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Technical Report 160

SUBSURFACE TRANSPORTATION METHODS IN DEEP SNOW

by

Gunars Abele

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PREFACE

This work was performed as part of the project, Development of trafficable surfaces, during the 1962 test season at Camp Century, Greenland.

The study was conducted by Gunars Abele, Civil Engineer, Applied Research Branch, under the supervision of Mr. Albert F. Wuori, present Chief, Applied Research Branch, and Dr. Andrew Assur, then Chief, Applied Research Branch, as a project of the Experimental Engineering Division, Mr. K. A. Linell, Chief.

The author was assisted in the field and laboratory work by Mr. North Smith, Civil Engineer, Applied Research Branch, and Messrs. Earl Ollila, Frederick Scheuren, Carr Baldwin, Baird Fortson, and Carl Enfield, contract personnel. SP/4 Paul Benson, USA CRREL, assisted in the field and laboratory work and in the analysis of test data.

Messrs. Paul Szarka (President) and Gordon Potter of the Spur and Siding Constructors Company, Inc., Detroit, Michigan, provided technical assistance during the construction of the test railroad. The cost estimate report (Appendix D) was prepared by Mr. Szarka.

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DA Project IV025001A13001

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SUMMARY

During the 1962 test season in Greenland, a study was performed on subsurface transportation methods.

A 1600 ft long, covered test trench containing horizontal curves and a 400 ft long processed snow floor section was constructed.

Wheel trafficability tests on the snow trench floor were conducted with two types of low-pressure tires as well as with standard truck tires. An M-54 5-ton truck with a 5-ton load was used as the test vehicle.

Skid tests were performed with the three types of tires on the processed snow floor, and the coefficient of friction between the tires and a hard snow surface was determined.

A 1300 ft long, standard gage railroad track was installed in the trench after completion of the wheel traffic tests. A standard size flatcar with a 30-ton load, towed by a 5-ton truck equipped with rail wheels, was used as the test vehicle for the rail traffic tests.

It was determined that the natural, unprocessed snow surface in a trench 26 ft below the snow surface is not suitable for extensive traffic with vehicles such as 5-ton trucks even when equipped with low-pressure flotation tires. However, a Peter plow-processed, age-hardened snow surface is capable of supporting a virtually unlimited amount of vehicle traffic using standard tires. Indications are that even heavier wheeled vehicles could be easily supported by a processed-snow trench floor.

The coefficient of friction between rubber tires and a hard snow surface was found to be in the general range of 0.2 to 0.3.

For transporting extremely heavy items, the use of a railroad system installed on an unprocessed snow trench floor appears to be a feasible but somewhat expensive method. The installation of a railroad system in a covered snow trench presents no serious problems.
SUBSURFACE TRANSPORTATION METHODS IN DEEP SNOW

by

Gunars Abele

INTRODUCTION

Military as well as research activities in the polar regions require year-round support. A dependable method of transportation between a support or supply station and a military or research outpost is required. For a continuous, large-scale operation, particularly one of a military nature, the reliability of a transportation system becomes extremely important. Delays caused by adverse weather or the inability to provide surface transportation during extended periods of unfavorable weather may seriously affect military and research operations.

The concept of subsurface transportation on the Greenland Ice Cap may have to be considered as a possible solution. This method would be less affected by climatic conditions and also troop and supply movements would be more difficult to detect.

Preliminary studies of the trafficability of various types of snow trench floors were initiated during the summer of 1960 at Site 2, Greenland (Abele, 1963b). The study was continued at Camp Century, Greenland, in a curved, 1600 ft long, covered test trench. Production data were obtained during the construction of the trench (Abele, 1964) to determine the time and effort that would be involved in constructing a subsurface transportation system. Supporting capacity and traffic-ability of processed and natural snow surfaces with various types of tires and rail traffic were studied to determine the most feasible type of subsurface traffic and the type of trench floor surface required.

DESCRIPTION OF STUDY

Construction of test trench

The test trench, 1600 ft long and 18 ft wide at the base, was cut with a Peter plow (Fig. 1). The trench consisted of three curved sections, the radii being 150, 200, and 400 ft, and two straight sections, approximately 300 and 400 ft long (Fig. 2).

The trench was covered with steel arches (Waterhouse, 1959) and processed snow. After allowing the snow to age-harden for 3 to 4 days, most of the steel arches were removed.

The snow floor of the 400 ft straight section was processed to a depth of approximately 3 ft with the Peter snow plow and compacted with a D-8 bulldozer. The remaining sections of the trench were left unprocessed (Fig. 3). A snow planer (Wuori, 1964) was used to level the entire trench floor.

An electrical system was installed in the trench to provide lighting and operate three 1000 ft³/min capacity ventilating fans.

A trail between the two entrance ramps of the trench was compacted and leveled to enable continuous traffic to be maintained through the trench during the wheel tests (Fig. 2).

Construction of the trench is described in detail and the production results analyzed in a previous report (Abele, 1964).
SUBSURFACE TRANSPORTATION METHODS IN DEEP SNOW

Figure 1. Cross section of test trench.

Figure 2. Layout of test trench.
Wheel traffic tests

The objectives of these tests were:

1. To determine the trafficability of a natural, unprocessed snow trench floor surface with low-pressure tires.
2. To compare the performance of two different types of low-pressure tires.
3. To study the effect of horizontal curves on trench floor trafficability.
4. To determine whether low-pressure tire traffic on a natural snow trench floor or standard tire traffic on a processed snow floor would provide a more feasible method of wheeled vehicle traffic.

A study involving the wheel traffic supporting capacity of a processed snow surface, the degree of increase in the strength of a processed snow floor, and the use of various landing mats was conducted earlier (Abele, 1963b).

Three types of tires were used for the trafficability study (Fig. 4):

<table>
<thead>
<tr>
<th>Tire</th>
<th>Width</th>
<th>Diam</th>
<th>Ply</th>
<th>Inflation pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>11 in.</td>
<td>44 in.</td>
<td>12</td>
<td>68 psi</td>
</tr>
<tr>
<td>Terra</td>
<td>24 in.</td>
<td>48 in.</td>
<td>8</td>
<td>13 psi</td>
</tr>
<tr>
<td>Harmo</td>
<td>18 in.</td>
<td>48 in.</td>
<td>24</td>
<td>16 psi</td>
</tr>
</tbody>
</table>

The Harmo tire is a comparatively smooth tire, while the Terra tire has heavy grip treads.

Imprints of the three tires were made to determine the actual contact area and compute the average contact pressure produced by the tires.

A standard U. S. Army M-54 truck with a 5-ton load was used as the test vehicle (Fig. 5). The total load distribution on the axles and wheels was as follows:
Figure 4. Types of tires used during trafficability tests (left to right: Standard, Terra, Harmo). (Official U. S. Army photograph).

Figure 5. Test vehicle, M-54 truck. (Official U. S. Army photograph).
Field and laboratory measurements of the mechanical properties of the trench floor snow were made both before and during the traffic testing. Ram hardness, density, and unconfined compressive strength tests were performed at approximately 50-ft intervals on the centerline of the trench before traffic tests began. During the traffic testing, additional ram hardness, density, and strength tests were performed, particularly in significant areas, i.e., in areas where definite surface failure occurred at definite times and in areas where no signs of failure were observed. The manner of failure or sinking of the wheels and the type, extent, and rate at which sinking or surface wearing was produced by progressive traffic were noted and recorded. The effect of wheel traffic on the snow surface in comparatively sharp horizontal curves was observed.

Trafficability tests with the Terra tires were performed first. A total of 120 coverages with the vehicle were made on one side of the trench. Tests with the Harmo tires, a total of 250 coverages, were performed beside the Terra tire tracks, i.e., on a surface comparatively undisturbed by previous traffic. Tests with the standard tires, a total of 1000 coverages, were confined to the processed snow floor area. (The test vehicle became immobilized during the first trip over the unprocessed floor surface, primarily because of the serious surface failures produced in some areas by previous traffic tests.)

It should be noted that each coverage or traffic repetition represents three wheel-load applications.

The average speed of the vehicle through the trench was approximately 15 mph. It was necessary, however, to slow down to approximately 10 mph in the 150 ft radius curve and at the beginning of the 200 ft radius curve. This was necessary to keep the vehicle on the desired area and to prevent it from sliding into previously produced ruts, as occurred during the Harmo tire tests.

The behavior and traffic-supporting capacity of the area outside the test trench, between the entrance ramps, was also observed.

Air temperature in the trench, as well as the temperature of the snow floor surface, was recorded during the testing period. A carbon monoxide detector was used to monitor the condition of the air in the trench and detect any contamination due to the exhaust from the test vehicle.

Skid tests

During the trafficability tests it became apparent that it would be of considerable interest to determine the skid properties of the various rubber tires on the trench floor surface, i.e., the required stopping distance on a surface of this type. From this it would be possible to determine an approximate coefficient of friction between a rubber tire and a hard snow surface.

Because of the condition of the unprocessed snow trench floor section after the trafficability tests, only the processed snow floor was suitable for skid tests.

The trench floor had been previously subjected to 370 coverages of wheeled traffic. The floor was not entirely smooth (Fig. 4); the roughness was caused primarily by tractor tracks during leveling. No loose snow was present on the floor surface.
The skid tests were performed first with the Harmo tires, then with the Terra and standard tires. Tests at the lower speeds were performed first; the speeds were then increased up to 20 mph and then decreased again (see Appendix C for sequence of runs). Because of the limited length of trench floor, tests at speeds higher than 20 mph could not be performed.

The driver was instructed to apply the brakes abruptly when the desired speed was attained. An observer, seated beside the driver, noted the speed on the speedometer at the instant before the brakes were applied.

Two observers in the trench noted the exact location where the wheels started to skid and where the truck stopped. One of the observers used a stopwatch to observe the skid time (time observations were not made during the Harmo tire tests). A 50-ft tape was used to measure the skid distance.

Because of the manner in which the tests were performed (the driver anticipated the stop and applied the brakes upon reaching a predetermined speed), the reaction time of the driver could not be measured.

Since skid tests had not been planned, instrumentation required to measure the total braking distance was not available. Since braking distance is measured from the instant the brake application is initiated, the distance traveled during the brake application before the wheels locked could not be determined. In other words, only one part of the braking distance — the skid distance — was observed. The same is also true with the time observations.

It was impossible to determine whether or not all wheels locked at the same instant. It appeared that they did; however, this assumption is not reliable from visual observations alone.

It was more difficult to read the speedometer at low speeds than at higher speeds because of the vibration of the speedometer needle. The needle vibration decreased as the speed was increased. No facilities were available to check the accuracy of the speedometer.

Skid distance measurements at low speeds, 5 mph for example, could be obtained with a ±6-in. accuracy. The average skid distance at 5 mph was 5 ft; this gives a possible error of 10%. At a speed of 20 mph, measurements could be made with an accuracy of ±2 ft. The average skid distance at this speed was approximately 50 ft, which indicates a possible 4% error.

It was assumed that the reaction time for starting the stopwatch would be the same as for stopping it and, therefore, introduce no error. As will be seen later, the time vs speed plot gives considerably more scatter than the distance vs speed plot. Since it was easier to anticipate the instant when the vehicle came to a stop than the instant when the wheels locked, the reaction times may not be the same and, therefore, may introduce an error in the observations.

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It was assumed that the reaction time for starting the stopwatch would be the same as for stopping it and, therefore, introduce no error. As will be seen later, the time vs speed plot gives considerably more scatter than the distance vs speed plot. Since it was easier to anticipate the instant when the vehicle came to a stop than the instant when the wheels locked, the reaction times may not be the same and, therefore, may introduce an error in the observations.

The snow surface roughness was not exactly uniform throughout the length of the test section, although no significant variations were noticed. To minimize this effect, as well as that of increased slickness from previous skid tests, skid locations were shifted as much as possible.

Installation of test railroad

After the completion of the wheel traffic and skid tests, the trench floor was prepared for the railroad installation. The floor surface was surveyed and leveled again with the snow planer. Final surveying was then performed to establish the location of the proposed track.

In order to eliminate most of the results and effects from the previous traffic tests and provide a reasonably undisturbed surface beneath the railroad ties, a 6 in. deep, 9 ft wide cut was made in the trench floor with a Peter plow (Fig. 6).
Density and ram hardness profiles of the snow beneath the proposed track were determined before the installation work began.

Rails, ties and other installation equipment were moved into the trench and distributed along the edges of the trench floor. Standard 90-lb and 100-lb rails, 39 ft long, and 8 ft 6 in. x 8 in. x 6 in. untreated oak ties were used. The ties were placed in the 6-in. cut, spaced approximately 20 in. center to center. Spike holes were predrilled to facilitate spiking. The rails were then placed on the ties and spiking begun. The standard 56\(\frac{1}{2}\)-in. gage was used.

Because of the comparatively low-speed rail traffic and small lateral forces anticipated during this test, it was considered unnecessary to fasten the rails to every tie. The rails were, therefore, spiked only to every other tie. Also, spirals between the curves and tangents were considered unnecessary.

Bending of the rails was accomplished by the following method. Two rail sections were bolted together and connected to the end of a rail section already spiked to the ties. The free end of this 78 ft long rail assembly was moved with crow bars until the joint between the two sections was at the desired location. The first section of the rail was then spiked to the ties and another rail section bolted to the end of the free rail. This method, utilizing a 78 ft long rail section as a lever arm and each time securing half of its length to the ties, produced a very smooth horizontal curve which was quite close (within \(\frac{1}{2}\) in.) to the desired circular curve.

Ballast, which in this case would be snow, was not used between ties. It was felt that a snow ballast would be of little value. To minimize lateral movement of the ties in the curved sections of the track, snow and lumber wedges were placed between the ends of the ties and the wall of the 6-in. cut.

Because of the somewhat uneven surface beneath the ties, shimming of a number of ties was necessary. Scrap lumber was used as shims.
SUBSURFACE TRANSPORTATION METHODS IN DEEP SNOW

Figure 7 shows part of the 150 ft radius curve in the foreground and the 300 ft long straight section. Figure 8 shows part of the 200 ft radius curve.

Installation of the 1300 ft long railroad section was completed by a crew averaging 10 men in a period of approximately 40 actual work hours, under the supervision of two railroad construction foremen. Only two men in the crew, besides the foremen, had any track construction experience. The 40-hr figure includes placing ties, placing and bending rails, drilling spike holes, spiking, shimming, and lining, but does not include moving equipment into the trench.

Rail traffic tests

A 40 ton capacity railroad flatcar, connected to a 5-ton truck, was used as the test vehicle.

The flatcar was lifted on a rail and ski assembly and lowered via the entrance ramp into the trench and on the track with the help of a D-8 bulldozer.

A railroad conversion unit was installed on the 5-ton truck (Fig. 9). The unit consists essentially of rail conversion wheels mounted at the front and rear of the truck, which enable the truck to travel on a railroad track. The inner and rear axle inside dual wheels, which match the gage of the track, operate as drive wheels. The front wheels and the outside dual wheels are inactive. The sole purpose of the rail conversion wheels is to keep the vehicle on the track.

A 30-ton load was placed on the flatcar, and the rail traffic tests were performed by moving the flatcar with the truck back and forth over the track.

The rail conversion unit, being a rigid axle assembly, is designed primarily for use on straight track. Some difficulties were experienced in negotiating the sharp curves with the truck. (No difficulties were encountered with the flatcar itself.) Therefore, only a small amount of traffic testing could be performed in the curved track sections. In the straight sections, however, 200 coverages with the test vehicle were completed. Because of the difficulties with the rail conversion wheels, traffic tests at speeds of more than 5 mph could not be performed.

During the rail traffic tests, behavior of the rails and ties and especially the snow surface beneath the ties was observed. Any sinking or settlement of the track was noted. A level survey was performed before traffic testing began and again after completion of the tests.

DISCUSSION OF RESULTS

Mechanical properties of the trench floor

The mean density profiles of both the unprocessed and processed snow trench floor sections are shown in Figure 10. The cross-sectional density profile of the entire length of the trench floor is shown in Figure 11. (The vertical contour lines are based on the data from 49 individual density profiles obtained before and during the wheel trafficability tests.) The cross-sectional profile gives a more comprehensive representation of the snow density through the trench. It should be noted, however, that the vertical scale is greatly exaggerated in comparison to the horizontal scale. While the range of the density values is indicated on the mean profile (Fig. 10), the actual distribution of the density in respect to the location in the trench appears only in the cross-sectional profile.

Figure 12 shows the mean ram hardness profiles of the unprocessed and processed floor sections and also of the trail between the entrance ramps. The cross-sectional ram hardness profile is shown in Figure 13.
Figure 7. A view of the railroad track shortly after installation.

Figure 8. A view showing the railroad track in the 200-ft radius curve.
Figure 9. Railroad wheel conversion unit installed on M-54 truck. (Official U. S. Army photograph).

Figure 10. Density profile of trench floor.
Figure 11. Cross-sectional density profile of trench floor.

Figure 12. Ram hardness profile of trench floor.

Figure 13. Cross-sectional ram hardness profile of trench floor.
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The mean unconfined compressive strength profiles are shown in Figure 14. (The amount of compressive strength data was not sufficient for constructing a cross-sectional profile.)

From the above figures it can be observed that the Peter plow-processed floor section exhibits considerably improved mechanical properties compared with the unprocessed section. Strength characteristics show a significant increase and, in general, follow a more desirable vertical distribution pattern, the strength being highest near the surface and decreasing gradually with depth. The homogeneity in a horizontal direction has been improved (Fig. 13).

Wheel traffic

For all practical purposes, the limiting factor in failure criteria for trafficability of any surface would be excessive wheel or track sinkage due to the physical characteristics of both the supporting medium and the vehicle.

In this case, failure of the snow surface was considered to be a depth of wheel penetration or sinking of 5 cm (2 in.) or more. The reasons for this criterion have been discussed earlier (Wuori, 1962). It has also been observed that the operation and control of a vehicle becomes difficult if sinking of the tires exceeds a 5-cm depth. Tire penetration of less than 5 cm is, therefore, not considered excessive for tires of this size, since neither trafficability of the surface nor mobility of the vehicle is greatly affected.

Of course, a tire penetration of 3 or 4 cm into a snow surface may indicate that the surface is not fully capable of supporting that particular wheel load. The definition of surface failure with respect to trafficability would vary with the size and type of the tire, the characteristics of the vehicle, and the degree to which trafficability is affected. A 5-cm penetration of an aircraft wheel during a take-off on a snow runway may be considerably more critical than a 5-cm penetration of a truck wheel on a snow road.
Wuori (1962) found from static wheel load tests that the zone of disturbance or vertical deformation in a uniform snow mass beneath a tire does not generally exceed a depth of 1.5 times the effective width of the tire when the tire penetration is approximately 5 cm and the snow density is between 0.49 and 0.56 g/cm³. For the three types of tires used in this study the zone of disturbance would be confined to a depth of less than 80 cm.

Because of the considerable variation in the mechanical properties of the snow pavement between the surface and an 80-cm depth, it is necessary to evaluate the supporting capacity in terms of smaller depth increments, such as the radius of an equivalent circular contact area, for example.

The approximate average contact areas between the tires and the snow surface and the radii \( r \) of the equivalent circular areas were as follows:

<table>
<thead>
<tr>
<th>Tire</th>
<th>Contact area (cm²)</th>
<th>( r ) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>500</td>
<td>13</td>
</tr>
<tr>
<td>Harmo</td>
<td>1300</td>
<td>20</td>
</tr>
<tr>
<td>Terra</td>
<td>2000</td>
<td>25</td>
</tr>
</tbody>
</table>

A 20-cm depth increment was considered the most realistic and the most convenient for the analysis and evaluation of the test data. Boussinesq's vertical stress distribution curve for soil under a circular load indicates that at a depth of \( r \) the vertical stress is approximately 67% of the surface stress, at a depth of 2\( r \) approximately 30%, and at 3\( r \) approximately 15%. The top 20 cm could then be considered the critical surface layer whose strength characteristics would be the most significant factor in determining the supporting capacity of a snow pavement. (Boussinesq's analysis assumes a homogeneous, elastic medium, which is not necessarily the case here, but Wuori's test results seem to indicate that for processed snow Boussinesq's curve could be used for a rough approximation.)

The data on the average strength characteristics, in this case ram hardness, for a depth \( r \) (i.e., 0 to 20 cm) were correlated with the number of moving wheel load applications, provided the data showed the hardness for the \( r \) to 2\( r \) depth to be at least 50% of that of the surface 20 cm.

The first failures, as expected, occurred on the trail between the two entrance ramps. Areas having an average ram hardness of approximately 150 (for the 0 to 20-cm depth) supported only two coverages (traffic repetitions with the test vehicle) with the Terra tires. After two coverages, wheel penetration exceeded 5 cm, and the ruts became progressively deeper. Areas having an average ram hardness of approximately 200 could support six to ten coverages before wheel sinkage became excessive. Ram hardness of 250 was sufficient to hold about 20 coverages.

Compaction of a natural snow with a bulldozer is not very effective beyond a 30-cm depth (Abele, 1962). In general, the trail's surface layer was reasonably hard (Fig. 12), but the hardness decreased sharply below a 10-cm depth. Therefore, the snow pavement offered very little resistance to wheel penetration once the surface layer had begun to fail. It was necessary to use aluminum landing mats in the areas of serious failures. Deterioration of the trail's surface was further increased by its exposure to direct sunlight.

It appears that the heavy grip treads of the Terra tires were doing a considerable amount of damage to the snow surface.

After 20 coverages, failures of 5 cm or more were present in the trench floor at stations 6+50 and 11+00. (For location of stations refer to Figure 2, and for hardness profile at any location in the trench to Figure 13.) After 40 coverages ruts in these areas were 8 to 10 cm deep, and wheel penetration at sta 9+60 had reached 3 cm. After 80 coverages the area around sta 5+00 showed wheel penetration
of approximately 5 cm. In three areas of the unprocessed floor section (sta 0+00 to 4+75, 8+50 to 9+25, and 10+00 to 10+60) wheel penetration after 120 coverages was less than 5 cm. No failures or signs of any surface wearing were observed on the processed snow section.

In the two weakest areas, sta 6+50± and 11+00±, from visual observations it appeared that the wheel penetration was caused primarily by the failure of the surface in consolidation, the wearing action of the tire treads being only of secondary importance. However, in the area between 4+00± and 6+00± the surface wearing was predominant. The surface was slowly but progressively disaggregated by the tire treads. While the wheel penetration here did not exceed 5 cm after 120 coverages, indications were that with continued traffic disaggregation would continue until a harder snow layer was encountered. Similar results were observed between sta 0+00 and 4+00±, but to a somewhat lesser extent.

The Harmo tires, which were essentially smooth but had a higher average contact pressure (27 psi as compared with 16 psi for Terra tires), performed somewhat more satisfactorily. Except for a few failures on the trail and very little abrasion in some areas on the trench floor, no failures had occurred during 40 coverages. In the areas where failures with Terra tires occurred after 40 coverages, traffic with the Harmo tires produced failures only after about 80 coverages.

![Image](Image)

a. Surface wearing, sta 1+00 to 2+75. (Official U. S. Army photograph).

Figure 15. Unprocessed trench floor after 120 coverages with the Terra tires and 200 coverages with the Harmo tires.
b. Partial failure, sta 7+75 to 10+75. (Official U. S. Army photograph).

c. Complete failure, sta 11+00 to 12+00. (Official U. S. Army photograph).

Figure 15 (Cont'd). Unprocessed trench floor after 120 coverages with the Terra tires and 200 coverages with the Harno tires.
In general, the extent of failure of the trench floor after 200 coverages with the Harmo tires was comparable to the extent of failure produced by 120 coverages with the Terra tires.

Figures 15a-c show the condition of the unprocessed trench floor after 120 coverages with the Terra tires and 200 coverages with the Harmo tires.

The section between sta 1+00 and 2+75 is shown in Figure 15a. The Terra tire tracks are partly obscured by the effects of the Harmo tire traffic. (The loose snow on the edges of the trench floor, particularly on the left or outside edge, is the excess snow deposited by the snow planer during the floor leveling and is not the result of the traffic tests.) No consolidation (or shear) failures occurred here; however, surface wearing was present to some extent.

In the unprocessed, straight section of the trench (sta 7+75 to 10+75) both consolidation failures as well as considerable surfate wearing occurred (Fig. 15b). (On the 185th coverage the left rear Harmo tire developed an air leak and had to be replaced with a Terra tire for the remainder of the tests.)

Figure 15c shows a section of the 150 ft radius curve (sta 11+00± to 12+00±) where the most serious failures occurred.

In Figure 16 is shown a comparison of the mean ram hardness values obtained in three distinctive areas where 250 coverages with Harmo tires produced 1) surface wearing not exceeding a 2-cm depth; 2) surface failure of approx. 5 cm; and 3) surface failure exceeding 10 cm.

The mean values were computed for the 0 to 20-cm depth, as well as for each 5-cm increment within the 20-cm surface layer. The range and standard deviation show the great variability in strength properties of an unprocessed snow pavement.

The processed snow surface appeared to be virtually unaffected by the Harmo tire traffic.

The effect of the horizontal curves on trafficability was difficult to estimate. The weakest floor section unfortunately happened to be in the area of the 150 ft radius curve (Fig. 13); therefore, any comparisons with straight sections having

---

**Table: Ram Hardness Values**

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Range</th>
<th>Mean</th>
<th>Std. dev.</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>132-1696</td>
<td>306</td>
<td>146</td>
<td>10</td>
</tr>
<tr>
<td>5-10</td>
<td>218-1159</td>
<td>599</td>
<td>277</td>
<td>10</td>
</tr>
<tr>
<td>10-15</td>
<td>124-994</td>
<td>478</td>
<td>267</td>
<td>10</td>
</tr>
<tr>
<td>15-20</td>
<td>124-544</td>
<td>298</td>
<td>126</td>
<td>10</td>
</tr>
</tbody>
</table>

**Figure 16.** Comparison of supporting and failing ram hardness profiles, unprocessed snow. After 250 traffic coverages with Harmo tires.
the same strength properties could not be made. It did appear, however, that the horizontal forces introduced by the tires when traveling in a horizontal curve promoted failures. In the curved sections the penetration of the outside wheels was generally deeper than that of the inside wheels. This was particularly noticeable in the 150 ft and 200 ft radius curves (Fig. 15c).

Traffic tests with the standard tires produced no failures or surface wearing on the processed snow surface after 1000 coverages (Fig. 17). On the other hand, some areas of the unprocessed surface could not support even one coverage.

The most comprehensive method of evaluating the results of the traffic tests would be to determine the relationship between some mechanical property and the supporting capacity of the snow pavement for a particular wheel or vehicle load. The greatest amount of field data pertaining to the mechanical properties of the snow was obtained with the Rammonde cone penetrometer. Ram hardness is also probably one of the more reliable (when compared with density and unconfined compressive strength) indicators of the supporting capacity of snow (Wuori, 1962; Abele, 1963a). Relating ram hardness to the number of vehicle coverages supported by the snow pavement would, therefore, be the most convenient and reliable method.

The points in Figure 18 represent the highest ram hardness values of the snow surface (i.e. the mean for 0 to 20 cm) which failed shortly after the indicated number of coverages. For example, in one area where a 5-cm Terra tire penetration was obtained shortly after 10 coverages (but before 15), the highest mean value for 0 to 20-cm depth from several ram hardness profiles (taken not more than 10 cm from the tire track) was 220. R = 220 is plotted against N (number of coverages) = 10. In other areas which failed shortly after 10 coverages, the highest mean hardness values were 185 or less. In Figure 18 only the highest two or three hardness values are shown for each number of coverages.
SUBSURFACE TRANSPORTATION METHODS IN DEEP SNOW

Figure 18. Traffic supporting capacity vs ram hardness.

Until 10 coverages, observations were made after each coverage. After 10 coverages close inspection of the tire tracks and the extent of failure was performed only after each 10 coverages. Therefore, the respective hardness values were usually plotted at 10-coverage intervals.

The lines in Figure 18, which were drawn so that they would be located on the right of all the respective points, represent the failure envelopes for the three types of tires. From the data shown it could be assumed that the area below the envelope represents safe conditions, while the area above the envelope indicates unsafe conditions.

The relationship was assumed to be in an exponential form:

\[ N = a R^b \]

where:

- \( N \) = number of traffic coverages with the test vehicle
- \( R \) = mean ram hardness for 0 to 20-cm depth
- \( a \) and \( b \) = constants.

The equations for the three envelopes are:

- Standard tires: \( N = 2.98 \times 10^{-13} R^5 \)
- Terra tires: \( N = 4.78 \times 10^{-13.64} R^{5.88} \)
- Harmo tires: \( N = 10^{-7.69} R^{3.85} \)

Unfortunately, the constants in the equations are not very convenient numbers. A theoretical analysis of the relationship between the mechanical properties of snow and its traffic supporting capacity would probably produce a different expression.

If the number of expected traffic coverages is known and it is desired to determine the required ram hardness of the proposed snow pavement, the equations would be:

- Standard tires: \( R = 320 N^{0.20} \)
- Terra tires: \( R = 160 N^{0.17} \)
- Harmo tires: \( R = 100 N^{0.26} \).

Since only the highest mean hardness values of the failure areas were used, a great number of points obtained in the areas with no failures would fall in the "unsafe" area above the envelope in Figure 18. In other words, occasionally ram hardness values obtained in a no-failure area were lower than hardness values in a failure area. Therefore, the envelopes and their equations may contain a safety factor. The inconsistencies in the ram hardness values could be attributed to the
great variation in the strength properties within short distances in an unprocessed snow pavement. The presence of ice lenses and depth hoar layers contributes greatly to the variation of the ram hardness within a small area.

It would be desirable to conduct a statistical analysis to determine the variance of the mechanical properties of various types of snow pavements, so that the reliability of a certain number of observations or tests could be predicted.

Extrapolation beyond 300 coverages should not be made without further data in that range. It is assumed that with increasing \( R \) the envelopes will eventually approach a vertical line. For example, a snow pavement with ram hardness of 1000 or above will support a considerably higher number of traffic coverages than indicated by present envelope equations.

Figure 19. Skid distance vs speed \( V^2 \).

**Skid tests**

It is commonly assumed that the braking distance of a vehicle varies as the square of its velocity and is represented by:

\[
d = \frac{V^2}{30f}
\]

where:

\( f \) = average coefficient of friction and the braking distance \( d \) includes the distance traveled during brake application time.

The above expression is derived from the energy equation

\[
\frac{W V^2}{2g} = W f d.
\]

If, for the present purposes, it is assumed that the skid distance \( d_s \) also varies as the square of the speed, the data can be plotted as shown in Figure 19. Using the method of least squares and assuming the relationship to be in the form

\[
d_s = a V^2 + b
\]

the following equations are obtained:
Standard tires: \[ d_s = 0.121 V^2 + 4.5 \]
Harmo tires: \[ d_s = 0.143 V^2 + 2.5 \]
Terra tires: \[ d_s = 0.097 V^2 + 3.1 \]
Combined data: \[ d_s = 0.118 V^2 + 3.4 \]

where: \( d_s = \) skid distance (ft)
\( V = \) speed of vehicle (mph).

The intercept on the \( d_s \) axis (the constant \( b \) in the equation) is not realistic and is a result of the method used in computing the equation. The actual point distribution below \( V^2 = 30 \) indicates that the curve would indeed go through the origin.

The standard error of estimate (\( S_{y.x} \)) and the coefficient of correlation \( r \) for each line are shown in Figure 19. A complete table of statistical values for the skid test analyses is shown in Appendix A.

It has been shown (Normann, 1953) that full deceleration does not start immediately when the brake pedal is touched. It takes some time to depress the pedal completely and some additional time for the brakes to take full effect. While it is true that the kinetic energy of a vehicle in the direction of travel varies as the square of the speed, the rate at which the brakes can absorb this energy is limited.

Normann found that the braking distance vs speed relationship is more accurately represented by the expression

\[ d = a V^n + bV \]

where \( a, b, \) and \( n \) are constants. The term \( bV \) represents the distance traveled during the brake application time and until the brakes take full effect.

From the test data he found the equation to be

\[ d = 0.00101 V^{2.92} + 0.82 V \]

or, for approximate calculations,

\[ d = 0.00069 V^3 + V. \]

Starks (1955) from his tests found

\[ d = 0.053 V^2. \]

The various results are compared in Figure 20. The equation \( d = V^2/30f \) may serve satisfactorily for determining approximate stopping distances. Between speeds of 20 and 80 mph the \( d \) values may contain a safety factor. For speeds over 90 mph, however, a lower \( d \) than actually required will be obtained.

If it is assumed that the relationship between the skid distance \( d_s \) and \( V \) is in the general form

\[ d_s = a_1 V^n \]

where \( a_1 \) and \( n \) are constants, the data can be presented on a log-log plot (Fig. 21). The equations for the regression lines can be computed by the method of least squares assuming the expression to be

\[ \log d_s = n \log V + a_0 \]
Figure 20. Skid distance vs speed comparison.

Figure 21. Skid distance vs speed $V$. 
and the following equations are obtained:

- Standard tires: \[ d_S = 0.435 V^{1.60} \]
- Harmo tires: \[ d_S = 0.450 V^{1.61} \]
- Terra tires: \[ d_S = 0.312 V^{1.63} \]
- Combined data: \[ d_S = 0.417 V^{1.58} \]

where: \( d_S = \text{skid distance (ft)} \)
\( V = \text{speed (mph)} \).

The combined data regression line is also shown in Figure 22.

Comparing the corresponding coefficients of correlation of the two plots (Fig. 19 and 21), it appears that the log \( d_S \) vs log \( V \) plot gives a somewhat better relationship than the \( d_S \) vs \( V^2 \) plot.

Solving for the coefficient of friction \( f \) from \( d = V^2 / 30f \), by using the skid distance \( d_S \) for \( d \) (since the total braking distance could not be observed), substituting \( a_1 V^n \) for \( d_S \) (Fig. 21) and the respective values for the constants \( a_1 \) and \( n \), the following expressions are obtained:

- Standard tires: \[ f = 0.077 V^2 / V^{1.60} \]
- Harmo tires: \[ f = 0.074 V^2 / V^{1.61} \]
- Terra tires: \[ f = 0.107 V^2 / V^{1.63} \]

which indicate that the coefficient of friction increases with an increase in speed (Fig. 22). This was not expected; however, it is interesting to note that Wehner's (1959, 1960) results indicate that the coefficient of sliding (locked wheel condition) between a rubber tire and compacted snow and ice surfaces either remains constant or shows a tendency to increase with an increase in speed from 20 to 60 km/hr (Fig. 22).
The variation in $f$ at various speeds for rubber tires on various highway pavements is also shown for comparison purposes.

A more realistic $f$ would be obtained if the actual speed of the vehicle at the instant the wheels locked was used for $V$. The average $f$ would be somewhat lower and, perhaps, more constant with an increase in $V$. Of course, the use of the total braking distance would also give a lower $f$, but the apparent increase in $f$ with an increase in $V$ would still be present.

From the present data, which are quite limited, it should not necessarily be assumed that the coefficient of friction between a rubber tire and a hard, somewhat rough snow surface actually increases with an increase in the vehicle speed. Wehner's data, nevertheless, show that this may be possible.

As the speed of the vehicle was increased, more side skidding was noticed. Since $f$ for skidding sideways is greater than $f$ for skidding straight ahead (Moyer, 1934), this may account for some increase in the $f$ values.

If the energy equation

$$v^2 = 2gf \, d$$

is expressed as

$$d = \frac{v^2}{64.4 \, f}$$

where $v$ = speed in ft/sec

and $f$ = coefficient of friction

and the expression

$$d_s = a \, V^2 + b \text{ (Fig. 19)}$$

is expressed as

$$d_s = \frac{a \, v^2}{2.152}$$

where $v$ = speed in ft/sec

and the constant $b$ is disregarded.

Considering $d = d_s$, then

$$\frac{v^2}{64.4 \, f} = \frac{a \, v^2}{2.152}$$

and

$$f \text{ (approx.)} = \frac{0.0334}{a}$$

where $a$ = constant in the equation of the regression line.

Solving for the approximate coefficient of friction, the following results are obtained:

- Standard tires: $f = 0.28$
- Harmo tires: $f = 0.23$
- Terra tires: $f = 0.34$
- Combined data: $f = 0.28$. 
Another approach in solving for $f$ involves using the expression for the conservation of momentum:

$$\frac{W \cdot v}{g} = W \cdot f \cdot t$$

or

$$t = \frac{v}{f \cdot g}$$

where

$t = \text{braking time, or the time required for the vehicle to stop.}$

By plotting the skid time $t_s$ vs $V$ (Fig. 23), assuming the relationship to be in the form

$$t_s = a_2 \cdot V + b_2$$

and using the method of least squares, the resulting regression lines cross the y-axis at approximately 0.5 sec (constant $b_2$). This does not represent a realistic relationship at speeds below 10 mph, and is not justifiable (the data confirm that), since the reaction time was not taken into consideration.

By setting the intercept $b_2$ equal to zero, the following equations are obtained:

- **Standard tires:**
  $$t_s = 0.223 \cdot V$$

- **Terra tires:**
  $$t_s = 0.167 \cdot V$$

- **Combined data:**
  $$t_s = 0.192 \cdot V$$

where $t_s = \text{skid time (sec)}$

$V = \text{speed (mph)}$.

It should be noted that while the coefficients of correlation $r$ shown in Figure 23 represent the degree of relationship between the two variables, the lines, having been forced through the origin, indicate the more realistic relationship but not the best fit according to the point distribution. That is, the lines do not represent the same degree of relationship as indicated by the coefficients of correlation.

From

$$t = \frac{v}{f \cdot g}$$

and

$$t_s = a_2 \cdot V + b_2 \approx 0.682 \cdot a_2 \cdot V$$
where

\[ V = \text{speed in mph} \]
\[ v = \text{speed in ft/sec} \]

neglecting \( b_2 \) and assuming \( t_s = t \), the constant

\[ 0.682 \ a_2 = \frac{1}{f g} \]

and

\[ f \ \text{(approx)} = \frac{0.0455}{a_2} \]

where \( a_2 = \) constant in the equation of the regression line.

Solving for \( f \), the following coefficients of friction are obtained:

- **Standard tires:** \( f = 0.20 \)
- **Terra tires:** \( f = 0.27 \)
- **Combined data:** \( f = 0.24 \)

The \( f \) values computed from the skid time vs speed data are somewhat lower than those computed earlier from the skid distance vs speed data (\( f \) for Standard tires = 0.28 and \( f \) for Terra tires = 0.34), but compare quite well with the median values in Figure 22 from \( f = V^2/30 \). 

All the above \( f \) values also compare reasonably well with Wehner's range of values of 0.15 to 0.35 for rubber tires on compacted snow surfaces at comparable temperatures but obtained at higher speeds (see Appendix B for comparison). Wehner's snow surface may have been smoother than that of the trench floor in this study, which may account for his \( f \) values being slightly lower at comparable speeds (Fig. 22). Also, there may be a difference in the types of tires used. Furthermore, Wehner used the skid trailer method, which gives lower \( f \) values than the skid distance method (Whitehurst, 1955).

**Rail traffic**

As explained earlier, the difficulties with the rail conversion wheel units caused the rail traffic tests to be confined to the two sections between sta 6+00± to 11+00± and sta 12+00± to 16+00.

Both the processed and unprocessed snow surfaces were easily capable of supporting the loaded flatcar traffic and after 200 traffic coverages gave no indications of potential failures or excessive settlement. The maximum tie settlement observed was 0.4 in. and occurred in the section between sta 8±50 and 9±25. Tie settlement not exceeding 0.2 in. was observed at sta 7±50 to 8±00 and 10±00± to 11±00. No noticeable settlement (0.1 in. or more) could be observed in the processed snow section (sta 12+00 to 16+00).

In general, the snow surface appeared to be perfectly suitable as a base for a standard size railroad. Considering the very effective load distribution with a regular rail and tie arrangement, this was not surprising.
Production data

A detailed production data analysis for the construction of a cut-and-cover trench suitable for subsurface traffic has been presented in a previous report (Abele, 1964).

A comprehensive summary of the production data results is shown below.

Trench cutting: Excavation of the trench (having a cross section as shown in Figure 1 and containing horizontal curves as shown in Figure 2) with a Peter plow. This includes only the actual time spent in excavating the spoil cuts, the trench, and the entrance ramps, but does not include maintenance time or any other "no-cut" machine time.

Rate of cutting = 24.7 ft of trench/hr.

Trench covering: Installation of arches and covering them with snow to a depth of 3 ft. A five-man crew was used for arch installation and a Peter plow for covering.

Rate of arching = 5.5 ft of roof/man-hr.
Rate of covering = 100 ft of roof/plow-hr.

Floor preparation: Processing a 400-ft length of floor and leveling the entire trench floor surface with a snow planer.

Rate of processing = 160 ft of floor/hr.
Rate of leveling = 400 ft of floor/hr.

Output: The mean excavating capacity of the Peter plow during the trench cutting.

Rate = 359 yd³/hr
or = 134 tons/hr.

Fuel consumption (diesel fuel).

Rate = 2.2 ft of trench/gal
or = 15 tons of snow/gal.

The production rate of the track installation was:

\[
\frac{1300 \text{ ft of track}}{10 \text{ men} \times 40 \text{ hr}} = 3.25 \text{ ft/man-hr}
\]

or

= 32.5 ft/crew-hr.

The production rate would, of course, be considerably higher if an experienced crew were used.

Figure 24. Test trench temperature.
CONCLUSIONS

Test results indicate that the natural snow surface of a trench floor does not have the required strength for high-volume traffic with vehicles such as 5-ton trucks. The average supporting capacity of the snow floor, as determined from the mechanical properties of the snow, may be quite adequate for up to 100 coverages with a 5-ton truck equipped with low pressure tires. However, the variance of the strength properties of a naturally compacted snow is too great, and the mean cannot be considered as a reliable indicator of the supporting capacity. The weakest areas of the trench floor represent the critical values from which the overall traffic supporting capacity has to be determined. Using this criterion, the trench floor will support only 10 or even fewer such traffic coverages without excessive wheel penetration.

In general, a mean ram hardness of 350 for the 0 to 20-cm depth is required to support 100 coverages with a loaded 5-ton truck equipped with low pressure tires such as the Harmo or Terra tires. For 200 coverages, ram hardness of at least 400 is required.

Since the design criteria of a trench floor will have to be in accordance with the highest expected wheel loads, processing the snow floor with a Peter plow appears to be necessary in most cases. If the snow is compacted immediately after processing, a snow pavement having ram hardness of approximately 800 or unconfined compressive strength of 150 psi is produced after a week of age hardening. This type of snow pavement is capable of supporting heavy, continuous truck traffic without the need for low pressure tires. The effort involved in processing the trench floor is minor compared with the construction of the trench itself.

A subsurface railroad system appears to be a feasible transportation method. The initial cost of this method, however, would be prohibitive unless a long-range, heavy supply transportation requirement, not subject to weather conditions, exists for a considerable period of time. Installation of the railroad itself presents no serious problems, and the natural snow surface in the trench has adequate strength properties as a bearing surface.

The problem of ventilation exists, but is by no means critical. The use of electrically powered vehicles could be considered, or ventilating fans can be employed for standard vehicle traffic.

The subsurface transportation concept as a whole has distinct advantages. Dependence on climatic conditions is virtually eliminated. Visual detection from the air is more difficult. The variation of the temperature in a covered snow trench is comparatively small throughout the year. Consequently, the dependability of this type of transportation method is high. So is the capacity and rate of supply and personnel movement. The cost of transportation in terms of weight per distance per time would be reduced as compared with the present surface and air methods.

The extremely high initial cost is, of course, the principal disadvantage.

The skid test data presented in this report represent a very limited amount of field tests for a limited range of variables. While it is possible to get some idea of the required stopping distance of a wheeled vehicle on a processed snow surface and the probable coefficient of friction between rubber tires and this snow surface, no definite conclusions can be drawn at this time.

It should be noted that the apparent coefficients of friction described here represent only the approximate coefficients of friction between the particular tires and the particular snow surface used. It is expected that the coefficient of friction
between a rubber tire and a smooth snow surface would be considerably lower. On the other hand, the type of snow surface tested is, perhaps, the type most likely to be found on a snow road.

It may be desirable to investigate the coefficient of friction of a snow surface by the skid trailer method (Whitehurst et al., 1955). This method, however, gives a lower \( f \) than the stop distance method.

It was the opinion of the investigator that, judging from visual observations alone, the vehicle did not decelerate at a constant rate during its skid distance. (Of course, it is rather difficult to determine by eye whether the rate of deceleration is constant or not.) It appeared that during the last several feet of skidding the rate of deceleration increased, that is, the vehicle stopped more suddenly than expected. Starks et al. (1955) has shown that the rate of deceleration is not necessarily constant during the braking distance, although his results on standard highway pavements show a decrease in deceleration near the end of the braking distance. The equations used in computing \( f \) assume a constant deceleration.

**LITERATURE CITED**


Wehner, B. (1959) *Special observations on the resistance to sliding on snow-covered or icy road surfaces*, Rev. gen. caoutchouc, vol. 36, no. 10; p. 1442-1447.

LITERATURE CITED (Cont'd)


(1964) Performance testing of a modified field planer on processed snow, USA CRREL Special Report 53.
APPENDIX A: SKID TEST STATISTICAL VALUES
(Computations performed with a Bendix G-15 computer)

<table>
<thead>
<tr>
<th>Equation</th>
<th>Type of Tire</th>
<th>n</th>
<th>S_y,x</th>
<th>r</th>
<th>t</th>
<th>A</th>
<th>B</th>
<th>x</th>
<th>y</th>
<th>s_x</th>
<th>s_y</th>
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<tr>
<td>( d_s = A V^2 + B )</td>
<td>Standard</td>
<td>14</td>
<td>3.43</td>
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<td>15.1</td>
<td>0.121</td>
<td>4.53</td>
<td>138.9</td>
<td>21.4</td>
<td>114.4</td>
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<tr>
<td></td>
<td>Harmo</td>
<td>14</td>
<td>2.86</td>
<td>.987</td>
<td>21.5</td>
<td>0.143</td>
<td>2.51</td>
<td>133.4</td>
<td>21.6</td>
<td>115.2</td>
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<td></td>
<td>Terra</td>
<td>17</td>
<td>1.47</td>
<td>.992</td>
<td>29.9</td>
<td>0.097</td>
<td>3.14</td>
<td>147.7</td>
<td>17.5</td>
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<td></td>
<td>Combined</td>
<td>45</td>
<td>4.34</td>
<td>.953</td>
<td>20.5</td>
<td>0.118</td>
<td>3.43</td>
<td>142.6</td>
<td>20.3</td>
<td>113.6</td>
<td>14.1</td>
</tr>
<tr>
<td>log ( d_s = A \log V + B )</td>
<td>Standard</td>
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<td>Harmo</td>
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<td>.047</td>
<td>.995</td>
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<td>.441</td>
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<td>Terra</td>
<td>17</td>
<td>.045</td>
<td>.992</td>
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<td>1.63</td>
<td>-.507</td>
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<td>1.138</td>
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<td>.330</td>
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<td>Combined</td>
<td>45</td>
<td>.078</td>
<td>.978</td>
<td>30.7</td>
<td>1.58</td>
<td>-.381</td>
<td>981</td>
<td>1.171</td>
<td>.226</td>
<td>.366</td>
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</tbody>
</table>

| t_s = AV         | Standard     | 14 | .446  | .907| 7.5  | 0.223| 0   | *  | 10.8 | 2.41 | 4.67 | 0.98 |
|                   | Terra        | 17 | .440  | .795| 5.1  | 0.167| 0   | *  | 11.2 | 1.88 | 4.63 | 0.68 |

*B was set equal to zero

- \( n \) = number of observations
- \( S_{y,x} \) = standard error of estimate
- \( r \) = coefficient of correlation
- \( t \) = ratio of \( r \) to its standard error, corrected for \( n \) introduced
- \( A, B \) = constants of regression line

**APPENDIX B: SUMMARY OF SKID TEST RESULTS**

<table>
<thead>
<tr>
<th>Equation</th>
<th>Type of Tire</th>
<th>Standard</th>
<th>Harmo</th>
<th>Terra</th>
<th>Combined data</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_s = a_1 V^2 + b )</td>
<td>Standard</td>
<td>0.121 V^2 + 4.5</td>
<td>0.143 V^2 + 2.5</td>
<td>0.097 V^2 + 3.1</td>
<td>0.118 V^2 + 3.4</td>
</tr>
<tr>
<td></td>
<td>Harmo</td>
<td>0.435 V^{1.60}</td>
<td>0.450 V^{1.64}</td>
<td>0.312 V^{1.63}</td>
<td>0.417 V^{1.58}</td>
</tr>
<tr>
<td></td>
<td>Terra</td>
<td>0.223 V</td>
<td>------</td>
<td>0.167 V</td>
<td>0.192 V</td>
</tr>
<tr>
<td>( f = 0.0334/a )</td>
<td>Standard</td>
<td>0.28</td>
<td>0.23</td>
<td>0.34</td>
<td>0.28</td>
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<tr>
<td></td>
<td>Harmo</td>
<td>0.14 to 0.25</td>
<td>0.13 to 0.24</td>
<td>0.18 to 0.33</td>
<td>------</td>
</tr>
<tr>
<td></td>
<td>Terra</td>
<td>0.20</td>
<td>------</td>
<td>0.27</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Wehner's results on compacted snow: \( f = 0.15 \) to \( 0.35 \)

- \( d_s \) = skid distance (ft)
- \( t_s \) = skid time (sec)
- \( V \) = speed of vehicle (mph)
- \( f \) = coefficient of friction
- \( a, a_1, a_2, b, n \) = constants
APPENDIX C: SKID TEST FIELD DATA

<table>
<thead>
<tr>
<th>V</th>
<th>d_s</th>
<th>V</th>
<th>d_s</th>
<th>t_s</th>
<th>V</th>
<th>d_s</th>
<th>t_s</th>
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<tr>
<td>10</td>
<td>20</td>
<td>5</td>
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<td>4.5</td>
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<td>15</td>
<td>36</td>
<td>4</td>
<td>3.0</td>
<td>0.6</td>
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<td>16</td>
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<td>4.4</td>
<td>0.6</td>
<td>6</td>
<td>8.5</td>
<td>1.2</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
<td>10</td>
<td>12.8</td>
<td>2.0</td>
<td>8</td>
<td>11.4</td>
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</tr>
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<td>17</td>
<td>9</td>
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<td>44.0</td>
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<td>41.0</td>
<td>2.1</td>
<td>9</td>
<td>15.1</td>
<td>2.4</td>
</tr>
</tbody>
</table>

V = speed of vehicle (mph)

d_s = skid distance (ft)

t_s = skid time (sec)

The data for each type of tires are shown in the sequence in which test runs were performed.
APPENDIX D: INSTALLATION METHODS AND COST ESTIMATE OF A RAILROAD TRACK SYSTEM IN DEEP SNOW POLAR REGIONS

Prepared by
Paul J. Szarka, President, "Spur and Siding Constructors Company, Inc.," Detroit, Michigan

Introduction

To summarize and provide necessary information, data, methods, cost estimate, etc., for establishing a railroad network to service a subsurface transportation system in a deep snow polar region, including various sites located on, under, and/or adjacent to an area such as the Greenland Ice Cap (Fig. D1).

For identification purposes the various sites will be noted as follows:

1. Thule Air Base (Base operations and receiving terminal)
2. Camp Tuto (Distribution center and car marshalling area for all sites)
3. Camp Century
4. Future bases, weather stations, experimental depots, launching sites, etc.

TRACK SUMMARY

<table>
<thead>
<tr>
<th>Location</th>
<th>No. of turnouts</th>
<th>Track distance (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-B Thule complex</td>
<td>7</td>
<td>25,000</td>
</tr>
<tr>
<td>B-C Thule to Tuto</td>
<td>-</td>
<td>73,920</td>
</tr>
<tr>
<td>C-D Tuto complex</td>
<td>5</td>
<td>10,000</td>
</tr>
<tr>
<td>D-E Tuto to Ice Cap edge</td>
<td>-</td>
<td>7,500</td>
</tr>
<tr>
<td>E-F Ice Cap edge to Century</td>
<td>3</td>
<td>728,640</td>
</tr>
<tr>
<td>G-H Turnout</td>
<td>1</td>
<td>3,500</td>
</tr>
</tbody>
</table>

Total = 848,560 ft = 160.7 miles

Figure D1. Proposed overall track layout.
General description

Thule Air Base: This area would be the receiving terminal of all freight, equipment, personnel, merchandise, construction materials, etc., whether delivered to Thule by air, sea, or ship-delivered freight cars. At the Thule docking facilities, boat-side tracks would be provided to receive all freight direct from inbound vessels; at the airstrip, a track would be provided to receive all inbound airfreight (Fig. D2). All inbound freight would be moved to Thule warehousing facilities, each provided with a track into or adjacent to the warehouse. Thule requirements would be unloaded here, and all remaining items dispersed to Camp Tuto for classification, reloading, etc., for dispatching to Camp Century and other sites. Trains and all cars leaving for Camp Tuto would be earmarked for simplicity in delivery of cars to consigned sites.

Camp Tuto: Warehousing facilities and open-area storage would be provided with tracks (Fig. D3). At Tuto, cars would be "marshalled" for shipment to their respective sites.

Camp Century; Other sites: Each site would be provided with a receiving track for inbound freight, and an "empty track" for unloaded cars to be returned to Camp Tuto.

All sites would be provided with a "runaround track" to enable locomotive equipment to reverse their position for return trips (Fig. D4).

Construction

Thule Air Base: Tracks at Thule Air Base would be of standard construction, "uncovered tracks." Warehouse tracks can be built into each building, alongside an unloading ramp, or provided with a lean-to roof shelter.

Tracks between Thule and Tuto would be of standard construction on crushed rock or gravel subgrade. If necessary, the track may be constructed on a 4 to 6 ft elevated subgrade to minimize snow drifting problems.

This section of track could also be constructed as a fully enclosed "surface tunnel" using metal plate culvert sections.

Camp Tuto: Tracks at Camp Tuto would be of standard construction, uncovered tracks. Warehouse tracks can be with a lean-to roof shelter, or built into each warehouse. Storage area tracks would be uncovered. The "surface tunnel" method could also be used for the track section between Tuto and the edge of the Ice Cap.

Camp Century; Other sites on the Ice Cap: Tracks for these areas would be fully enclosed in a cut-and-cover trench or subsurface tunnel. This tunnel would be of sufficient width to provide for vehicular traffic, if required.

Figure D2. Track layout at Thule AB.
Figure D3. Track layout at Camp Tuto.

Figure D4. Track layout at Camp Century.
Subgrade Preparation

General

Prior to the start of any track laying, all subgrade to the Ice Cap and a large percentage of the cut-and-cover trench (or subsurface tunnel) should be completed or well under construction.

Engineering

An accurate aerial and surface survey should be made for the route of the railroad. It is suggested that existing traveled overland routes be considered from Thule and the beginning of the Ice Cap. Existing tractor-train routes should be considered for the subsurface segments of track. Engineering and layout should be well established ahead of all work. A proper route-location would tend to avoid large crevasse openings and high rate of movement and perhaps confine crevasse openings to widths of a few inches to 3 to 4 feet.

Curvature

It is recommended that a maximum 7 degree curve be maintained throughout the entire network to provide reasonable speeds of 30 to 45 miles per hour over the system.

Elevation

Maximum grade over any given distance should be maintained at no more than 2%. To accomplish grade change from Camp Tuto to Camp Century, for example, the 2% grade could be utilized in increments of two (2) miles, with level track between. This method should provide maximum effort from the locomotive power (a constant grade would restrict speed and require additional and heavier locomotive power).

Surface grade

All track at Thule, Tuto, and between will be constructed on above-surface grade (Fig. D5). All blasting, formation, etc., of subgrade should commence three (3) months ahead of track construction. All excavated and blasted rock to be used for the subgrade would be processed and graded to 1/2 in. x 1 1/2 in. gradation. Excavated rock will be used either for this track ballast, and/or riprap support of the fourteen (14) mile surface culvert between Thule and Tuto.

Surface tunnel

The fourteen (14) miles of track between Thule and Tuto can be constructed in an Armco Multi-Plate corrugated metal culvert, 26 feet in diameter (see Fig. D5). Subgrade for this must be prepared and bottom panels of culvert assembled prior to track construction. The culvert can be completely assembled and supported with riprap after the track is completed.

Subsurface tunnel

Construction of the subsurface tunnel should precede all track construction.

To provide maximum use of the tunnel, it is suggested that sufficient width be maintained to anticipate 4 to 5 years of ice movement and closure and also to provide added width for vehicular traffic (for maintenance, etc.). The sub-base would be cut and shaped to within a 1/2 in. tolerance in depth and 6 in. in width, to provide exact and uniform bearing. Leveling of tracks would be accomplished over a period of time with periodic maintenance, by using processed snow as a ballast material, until full, level, and even bearing has been attained. The 1/2 in. tolerance of sub-base snow or ice surface should create no restrictions to train movements. The base surface of the snow tunnel would be formed with an 8 1/2 in. insert for placement track to "hold" the track to predetermined alignment (Fig. D6).
Typical ground level track section.
(May be used for sections A-B and C-D.)

Typical Armco Multi-Plate tunnel section.
(May be used for sections B-C and D-E.)

Figure D5. Typical cross sections of on-the-surface track.

Figure D6. Typical cross section of subsurface track.
(To be used for sections E-F and G-H.)
APPENDIX D

Track Construction

Surface tracks (open)

All tracks and switches at Thule Air Base and Camp Tuto would be standard track construction, constructed on wood ties, then aligned, leveled, raised, tamped, and dressed to grade on 12 in. (or more) of crushed rock ballast under track (see Fig. D5). Any required super-elevation on curves, expansion of joints, gauge variations on curves, etc., would all be "standard-good-practice" work methods to provide a first class rail system.

Surface tracks (enclosed)

The fourteen (14) mile single track between Thule and Tuto could also be constructed in a 26 ft. diameter Armco Multi-Plate encasement pipe, constructed on 12 in. of rock ballast (see Fig. D5). The encasement pipe would be placed on top of existing graded terrain and leveled as required to maintain uniform grades. Support of this encasement would be by bracing each side from existing grade to the top of the encasement with crushed rock (riprap). This same method could also be used for the short segment of track from Camp Tuto to the beginning of and, if feasible, for entering into the Ice Cap.

Subsurface track

This track would be constructed in a previously prepared tunnel. The track would be standard construction, on wood ties, with no ballast.

The type of subgrade and the actual method of track construction in the area between the edge of the Ice Cap and approximately Mile 60 cannot be specified at this time. At the edge of the Ice Cap the movement of the snow mass is quite significant (up to 13.5 ft annually in the existing ramp road area), the summer temperatures are sufficiently high to produce a considerable amount of melt water, and the size and frequency of crevasses can be quite serious. The feasibility of a cut-and-cover trench method for a subsurface railroad track system in this area is questionable.

Time of construction

Assuming a major start has been accomplished in preparing the cut-and-cover trench (or subsurface snow or ice tunnel) and that all grade is prepared at Thule Air Base and Camp Tuto, it is estimated that the track network at Thule, Camp Tuto and to Camp Century can be accomplished in less than nine (9) months, based on a work force of no less than 120 men, working six (6) days per week, on a two-shift per day basis. To provide maximum efficiency and expediency, the work should be scheduled so that all "exposed" track work at Thule and Tuto can be performed during most favorable weather periods (June-July-August and September).

Housing

During construction of tracks at Thule and Tuto, all personnel could be housed at either Thule or Tuto, thereby eliminating need of camp cars or special provisions.

During construction of the single track from Tuto to Camp Century, men can be transported over partially completed track to either Tuto or Century for quarters. As an alternate, camp cars can be maintained for manpower and can be moved at regular intervals to remain at the rail-head.

Manpower

It is suggested that the nucleus of the proposed 120-man force be thoroughly experienced track supervisory personnel and that a minimum of 25% of the labor force be experienced "gandy-dancers." A minimum number of equipment operators
would be required. The balance of manpower should have some limited knowledge of railroad construction.

Material Specifications

General specifications

All items of material furnished to be new, of standard manufacture, based on costs delivered, F.A.S., Norfolk, Virginia. No taxes are included. All materials to meet applicable Federal Specifications and/or American Railway Engineering Association Specifications.

Rails

To be of 39 ft -0 in. lengths, with nominal percentage of shorter rails for use on curves. Rail to be of 10020 (100#) ARA-A Section rail, punched for six (6) hole bars.

Joint bars

To be 100# ARA-A Section bars, punched for six (6) hole rail. Joint bars to be 36 in. in length.

Tie plates

To be punched for base of 10020 ARA-A Section rail and to be double shouldered plates. Each plate to have standard 8-hole punch to provide for anchor-spiking and double spiking on curves.

Cross ties

To be 7 in. x 9 in. x 8 ft-6 in. creosoted oak cross ties, with 8# of creosote coal tar solution per cubic foot of wood. Each tie to be grade 5 tie, adzed and bored for specified tie plates.

Switch ties

To be 7 in. x 9 in. x required lengths for all turnouts used.

Spikes

To be $5/8$ in. x 6 in. reinforced throat track spikes.

Bolts

To be buttonhead, oval neck 1 in. x $5\frac{1}{2}$ in. long, with rolled threads and heavy duty square nuts. A nut-lock (washer) to be provided with each bolt.

Turnouts

To be Number 8, complete, with self-guarded manganese frogs, switch points, switch stands, and all fastenings. Switch stands to be spring-loaded type.

Switch point heaters

Each turnout to be equipped with modern switch point heaters to provide maintenance-free switch operations.

Ballast

1. Ballast material in ice tunnel, where required, to be processed snow or ice.
2. Ballast for all exterior tracks (and "surface tunnel" track) to be crushed rock, prepared at the site, and graded to $\frac{1}{2}$ in. x $1\frac{1}{2}$ in. gradation.
APPENDIX D

Rail anchors

Woodings-Verona type rail anchors to be furnished for all track to beginning of the Ice Cap. This item to prevent and restrict rail "movement" due to variations in temperature. Track in the ice tunnel will be under a comparatively constant temperature and would not require anchoring.

Miscellaneous

Track bumpers at ends of track; switch lamps; derailing devices, etc., to be of standard manufacture and be provided as needed.

Special Provisions - Crevasse Bridging

Sudden crevasse openings would appear to be the major concern of this railroad system. Any crevasse openings up to 9 in. would create no undue problems; however, a "slow order" should be issued to train crews and train speeds restricted to a minimum over these areas. Regular maintenance would detect the openings, and crews could be alerted of this danger and the location. Therefore, "mile post" identification should be established along the route. Crevasse openings from 9 in. to 4 ft 0 in. could be bridged by two (2) methods, as a temporary means of maintaining traffic (Fig. D7). The temporary measures would suffice until permanent blasting or filling of the crevasse could be accomplished. For this purpose, 39 ft bridge panels can be constructed at Tuto. They could be loaded on flat cars, transported to crevasse areas, and installed with mobile cranes in a minimum amount of time.

Figure D7. Proposed crevasse bridging methods.
The most serious difficulties would be expected in the section between the edge of the Ice Cap and Mile 30.

Method I - To install bridge panels 39 ft long (see Fig. D7).

Method II - To dig in 7 in. x 9 in. x 16 ft bridge support ties under track (see Fig. D7). Crevasse openings in excess of 4 ft 0 in. should be corrected immediately by previously utilized procedures as presently used by oversnow tractor-train units.

Items not Included in Cost Estimate

Lighting
No provisions have been made for any required electrical power and/or lighting of the subsurface tunnel to Camp Century and other sites. No lighting would be required in the "surface tunnel" between Thule and Tuto.

Ventilation
No provisions have been made for any required ventilation in the tunnel to Camp Century or other sites. If the system is to be under security restrictions, any ventilation would necessarily have to be of a subsurface design.

Communications
No provisions have been made for any required communication for the railroad system.

It is recommended that constant two-way radio communication be established between Thule AB, Camp Tuto, Camp Century or other sites, and all locomotives, the caboose and all patrolling maintenance equipment. A two-way radio communication should be established during construction between all major equipment, supervisory personnel, engineering crew, camp cars, etc. This same system could then be later installed for use by the operating railroad.

Ice tunnel
No provisions have been made for any construction required to prepare the snow or ice tunnel from Camp Tuto to Camp Century and all other sites.

Unloading ramps
No provisions have been made for unloading ramps or facilities at Camp Century or other sites or at the docks, warehouses, etc.

Material handling equipment
No provisions have been made for any unloading/loading of equipment. All existing facilities can be utilized for this purpose.

Others
No provisions have been made for the following: warehouse facilities, outdoor storage areas, manpower transportation, meals, lodging, arctic clothing, and medical facilities.

Maintenance and Related Equipment

Equipment
All track equipment employed in the construction of the railroad should be made serviceable and stored at Camp Tuto.
Pickup trucks and motor cars (with rail wheels) can be used for inspection patrols. Since this equipment will be used during construction and will be equipped with radio communication, they can also suffice for patrolling the completed railroad system. No added equipment would be anticipated.

Exposed tracks

Since the exposed tracks would be subject to covering by heavy snows, one (1) snow plow attachment should be made available for easy installation to either of the locomotives. Clearing of snow-covered tracks would be a simple maintenance operation. This snow plow attachment could possibly be adapted or improved to such an extent that it could be utilized to "shave" walls of the ice tunnels.

Basic maintenance would, therefore, consist of cleaning snow off the tracks and correcting crevasse openings and snow tunnel closure. Periodic patrols of the track can be established to determine requirements.

Extensive maintenance requirements, however, can be anticipated during summer in the edge of the Ice Cap area.

Broken track, derailment, etc.

A minimum stock of all track material items should be maintained at Camp Tuto and Camp Century to provide for immediate repairs, resulting from derailments, broken rails, etc.

Equipment Required and Estimated Costs

Locomotive power

It is suggested that a minimum of four (4) Diesel electric locomotives be utilized on this railroad, each with a minimum capacity of 1400 horsepower, rated at 120 tons per unit. Each unit should be equipped with special exhaust dispersion units and with dual controls. The locomotive power to be assigned as follows:

1. One (1) unit at Thule Air Base - for base operations and "short haul" runs to Camp Tuto, and return. This unit to be used for necessary switching of cars from dock side and runways to assigned tracks at Thule AB.

2. One (1) unit at Camp Tuto - for final assembly of train, and as a standby unit.

3. Two (2) units, coupled with dual-controls, (for single train crew operation), for all trips to Camp Century and return, and to other future sites.

Each locomotive to be specially equipped with dual controls, latest "heat dispersing" modifications, and to be "special ordered" for this railroad. A full complement of repair parts, as recommended by the manufacturer, should be available for at least two (2) units. Provisions for crew, fuel, water, lubricants, sand, etc, are not included.

Cost per unit - F.A.S., Norfolk, Virginia:

<table>
<thead>
<tr>
<th></th>
<th>4 ea. at $200,000.00</th>
<th>$800,000</th>
</tr>
</thead>
</table>

Cost per "repair parts list" as recommended by manufacturer:

<table>
<thead>
<tr>
<th></th>
<th>2 ea. at 45,000.00</th>
<th>90,000</th>
</tr>
</thead>
</table>

Freight

<table>
<thead>
<tr>
<th></th>
<th>500 T. at 37.50</th>
<th>18,750</th>
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</table>

**TOTAL:** $908,750

It is suggested that nuclear powered locomotives be studied for this purpose. At this writing no information or costs are available, although it is suggested less heat dissipation would be evident.
APPENDIX D

Work train assembly

A suggested makeup of cars for this purpose would be as follows:

Flat cars - 60 ft in length - lightweight - 55000#/ 15 each
Box cars - 50 ft in length - lightweight - 55000#/ 6 each
Refrigerated cars (for handling foodstuffs, perishables, medicines, etc.).
(Refrigerated cars are suggested as means for maintaining constant
temperatures for perishables when being processed from dockside
or runways to Camp Tuto, prior to entering ice tunnels.) This
during climates above freezing.

Caboose - standard 4 each
Pullman passenger cars - standard equipment 1 each

These cars can be of standard manufacture and assembly; no
special equipment required.

<table>
<thead>
<tr>
<th>Car Type</th>
<th>Quantity</th>
<th>Price</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat cars</td>
<td>15 each</td>
<td>$15,000</td>
<td>$225,000</td>
</tr>
<tr>
<td>Box cars</td>
<td>6 each</td>
<td>$17,000</td>
<td>$102,000</td>
</tr>
<tr>
<td>Refrigerated cars</td>
<td>4 each</td>
<td>$25,000</td>
<td>$100,000</td>
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<tr>
<td>Caboose</td>
<td>1 each</td>
<td>$14,000</td>
<td>$14,000</td>
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<tr>
<td>Passenger cars</td>
<td>2 each</td>
<td>$40,000</td>
<td>$80,000</td>
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<tr>
<td>Repair parts</td>
<td>1 L.S. at</td>
<td>$25,000</td>
<td>$25,000</td>
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<tr>
<td>Freight</td>
<td>1540 Tons</td>
<td>$37.50</td>
<td>$57,750</td>
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</table>

TOTAL: $603,750

Except for "special haulage," i.e., extraordinary construction equipment and
other items of excessive weights and sizes, this makeup should provide adequate
hauling capacities for manpower, construction materials, food supplies, etc.

A minimum supply of repair parts, applicable to all above cars, is recommended,
such as journal boxes, air hose, flanged wheels, etc.

Track construction equipment

<table>
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<th>Item</th>
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<th>Price</th>
<th>Total</th>
</tr>
</thead>
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<td>1. Power rail drills</td>
<td>6 ea</td>
<td>$600.00</td>
<td>$3,600</td>
</tr>
<tr>
<td>2. Power rail saws</td>
<td>3 ea</td>
<td>$650.00</td>
<td>$1,950</td>
</tr>
<tr>
<td>3. Power bolting machines</td>
<td>4 ea</td>
<td>$3,200</td>
<td>$12,800</td>
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<tr>
<td>4. Power spikers</td>
<td>4 ea</td>
<td>$8,000</td>
<td>$32,000</td>
</tr>
<tr>
<td>5. Power tamper and raising</td>
<td>1 ea</td>
<td>$65,000</td>
<td>$65,000</td>
</tr>
<tr>
<td>6. Power track jack</td>
<td>1 ea</td>
<td>$5,200</td>
<td>$5,200</td>
</tr>
<tr>
<td>7. Compressors</td>
<td>3 ea</td>
<td>$5,500</td>
<td>$16,500</td>
</tr>
<tr>
<td>8. Air spikers</td>
<td>12 ea</td>
<td>$800.00</td>
<td>$9,600</td>
</tr>
<tr>
<td>9. Air wrenches</td>
<td>6 ea</td>
<td>$700.00</td>
<td>$4,200</td>
</tr>
<tr>
<td>10. Pickup w/steel wheel</td>
<td>6 ea</td>
<td>$3,300</td>
<td>$19,800</td>
</tr>
<tr>
<td>11. 2½ T. stake body dump</td>
<td>6 ea</td>
<td>$5,000</td>
<td>$30,000</td>
</tr>
<tr>
<td>12. Motor cars</td>
<td>3 ea</td>
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<td>$15,000</td>
</tr>
<tr>
<td>13. On-track crane</td>
<td>1 ea</td>
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</tr>
<tr>
<td>14. Off-track crane (rubber)</td>
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<td>15. Power liner</td>
<td>1 ea</td>
<td>$12,500</td>
<td>$12,500</td>
</tr>
<tr>
<td>16. Cutting torch/welding</td>
<td>2 ea</td>
<td>$1,500</td>
<td>$3,000</td>
</tr>
<tr>
<td>equipment</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$301,150
Track tools

Tool boxes, small hand tools, complete complement of tools
for 100 men

Grading equipment

1. Blasting equipment
   1 L.S. at $100,000.00
   100,000

2. Bulldozer
   4 ea at 20,000.00
   80,000

3. Cranes (crawler shovels)
   2 ea at 90,000.00
   180,000

4. Large trucks (haul pak rear dump trucks)
   8 ea at 60,000.00
   480,000

5. Rock crushing and screening equipment
   2 ea at 175,000.00
   350,000

Freight
   350 tons at 37.50
   13,125

TOTAL
   $1,554,275

Track Cost Estimate

Thule AB (Section A-B)

Standard track construction, built on 12 in. of crushed rock ballast, with all new materials.

Based on 25,000 lineal feet of track (T.F.) and 7 turnouts.

Engineering, track and subgrade layout, all engineering supplies:
   25,000 T.F. at $0.40
   $1,000

Subgrade preparation, processing of crushed rock for ballast, and hauling:
   25,000 T.F. at $12.00
   $300,000

Track construction, labor and materials:
   25,000 T.F. at $25.00
   $625,000

Turnout construction, labor and materials:
   7 ea at $6,000
   $42,000

Freight, at 700 tons/mile of track and at 8 tons/turnout, including loading and unloading:
   3,548 tons at $37.50
   $133,050

TOTAL:
   $977,000

Thule AB to Camp Tuto (Section B-C)

Standard track construction, built on 12 in. of crushed rock ballast, with all new materials.

Based on 73,920 lineal feet of track (T.F.).

Engineering, track and subgrade layout, all engineering supplies:
   73,920 T.F. at $0.40
   $29,568

Subgrade preparation, processing of crushed rock for ballast, and hauling:
   73,920 T.F. at $12.00
   $887,040

Track construction, labor and materials:
   73,920 T.F. at $25.00
   $1,848,000

Total:
   $2,764,608

Freight, at 700 tons/mile of track, including loading and unloading:
   9,800 tons at $37.50
   $367,500.
APPENDIX D

Using 26-ft diameter Armco multiplate "surface tunnel" method:

Additional costs for:

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering</td>
<td>$7,392</td>
</tr>
<tr>
<td>Riprap preparation, hauling and placing</td>
<td>$295,680</td>
</tr>
<tr>
<td>Track construction</td>
<td>$184,800</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td>$487,872</td>
</tr>
<tr>
<td>Materials</td>
<td>$14,414,400</td>
</tr>
<tr>
<td>73,920 T.F. at $195</td>
<td></td>
</tr>
<tr>
<td>Labor</td>
<td>$2,212,600</td>
</tr>
<tr>
<td>73,920 T.F. at $30</td>
<td></td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td>$16,627,000</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>$17,114,872</td>
</tr>
</tbody>
</table>

Freight, 1080 lb/ft:

- 40,000 tons at $37.50 = $1,500,000

**TOTAL** (using "tunnel" method freight excluded) = $19,879,480

Camp Tuto (Section C-D)

Standard track construction, built on 12 in. of crushed rock ballast, with all new materials.

- Based on 10,000 lineal feet of track (T.F.) and 5 turnouts.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering, track and subgrade layout, all engineering supplies:</td>
<td>$4,000</td>
</tr>
<tr>
<td>10,000 T.F. at $0.40</td>
<td></td>
</tr>
<tr>
<td>Subgrade preparation, processing of crushed rock for ballast, and hauling:</td>
<td>$120,000</td>
</tr>
<tr>
<td>10,000 T.F. at $12.00</td>
<td></td>
</tr>
<tr>
<td>Track construction, labor and materials:</td>
<td>$250,000</td>
</tr>
<tr>
<td>10,000 T.F. at $25.00</td>
<td></td>
</tr>
<tr>
<td>Turnout construction, labor and materials:</td>
<td>$30,000</td>
</tr>
<tr>
<td>5 ea at $6,000</td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>$404,000</td>
</tr>
</tbody>
</table>

Freight, at 700 tons/mile of track and 8 tons/turnout, including loading and unloading:

- 1,440 tons at $37.50 = $54,000

Camp Tuto to the edge of the Ice Cap (Section D-E)

Standard track construction, built on 12 in. of crushed rock ballast, with all new materials.

- Based on 7,500 lineal feet of track (T.F.).

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering, track and subgrade layout, all engineering supplies:</td>
<td>$3,000</td>
</tr>
<tr>
<td>7,500 T.F. at $0.40</td>
<td></td>
</tr>
<tr>
<td>Subgrade preparation, processing of crushed rock for ballast, and hauling:</td>
<td>$90,000</td>
</tr>
<tr>
<td>7,500 T.F. at $12.00</td>
<td></td>
</tr>
<tr>
<td>Track construction, labor and materials:</td>
<td>$187,500</td>
</tr>
<tr>
<td>7,500 T.F. at $25.00</td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>$280,500</td>
</tr>
</tbody>
</table>

Freight, at 700 tons/mile of track, including loading and unloading:

- 1,050 tons at $37.50 = $39,375.
Using 26-ft diameter Armco multiplate "surface tunnel" method:

Additional costs for:

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost 1</th>
<th>Cost 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering</td>
<td>$ 750</td>
<td></td>
</tr>
<tr>
<td>Riprap preparation, hauling and placing</td>
<td>$ 30,000</td>
<td></td>
</tr>
<tr>
<td>Track construction</td>
<td>$ 18,750</td>
<td></td>
</tr>
</tbody>
</table>

Subtotal: $ 49,750

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost 1</th>
<th>Cost 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>$1,462,500</td>
<td></td>
</tr>
<tr>
<td>Labor</td>
<td>$225,000</td>
<td></td>
</tr>
</tbody>
</table>

Subtotal: $ 1,687,500

Freight, 1080 lb/ft:

4,050 tons at $37.50 $151,875.

TOTAL (using "tunnel" method, freight excluded): $2,017,500.

Edge of the Ice Cap to Camp Century, including a set-off track (Sections E-F and G-H)

Track construction in a cut-and-cover snow trench or a subsurface ice tunnel.

(Note: For the purposes of the cost estimate for this section of the railroad track, the assumption is made that the cut-and-cover snow trench or a subsurface ice tunnel will begin at the edge of the Ice Cap. In reality this may not be possible because of the above freezing temperatures in summer, the high rate of movement of the snow mass, and the flow of melt water during warm periods. Consequently, the cost estimate here considers only the track installation on an already prepared subgrade, the type and material of which is not specified. The cost of subgrade preparation, therefore, cannot be estimated.)

Based on 737,140 lineal feet of track (T.F.) and 4 turnouts: 728,640 T.F. (138 miles) from the edge of the Ice Cap to Camp Century, 3,500 T.F., and 1 turnout for the set-off track, and 5,000 T.F. and 3 turnouts for the Camp Century complex.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost 1</th>
<th>Cost 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering, track and subgrade layout, all engineering supplies:</td>
<td>$ 231,142</td>
<td></td>
</tr>
<tr>
<td>Track construction, labor and materials:</td>
<td>$14,742,800</td>
<td></td>
</tr>
<tr>
<td>Turnout construction, labor and materials:</td>
<td>$ 20,000</td>
<td></td>
</tr>
</tbody>
</table>

TOTAL: $14,993,942

Freight, at 700 tons/mile of track and 8 tons/turnout:

98,032 tons at $37.50 $3,676,200.
### Cost Summary

<table>
<thead>
<tr>
<th>Section</th>
<th>Distance (miles)</th>
<th>Construction, labor, materials</th>
<th>Freight CONUS to Thule AB</th>
<th>Total</th>
<th>Cost, additional, for using &quot;surface tunnel&quot; method</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-B</td>
<td>4.7</td>
<td>977,000</td>
<td>133,050</td>
<td>1,110,050</td>
<td>17,114,872</td>
</tr>
<tr>
<td>B-C</td>
<td>14.0</td>
<td>2,764,608</td>
<td>367,500</td>
<td>3,132,108</td>
<td>1,500,000</td>
</tr>
<tr>
<td>C-D</td>
<td>1.9</td>
<td>404,000</td>
<td>54,000</td>
<td>458,000</td>
<td>1,737,000</td>
</tr>
<tr>
<td>D-E</td>
<td>1.4</td>
<td>280,500</td>
<td>39,375</td>
<td>319,875</td>
<td>151,875</td>
</tr>
<tr>
<td>E-F</td>
<td>140.0</td>
<td>14,993,942</td>
<td>3,676,200</td>
<td>18,670,142</td>
<td>1,888,875</td>
</tr>
<tr>
<td>G-H</td>
<td>162.0</td>
<td>19,420,050</td>
<td>4,270,125</td>
<td>23,690,175</td>
<td>20,503,747</td>
</tr>
</tbody>
</table>

**Construction equipment**

- Freight: 1,554,275
- Total: 25,244,450

**Total for track installation**

- Freight: 25,244,450
- Total: 45,748,197

**Work train assembly**

- Freight: 603,750
- Total: 25,244,450

**Locomotive power**

- Freight: 908,750
- Total: 1,512,500

**TOTAL**

- Freight: 6756,950
- Total: 47,260,697
Railroad Track Construction Cost Rates

Construction on surface (Sections A-B through D-E):

\[ \$4,426,108/22 \text{ miles} = \$201,186/\text{mile} \approx \$201,000/\text{mile} \]

(Including freight; \( \approx \$228,000/\text{mile} \)).

Construction on surface using "surface tunnel" method (Sections B-C and D-E):

\[ \$21,986,980/15.4 \text{ miles} = \$1,421,882/\text{mile} \approx \$1,422,000/\text{mile} \]

(Including freight; \( \approx \$1,556,000/\text{mile} \)).

Construction in a subsurface cut-and-cover snow trench or ice tunnel, excluding the trench or tunnel preparation (Sections E-F and G-H):

\[ \$14,993,942/140 \text{ miles} = \$107,100/\text{mile} \approx \$107,000/\text{mile} \]

(Including freight; \( \approx \$134,000/\text{mile} \)).

(Note: The above rates do not include construction equipment (page 44), since the amount of construction equipment required is not proportional to the length of track to be constructed.)

Conclusions

This subsurface railroad system would provide an all-weather, all-year transportation system. Travel from Camp Tuto to Camp Century could be reduced from present average standards of 3 to 4 days (sometimes 3 weeks) to a normal run of five (5) hours.

Current tractor-train freight costs are estimated at $1.50 per ton-mile, or basically $207.00 per ton for delivery from Camp Tuto to Camp Century. Once the railroad network is established, estimated freight costs could be reduced to $0.24 per ton-mile or $33.12 per ton delivered. Actually, it is believed this cost could conceivably be reduced to $0.17 per ton-mile, or $23.46 per ton of freight delivered; the basic factor affecting the rates would be delays caused by crevasse openings, if such occur. With an estimated cost of $0.24 per ton-mile, as compared with estimated present costs of $1.50 per ton-mile, or an estimated saving of $173.88 per ton of freight delivered, it is not difficult to visualize the track network amortizing itself in a very short period of time.

Since Ice Cap air travel is restricted by weather, it is conceivable that all air travel equipment could be virtually eliminated, producing additional savings.
Wheel traffficability tests on a snow trench floor were conducted at Camp Century, Greenland, in 1962, with 2 types of low-pressure tires and with standard truck tires on an M-54 5-ton truck with a 5-ton load. Skid tests were performed and the friction coefficient between the tires and the processed snow surface was determined. A 1300 ft long, standard gage railroad track was installed in the trench after the wheel traffic tests. A standard size flatcar with a 30-ton load, towed by a 5-ton truck equipped with rail wheels, was used for rail traffic tests. It was found that the natural, unprocessed snow surface in a trench 26 ft below the snow surface is not suitable for extensive traffic with vehicles such as 5-ton trucks even when equipped with low-pressure flotation tires. However, a Peter plow-processed, age-hardened snow surface is capable of supporting a virtually unlimited amount of vehicle traffic using standard tires. Even heavier wheeled vehicles could be supported by a processed-snow trench floor. The friction coefficient was found to be in the range of 0.2 to 0.3. For transporting extremely heavy items, the use of a railroad system installed on an unprocessed snow trench floor is feasible but expensive. The installation of a railroad system in a covered snow trench presents no serious problems.
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