normal apparent resistivity-electrode spacing curve and also in the form of a cumulative curve. ρ_a, the apparent resistivity, is assumed to be given in ohm–centimeters. Roman suggests that

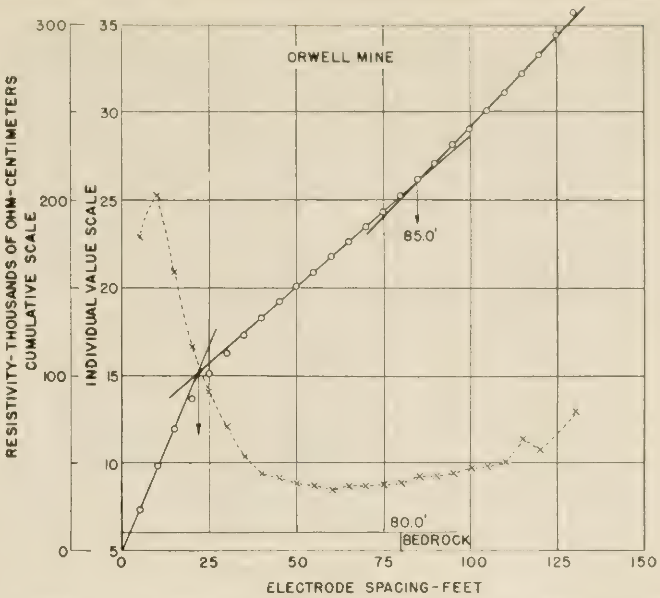


FIGURE 10.—CUMULATIVE RESISTIVITY CURVE METHOD OF ANALYSIS APPLIED TO DATA REPORTED BY ROMAN.

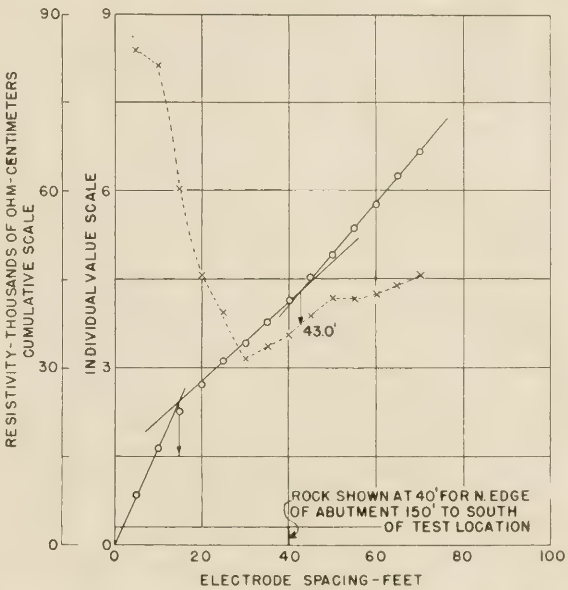


FIGURE 11.—RESULTS OF A RESISTIVITY TEST NEAR THE WEST ABUTMENT OF ARLINGTON MEMORIAL BRIDGE.

further theoretical studies are required to make possible the interpretation of such curves. Although use of the original apparent resistivity and electrode spacing data would have resulted in a more accurate curve for use in the empirical analysis which is proposed, the data shown in figure 10 indicate that the cumulative curve method of analysis has given a reasonably accurate depth determination. The depth of 80 feet to bedrock was given in the discussion which followed the presentation of Roman's paper. Mention also was made in the discussion of the presence of swampy materials on the surface overlaying the hardpan which overlay the rock at the test location. The change indicated in the cumulative curve at a depth of approximately 22 feet may be at the boundary between these two surface materials.

Many other published data have been replotted and analyzed using the cumulative curve method with about

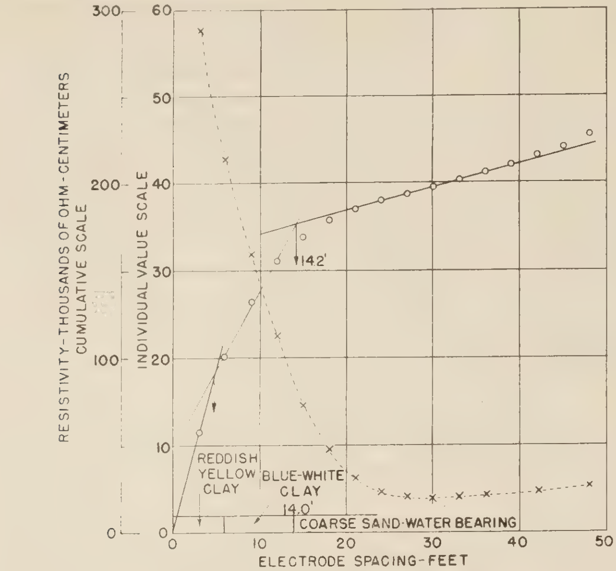


FIGURE 12.—RESULTS OF A RESISTIVITY TEST AT LOCATION OF PROPOSED UNDERPASS NEAR PETERSBURG, VA.

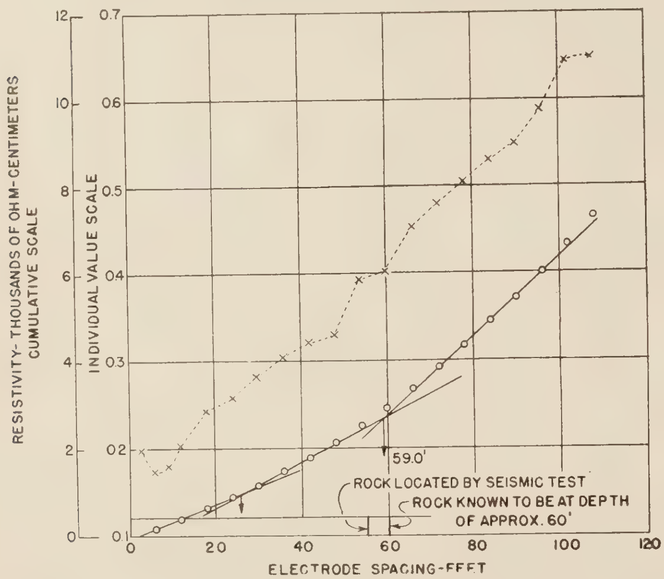


FIGURE 13.—RESULTS OF A RESISTIVITY TEST IN SALT MARSH NEAR HAMPTON, N. H.

the same general degree of success as indicated in the examples given. There are border-line conditions of test which do not lend themselves to an analysis by this method. As stated previously, both the Gish-Rooney and the cumulative curves are used in interpreting the data from a particular test. The general shape of the Gish-Rooney curve serves to indicate the probable ground conditions, whether two-layer or more, and it may also give some clue to the approximate depth of the surface layers.

FIELD TESTS CONDUCTED BY THE PUBLIC ROADS ADMINISTRATION

The results of tests conducted by the Public Roads Administration that involve a variety of surface and subsurface conditions in the vicinity of Washington, D. C., and in New Hampshire are shown in figures 11 to 14. The curve shown in figure 11 was obtained near the west abutment of the Arlington Memorial Bridge across the Potomac River entering Washington, D. C. At this location a few feet of earth fill

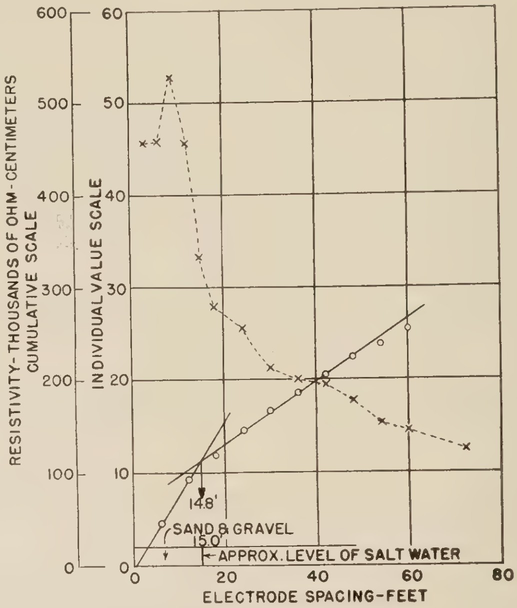


FIGURE 14.—RESULTS OF A RESISTIVITY TEST ON SAND AND GRAVEL FILL APPROXIMATELY 15 FEET ABOVE SEA LEVEL NEAR HAMPTON, N. H.

overlay soft mud which was underlain in turn by a rock formation. The depth of 43 feet to rock indicated by the cumulative curve is in reasonable agreement with the depth of 40 feet found by drilling at the abutment location about 150 feet to the south. The change shown by the cumulative curve at a depth of about 15 feet is probably where the fill material merges with the underlying mud.

Figure 12 shows data from a test where heavy clay was underlain by coarse, water-bearing sand at a depth of 14 feet. The relatively smooth individual value or Gish-Rooney curve shows no indication of the sand stratum at that depth but the stratum is indicated at 14.2 feet on the cumulative resistivity curve.

Figure 13 shows the resistivity curve for a location in the salt marshes near Hampton, N. H., where rock was known to be at a depth of approximately 60 feet. The Gish-Rooney curve shows an increased upward trend at an electrode spacing of 48 feet. The determination with the cumulative curve checked the known depth and the depth indicated by refraction seismic tests made nearby within 1.7 and 6.9 percent, respectively. In the absence of previous knowledge of the general nature of the subsurface formation it may be necessary to put down one or two drill holes to establish the significance of data which show several changes in direction or breaks in the cumulative curve.

Figure 14 shows the result of a test made on a sand and gravel fill near the sea and about 15 feet above sea level at Hampton, N. H. The cumulative curve indicates a low resistivity medium such as salt water at about 15 feet.

Curves representative of tests made with the resistivity apparatus over peat bogs are shown in figure 15. In this series of tests the cumulative curve proved to be a satisfactory means of analyzing the data obtained. These tests are of interest because it seemed probable that the peat and marl formations overlying the sand or hardpan usually comprising the bottom formations of the bogs would approach the uniform

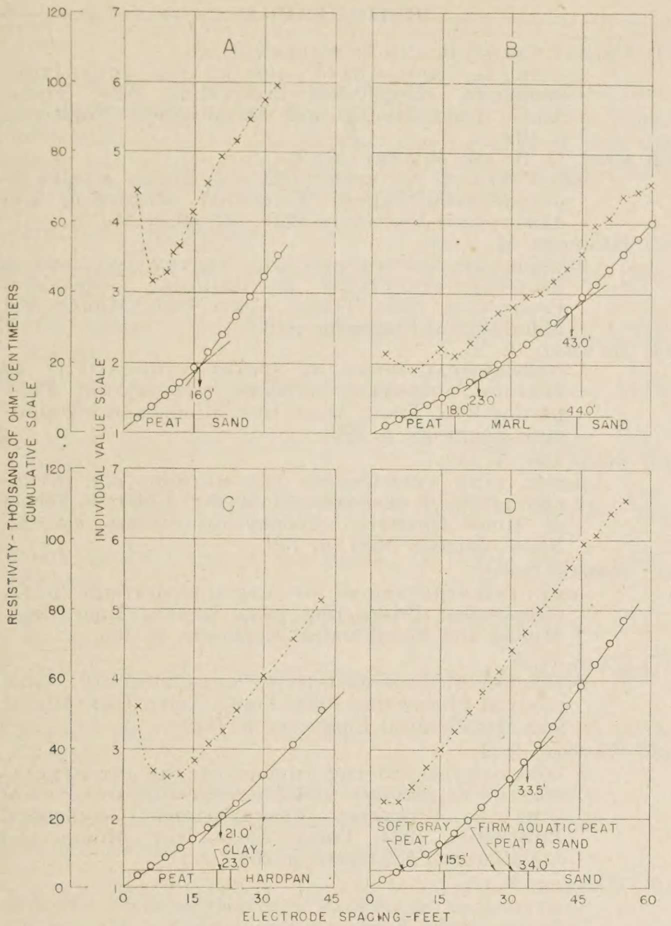


Figure 15.—Results of Resistivity Tests Over Peat Bog Formations.

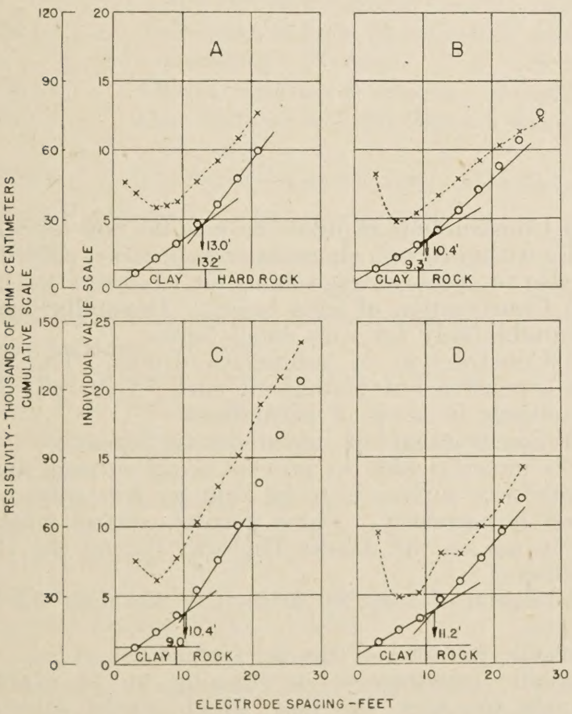


Figure 16.—Empirical Method of Analysis Applied to Resistivity Curves for a Clay Stratum Underlain by Rock in the Vicinity of Washington, D. C.

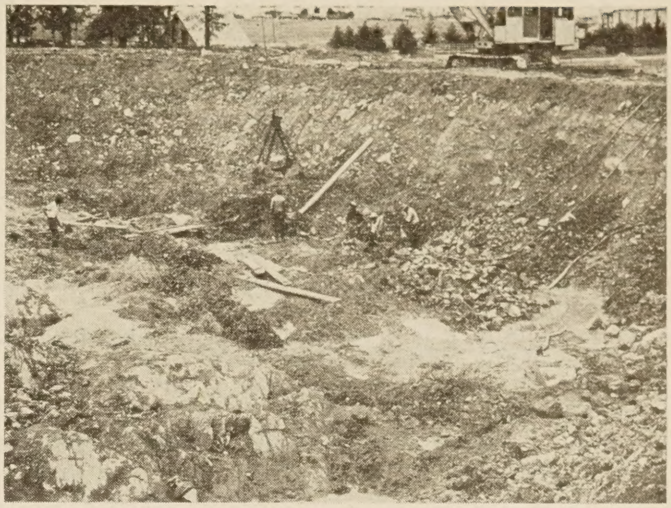


Figure 17.—View of Excavated Area Showing Irregular Surface of Rock Formation Involved in Resistivity Tests.

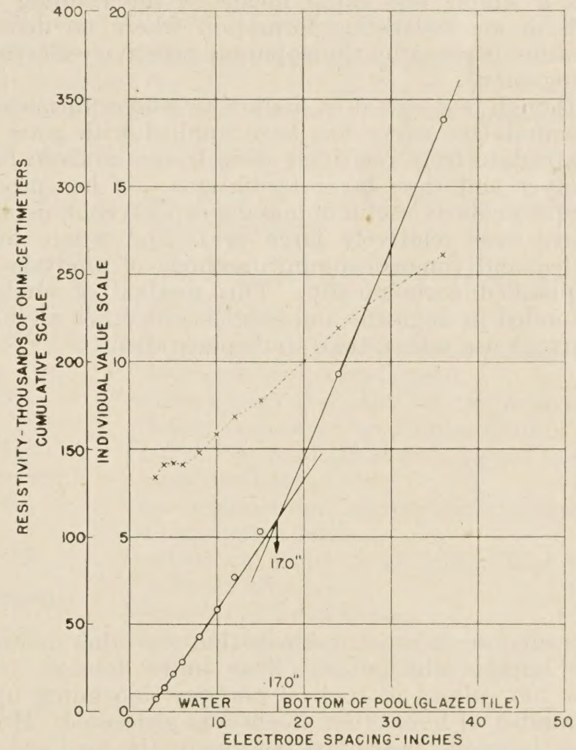


Figure 18.—Results of a Resistivity Test in a Tiled Pool.

layers of homogeneous materials assumed in theory, thus presenting a condition that would be particularly suitable for a satisfactory analysis by the resistivity method. Furthermore it was relatively simple to check directly the indications of the resistivity tests by means of rod soundings with equipment capable of taking samples at any desired depth.

Figure 16 shows data from an extensive resistivity survey completed in the spring of 1942 in the vicinity of Washington, D. C. Based upon some 475 to 500 depth tests and about 10.5 miles of "resistivity traverse" covering an area of about 150 acres, a map was prepared showing subsurface rock elevations by means of rock surface contours. Numerous check borings, with post-hole augers, and direct observations in excavations made subsequent to the preparation of the map, indicated an average accuracy within 1 to 2 feet for the rock contours as established. The depth of the surface clay varied from about 4 feet to 30 feet. The underlying rock was a granite formation of quite irregular contour, as shown in figure 17. The excavation showed differences in elevation of as much as 6 feet in horizontal distances as little as 6 feet at places where irregularities were more pronounced. Under such conditions the resistivity test should offer more dependable over-all depth values than a limited number of individual borings.

The results of a test conducted in the tiled pool in the plaza of the National Academy of Science, Washington, D. C., are given in figure 18. The Gish-Rooney method of plotting the data showed no indication of the depth of the water in the pool, whereas an analysis with the cumulative curve shows a remarkable correlation with the measured depth of 17 inches.

SUMMARY

The cumulative resistivity curve method of analysis offers a simple and rapid means of determining the depth to an underlying formation where no definite indication is given by the apparent resistivity-electrode spacing curve.

Although best suited to shallow two-layer formations the cumulative curve has been applied with good results to data from relatively deep tests and from both two-layer and three-layer formations. It has proved to be particularly useful in making rapid reconnaissance surveys over relatively large areas and where more detailed and time-consuming methods of analysis are not justified economically. This method of analysis is intended to augment and supplement other methods in current use rather than to displace them.

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(Continued from p. 74)

much superior to other methods that the other methods were largely abandoned. The units burned from 50 to 100 gallons of fuel oil per day depending upon the number of hours that steam was generated. Housing on the trucks prevented freezing on the road and the trucks were ordinarily driven into heated garages when not being operated. Two men were required for operation of each unit.

A disadvantage of the equipment is that it is easily damaged and repairs may be difficult. Delays in making repairs may permit ice formation on the road. Careful and skilled operators are required.

CONCLUSIONS

Lasting improvements for prevention of icing should be adopted in preference to winter control expedients wherever the cost and difficulties of control in winter are large. Such work can be performed best during the summer and early fall. Some of the measures which may be applicable under different conditions are:

(1) Improvement of drainage channels and structures.

(2) Raising the grade of the road.

(3) Construction of dikes to confine flow of water and ice within certain channels or to divert it elsewhere, and also to act as storage dams for ice formation.

(4) Construction of icing basins. Generally, basins are suitable only for very small flows.

(5) Construction of subsurface drains. This is a more expensive but permanent cure. Generally it is not suitable in areas of permafrost.

(6) Construction of induced-icing areas.

It is impracticable to prevent icing entirely and if the roadway surface is to be kept ice free some icing control is necessary. Three general control methods were in use on the Alaska Highway during the 1943-44 winter:

Prevention of icing by artificially warming the flow of water.

Periodic removal of the ice formed.

Periodic construction or opening up of drainage channels to carry the flow which would otherwise result in icing. The last method appears to be the most efficient but under certain conditions it may be necessary to resort to other methods.

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