INTERIM REPORT NO 3

TOWARDS AN ENVIRONMENTAL IMPACT ASSESSMENT

OF THE PORTION OF THE MACKENZIE GAS PIPELINE

FROM

ALASKA TO ALBERTA

APPENDIX VI

WINTER ROAD STUDY

ENVIRONMENT PROTECTION BOARD
SPONSORED BY
CANADIAN ARCTIC GAS STUDY LIMITED
MARCH 1973
WINTER ROAD STUDY

Prepared for the

ENVIRONMENT PROTECTION BOARD

Sponsored by

CANADIAN ARCTIC GAS STUDY LIMITED

FINAL REPORT

Prepared by:

Dr. Kenneth M. Adam, P.Eng.

TEMPLETON ENGINEERING COMPANY
528 St. James Street South
Winnipeg, Manitoba

November, 1972
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>List of Figures and Tables</th>
<th>i</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abbreviations and Terminology</td>
<td>iii</td>
</tr>
<tr>
<td>Summary</td>
<td>iv</td>
</tr>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Conclusions and Recommendations</td>
<td>4</td>
</tr>
<tr>
<td>A. General Conclusions</td>
<td>4</td>
</tr>
<tr>
<td>B. Planning</td>
<td>7</td>
</tr>
<tr>
<td>C. Construction</td>
<td>8</td>
</tr>
<tr>
<td>D. Ice Bridges</td>
<td>10</td>
</tr>
<tr>
<td>E. Environmental Considerations</td>
<td>12</td>
</tr>
<tr>
<td>F. Research and Recommendations for Further Study</td>
<td>14</td>
</tr>
<tr>
<td>Northern Roads (In General)</td>
<td>18</td>
</tr>
<tr>
<td>A. History and Existent Roads</td>
<td>18</td>
</tr>
<tr>
<td>B. Planning of Northern Roads</td>
<td>24</td>
</tr>
<tr>
<td>C. Types of Roads (In General)</td>
<td>28</td>
</tr>
<tr>
<td>1. Classification System</td>
<td>28</td>
</tr>
<tr>
<td>2. Construction Methods (Permanent Roads)</td>
<td>31</td>
</tr>
<tr>
<td>3. Equipment</td>
<td>32</td>
</tr>
<tr>
<td>4. Costs</td>
<td>32</td>
</tr>
<tr>
<td>5. Vehicles</td>
<td>34</td>
</tr>
<tr>
<td>D. Types of Winter Roads</td>
<td>35</td>
</tr>
<tr>
<td>1. Classification System (Winter Roads)</td>
<td>35</td>
</tr>
<tr>
<td>2. Relevant Snow Properties for Trafficability</td>
<td>36</td>
</tr>
<tr>
<td>3. Equipment</td>
<td>38</td>
</tr>
<tr>
<td>4. Construction Methods</td>
<td>43</td>
</tr>
<tr>
<td>(a) Winter Trails</td>
<td>43</td>
</tr>
<tr>
<td>(b) Snow Roads</td>
<td>43</td>
</tr>
<tr>
<td>(i) Compacted Snow Roads</td>
<td>43</td>
</tr>
<tr>
<td>(ii) Processed Snow Roads</td>
<td>60</td>
</tr>
<tr>
<td>(c) Ice Roads</td>
<td>74</td>
</tr>
<tr>
<td>5. Costs</td>
<td>77</td>
</tr>
<tr>
<td>(a) Winter Trails</td>
<td>77</td>
</tr>
<tr>
<td>(b) Snow Roads</td>
<td>77</td>
</tr>
<tr>
<td>(c) Ice Roads</td>
<td>78</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Trafficability of Winter Roads</td>
<td>80</td>
</tr>
<tr>
<td>A. Climate</td>
<td>80</td>
</tr>
<tr>
<td>B. Travel Season</td>
<td>87</td>
</tr>
<tr>
<td>C. Vegetative Cover</td>
<td>88</td>
</tr>
<tr>
<td>D. Snow Drifting</td>
<td>88</td>
</tr>
<tr>
<td>E. Drainage and Icings</td>
<td>92</td>
</tr>
<tr>
<td>F. Snow/Vehicle Trafficability</td>
<td>95</td>
</tr>
<tr>
<td>G. Vehicles and Loads</td>
<td>99</td>
</tr>
<tr>
<td>(a) Winter Trails</td>
<td>99</td>
</tr>
<tr>
<td>(b) Snow Roads</td>
<td>102</td>
</tr>
<tr>
<td>(c) Ice Roads</td>
<td>106</td>
</tr>
<tr>
<td>H. Maintenance</td>
<td>113</td>
</tr>
<tr>
<td>Ice Bridges</td>
<td>115</td>
</tr>
<tr>
<td>A. Construction Methods</td>
<td>115</td>
</tr>
<tr>
<td>B. Equipment</td>
<td>117</td>
</tr>
<tr>
<td>C. Capacity</td>
<td>117</td>
</tr>
<tr>
<td>D. Maintenance</td>
<td>121</td>
</tr>
<tr>
<td>E. Travel Season</td>
<td>121</td>
</tr>
<tr>
<td>Environmental and Terrain Degradation Aspects of Winter Roads</td>
<td>125</td>
</tr>
<tr>
<td>A. Planning</td>
<td>126</td>
</tr>
<tr>
<td>B. Soils Classification</td>
<td>132</td>
</tr>
<tr>
<td>C. Terrain Damage</td>
<td>135</td>
</tr>
<tr>
<td>D. River Crossings</td>
<td>149</td>
</tr>
<tr>
<td>E. Admixtures</td>
<td>150</td>
</tr>
<tr>
<td>F. Indirect Environmental Aspects</td>
<td>151</td>
</tr>
<tr>
<td>G. Revegetation, Erosion and Siltation</td>
<td>155</td>
</tr>
<tr>
<td>H. Remedial Measures</td>
<td>167</td>
</tr>
<tr>
<td>Alternative Modes of Transportation</td>
<td>170</td>
</tr>
<tr>
<td>A. Off-Road Vehicles</td>
<td>170</td>
</tr>
<tr>
<td>B. Cost Comparisons</td>
<td>172</td>
</tr>
<tr>
<td>Appendix &quot;A&quot; - Interviews</td>
<td></td>
</tr>
<tr>
<td>Appendix &quot;B&quot; - Bibliography and Abstracts (Separate Volume)</td>
<td></td>
</tr>
</tbody>
</table>
# LIST OF FIGURES AND TABLES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>Regional Roads 1972</td>
<td>23</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Normal Hardness Distribution in Compacted Snow</td>
<td>45</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Improved Hardness Distribution in Compacted Snow After Special Rolling</td>
<td>45</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Distribution of Hardness-Roller type Vibrator</td>
<td>46</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Minimum Month End Accumulated Snow Depth at Selected Stations Along the Mackenzie Valley</td>
<td>83</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Maximum Month End Accumulated Snow Depth at Selected Stations Along the Mackenzie Valley</td>
<td>84</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Median Month End Accumulated Snow Depth at Selected Stations Along the Mackenzie Valley</td>
<td>85</td>
</tr>
<tr>
<td>Table I</td>
<td>Data Sheet - Compaction Trials</td>
<td>103</td>
</tr>
<tr>
<td>Table II</td>
<td>Trafficability Success Trials</td>
<td>107</td>
</tr>
</tbody>
</table>
ABBREVIATIONS AND TERMINOLOGY

BuDOCKS - U.S. Department of the Navy, Bureau of Yards and Docks.

DED - Directorate of Engineering Development, Canadian Army.

ERDL - Engineering Research and Development Laboratories

HARDNESS - is a parameter of the strength and trafficability of winter roads, as indicated by a density or Rammsonde reading.

ICE BRIDGE - is an artificially thickened ice cover used as a river crossing or for ice travel.

ICE ROAD - is a snow road compacted to a density of the order of 0.60 gms/c.c. accomplished by the addition of water obtained by heat or by sprinkling.

PULVIMIXER - is a machine used to agitate the snow cover during a "processing" operation.

RAMMSONDE - is a commercially available Swiss instrument that measures the relative hardness of snow.

RCAF - Royal Canadian Air Force

SNOW ROAD - is a winter road for which snow has been used as the cut or fill material. Snow roads are generally of two types: Compacted - no agitation of snow cover; Processed - agitation of snow cover, followed by compaction.

TRAFFICABILITY - is the ease with which traffic can progress on a winter road.

TRAVEL SEASON - is the period bounded by the earliest date in the Fall and latest date in the Spring that a winter road can be trafficked without serious damage to the terrain.

WINTER ROAD - is generally one of three types: winter trail, snow road, or ice road.

WINTER TRAIL - a winter road constructed by simple "blading" of the right-of-way.
SUMMARY

The winter construction of a gas pipeline through the Mackenzie Valley and Yukon from Prudhoe Bay, Alaska will require extensive transportation facilities in order to meet project deadlines. Winter roads will form an important part of this transportation system. However, great care must be taken to minimize terrain degradation due to winter road use. While contractors will continually be interested in extending winter road use in order to maximize the winter construction period, this desire is likely to be in direct conflict with the need to minimize terrain degradation by halting winter road use before irremediable damage occurs. To resolve this dilemma, hardness readings of the snow road surface are the only available criteria to regulate the construction period on a rational basis.

Overall, the literature indicates that there is reason to be optimistic about intensive winter road use with minimal terrain degradation or detrimental effect on the environment. Although industry and the military have left extensive scars on the arctic terrain from past activities, more recent controlled practice indicates that with better planning, construction techniques, and controls, extensive activities can be carried out with minimal effect on the terrain or the environment. The literature and recent experience both indicate that hills and approaches to ice bridges (artificially built-up ice at river crossings) are potentially the most critical problem areas. Retention of the vegetative mat
or peat cover over the permafrost during the initial construction or during the operation of a winter road is essential.

To date, winter road construction in the Yukon and Northwest Territories has been relatively primitive in comparison with the methods described during snow compaction trials carried out by the military. Even though the military were not particularly environmentally concerned, their methods of construction for snow roads and ice roads promise to be superior from both a trafficability and an environmental standpoint. Construction and testing by industry of compacted snow and ice roads in the tundra area over the past two years have validated the degree of optimism for winter roads that has been drawn from the literature. With the combination of thorough planning, reconnaissance, construction technology and strict field controls, winter roads can be heavily trafficked over a strictly enforced winter construction period with little effect on the terrain or environment.

It is recommended that field trials be initiated immediately to monitor the effectiveness of various winter road construction techniques, so that both trafficability and impact of construction and use can be assessed. In particular, observations should begin in the spring of 1973 to determine the criteria of surface hardness indicators, from which more rational opening and closing dates for winter roads in various terrain types and locations throughout the area of concern can be established.
INTRODUCTION

The Environment Protection Board, having recognized the potential for severe terrain degradation due to the use or mis-use of winter roads in the western Arctic during the construction of a gas pipeline through the Mackenzie Valley and Yukon, initiated a study of winter roads. The major emphasis of the study was directed to be the establishment of limits or criteria for the earliest possible utilization in the fall and latest possible utilization in the spring of winter roads; the intent was to establish dates that would maximize the winter construction period, but concurrently minimize terrain degradation to an acceptable level. In addition, the further requirements of the office study were:

* Examination of terrain, geotechnical and vegetation data from pipeline route maps, aerial photography and geologic survey maps.
* Collection of past records and data from existing meteorological stations.
* Review of current practices of winter road construction and discussions with operators regarding operating methods and problems.
* Gathering of data from Gas Arctic on their concepts and requirements of winter road construction and their use, plus a review of work at Prudhoe Bay test site on similar aspects.
* Initial choice of winter roads and tentative location of sections to be investigated in the field.
After Templeton Engineering Company had become involved in the study, the Arctic Institute of North America was engaged to aid in the compilation of this material. In total, well over 300 abstracts, scientific papers, articles and volumes were obtained, from which pertinent data was extracted. (Approximately half of the volumes were supplied by AINA).

As this phase of the work progressed, some uncertainty evolved as to the location of the pipeline, which tended to negate some of the requirements of the study as originally directed. For this reason, the Winter Road Study became of a more general nature, so that the extracted information could be applied to any winter road in the region, rather than to a winter road along a specific alignment. The literature was reviewed, then, with this limitation, but keeping in mind the need to determine the use to which winter roads could be put without causing terrain degradation. In this regard, it was recognized that there was a need to gather some data on climatic and hydrologic factors to determine seasonal limits for different regions, to assemble the terrain factors relevant to construction travel, and to summarize the methods of construction, vehicle types, load ranges, frequency of passes, etc.

Finally, the need to assess the available data and to determine the need for additional research in terms of field tests was recognized as a major requirement of the study.
All the objectives of the study have been considered and fulfilled in the context of the available data and information. It is hoped that this report has abridged the past and current literature on winter roads to the extent necessary to expose the areas of deficient knowledge, so that future efforts will be directed to the most relevant research.
CONCLUSIONS AND RECOMMENDATIONS

The Winter Road Study, which entailed an extensive literature survey, interviews (Appendix "A"), and the compilation of numerous abstracts (Appendix "B"), warrants the listing of a number of conclusions and recommendations. Since the conclusions pertain to a wide variety of topics, they will be listed under six major discussion categories.

A. General Conclusions:

1. Winter road construction technology is much more advanced than current practice in the Mackenzie Valley and Delta area indicates.

2. It is only in the past two years (1970 onward) that any of the more sophisticated winter road technology has been utilized in the area of concern.

3. Winter road technology has primarily been advanced by the military, and, in general, very little consideration, if any, has been shown for the environment. For this reason, environmental aspects of winter roads are several years behind the construction technology.

4. Although based only on environmental observations over the past two years, the literature indicates that there is little doubt that arctic transportation for pipeline construction can be realized by winter road use without serious damage to the terrain. This will,
of course, require the use of the best of available past and current technology.

5. The literature indicates that the prime method to minimize environmental damage is through detailed reconnaissance, planning and route location.

6. No proper classification system for winter roads currently exists. It is recommended that winter roads be referred to as one of three types:
   (a) Winter trail
   (b) Snow road (Compacted or Processed)
   (c) Ice road

These types of winter roads can normally be classified by the construction method or attained compacted density.

7. Trafficability of winter roads can potentially be measured at least in a relative manner by "hardness", as indicated by density or Rammsonde readings. By these methods, a more rational basis for opening and closing dates for winter roads is anticipated.

8. The most extensive tests to date indicate that the optimum conditions for building winter roads are a snow depth of from 12 to 40 inches, an initial snow density greater than 0.15 gms/cc, a mean temperature not greater than 15°F., and a decreasing temperature after compaction.

9. In the area of concern, records indicate that the probability of optimum climatic conditions for snow road construction is high. A deficient amount of snow in the Tuktoyaktuk area of less than eight inches as of December 31, that occurs on average in one out of three years, poses the greatest climatic limitation. However, use of ice
roads or windrowed snow for collection of snow can probably overcome this difficulty.

10. From an economic point of view, winter roads are the cheapest mode of transportation, provided access is not required for a time period greater than three successive winters. For this reason, winter roads appear particularly adaptable as a pipeline right-of-way haul road, where winter road construction can proceed simultaneously in time, but physically ahead of pipeline construction. Also, winter roads appear useful for access to borrow areas, storage areas, and fuel dumps. There is a need, however, to verify that ice or snow roads can withstand the volume of traffic anticipated for winter road use.

11. The technology of ice bridge construction is the most advanced and documented aspect of winter roads. Ice bridges pose few major problems, except for their approaches. Application of more sophisticated winter road construction to the approaches can probably reduce this one concern.

At all river crossings, great care must be taken to obtain at least a 12 inch depth of compacted "ice" road in order to protect the banks at the approaches. This will require surface densities in the range of 0.55 - 0.60 gms/cc. which can only be achieved by the addition of water. This should be easily attainable at river crossings. This procedure can potentially extend the travel season of some winter roads; however, it does require field trial verification of its effectiveness, both structurally and in terms of environmental considerations.

12. Throughout the duration of the project, continuous inspection will be required by individuals competent to anticipate or to
evaluate and recommend remedial action in relation to terrain degradation. Moreover, such inspectors must be trained to suggest viable alternatives in the event that damage occurs or is pending; but, more important, the inspectors must have the authority to close a winter road within a minimum time period. Experience indicates that stranded vehicles can be removed during deteriorating conditions by night (lower temperature) travel, without causing damage to the terrain.

B. Planning:

1. Planning of winter roads should be incorporated into the overall planning of the project.

2. Comprehensive planning of winter roads is potentially the most positive method to limit terrain degradation due to winter roads. In the past, the conquering of nature has been the custom; in the future, design with nature must be practised. In relation to winter roads, for example, this means that the potential of a gravel pit must be measured in terms of winter road access as well as "% finer than"; and summer storage areas must be chosen in terms of winter road access as well as in terms of "docking facilities".

3. Winter road access should be evaluated and compared on the basis of: slope, elevation, general topography, vegetative cover, minimum clearing, surface and groundwater conditions, icing potential, soil type, peat layer thickness, permafrost condition, minimum cuts, etc., as well as the ease of construction and minimum distance.
4. The classification of winter roads required must be in terms of all the factors listed above. For instance, for a particular winter road, a winter trail might suffice through the forested areas, a built-up snow road may be required in the relatively open areas, and ice roads will be required at approaches to river crossings and over exposed or shallow ground ice formations, and possibly also over tundra. Furthermore, due to excessive run-off resulting from built-up snow or ice roads on hills, and inherent drainage problems on hills, permanent grades and drainage systems may be required in order to limit degradation.

5. In forested areas, clearing of the pre-planned rights-of-way for winter road routes should be completed the winter prior to anticipated use. This procedure would assure that sufficient snow could be accumulated along the right-of-way in years of low snow quantities for winter road construction; and it would also speed the construction of the winter road in the first year the road is required for use. Furthermore, it would ease snow clearing procedures in case of excessive snowfall.

C. Construction:

1. It is recommended that the construction of Winter Trails continue utilizing current practise, which retains the vegetative mat and peat layer. If it is considered that the vegetative cover or peat layer is deteriorating, or if it shows signs of significant vertical compression during use, the Winter Trail should be immediately abandoned. Alternatively, construction of a higher class of winter road should
begin before such conditions exist.

2. Until a better method is required, the construction of Snow Roads should follow the guidelines suggested below for the construction of Compacted Snow Roads.

   (a) Construction of a Snow Road should be delayed until eight inches of snow is on the ground and several inches of frost has penetrated the active layer.

   (b) If snow depths are minimal, snow should be bladed or blown onto the right-of-way until a depth of at least 12 inches of compacted snow at an equivalent density of 0.4 gm/cc. is attained.

   (c) If 12 inches of compacted snow exists on the right-of-way, drags should be utilized to level the surface, after which heavy, large diameter rollers should be used until a surface density of the order of 0.55 gms/cc. is attained. (If this density cannot be attained, Processed Snow Roads will be required).

   (d) At least 12 hours should elapse before traffic is allowed to travel the finished road.

   This procedure should be field-tested in the area of concern and, if these final conditions cannot be attained, the more elaborate "snow processing" techniques should be field investigated.

3. If Compacted Snow Roads constructed as described above deteriorate under use, rather than improve in hardness and trafficability, Processed Snow Roads should be utilized.

4. Processed Snow Roads should be constructed in a similar manner to Compacted Snow Roads, except after the dragging operation, but prior to the compaction effort, 2 or 3 passes of a pulvimixer may be necessary to achieve a density of 0.55 gms/cc. or higher.
5. If deterioration of Processed Snow Roads is experienced under use, Ice Roads can be constructed by the addition of heat during the pulvimix operation, or by the addition of water by sprinkling. After compaction with heavy rollers, densities of 0.60 gms/cc. should be attained. This condition, according to the available literature, should assure continued use by wheeled vehicles using sand tires with pressures as high as 65 psi; at the same time, the hardness of the road should increase with use.

6. It is suggested that localized areas of deterioration of Winter Trails and Compacted or Processed Snow Roads be repaired by immediate construction of a section of Ice Road.

7. Statistical analysis of existing climatic data would be valuable in assessing the probable number of lost days of winter construction due to fog, extreme temperatures, snow drifting, soft roads, etc.

D. Ice Bridges

1. In themselves, ice bridges pose little problem from an environmental point of view provided that:
   
   (a) Sawdust or other extraneous material is not used in the vicinity of streams or well drained areas.

   (b) Well constructed and maintained approaches are utilized.

   (c) Removal of approaches and the ice bridge itself can be accomplished without damage to the banks or bottom.

   (d) Fish do not inhabit or migrate in streams that could be frozen to the bottom.
2. Technically, one problem related to ice bridges that should be understood in more detail is the effect of resonance waves created under ice sheets due to moving loads. Ice failures pose a severe problem to machine and human safety. Severe environmental problems could arise from the spillage of fuels during such occurrences.

At present, several notable considerations can be taken from the literature:

(a) Vehicles meeting on ice pose a potential problem.
(b) Vehicles passing or overtaking on ice pose a potential problem.
(c) High frequency of passes on ice potentially deepens temperature cracks. (Shifting alignments can alleviate this problem).
(d) Optimum speeds exist to minimize potential danger due to resonance waves. Depth of water (and hence ice thickness) are variables known to affect the optimum speed.
(e) Travel parallel to cracks should be avoided.
(f) Vehicles with low speed motors are potentially less dangerous than those with high speed motors.
(g) For an ice bridge where the water is over 5 feet deep, a velocity below 7 mph. assures little danger from the standpoint of critical velocity. (Substantially higher velocities can also be used to avoid the critical velocity.)

3. Ice thickness measurements should be taken at various sites, and correlated with mean daily temperature parameters; from these, it should be possible to predict the dates of "safe" or "unsafe" travel.

4. Use of the formula \( P = 0.025h^2 \) where \( P \) is in tons and \( h \) is the ice thickness in inches will assure very conservative design practice for ice bridges or travel on ice.
E. Environmental Considerations:

1. The literature gives reason to be optimistic with regard to the use of winter roads with minimal terrain damage resulting, provided good planning, construction, maintenance, control and co-operation are exercised.

2. Environmentally, as well as practically, the most pertinent question still to be answered is the minimum classification of winter road that can be constructed for various types and volumes of traffic, in relation to the various terrain types, which will assure a minimum or acceptable level of terrain degradation.

3. A snow depth of 8 inches minimum, plus 3 or 4 inches of frozen tundra or muskeg, will virtually assure no damage to the terrain due to off-road vehicles or initial-access vehicles.

4. From an environmental and practical point of view, it appears prudent and expedient to test winter roads from the most trafficable (Ice Road) down to potentially the least trafficable, rather than vice versa. The advantages to this are:

   (a) Elimination of the Ice Road to carry the volume of traffic required for pipeline construction would eliminate winter roads as a major mode of transportation.

   (b) Acceptance of the Ice Road to carry the required volume of traffic would assure the Industry that a practical mode of transportation for winter pipeline construction exists.

   (c) Lesser classes of winter roads could be evaluated structurally, economically and environmentally in the knowledge that they are potentially useful.
(d) Unnecessary terrain degradation and expense could be avoided by at least minimizing, if not eliminating, testing of the lower classes of winter roads that potentially are least acceptable from both a terrain degradation and trafficability point of view.

5. Steep grades in any type of terrain appear to be potentially the greatest problem from a terrain degradation standpoint. Possibly construction of permanent grades, which also pose severe problems, may be required to assure a continuous flow of traffic. Alternatively, if the volume of traffic will permit, permanent means of assistance at steep grades will probably be required for most types of wheeled vehicles.

6. In tundra areas, if winter road use is anticipated for a period to exceed three successive winters, there is ample evidence from both an environmental and economic point of view that a permanent road should be considered as an alternative. (No definite statement can be made on this topic, since the availability of local gravel supplies, haul distances, construction time, etc. would influence such a decision).

7. Although a conflict in the literature exists (See Kerfoot and Lambert, compared to Bliss and Wein), there appears to be more reason to utilize the same right-of-way for winter roads from year to year than to extend the use over a widespread area.

8. Ice bridges do not pose an environmental problem so long as the approaches are well constructed and maintained. In all cases, the elimination of corduroy, sawdust and blasting in the vicinity of streams will virtually assure this statement to be true. However, in shallow streams, care must be taken not to freeze the ice cover to the bottom if fish inhabit or migrate during the winter period.
9. An efficient method for removing ice bridges and snow road sway-backs at river crossings is required. The method must effect removal without causing damage to the banks or damming of the stream.

10. Correct placement of windrowed trees or snow can potentially aid the efficient and earliest possible collection of snow depth on which to construct winter roads. This could assure large volume traffic access to an area by minimizing potential terrain degradation.

F. Research and Recommendations for Further Study:

The literature indicates that the technology of construction of winter roads is several years advanced in comparison to understanding the effect of such roads on the arctic and subarctic environment. With the exception of experience gained on compacted snow roads and ice roads of very limited extent over the past couple of years, virtually no environmental data exists with regard to the more sophisticated winter road construction techniques; nevertheless, the success of the relatively primitive winter trail for low volume traffic gives reason to believe that the more advanced methods of construction can accommodate the larger volumes of traffic with equal or less environmental impact.

However, the effect of such large volumes of anticipated traffic associated with pipeline construction (35,000 passes) on winter roads cannot be evaluated on the basis of the literature. Indications are that, if a compacted density in the order of 0.60 gms/cc. or a Rammsonde reading of 450 can be achieved, winter roads will generally improve under traffic.
On the basis of the literature review, some pertinent recommendations regarding winter road research are warranted:

1. It would be prudent to establish as soon as possible if the highest class of winter road (Ice Road) can sustain the volume of traffic anticipated for pipeline construction, or to establish the trafficability limits to which such a road can be utilized. Therefore, it is recommended that an Ice Road test loop be constructed to establish that winter roads can carry the necessary volumes of traffic. If such tests prove successful, similar tests can be conducted to establish the lower limits of winter roads that are structurally and environmentally acceptable.

2. It is recommended that a data bank of "snow hardness" and trafficability observations be initiated. Snow hardness is potentially the only method to define the travel or construction season on a more rational basis.

3. It is recommended that, in order to optimize the research dollar in terms of winter road - terrain degradation inter-relationships, the majority of research should be conducted by monitoring a variety of classes of winter roads that are required and would be put under use. As a reward for contributing sections of road to be trafficked and monitored for research purposes, the operator of the winter road should be relieved of the responsibility for terrain degradation over that section. Remedial procedures should be applied to damaged areas of the terrain, and these areas should be monitored as part of the research effort.

4. It is recommended that the monitoring of winter roads in use be carried out in the general areas of Fort Simpson, Fort Good Hope and Tuktoyaktuk, and that such monitoring be carried out in terms of:
(a) Type of terrain.
(b) Subsurface data, including ground temperatures.
(c) Condition of right-of-way prior to construction.
(d) Class of winter road.
(e) Density or Rammsonde readings before and after construction.
(f) Vehicle type, weight, axle loads, tire pressure, etc.
(g) Frequency and total volume of traffic.
(h) Density or Rammsonde readings during use.
(i) Climatic conditions.
(j) Summer condition of right-of-way.
(k) Effectiveness of remedial procedures (where necessary).

5. It is recommended that a research program be initiated immediately to evaluate the use of snow roads or ice roads on steep grades and ice bridge approaches. If, during use, they prove to be effective protection against terrain degradation, but during the spring break-up concentrated melt-water causes thermal erosion on hillsides, methods for removal of such snow or ice structures must be investigated.

6. Efficient removal of snow sway-backs and ice bridge approaches at river crossings should be investigated immediately. Removal is required by Land Use Regulations, but removal procedures have not been satisfactory to date.

7. It is recommended that, since the most pertinent studies of winter roads in terms of terrain degradation and construction have been conducted since 1970, and since several oil companies have gained experience (particularly in the Mackenzie Delta and Tuktoyaktuk areas), the Environment Protection Board should initiate and encourage
participation in a central data bank of information concerning winter roads.
A. History and Existent Roads

Northern transportation has been enhanced by winter roads for many years. They have been particularly utilized for logging and mining operations, where they have facilitated transportation of bulky and cumbersome loads that are not conducive to economical air freight. In this context, winter roads have contributed greatly to northern development. Although often winter roads are in competition with marine transportation, the type of freight carried and speed of delivery of these competitors are unusually similar.

The most pronounced difference between these modes of transportation is their respective seasons of operation. While marine travel must take place during the ice-free summer months, the winter roads find use only during the freeze-up to break-up period. Thus, the two methods of transportation are complementary and, with adequate docking and storage facilities, could combine to provide an economical and efficient transportation system for northern pipeline construction. With sufficient planning of logistics, such a combined transportation system could find extensive use in the future.
Knowledge of their history and pattern of existent roads in the Mackenzie District, Yukon and northern Alaska will aid in establishing the trends and weakness of past road development. It is hoped that through an understanding of this history, repetition of weaknesses can be avoided, and sound past experience can be incorporated into future roads in the area associated with a gas pipeline.

Weick (1967), and Wonders (1966) both give history of the Yukon and Mackenzie Valley regions, respectively. Weick indicates the only access to the Yukon from 1900 was by railroad and this continued until the Alaska Highway was completed in 1942. The Canal Road built during wartime (1942), and the Ross River-Carmacks road of the 1950's, are the only major road construction in the Yukon up to recent times. Wonders indicates that marine transportation has traditionally been the dominant transportation mode in the Valley. As late as 1962, less than 800 miles of permanent road existed in the Mackenzie Valley area, virtually all of which was south of Yellowknife. These accounts certainly indicate that the history of roads in that northern area is of relatively recent significance.

The Contractors' and Engineers' Magazine, (1969), Pallister (1967) and DIAND (1968), which each deal at least in part with existent roads, have facilitated the compilation of the map of the regional roads shown in Figure I, which has been updated to 1972.
The philosophy of northern road development appears to have gone through a complete cycle. In early times, roads were constructed for a readily identifiable purpose, usually for mine development and resource transportation to the south. In 1965, a new northern roads policy was developed which, instead of placing the emphasis of northern road location on resource potential alone, prescribed that future programs were to be based on a multi-purpose concept having its emphasis on road loops serving all requirements. This concept recognized four main factors:

(a) That the Federal Government has a quasi-provincial role to discharge in the Territories, through and in co-operation with the Territorial Governments, and thus has the responsibility for gradually building a network of roads connecting centres of population.

(b) That the provision of improved access facilities at public expense is an important way in which private costs can be reduced throughout the north. A reduction of private costs would make the north a more attractive area for economic activity.

(c) That exploitation of the north's resource potential is vitally necessary to the future development of the north. Transportation facilities, and roads in particular, must be provided in order that sufficient capital can be attracted to develop the resources.
(d) That lateral roads to specific scenes of resource exploitation should be built where required and justified.

This Northern Road Policy certainly shows an awareness by the Government of the impact of road development in the north. It does not appear, however, that this awareness either has been or will be properly assessed before many northern roads are started, and some even completed. Nevertheless, this policy was considered successful by the Northern Affairs and Natural Resource Department, since it fulfilled the original objective which was to encourage developers to invest in the north.

In 1967, a Fact-finding Committee was established to conduct meetings in several northern communities to seek the views and advice of northern residents, of business interests, and of other organizations, on the priorities of road construction and the adequacy of the Northern Roads Policy. These meetings brought to light several needs; specifically:

(1) the need for provision in the Northern Roads Policy for low-standard access and communication roads (including winter roads) as primary network roads;

(2) the need for increased annual expenditures on roads in the north, to compensate for escalated costs since the policy was established in 1965; and the need to eliminate cost-shared resource roads from inclusion under the $10 million ceiling; and
(3) the need for continuing informal discussions with the State of Alaska and the provinces which adjoin the Yukon and Northwest Territories on the establishment of border crossing points for future connecting roads and other technical matters.

These points have initiated appropriate amendments to the Northern Roads Policy.
B. Planning of Northern Roads

Past and current history of road construction in the north leads to one conclusion expressed (sometimes indirectly) by several authors (Dunne, Manders, the Dynamic North (Book II), Bliss and Wein, Pemcan Services, and The Northern Engineer, Vol. 1, No. 3, 1969): that is, planning with regard to roads in the north should incorporate interdisciplinary planning. The responsible authorities have not, in general, taken heed of all the factors involved to assure good planning.

In Northern Alaska, it seems that policy for and philosophy of road development are in a similar state as in the Canadian North. Expedience seems to have been the criteria in descriptions of the Fairbanks, Bettles-Sagwon winter road (Engineering News-Record, April 24, 1969). This 540 mile overland route to near Prudhoe Bay was pushed through at a rate of 2 miles per construction day. The philosophy is further illustrated in the following statement of the Alaskan State Highway Commissioner:

"There was no engineering involved either in design or construction; none was required."

From this it can be easily concluded that the need for environmental impact statements, or even mild environmental concern, was given equal or even less emphasis than the engineering aspects. Such an attitude, exhibited by the agencies actually responsible for the construction of winter roads, clearly establishes the need for environmental and engineering
input into future winter road route selection. As has been the case in the past, many northern roads are upgraded as traffic increases (North, 1969); indeed, roads tend to generate their own traffic to justify such improvement. This fact alone points to the extreme importance for planning the initial route of a trail or winter road.

Bliss and Wein conclude in their terrain disturbance studies that winter road routes should be selected in summer, when it is possible to locate sources of coarse-textured materials and to determine the least sensitive sites in terms of disturbance.

Pemcan Services in the Corridor Study illustrate the need for an appraisal of geological conditions, determined by photo-interpretation. They further state that: "Ideally the access road should be located between the pipeline and the river, so that the road ditch and the berm could act as channelling and containment devices: Although they are clearly referring to permanent roads, it does illustrate recognition of an interdisciplinary approach.

Havers and Morgan also recognize the need for comprehensive route planning. They state that:

"Planning winter construction operations requires a knowledge of basic site data. Such data might include local weather conditions; hydrology and drainage; potential water supply and sanitation; topography; accurate surface and subsurface information; location of suitable sources of construction materials; existing or potential transportation facilities; and availability of labour, construction equipment and supplies. These data may be collected partly from reports, records and maps. However, further reconnaissance of a site (by personal visits), supplemented where necessary by surveying and subsurface explorations) is essential."
In a section dealing with the planning of roads and airfields, the Dynamic North Book II states that advance preparation should include the gathering of all available information. It goes on to say that:

"All information collected before and during the site reconnaissance should be assembled, including the approved reconnaissance report, photographs, sketch maps, soil profiles, and logs of test holes."

The Northern Engineer (1969), in an article by Dr. F. L. Bennett of the University of Alaska, illustrates the need for an interdisciplinary approach in an article entitled "A Systems Approach to Alaskan Transportation". This article is of a broader nature, in that the total transportation system would come under scrutiny.

J. W. Pickersgill, in the book, "Arctic and Middle North Transportation", also expounds the need for a broad overview of transportation needs.

Quoting from the above source, he states that:

"In a recent report to the Department of Indian Affairs and Northern Development and the government of the Yukon Territory, a consulting firm calculated that $1.3 billion in additional capital would be required between now and 1985 to implement the programs (many in the transportation area) contemplated in their report for the Yukon, an area which has a present population of a little over 14,000. That sum of money is more than six times greater than the cost of building a causeway to Prince Edward Island with its more than 100,000 population. Moreover, it would be sufficient to build all the roads that might be required by the Atlantic Provinces until the 1990's. The latter expenditure would benefit more than two million Canadians as opposed to 14,000 in the Yukon. That same sum of money could also build some 65,000 single-family dwellings and might finance the construction of many times that number."
By these comparisons, I am not suggesting that public investment in the development of the Yukon or the Northwest Territories is not justified. What I am suggesting is that in a huge country where capital is scarce we must make the best choices for the investment of that capital both for economic development and for the transport facilities to support such development."

That such large sums of money are required for the development of the Yukon Territory illustrates the need for good planning, if only from an economic point of view. But the activities of both the public and private sectors, where road planning is concerned, seem to indicate that the authorities believe that planning pays dividends only in the south. Planning may be twice as costly for northern projects, but the savings to be achieved by adequate initial planning could yield twice the return or more in comparison to southern projects.
C. Types of Roads (In General)

1. Classification System

It is apparent that some classification of winter roads must evolve for better communication among participants of this project. Pemcan services (1971) considered four classifications for roads, designated as:

Group I: All-weather roads generally meeting the specifications now being followed for 24-foot wide highways in the north.

Group II: Omits gravel fill and reduces the minimum amount of fill in permafrost areas. This type of road would allow intermittent light traffic during the summer. If not used and maintained regularly, these roads deteriorate rapidly. These roads can be up-graded to Group I road if desired.

Group III: Same sub-grade construction as Group II, but constructed to minimum alignment, width, grade and drainage specifications. These roads cannot be up-graded to Group I road. They do allow intermittent light traffic in summer.
Group IV: Provides absolute minimum access and available for winter period only; they would be available for winter construction of the pipeline.

This is one of two actual classifications of northern roads obtained from the literature. Since it appears logical and useful, it serves as a good base for a more refined classification system. Obviously, this refinement will deal with Group IV. Several descriptions of various types of winter road appear in the literature, which will be utilized for the refined Group IV classification in Part D.

The other reference to a classification of roads is by DIAND, 1968, which developed a classification system for its Northern Roads Policy. In this classification, there are two main categories of roads - (a) Communication and Network Roads, and (b) Lateral Roads. Communication and Network Roads are those highways and roads which provide a primary network of roads in both Territories with connecting links to the Provinces. Lateral Roads are those roads which lead from a communications and network road to a location where resource exploration, development or exploitation is being carried out or may in the near future be carried out. As indicated on the chart, the Communications and network Road category is made up of Trunk Highways, Secondary Trunk (Pioneer) Roads, Airport Roads and Local Roads.
With the exception of the Cost Sharing Roads, the cost of maintenance of all northern roads is shared by the Federal and Territorial Governments on a ratio of 85% by the former and 15% by the latter. Both the cost of maintenance and the actual maintenance itself of Cost Sharing Roads is the responsibility of the individual, group, or company that is developing the resource.

It is obvious from these two references that no adequate classification system currently exists for winter roads. Therefore, Part D of this section of the report will discuss a suitable classification system.
2. Construction Methods (Permanent Roads)

From a strictly mechanical point of view, the construction of permanent roads in the north has in the past differed very little from the techniques used in the south. The design and construction practices seem to have evolved to the stage where, with the proper application of the technology available, a reasonable result can be obtained.

Technically, the philosophy in the construction of roads is to maintain the permafrost in a frozen state. This is normally accomplished by the use of adequate natural granular fill, although numerous references mention other insulative materials (Goodyear, Stehle (1970), US Naval Civil Eng. Laboratory, and Williams). It is this author's belief that, the tediousness and expense of installation of these materials will prevent them from being widely used; however, they may be practical as a remedial procedure in maintenance operations or where extreme problems are anticipated.

The present technology for constructing fills as an insulative material is summarized in Appendix "B" to the Canadian National Railways April, 1971 Report. A more complete discussion on this subject is not warranted in this report.
3. **Equipment**

Standard road building equipment is used in the construction of northern permanent roads. No special equipment is necessary, although the technique of operation of equipment is usually altered.

4. **Costs**

A rough cost figure on a 'per mile' basis is given for the various types of permanent roads. This is necessary since if winter roads are to be constructed and used over an extended number of years, they will be subject to a cost comparison with permanent access roads.

Numerous references are available relating to cost figures. In some cases, it is difficult to relate the cost figure to the specifications of the highway; nevertheless, some estimate of these costs is relevant to the present study.

The estimated cost of a permanent road (Engineering News-Record, April 24, 1969) to replace the winter road from Fairbanks to Sagwon was $35 to $40 million. This represents a cost of approximately $80,000 per mile for what was described as a "full-fledged highway."
In North, 1969, a complete cost and standards comparison is given. These descriptions are quoted below:

"The present Northern Roads Policy was drawn up in 1965 not only to meet the immediate needs of the territories but also to complement the anticipated development pattern.

First, there is provision for tote trails and initial access roads. There are minimum standard access roads to serve resource properties, be they mines, oil wells or tourist camps. They are usually adequate to meet exploration and development needs and cost about $5,000 a mile or less. The cost is shared 50% with the resource exploiter. The road is open to the public but maintained by the resource exploiter. Winter roads often fall into this category. The deliberate low standard minimizes loss whether the exploration comes to naught or a mine is developed, goes into production and necessitates a much higher standard road.

The most common type of road is the Permanent Access Road. This is a high standard gravel road, 24 feet in width shoulder to shoulder with curvatures of less than 20° and gradients less than 10 per cent. It is built by a resource exploiter to serve a resource development going into production. Up to 2/3 of its cost may be borne by the Federal government which retains ownership as a public highway. The road is maintained, however, by the resource exploiter. Such a road may cost up to $60,000 a mile but if it exceeds this amount, the excess must be borne entirely by the resource exploiter. Such roads, because of the substantial federal contribution, can be located so as to serve the best needs of the overall network plan as well as those of the specific mine or resource.

There is provision, too, for a Resource Development Road serving several resource properties. The policy provides for this type of road to be built and maintained by the government. None has been built to date, however, although some of the Area Development Roads almost fall into this category.
The most significant provision in the policy is for Area Development and Communications Roads. The former is to extend into areas of promising resource potential and the latter to link up centres of population. They may cost anything up to $100,000 per mile depending on terrain, have shoulder to shoulder width up to 32 feet with maximum curvatures reduced to as low as 7° and gradients to 5 percent. All bridges are now constructed to carry loads up to 90,000 lbs. gross, a standard equivalent to that provided on the best of main highways in Canada and the United States."

5. Vehicles

The roads described above as permanent access roads can accommodate most vehicles, although on the tote trails, initial access roads, and winter roads, automobiles could not be used under general conditions. Otherwise, the roads are open to all traffic which cares to venture upon them. An exception to this is possibly private or semi-private roads where the owner might exercise judgment as to use. Of course, any road may be subject to a particular load, wheel load, or tire pressure restrictions, usually during the spring break-up period.
D. Types of Winter Roads

1. Classification System

At present, there is no classification system applicable to winter roads, although sufficient applicable names are used to signify the various types. There is, therefore, a need for a common understanding by name for each type of winter road discussed in this report. This classification system is based primarily on the modes of construction.

(a) Winter Trail - a trail used only in winter between freeze-up and break-up, and which is established by a single pass of a wheeled or tracked vehicle using a "blade" if necessary to gain access.

(b) Snow Road - a road built primarily by using snow as cut and fill material to establish some resemblance to a constructed road grade. Compaction is part of the construction procedure. A snow road can be further classified by whether the snow is agitated or "processed" before compaction:

(i) Compacted Snow Road - the snow is compacted without 'processing'.

(ii) Processed Snow Road - the snow is processed before compaction.
(c) **Ice Road** - A snow road with the physical addition of water to form a bonding agent between snow particles in order to give added stability to the roadway itself. Ice roads are similar to snow roads, in that they can be sub-classified as compacted or processed. (Ice roads should not be confused with winter roads on lake or river ice, which are sometimes confusingly referred to as ice roads).

(d) **Winter Road** - This name applies to all three classifications; namely, winter trail, snow road and ice road. It is any road that carries traffic only over the winter period.

(e) **Ice Bridge** - an artificially thickened ice cover that provides the required weight capacity at river crossings or other bodies of water.

2. **Relevant Snow Properties for Trafficability**

Although many articles on snow compaction trials necessarily contain comments on snow properties, there are three in particular which contribute significantly to the discussion. A publication by the United States Navy, entitled "Arctic Engineering", contains a section on snow compaction for roads and landing fields that gives a good description of relevant snow properties for trafficability:
"The most important property of a snow surface from a trafficability standpoint appears to be hardness. Hardness may be defined as the ratio of intensity of pressure to depth of penetration and may be characterized by the resistance of the surface to the penetrating effects of wheels and skis. Tests indicate that under the proper conditions of temperature, snow covers having the higher density also have the higher hardness. Snow is a crystalline material, and its strength near its melting point is fixed by the number and strength of the intercrystalline bindings. The crystals, themselves, are stronger than the boundary layers, and to spread stress on as many boundary bindings as possible, it is necessary to consolidate the snow. The nearer snow is to the melting point, the more the crystal boundaries become liquid in form and the more unstable the crystals become. Also, milling the coarse-grained crystals and packing them together results in an ever more unstable condition. Compaction methods are therefore more efficient at high temperatures after the ice crystals have been milled and before they have developed a stable form. Intercrystalline cohesion and strength of snow crystals of the same form, size and density increase greatly at low temperatures. Snow should therefore be used for traffic at low temperatures.

Snow, immediately after it falls, may have a density as low as 0.05 g/cc (3.1 lb/cu ft), although the average density is more often about 0.1 g/cc (6.3 lb/cu ft). With natural pressure and age it will seldom attain a density of more than 0.3 or 0.4 g/cc (18.7 or 25.0 lb/cu ft). The density and hardness required to support and endure the traffic of heavy-wheeled vehicles can be determined, at present, only by traffic testing. Therefore, until representative loads have been imposed on snow surfaces of various densities and subgrade conditions, and the densities themselves have been produced under all the various atmospheric conditions expected, it is impossible to predict whether present snow-packing techniques and equipment, available or contemplated, will satisfy all the requirements of future operations."

In 1960, the US Civil Engineering Laboratory issued Technical Report 109, which contained this comment related to snow properties:

"Hardness of compacted snow is dependent upon several variables: the geographical location, the season of the year, the type and condition of the snow, the ambient and snow temperatures, and the length of the age-hardening period."
Gold (1956) studied snow in compression and found it to be an extremely variable property. He found that strength was related to hardness, and to a lesser extent, to temperature and crystal size.

Several other authors have indicated that the hardness of snow is best measured by the density of the snow pack. Although a bulk density test is a relatively simple field test, the Rammsone instrument has been proven to be the most reliable instrument to date to obtain a relative indication of snow hardness. The description of the Rammsone, as given in the U.S.-Canadian Snow Compaction trials is presented below:

"Ramsonde - (also spelled Rammsone, and abbreviated Ram). A Swiss instrument used to determine (1) the average hardness and depth of hardened snow layer and (2) the relative hardness and depth of a virgin snow depth of numerous layers. It consists of a tube and quide rod, over which weights slide to drive the tube into the snow for penetration readings. A hardness number is derived from a formula based on data obtained from introducing the instrument into layers perpendicular to the snow cover. High and low hardness numbers refer to hard and soft snow respectively."

3. **Equipment**

The equipment used for winter road construction has had many adaptations in the past in order to improve procedures. Rather than attempt to specify the necessary equipment for snow road construction, descriptions of the most common types of equipment are offered below.
Heavy tractors are probably the most basic snow road equipment. These are typically of the TD-14, TD-18A, D6 or D7 variety. The smaller TD-14 or D6 allow earlier entry onto frozen muskeg or ice.

Pulvimixers have been modified so drastically that to describe each adaptation is not attempted or warranted. A typical description is given of the model named the Woods Preparizer (from Canadian-US Snow Compaction Trials):

"The Woods preparizer is a standard pavement breaker turned out by the Woods Equipment Company. This machine had been modified by the US Navy by the addition of a cab to protect personnel and was fully winterized. The mechanical action of the Woods preparizer is similar to the Seaman pulvimixer except for the larger and more powerful motor, a 160 H.P. US 24 International Diesel, and the higher speed of rotation of the pavement breaking tines. The machine was mounted on two heavy skis. The rotor and body of the machine were raised and lowered by hydraulic rams. Adjustment to the canopy could be made and a vibrator was also mounted on the canopy cover."

The following are the major characteristics of these pulvimixers, taken from the same source:

"1) 120 H.P. GM 2 cycle series M1 Diesel Engine
2) 7'6" Rotor in an 8' hood
3) 5 speed transmission which in high gear will give 275 rpm to the rotor
4) Pulvimixer was mounted on four skis
5) Ether capsules starting on all engines.

Two pulvimixers were modified by the attachment of heaters to the canopies, one heater turning out approximately 1,000,000 BTU's and the other 5,000,000 BTU's per hour."
In general, all theories of snow hardening involve agitation. The pulvimixer accomplishes this by acting as a rotary tiller. The rotating tines agitate the snow mixing the warmer snow with the cold surface snow in such a manner that the mean temperature of mixed snow is above that of the ambient air temperature. Subsequent cooling produces a hard snow mass.

The addition of heat by introduction of hot gases to the snow through heat producing devices raises the snow temperature even higher than by cold processing and may even place a moisture film on the individual crystals.

General descriptions of rollers, drags and precompaction equipment is typified in the literature, again from the Canadian-US Snow Compaction Trials:

"Rollers

A family of rollers was used during the trials, ranging from a 10-foot segmented foot roller to a small four foot diameter roller.

The heaviest and the largest of the rollers in use at Kapuskasing was a segmented roller provided by the US Navy weighing some 22,400 pounds. This roller is constructed of four, two-foot segments individually mounted to a cross connecting yoke at the rear of the rollers and connected to a draw bar. Each roller works independently of the other and each unit also has an individual scraper unit. This tended to produce an even pressure on the surface being processed.

A large corrugated roller was also supplied by the US Navy from Port Hueneme. It weighed 7700 pounds, was ten feet in diameter, eight feet wide, and proved most satisfactory. This was a simple corrugated steel roller both larger and heavier than the Canadian corrugated roller but similar in all other respects.
Rubber tired roller manufactured by William Bros. and provided by ERDL consisted of four rigidly mounted rubber tires separated by 12" and supporting an unloaded tank. Empty this roller weighed 22,000 pounds but it could be loaded to 50,000 pounds. The highest loading at Kapuskasing was obtained by an addition of 16,000 pounds of sand bags giving a unit tire pressure of 110 pounds psi with a unit loading on the elliptic of 80-90 psi.

The smaller DOT rollers used in the bush were similar in weight to the Canadian roller of 3,200 lb. On hard snow they were effective.

Drags

All these drags employ the same principle and can be compared in effect to oversize wood planes.

All are essentially frames to which cutting edges were rigidly or non rigidly attached. In the case of the DOT drag the centre cutting frame was adjustable and had on the front edge a set of serrated teeth to cut up the hard snow. Depth of cutting, both on the front and rear edges, could be adjusted.

The US Navy drag was made up of a reinforced 10' x 12' steel frame which could be towed either with the long axis or the short axis pointing in the direction of tow. This drag was originally conceived in connection with the US Navy Snow Compaction Maintenance Train.

In conjunction with the ordinary maintenance of winter roads, most pulp and paper companies in northern Ontario use a very heavy timber drag. The Snow Compaction Teams at Kapuskasing built and used a lighter version of this type drag, too light in fact since it tended to ride the bumps rather than plane them.

The concept behind such a drag is a very heavy cutting edge which is so placed that on hard snow the smallest area of contact is available. This edge both compacts and planes the snow and is most effective on snow of medium densities and of shallow depth.

Kragelski (1945) states that in the range of low or medium densities up to 0.2 gms/cc the use of the drag is most effective. The same author considers the drag an efficient precompactor in light snow and once the snow has hardened becomes an efficient snow planer. It is in this latter connection that heavy drags are chiefly used by the pulp companies and the trial team.

Precompaction Devices

A number of devices were brought to Kapuskasing for this year's trials to be used as precompactors.
The idea of precompaction is primarily to break down a lane prior to the use of the main compacting devices. This is presumed to be especially applicable to deep snow, and in snow even 36" in depth, as it is essential to break a path for towing tractors. It is probable that the best and simplest way to do this is to have one tractor tow the other. However, one TD18 can break for the other if these are acting as precompactors.

Other considerations, such as soft ground and unfrozen muskeg effect the use of such a large precompactor as the TD18A or DB. In many instances, it is necessary to compact the snow by some lighter vehicle towing a roller to allow the bog to freeze sufficiently and allow heavy tractors together with roller and pulvimixers to further densify the snow.

The simplest precompactor, and that most commonly used by the Pulp and Paper Companies, is the Bombardier snowmobile. This vehicle is usually send down the bush roads several times in early winter after the first heavy snowfalls, compacting the snow and allowing the ground to freeze. The Canadian Army snowmobile can be equally effective at this task.

Several other pieces of equipment have been described in the above source, but since the conclusions reached were to eliminate such equipment for snow road construction, they are simply listed here as: stratamixers, disc harrows and long toothed harrows.

Wuori (1962) gives a good description (USA-CRREL Special Report 53) of the performance testing of a modified field planer. He found that this "finishing device" was a very promising tool for leveling processed snow.
4. Construction Methods

(a) Winter Trail:
The winter trail is constructed in a very simple manner, which usually entails a single pass of a wheeled or tracked vehicle using a blade if necessary to gain access. Usually the initial access is made with a caterpillar tractor, which is capable of moving heavy snow and levelling any ground features that would limit less maneuverable vehicles.

(b) Snow Roads:
Although the construction of a snow road initially appears almost as simple as for a winter trail, literally hundreds of pages in the literature describe the various methods of snow road construction. Obviously the use to which a snow road is to be subjected has a great bearing on the method and extent of snow road preparation.

(i) Compacted Snow Roads
The most basic snow road is one where snow is physically moved onto or off the right-of-way to establish the desired snow thickness. This is usually accomplished by simply blading snow into position by a caterpillar tractor, after which the snow is compacted into place by several passes of the same vehicle. Frequently a heavy snow drag is
used to generally level the road by cutting off mounts and filling in depressions. The US Naval Civil Engineering Laboratory, 1962, found that this procedure does not achieve a surface layer hard enough to stand repeated loading by a heavy wheeled vehicle, even though the surface hardness was doubled by use of the drag. These tests further showed that drags tended to harden the snow road from the top in a fashion similar to that achieved by rollers. This top hardening is illustrated in Figures 2 & 3.

Ager (1959) infers that Swedish experience has been similar; that is, compacted snow roads without depth processing simply will not stand up to wheeled vehicles. Ager refers to bottom compacted or surface compacted roads, which is common terminology in the European literature.

Both literature sources discussed above also studied the distribution of hardness growth with either time or atmospheric variables. The former found that hardening does increase with time, as shown in Figure 4. The latter found that by using vapor barrier one could distinguish between thermal and moisture effects. (This is not strictly true, as some heat is transferred in the moisture itself.) Nevertheless, the author concluded that the principal effect of the atmosphere on
Figure 2. Normal hardness distribution in compacted snow.

Figure 3. Improved hardness distribution in compacted snow after special rolling.
Figure 4. Distribution of hardness growth after treatment with rolling-type vibratory finisher. Sawdust cover used for insulation.
hardening of the road was due to temperature; however, moisture does influence the hardening process due to the condensation and resulting bonding effect.

Leijonhufvud (1965) also reported on field tests of Swedish snow roads. In relation to simple compaction by the use of drags, several pertinent conclusions were reached. (The main purpose of the research was to develop a bottom-compacted snow road with good strength properties so that it could be used for hauling timber by wheeled tractors.) In regard to surface compacted roads, this research found that:

"(1) Processing with a drag or roller resulted in approximately the same hardness.

(2) Surface hardness and bottom hardness are considerably increased by heavy traffic.

(3) At low temperatures, comparatively small changes in density result in comparatively great changes in surface hardness.

(4) In the compacted snow road, the surface hardness follows the snow temperature very closely, though with a slight lag.

(5) Relatively simple compaction methods can provide satisfactory bearing capacity to withstand traffic by wheeled tractors provided the road gradient does not exceed four percent.

(6) In Sweden, the use of the compacted snow road seems feasible in regions where the snow depth on February 1 is 40 cm or more (7.15") and the mean temperature is from -6°C to -8°C or lower."
The US Navy's book, "Arctic Engineering", describes the process of compaction as it might apply to a compacted snow road:

"Pressure for compaction is generally applied with some type of roller or drag. Satisfactory compaction has been accomplished by bolting wooden track extensions to tractor plates and utilizing the weight and vibration of the tractor unit in the same manner as compacting earthfills. Modified sheep's-foot rollers, slat rollers, and an air-driven vibrator mounted on a steel plate shaped like a toboggan have been used to a limited extent in snow compaction tests. Results are not conclusive, but they indicate that further investigations of such equipment are justified."

Basically, the compaction equipment described in the above reference were of two types: rollers and drags. Rollers are normally of large diameter (6 to 8 feet) and heavy weight (9,000 lbs. unballasted) so that rolling rather than plowing is completed. When used after pulvimixers (processors), large diameter rollers have been very successful. Indications are that the angle of approach or roller radius influences the compaction process, the larger radius giving superior results.

Light steel drags are effective in light snow for compaction purposes, and for levelling. However, the more cumbersome pontoon drags required in deep snow are not as effective as rollers.

This same reference indicates a similar experience with regard to the curing interval of snow roads:
"A notable property of snow is that its hardness continues to increase if it is left undisturbed after having been mechanically treated. After the absorbed air has been eliminated, the crystals in contact with each other continue to grow together, a process that continues for 10-12 or more hours after compaction. Tests have indicated that after progressive passes with a roller over a snow surface, the hardness measured 1 hour after completing the compaction was twice as great as that after a single pass and that a further increase in hardness of 8 to 10 times the value obtained after a single pass took place 12 hours after completing the rolling. Attempts to work hard, dry snow continuously without allowing for a curing interval will result only in a churning of the snow with no increase in compaction."

The report on Snow Compaction Trials 1952-53 conducted by joint US and Canadian agencies contains descriptions and results of tests carried out at several sites in North America. Although tests conducted at Kapuskasing were considered disappointing, some conclusions are noteworthy:

"The results of age hardening tests and studies may be summarized as follows:

(1) Rammsonde hardness rapidly increases usually up to a period of approximately 14 hours. In the three tests, this figure may be influenced by the time of lane placing, i.e. (1500 hours throughout the night until 0700 hours the following morning when the temperature usually commences to rise is a period of 14 hours)."
(2) Ramsonde hardness after the age hardening period showed little tendency to increase or decrease with temperature fluctuations provided the temperature remained below +10°F. (Test No. 3.)

(3) Ramsonde hardness increased throughout age hardening (14 hours) despite temperature fluctuations. (Test No. 1).

(4) Ramsonde hardness decreased rapidly after temperatures rose above +10°F. (Test No. 1).

(5) Densities in all tests showed no tendency to either increase or decrease with temperature.

(6) Densities in all tests showed no visible tendency to increase or decrease with an increase or decrease in Ramsonde hardness.

(7) The wide fluctuations observed in density readings are due to the method of sampling i.e. single samples every hour using at the beginning the 500 cc density sampling tube followed by the coring auger which immediately introduces a variation 9 times (at least -6%) the value of the variation caused by the sampling tube.

These tests show clearly the difficulty of correlating results with the present type of instruments. It is felt that these age hardening studies have only confirmed, perhaps with a little more precision, observations made at other trials on the behaviour of compacted snow.

The combined results of tests at Goose Bay and Kapuskasing yielded some interesting observations and results:

"1. A relationship can be found under conditions found at Kapuskasing and Goose Bay, between density and hardness. This is expressed in the Formula R = 3826ρ - 1618 ±12%. ρ = density.

2. An average hardness R = 350 should be obtained before a road can carry military traffic.

3. Using cold processes, dragging, rolling or pulvimixing densities between 0.47 - 0.53 gms/cc can be obtained.

4. Using heat processes densities higher than (3) above have been obtained at Kapuskasing."
5. When used with heaters the US Navy segmented roller gave the best results both as to hardness and density.

6. Mean snow temperature for all lanes laid during trials at Kapuskasing was found to be 19°F.

7. Mean ambient air temperature for the period of the trials at Kapuskasing was found to be 7.8°F.

8. Muskeg with density .997 and average moisture content of 80% when frozen to a depth of 12" and overlaid by 15" of snow will support aircraft up to 59,000 lbs.

9. Muskeg under the conditions found at Kapuskasing was found to have a compressive strength of 1428 psi.

10. Present day military vehicles do not become immobilized in snow under 12" if this snow overlies a firm base.

Tests carried out in Michigan, although in a completely different climate than the area of concern, also yielded some significant findings:

"It may be accepted that the cold-processing techniques studied may be used in snows of depth up to about 28 in. and will produce densities of up to 0.55 g/cc. This cannot reasonably be exceeded without moisture in the snow. The resulting hardness and trafficability will depend on the processing temperature, curing temperatures and the snow temperature at the time of test. These three temperatures may be intimately and continuously interrelated. At Fort Churchill, for example, good trafficking was obtained on two occasions at both high and low snow temperatures when the processing temperature was higher and the curing temperatures appreciably lower than the temperature at time of traffic. In any case, only under extremely favorable conditions will snow surfaces be produced by these methods which will be able to withstand powered-wheel traffic of even light vehicles."

At Fort Churchill, some very significant findings were made regarding trafficability as well as compaction methods:
"From traffic tests performed during this investigation, it was found that tire pressures were a controlling factor as to failure or success even with low ambient temperatures. Failures of a section were constant until tire pressures were reduced from 35 psi to 15 psi on 2½ ton dump truck loaded with 2½ tons and equipped with single rear tires. With the reduced tire pressures, failure did not exist as long as ambient temperatures remained near -20°F. Reduction in tire pressures increased track width of tire 1.75 inches.

The results of these tests in constructing snow compacted roadway are summarized as follows:

1. This method of snow compaction gave a definite increase in snow density regardless of trafficking success.

2. A longer period of age hardening than overnight is required for best results.

3. Temperatures are the controlling factors during and after this method of construction and should be at least -20°F for best results in this type of snow.

4. Densities obtained in unprocessed snow windrowed in by bulldozer were equal to those of processed snow by pulvimixer with low ambient temperatures.

5. This type of snow can be processed with proper temperature to withstand heavy traffic provided speed does not exceed 10 miles per hour and tire pressures of not more than 15 psi.

6. Roadway does drift over requiring snow removal after blow even though surface is smooth and extends two to three feet above surrounding area."

The Churchill tests also included trials using the Alaskan (Logging Road) Method. Due to the proximity of the originating location of this method to the area of interest, and due to the success achieved by the method, the complete description is given below:
"Alaskan (Logging Road) Method:

A roadway approximately 4.6 miles in length was constructed and maintained for use of US Ordnance Test Team vehicles under trafficking test. This roadway was first started by towing a small log drag over the previously staked right-of-way by a Penguin. Thus, a breakdown of the thin snow coverage was accomplished, which allowed the cold air to penetrate the muskeg and facilitate freezing. After lakes and muskeg had frozen sufficiently to support a D-7 tractor, the roadway was dragged and maintained with the ERDL constructed "H" shape drag. This drag was constructed from blueprints furnished by Spruce Falls Pulp and Paper Company, of Kapuskasing, Ontario, Canada. The drag was made from 14" x 14" timbers 10 feet wide overall and 30 feet long in an "H" shape with three cross-members. One cross-member was bolted at each end and one center cross-member which carried an 80 pound railroad rail set in so that rail flange was perpendicular to snow surface. When drag was towed in one direction a cutting action took place and when towed in opposite direction, a leveling action took place. Side timbers were scarfed from one end to centre rail in order to make rail perform a cutting action. Drag can be towed from either end by tow cables. This drag was towed by D-7 tractor. This method of cutting and levelling the snow by direction of towing drag produced a smooth surface. Maintenance of this section was continuous due to heavy trafficking and high speed of Ordnance vehicles. Since the Ordnance Team was only interested in mileage, the vehicles cut the road out faster than it could be maintained. This required some night work after Ordnance had stopped trafficking for the day.

Whenever a blow occurred, it was impossible to keep the roadway open during the blow. For this reason, it was necessary to remove the extra snow by windrowing with tractors and motorized grader and then blow the snow off with Sno-Go snowplow. The berm alongside was rolled down with steel rollers in order to prevent as much drifting as possible. Windrows were cut approximately 150 feet distant along each side of roadway to trap as much snow as possible before crossing roadway. One of these windrows partially filled in after a blow.

This method proved worthwhile although requiring an extra amount of time and effort. Windrows were reopened after each blow in preparation for trapping next blow. This method of construction, although requiring considerable maintenance when high speed and hard tires are used, is believed to be the most advantageous in this type of Arctic snow and terrain of Fort Churchill area. It is necessary to remove any standing timber alongside for at least 75 feet of each side of roadway to prevent drifts from forming on roadway during a blow. This is true of any method of construction, where drifting snow is such a menace.
Tests

The Ordnance Test Team used this roadway during month of Dec. 1952 through Feb. 1953. The total mileage placed on this roadway was 22,234 miles. Vehicles used were ¼ ton jeeps, 3/4 ton, 2½ ton, 5 ton trucks, light and medium tanks, all vehicles were loaded to capacity. The roadway was very rough at times due to heavy trafficking, but could be smoothed out by dragging with planing "H" type drag previously mentioned or bladed with a motorized grader. Due to special tests of Ordnance vehicles, speed and tire pressures could not be controlled. For a military roadway where control of speed and tire pressure could be maintained, it is thought maintenance could be cut by at least 50 per cent.

Summary of Findings

The following findings are listed for the Alaskan (Logging Road) Method:

1. This method of road construction in the Arctic type of terrain and snow of Fort Churchill area is believed to be the most advantageous and speediest.

2. A total of 22,234 miles were covered by Ordnance test vehicles, over this type of roadway, during this test period with all vehicles loaded to capacity.

3. Roadway will drift in during a blow requiring an extra effort of snow removal regardless of preparations made to prevent the snow drifting.

4. A faster vehicle for over snow is required for towing "H" type drag.

5. High speed (30 to 40 miles per hour) and high tire pressures (standard for military vehicles) break roadway down requiring extra maintenance.

6. It is necessary to remove any timber or obstructions from side of roadway for 75 feet in order to prevent drifting in this type of terrain.

7. A windrowed strip down to muskeg tractor blade wide and approximately 150 feet from side of roadway, and parallel to it, assists in preventing drifting snow from being deposited on roadway.

8. Low ambient temperatures are a definite factor in hardening of this type roadway (-20°F. or below).

9. Drag as used in this construction proved successful.
10. Further construction of this type of roadway construction should be made and trafficked with control of speed and tire pressure in order to determine most feasible speed, tire pressure with various loads."

Tests at Fort Nelson, BC were unsuccessful because adverse weather forced the abandonment of the trails before any results could be obtained.

Tests at Goose Bay were primarily for snow runways. All construction of runways was by the pulvimixer method, which will be discussed later in this report.

Tests were also carried out on the Greenland Ice Cap, but incomplete information limited their success.

Although documentation of unsuccessful tests (above) may initially appear unnecessary, it does serve a very important purpose; that is, to caution us that climatic or other factors may cause research under such adverse conditions to fail, regardless of the plans, equipment and instrumentation that have been assembled. This is one of several reasons why the present author prefers monitoring of existing or necessary winter roads rather than the construction of special test strips.

In general, the more recently reported research of simple compacting equipment has generally tended to substantiate earlier findings. In 1961, the US Naval Civil Engineering Laboratory (Technical Report 107) reported on snow rollers. It stated in its findings, conclusions and
recommendations, which are given here in part, that:

"1. A 10,240-pound, 8-foot diameter snow-compacting roller developed for compressively compacting snow is:

a. Effective at speeds up to 500 feet per minute and can cover up to 4.9 acres per hour under good conditions.

b. Easy to maneuver in all types of snow except extremely soft, deep, new snowfall and it can be used without difficulty in temperatures down to -50°F.

2. A 13-wheeled, pneumatic-tired roller selected as a surface-hardening roller is:

a. Effective at a speed of 300 feet per minute and will easily cover up to 2.9 acres per hour under good conditions.

b. Easy to maneuver only on relatively hard compacted snow where the tires penetrate 2 inches or less into the surface, but it is most effective as a surface compactor when the tire penetration is a half inch or less."

The above findings justified the following conclusions:

"1. Compressive compaction of both natural and processed snow increases its strength.

2. The 8-foot diameter, fixed-face, snow-compacting roller is satisfactory for general use in compressively compacting natural snow fields, depth-processed snow, new snowfall and drift.

3. The 13-wheeled, pneumatic-tired, standard commercial roller is satisfactory for rapidly increasing the surface hardness of compacted snow."

On this basis, the Naval Laboratory recommended that snow-compacting rollers be included in any equipment allowance for compacting snow where a Navy cold-processing technique is used for the construction
effort. Further, it recommended that when a high-strength surface is required, a 13-wheeled, 13-ton, pneumatic-tired, standard construction roller should be included in the allowance.

The same literature source issued Technical Report 109, which deals specifically with snow drags of two types. This report concluded that:

"The snow-levelling drag and the snow-finishing drag are necessary pieces of equipment for construction and maintenance of compacted-snow areas using the Navy cold-processing techniques."

and, more specifically, that:

"1. The 925-pound Douglas fir snow-levelling drag is needed to maintain level working surfaces for other compaction equipment.
   a. It is useful in maintaining light snowfalls and soft drift on compacted snow areas and around polar camps.
   b. It is highly maneuverable in all types of snow and can be used without difficulty in temperatures down to -50°F.
   c. It is effective at speeds up to 500 fpm and will easily cover up to 5.3 acres per hour under good operating conditions."

2. The 2,830-pound steel finishing drag is needed to produce hard, smooth finishes on compacted-snow areas.
   a. It is useful in maintaining snowfalls and drift on compacted-snow areas and around polar camps.
   b. It is very maneuverable in all types of snow but is most effective as a finisher when the skids penetrate 1 to 2 inches into the surface.
   c. It is effective at a speed of 350 fpm and will easily cover up to 5.3 acres per hour under good finishing conditions."
In the book by Kingery (1962), Maser makes the following statements on compressive compaction:

"Walking on snow is a primitive form of compressive compaction. A foot path used daily at a winter camp on the Greenland Ice Cap was compacted to a depth of 4 inches in a single month. Examination showed that this tough, hard layer of snow was almost twice as dense as natural snow (0.33 to 0.56 gm/cc) and over twelve times as hard (32R to 400R). While foot traffic is not advocated for snow compaction, this example does show the effectiveness of compressive compaction.

A variety of sizes and shapes of drags, rollers and other devices have been used many years for compressively compacting snow. Even so, it is only effective on shallow snow, for regardless of the weight of the compressive equipment, there is a limit to the degree of density and hardness that can be achieved by compressive compaction alone.

The Navy developed a relatively lightweight (10,240 pounds) 8-ft. diameter 8-ft. roller called a snow compacting roller for high-speed, compressive compaction of large snow areas. Tests have shown that the effective depth of compaction on natural snow by rolling alone is 8 to 10 inches."

Ager (1959, 1960, 1961) has given several reports on Scandinavian snow preparation techniques. Unfortunately, most of this work has concentrated on roads suitable for loads well below those which are of concern in the present study. It is encouraging to note that the same variables are considered and that the compaction techniques are basically the same. Ager does, however, mention the "snow whip", which is a Swedish snow processing machine that is basically an axle with chains mounted on it, having a canopy covering the mechanism. The chains whip the snow, pulverizing and agitating it to enhance other compaction techniques.
In summary, compacted snow roads are basically constructed of compacted-in-place snow or compacted processed snow. In both methods, compaction can be carried out by either heavy rollers or heavy drags, with heavy rollers and processing generally being required for snow roads expected to carry wheeled vehicles. Drags are also required for any compaction process in order to maintain a level surface and for maintenance purposes.
(ii) Processed Snow Roads

Processing of snow has been practised in the past to enable a better road surface to be achieved. The literature contains many references to processing techniques, and a wide range of success has been experienced, partly due to the numerous variables that affect snow road stability. It appears that a fair correspondence exists between snow roads that Europeans refer to as "Bottom-Compacted Roads" and those that North Americans refer to as "Processed Snow Roads".

Basically processing of snow is undertaken to achieve a uniform or homogeneous material with which to work, mainly with regard to material properties. Obviously any processed snow must be compacted in order to achieve a trafficable snow road.

Ager (1959) referred to harrowing, rolling and dragging as compacting and processing methods. For the present report, rolling and dragging will be referred to as compacting techniques and other processes will be referred to as "processing" techniques.

Le Jonhufvud (1960) gives a good account of the processing purposes:

"All these measures aim at strengthening the bonds between the snow particles or between complexes of snow crystals within which the bonds had already been strengthened before. This may be accomplished
chiefly in the following three ways:

(1) By expelling the air from the snow, whereby the snow particles are brought into contact with one another to a greater extent than before and the conditions for strengthening the bonds between them are increased.

(2) By breaking up the snow particles. Many points of contact are provided by this means as well, thus increasing the possibility of bonding between the snow particles.

(3) By mixing snow layers of different temperatures and snow consistencies, primarily at low air temperatures."

Eriksson (1959) also discusses the micro-mechanism of snow processing, as well as icing techniques:

"If the compacted snow road is constructed merely by compressing the snow to a higher specific weight, it is left to the snow alone to form the joints between the snow particles. However, this formation of joints can be promoted, partly by treatment with water, steam or heat and partly by intense mixing of the snow in conjunction with the compaction. In order to obtain satisfactory results by means of the methods mentioned, large quantities of heat are required, involving an unwieldy apparatus. The latter method, in which differences in temperature in the snow cover are utilized, is preferable since it permits the use of simple tools.

It appears possible to make the compact snow roads strong enough to support not only tractors, horses and sledges but even trucks. If the construction and maintenance costs can be kept close to the present low level, the economic importance of these roads should increase considerably. However, continuous practical tests are required in order to develop suitable methods and to determine the economical use of this road construction technique in different climatic regions."
Putkisto (1959) gives a good account of the climatic factors affecting processing and compacting techniques in Finland:

“It has been established that freshly fallen snow reflects approximately 80 - 88% of the radiation as compared with only 42 - 70% reflection of old "corn" snow. Thus radiation is more effective in melting coarse-grained snow than in melting fresh, fine-grained, snow. During the night, especially when the sky is cloudless, heat radiation takes place from the body of the road to atmosphere. This kind of heat transfer, which is typical for late winter conditions, has a hardening effect on the upper layers of the winter road.

The direct effect of the relative humidity of air on the hardening of snow is probably comparatively small. It, however, influences the occurrence of precipitations. In addition, exceptionally low relative humidity may cause so intense a sublimation of snow, that the upper layers of the road soften, or the hardening is restrained. Likewise, the direct effect of wind, if its drifting action is not considered, is rather similar to that of relative humidity. In other words, in exceptional cases wind may accelerate sublimation of snow to such an extent that the upper layers of snow become softer.

Snow compacted during a snow fall or immediately before does not harden, since fresh, loose snow collected on the packed snow layer acts as insulation. A layer of soft snow only 5 cm. deep, may have this insulating effect. If the road is hardened, fresh snow covering the compacted layers, prevents or slows down softening of dense snow during a thaw. Provided the ground and the road bed were warm before the fall of the insulating snow layer, the road softens since it becomes insulated from the cold atmosphere. Packed snow roads may thus soften from below.

Hardening which starts from the bottom has been found to be faster on peat soil than on mineral soil. In forest areas, due to local climate, the hardening is probably somewhat slower than in open areas, but the preservation of hardness is better in forest areas.
Up to a certain limit, the hardness values of the snow generally improve with time, especially if the roads are kept in continuous use.

Since under our conditions the weather during the winter changes considerably, the construction of snow roads has to be undertaken while the conditions necessary for hardening are favourable and the preservation of the hardness is assured. Compacting of a road bed should not be carried out during a period of heavy snow falls, since fresh snow will hinder the hardening of the road. On the other hand, favourable weather conditions for such undertakings exist immediately following a weakening or a cessation of the periods of low pressure. High pressure conditions with accompanying cool air currents and lack of precipitation are desirable. It is advisable to start the process of compacting during the early winter, even if the roads are not being used until a later date. A thin layer of snow hardens more rapidly than a thick one, and furthermore, the size of snow particles is, as pointed out previously, more advantageous in the early winter as regards to hardening.

Afternoon is considered the most favourable time of the day for compacting snow. The snow has then a relatively high temperature and accordingly there is plenty of water vapour and water between the snow particles. Furthermore, the temperature falls during the night so that freezing will occur."

Putkisko also discusses snow processing and compacting, but only for load ranges well below those required for the purpose at hand.

The U.S. Navy's "Arctic Engineering", Technical Publication (1955) gives extensive discussion to processing techniques:

"Pulvimixers, tooth harrows, and disk harrows are the most commonly used equipment for depth-processing.

a. Pulvimixers. A pulvimixer is a machine that scoops a layer of snow (usually 1 foot or less) into a closed compartment where it is pulverized
by a chain or hammer flail into fine particles before being redistributed on the snow surface. It may be self-propelled or towed by a tractor. If towed, it is usually ski mounted. The self-propelled type, to be effective in deep snow, should be track equipped. This equipment is often used in conjunction with some form of dry-heat apparatus by which heat is applied directly to the agitated snow surface. Pulvimixers preceded and followed by a proper pressure device are the most satisfactory equipment yet developed for producing trafficable surfaces.

b. Tooth Harrows. Tooth Harrows are simple and easy to maintain, because they have no moving parts. Usually, for snow consolidation, they are specially constructed of structural steel sections with steel bar teeth of various spacing and projection, depending on snow conditions. This equipment is difficult to maneuver in deep snow, lighter construction would probably overcome the difficulty, and weights could then be added as required. Another disadvantage of tooth harrows is the fact that there is no vertical intermixing of snow from different levels, and therefore no mixing of snow of different temperatures. Tooth harrows do not leave a smooth surface and must always be used in conjunction with rollers.

c. Disk Harrows. Disk harrows have been inadequate, primarily because of insufficient flotation or supporting devices. Test results are based on the use of gang harrows with 24-inch disks, which were so small that the drawbar and axles were always well down in the snow and plowed up the snow ahead. Had they been equipped with large-area support shoes, runners, or plates, the harrows would not have sunk into the snow. On a hardened strip the equipment was found to be quite effective in chopping up the surface."

This same source gives an account of test road sections at Fort Churchill, Point Barrow, Alaska, and Camp Hale, Colorado. These descriptions are so applicable that the discussion is presented
below in its entirety; in particular, the results at Barrow, Alaska should be noted:

"TESTS AT CHURCHILL, CANADA. Practical field trials consisting of actual construction and maintenance of a 12-mile section of road 45 miles from Churchill and 2 miles from the shore of Hudson Bay were conducted by the Royal Canadian Engineers in 1951. Winds here are common and of high velocity, and snow conditions are analogous to those occurring on flat, exposed Arctic coasts and for some considerable distance inland. The equipment consisted primarily of a Seaman pulvimixer and low-pressure roller. The pulvimixer was equipped with a chain flail consisting of 120 chains, 15 in. in length (chain diam. 5/8 in.). It was mounted on skis and towed by a tractor; the roller was 6 ft in diam and 8 ft in width, and its weight could be varied between 3,175 and 5,800 lb in 75-lb increments.

No difficulty was encountered in compacting snow in these tests when the atmospheric temperature was below 50 F, and no trouble was experienced with traffic on the road while the temperature was below 100 F. Temperatures during the test period ranged from -30 to 150 F. Compacted snow densities achieved were between 0.4 and 0.5. Traffic tests involved using 3-ton trucks loaded to a gross weight of 9 tons, developing axle loads of 11,500 lb.

No satisfactory answer was obtained to the question of optimum number of passes of equipment. A long interval between passes appeared to be definitely detrimental. A 4-hr period caused trafficability failures every time it was tried. A treatment interval of less than 1 hr produced good results from which the conclusion is apparent that with this equipment the time interval between passes should be kept to a minimum and in no case should be allowed to become greater than 2 hr. A recommended curing period for the treated snow, prior to its being opened to traffic, ranged from 19 to 24 hr.

When these road-making materials were used, the rate of construction of snow roads amounted to 3 miles during a 24-hr working day with the equipment at hand and under favorable conditions. Favorable conditions are defined as terrain open and flat, snow depth under 3 ft, wind chill factor less than 2,100, and visibility at least half a mile.
In these tests, the road surface was raised above the surrounding snowfield by a snowfill. Therefore, wind and drift swept over it, and snow fences were unnecessary. Equipment included a pulvimixer, 3 rollers and 5 tractors.

The buildup process was attained by spacing the initial passage of the tractors 45 ft apart, across the proposed centerline. After dragging the snow in toward the centerline, it was roughly leveled by the tracked tractors. The treatment with the pulvimixer and, in turn, the rollers, followed. A built-up roadway was constructed having about a 15-ft surface width, usually raising the road surface about 1 ft above the surrounding snow surface.

Great care was taken in smoothing off the snow-fill slopes, which were made no steeper than 1:5 with the shoulder corners smoothly rounded off. The buildup process was accomplished at the rate of 7 miles a day, but the progress on the road finishing depended entirely on the single pulvimixer unit. By using 2 such units, therefore, the construction progress could have been doubled.

The buildup process in detail was accomplished by starting 2 tractors on opposite sides of the centerline with blades angled toward each other, continuing forward a distance of half a mile. The two tractors were then reversed in direction, continuing to windrow the snow toward the center until they made their third and last pass in the direction of forward movement. The crests of the two final windrows were 10 to 13 ft apart. During this windrowing process the contraction in the snow volume, starting with a snow density of 0.3 g/cc (18.7 lb/cu ft), amounted to 40 or 50 percent. The windrows were then smoothed over the road surface and in turn followed by five passes with the pulvimixer-roller combination.

Within 36 hr the road was subjected to traffic, including 3-ton loaded trucks, 20-ton loaded sleds (moving at 25 mph), and tracked tractors. One section of the road, a crossing, was subjected to 50 tractor passes a day over a 5-week period without ill effects. No failures occurred over any part of the road. Traffic wore down the corrugations made by the rollers, the only evidence occurring on the surface.

The speed at which vehicles could move over the road was governed only by vehicle performance. No difficulty was experienced at 40 mph, and there was no indication of either sidesway or skidding. No evidence of deterioration of the road surface was visible at temperatures up to 20°F, which prevailed late in the season. The road was built in mid-February and, with temperatures as high as 30°F, up to 8 April had suffered no permanent damage. The effect of the heavy traffic to which it was subjected, if anything, appeared to have improved the road and its surface.
TESTS AT POINT BARROW, ALASKA

During the 1950-51 winter season, the Arctic Test Station at Point Barrow constructed 19 test strips built with various combinations of snow stabilization equipment. From these tests the most effective combinations were selected and used in the construction of a 5,000-ft snow road. The road was maintained at the same time that it was subjected to testing by wheeled traffic. Construction operations were on two parallel sites 75 ft apart, each 2,500 ft long by 31 ft wide, which were covered with drifted snow 6 to 18 in. deep. More snow was hauled to the sites so that the overall depth averaged 18 in.

Each of the 2,500 ft sites was divided into two 1,250 ft sections, and each of the four sections was stabilized by one best method established in the test strip studied. The four methods were:

Section I: Pulvimixer followed immediately by 8 ft roller.

Section II: Pulvimixer followed immediately by snow surface heater and sheepsfoot roller.

Section III: Pulvimixer followed immediately by water carrier and 8-ft roller, with the water carrier discharging water at the rate of 50 gal/lin ft or 0.5 lb/sq ft through a spray bar 8 ft long and 2½ in. in diam.

Section IV: Pulvimixer followed immediately by pontoon barge with a 6,300-lb load.

Each combination of equipment made 5 stabilization passes, and all equipment except the water carrier and the snow surface heater was towed at approximately 1.5 mph. The snow surface heater was towed at a speed of 0.85 mph and the water carrier at a speed of 1.0 mph. In making an 18-ft wide roadway, 3 equipment lanes were used for the pulvimixer, snow surface heater, 8-ft roller, and sheepsfoot roller, whereas only 2 equipment lanes were used for the water carrier and pontoon barge drag.

Passes with equipment combinations were made at 2-hr intervals on Sections I and II, except when the end of the workday intervened, causing a lengthening of the time interval.

The time interval between passes with the equipment combinations used on Sections III and IV was increased to 15 and 24 hr, respectively, in an attempt to compensate for relatively high ambient temperatures present during the stabilization of these strips.
Test data were collected on each section 2 hr after each pass with the equipment combinations and 24 hr, 1 week, and 2 weeks after completion of the snow roads. The data included ambient air temperatures; snow temperature; type of snow; depth of snow; snow density at the surface and the ground; hardness of the snow surface using the hand penetrometer, CBR field testing apparatus, and the bearing test frame; and Mark II soil truss readings. Data were as follows for tests on the various sections.

(1) Section I--Pulvimixer and 8-Ft Roller: The pulvimixer operated with ease, cutting about 12 in. into the snow on each pass, and a good traffic-bearing surface was produced by following each pass immediately with the 8-ft roller. Tests indicated that the density of the entire depth of snow was increased uniformly, and no stratification was observed in the test cores. The surfaces were subjected to hardness tests with the hand-operated penetrometer, CBR field testing apparatus, and field bearing test frame; but insufficient data were obtained for correlation.

The fact that the stabilization method produced a good traffic-bearing surface was proved when, after 20 continuous trips with a jeep and 10 with an empty GMC 2½ ton 6 x 6 cargo truck, the surface was only slightly marred; good condition was quickly restored with a single pass of the steel snow drag. For greater wheel loadings, a Caterpiller Model-12 motor grader, towing a loaded low-bed trailer with a gross weight of 26 tons, was moved over the roadway. This caused only shallow tire depressions along the line of travel, which were quickly removed with the wooden snow drag and 8-ft roller.

(2) Section II--Pulvimixer, Surface Heater, and Sheepfoot roller: The surface produced on this section was hard and stable, and a marked increase was observed in the density of the entire snow cover over that obtained in Section I, with greatest increase near the surface. The density of the section continued to increase with age. Several objections to using the snow surface heater as a piece of stabilization equipment were observed. Towing speed was slightly more than half as fast as the speed for most other pieces of stabilization equipment; constant operator attention was necessary to assure a maximum output of heat; and continual repair and modification were necessary for successful operation.
Ten trips with a jeep and 10 with an empty GMC 2½-ton 6 x 6 truck were made over Section II before a maintenance pass with the steel snow drag was necessary to restore the surface to good condition. In a single pass over the section, the motor grader and loaded 26-ton gross low-bed trailer caused very shallow tire marks on the road.

(3) Section III--Pulvimixer, Water Carrier and 8 Ft Roller: The surface density on the finished roadway was very high because of the added water, but the low density near the ground indicated that even with the aid of a pulvimixer the water did not penetrate the snow completely. The toboggan on which the water carrier was mounted provided a smooth surface to receive the water, and the pass with the roller was started 30 minutes behind the carrier to allow for freezing. This delay prevented adherence of the surface material to the roller. This section was stabilized in unusually warm weather and the traffic tests were inconclusive.

(4) Section IV--Pulvimixer and Pontoon Barge Drag: The density of this section was increased uniformly with each additional pass of the combination of equipment. During the construction of the test strips it was found necessary to load the barge with 6,300 lb for good compaction. This load, which did not cause the barge to plow into the processed surface, at times stalled the International T-9 towing tractor.

This section was stabilized in unusually warm weather, and traffic tests were inconclusive. The surface held up well under limited jeep traffic, but the unloaded GMC 2½ ton 6 x 6 truck and the motor grader bogged down. Maintenance with the pontoon barge drag was not at all satisfactory because of its bulk and lack of maneuverability.

From all these data it is apparent that a combination of agitation and rolling appears to be the most practical and effective means of stabilizing a snow road on the Arctic coastal plain. The best results were attained during the 1950-1951 winter test season with a pulvimixer followed by an 8-ft roller. The pulvimixer proved to be an excellent device for preparing a surface, and the ratio of the diameter of the roller to the weight permitted free rolling without plowing.

Using heat to increase the density of a snow road is considered inefficient because of the large quantity of heat lost to the atmosphere and the increased stabilization time. An actual evaluation of the benefits gained by using a surface heater is not possible with the data available; the benefits, however, are believed to be small.
Adding water to the surface has some effect, but in practice the test road was no better than the one built with only the pulvimixer and the roller. Further, water is at a premium on the Arctic plains.

The pontoon drag is unsatisfactory as a piece of snow stabilization equipment because of its size and weight. Moreover, these same factors, which affect its maneuverability, are also reasons for objecting to its use as a piece of maintenance equipment.

The best method of maintaining a snow road is with a weighted steel or wood frame drag. Either drag followed by the 8-ft roller is very effective in restoring the surface to good condition.

TESTS AT CAMP HALE, COLORADO

In 1950 the Bureau of Yards and Docks undertook a series of tests, as part of a snow compaction program, at Camp Hale. The purpose of the tests was to develop techniques and the equipment that could be used to improve the natural snow cover so that it would become capable of supporting heavy-wheeled traffic. Camp Hale is on Eagle River, 4½ miles west of the Continental Divide. The snow depths and temperature data for the test period (late January, 1950, to mid-March, 1951) follow.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Average snow depth</td>
<td>17 in.</td>
</tr>
<tr>
<td>Maximum snow depth</td>
<td>30 in</td>
</tr>
<tr>
<td>Average temperature</td>
<td>17°F.</td>
</tr>
<tr>
<td>Maximum temperature</td>
<td>64°F.</td>
</tr>
<tr>
<td>Minimum temperature</td>
<td>-28°F</td>
</tr>
</tbody>
</table>

The following equipment was used.

(1) 8-ft diam, variable weight snow roller
(2) Pontoon barge drag
(3) Seaman's 6-ft-wide pulvimixer
(4) Disk harrow
(5) 250,000-Btu/hr gasoline heater

The pulvimixer, harrow, and heater were either ski or toboggan mounted, exerting a maximum intensity of pressure of 2 psi. Of this equipment, the roller and pulvimixer were the most effective in producing suitable snow surfaces.
The conclusions that can be drawn from these tests resolve themselves into a discussion of the effects of the multiple-pass procedure, a discussion of the relative merits of the different categories of compaction techniques, and a discussion of the instrumentation used. It can be said that the multiple-pass procedure is more effective than the single-pass for increasing the density and in most cases for increasing the hardness. It appears that the use of the multiple-pass beyond the third or fourth pass is impractical.

A comparison of the density results obtained by the numerous techniques tried shows that the various techniques rank in the following order.

1. Drag, pulvimixer, roller
2. Roller, disk harrow, drag
3. Roller (ballasted)
4. Pulvimixer, roller
5. Roller
6. Pulvimixer, drag
7. Pulvimixer
8. Pulvimixer, heater
9. Drag
10. Disk harrow

The first two techniques successfully withstood limited traffic of a 4-ton 6 x 6 Army wrecking truck. Strips constructed by the other methods were not tested by subjection to traffic.

It is significant that, in the three reports, the results appear to vary tremendously, although at each site pulverizing and rollers were utilized to construct the roadbed. The wide discrepancy in the trafficability described leads this author to conclude that atmospheric conditions (associated with the various sites) play a tremendous role in the resulting load carrying capacity. It is encouraging to note that the most successful method of construction (that is, pulvimixer and 8-ft roller at Barrow, Alaska) allowed a
26-ton load to be transported with only shallow depressions resulting from its passage; however, one infers that substantial maintenance of the road would be necessary. Likewise, at Fort Churchill, several passes of a 20-ton load moving at 25 mph were possible.

In the joint US-Canadian Report on Compaction Trials (1952-53), the pulverizing technique was not separated specifically from the other cold processing techniques (dragging or rolling), which makes it difficult to separate the conclusions. For this reason, all the general conclusions are presented here:

"1. Encouraging results were obtained at Kapuskasing, Fort Churchill and Goose Bay. However, the inconclusive results from Houghton, Mich., and Thule, Greenland, definitely indicate that air, snow temperatures and snow types, influence the results to such a degree that it appears that only under favourable conditions, yet to be defined, will snow surfaces be produced which will withstand continual usage by vehicular traffic and airplane wheels. The most favourable conditions appear to be:

(a) Snow depth between 12" and 44".
(b) Initial snow density of at least 0.15 gms/cc.
(c) Mean ambient air temperature of not more than 15°F. together with a positive temperature gradient.

2. There appears to be a relationship between density and Rammsonde hardness number which might be used as an indication that a compacted snow surface will carry military vehicular traffic. Densities of 0.54 gms/cc or over and average Rammsonde hardness number of 350 or over indicate that the surface will probably support standard military vehicles. Densities of 0.46 gms/cc or over and average Rammsonde hardness numbers of 250 and over indicate a surface which will probably support single landings of aircraft of the Avenger, DC-3 or Lancaster types.

72
3. The methods used in these trials did not produce densities in excess of 0.54 gms/cc without the application of heat or addition of moisture followed by rolling with heavy rollers. The best results were obtained with the 22,400 lb segmented roller.

4. In a comparative test it was found that the same effort was required to build a road by snow compaction methods as by logging road methods. A road constructed by the latter method will withstand continued use by heavy vehicular traffic better than one constructed by snow compaction methods.

5. Tire type and pressures have a decided effect on the amount of deterioration caused to any compacted snow surface by vehicular traffic. US Marine Corps sand tires or commercial pattern tires with low pressure were found to be the least damaging.

6. It is considered that little improvement in present techniques and equipments can be expected until the reason for some of the phenomena observed is understood."

Due to the various degrees of success of snow road field trails, this author believes that some field trials incorporated into existing roads are warranted along the pipeline route so that the most reliable and efficient methods of construction can be established for each general area (Fort Simpson, Fort Good Hope, and Tuktoyaktuk).
(c) Ice Roads:

The term "ice roads" in the literature appears to refer to two completely different road conditions. The first conditions is one where water is physically placed on a snow road in order to form a snow-ice mixture which freezes into a solid road grade, which is referred to in this report as an "ice road". The other road condition is described as a snow road or ice road built on an ice cover (such as a lake or river). The latter should be referred to as a "snow road on ice" or an "ice road on ice". These descriptions would certainly eliminate much literary confusion on the subject.

Regardless of the foundation material, ice roads are constructed by a more or less standard procedure. This procedure entails building a snow road by either compaction or processing, after which water is introduced into at least the surface layer by usually one of two methods. One method entails spraying water directly onto the snow road. This procedure has been tested with regard to physical application by the US Naval Civil Engineering Laboratory and is described in Technical Report R111 and R111 Supplement. The other method entails the melting of the in-place snow road surface by the use of heaters. Most literature on these ice road processes concerns heaters, but generally little success (at least from a practical standpoint) has been realized. The joint US-Canadian snow compaction trials describe the heater techniques:
"Two heaters were used by the trial team, during the trials: a Surface Combustion Corporation heater and a Porta Products Company heater. These heaters were mounted on the rotor hoods of the pulvimixers so that the hot gases of combustion were discharged into and through the snow as it was agitated inside the rotor hood."

A reference is also made in this source as to the rates of production of the heater-pulvimixer units. In general, they are slower than the ordinary pulvimixer since the tractors operate at a lower gear range in order to introduce sufficient heat to the snow.

The data presented allows one general observation to be made with regard to the snow pulvimixers: the Surface Combustion pulvimixer is more efficient than the Porta Products burner (it utilizes approximately only one-third the amount of fuel with essentially the same results.)

Another unique idea to produce an ice road is mentioned by the same source. This method entails the admixture of a chemical, which is described below:

"It was anticipated prior to the trials that calcium carbide would react with snow at high snow temperatures in the range 20° - 32°F. Surprisingly enough the reaction was found to be possible with surface snow which was as low as -30°F.

The reaction of the snow even at these cold temperatures is violent, the flames sometimes reaching as high as 10 feet if the powder is applied to the snow in any quantity. When the gases from the powdered calcium and snow are ignited, the area literally explodes."
Initially small tests were made to test the efficacy of the idea. One test taking place with a snow temperature of 25°F. (on surface). Since the reaction was found to be satisfactory the full scale tests were then carried out. Two lanes were selected and a 100 lb container of powdered calcium carbide was emptied along each lane, equal to 0.12 lbs/sq.ft., from the rear of a sled drawn by a tractor. Behind this sled men with rakes, folded and blended the snow-carbide mixture. After the passage of the sled, a match was thrown on the upwind end of the lane producing a considerable amount of heat. In places the heat produced was insufficient to produce any large amount of moisture due to the scanty concentration of carbide. The lane was immediately rolled with the 22,000 lb rollers but due to poor mixing neither the densities or hardness were found to be homogeneous.

It was considered too dangerous to employ pulvimixers to mix the snow since the large amount of methylene gas generated might be drawn into the manifolds of the tractors and pulvimixers.

While neither lane was particularly successful, it was surmised, though not attempted, that the method could be used to patch ruts in snow roads where water was not readily available."

Environmental concern would certainly require residue testing following the use of such a method. Nevertheless, the method could have some application, in special cases, as a maintenance procedure.
5. Costs

The costs of winter roads depend mainly upon the effort required to obtain the degree of compaction (or density) required for the weight of load being transported. For this reason, the various types of winter roads will be discussed separately.

(a) Winter Trails

The Engineering News-Record (April 24, 1969) reported that the 540 mile Fairbanks-Sagwon winter road was initially pushed through at a cost of $350,000. This reduces to $666/mile. Re-opening costs are expected to be slightly less than $500/mile. At least two other reports confirm these cost figures.

The Royal Commission on Northern Transportation, Province of Manitoba, (1969) gives the cost of constructing a winter trail at $500/mile with an annual maintenance cost of $50/mile.

In summary, a winter trail can be constructed for a cost in the order of $500 to $1000 per mile.

(b) Snow Roads

A snow road will vary in cost considerably depending on the construction procedure, depth of snow, etc. Although cost figures for snow roads do
not appear in the literature, the Canadian-US Snow Compaction Trials listed typical machine and man-hours, and the fuel required to construct and support a mile of snow road. The unit-cost figures presented are typical of engineering estimating costs currently in use. The resulting cost figure is derived as:

\[
\begin{align*}
72 \text{ Man Hours @ } \$15/\text{hr} & = 1080 \\
40 \text{ Machine Hrs @ } \$20/\text{hr} & = 800 \\
180 \text{ Gals. of fuel @ } \$1/\text{gal.} & = 180 \\
\end{align*}
\]

$2060/$mile

Add 10% (Maintenance) = 206

Total (Approximate) = $2300/$mile

From these figures, it can be concluded that a high quality snow road can be completed for a cost in the order of $3000/$mile.

(c) **Ice Roads**

The methods used to construct ice roads permit the cost of construction to be estimated by adding the cost of sprinkling or heating and the extra compacting passes to the cost of a snow road:

\[
\begin{align*}
10 \text{ extra Man Hours @ } \$15/\text{hr} & = 150 \\
5 \text{ extra Machine Hrs @ } \$20/\text{hr} & = 100 \\
100 \text{ extra Gals. Fuel @ } \$1/\text{gal.} & = 100 \\
\text{Extra cost of Icing} & = 350/\text{mile}
\end{align*}
\]
Pemcan Services estimate their Class IV, winter only access road to cost in the order of $6,000/mile. Thus, a first class winter road should be constructed for a cost in the order of $3,000-$6,000/mile.

A rough comparison between the cost of constructing snow roads and permanent roads demonstrates that a snow road built every winter at a cost of $6,000/mile is comparable in annual charges (interest at 8%) to a permanent road at a capital cost of $80,000/mile. Thus, on an annual cost basis, it seems to matter little which type of road is constructed.

The decision to build one or the other type of road, therefore, must be made on some basis other than annual cost. Decisions made by individual companies should be based on the length of time the road is to be used. For example, in the comparison above, unless at least 20 years or more of use can be guaranteed for an $80,000/mile road, the capital investment is not justified. A recommendation for winter roads as an alternative assumes that virtually no summer access will be required.
TRAFFICABILITY OF WINTER ROADS

In the Western Arctic the trafficability of winter roads can depend on many factors with climate being one of the most predominant. The travel season, vegetative cover, snow drifting, drainage problems and icings can also limit the trafficability of winter roads.

A. Climate

Records of the climatic conditions in the western Arctic are probably the most heavily documented topic of the region. For this reason only a brief description of factors directly related to winter roads will be included here.

Snow depth and distribution are probably the two most important climatic factors related to winter roads other than temperature itself. Klein et al in NRC of Canada Technical Memorandum No. 18 give a good description of snow and significant characteristics of snow cover.

Potter (1965) gives one of the most complete and recent summaries of snow cover parameters. Charts are presented for many significant parameters related to snow roads, such as least depth of maximum snow cover, greatest depth of maximum snow cover, etc. This information is presented for all of Canada, including the Arctic and Arctic Islands.
Frequency of depths "greater than" a certain magnitude are also presented for selected stations.

Analysis of data from the Monthly Record, Meteorological Observations, Environment Canada, from 1922 to 1971, shows that on December 31 snow cover of less than 8" can be expected at:

- Tuktoyaktuk - 33% of the time
- Inuvik - Aklavik area - 8% of the time
- Fort Good Hope - South - 3 to 6% of the time.

On this basis, it appears that winter trails, snow roads or ice roads are all viable alternatives to other transportation modes for construction in the western Arctic. Only in the area of Tuktoyaktuk does a lack of snow occur with sufficient frequency to inhibit the construction of snow roads. However, in this area the treeless and relatively flat terrain would facilitate the collection of snow adjacent to the right-of-way from which a workable depth of snow could be built up.

A factor worth noting, both from a transportation and a construction viewpoint, is that in 1932 Fort Good Hope had an accumulated snow depth of 92" as of December 31. Under such conditions the construction of transportation facilities, and of a pipeline and its subsequent maintenance, would be severely hampered. It illustrates, too, that there will be an-ever present need to make decisions regarding modes of transportation in the field, or existing conditions dictate.
Further analysis of Potter's data allows the construction of Figures 5, 6, and 7, which show the minimum, maximum and median month end accumulated snow depth for selected stations along the Mackenzie River Valley. This data indicates that there will be serious problems in the construction of western Arctic snow roads, since the optimum depth of snow for a processed snow road is between 12" and 44", whereas in some winters on record snow depths have certainly been less than 12". In practice, if processed snow or ice roads are to be an acceptable mode of transportation, at least 8" of snow should be available by December 31, if a snow road is to be in service by the middle of January. This conclusion has been reached by analysis of "raw" data.
MINIMUM MONTH END ACCUMULATED SNOW DEPTH AT SELECTED STATIONS ALONG THE MACKENZIE VALLEY.
(20 YEARS OF RECORD)

FIGURE 5

TEMPLETON ENGINEERING COMPANY
MAXIMUM MONTH END ACCUMULATED SNOW DEPTH AT SELECTED STATIONS ALONG THE MACKENZIE VALLEY.
(20 YEARS OF RECORD)
MEDIAN MONTH END ACCUMULATED SNOW DEPTH AT SELECTED STATIONS ALONG THE MACKENZIE VALLEY.
(20 YEARS OF RECORD)

FIGURE 7
TEMPLETON ENGINEERING COMPANY
For the region of concern, the minimum winter snow depth on the average is 12 inches and the maximum winter snow depth is 30 inches. The consistency of these depths over the western Canadian Arctic is surprising. Records over a period of 20 winters also indicate that a 30-day difference in the number of days with 1 inch of snow cover or more exists between Yellowknife and Inuvik.

Environment Canada publishes meteorological observations daily and monthly records also are available. (Some data for the western Arctic even dates back to the early 1920's.) At present, daily temperatures, precipitation and summaries of pressure, temperature, humidity, cloud, visibility and wind are recorded; so are details of sunshine, soil temperature, total daily solar radiation, and rain gauge and class "A" pan evaporation.

Information on freeze-up and break-up dates of water bodies in Canada is available from Allen (1964) and Allen and Cudbird (1971), but this data is more or less raw, in that no analyses or charts are given.

Temperature, humidity, visibility and wind could drastically affect winter road use. Some restrictive factors would be abnormally high seasonal temperatures, low humidity (which could cause sublimation and limit road capacity) and poor visibility due to fog or blowing snow.
A statistical analysis of the expected number of days that winter roads could be utilized due to restrictions from all factors would be useful. Ample data is available in the literature, but statistical analysis of some data is warranted.

B. Travel Season

The length of travel season for winter roads along the Mackenzie Valley varies considerably from year to year. However, variations from place to place within a given year appear to be quite consistent. About 4-6 weeks difference in length of winter road use can be expected between Ft. Simpson and Inuvik, due mainly to the lower temperatures experienced in the more northerly region early in the fall and late in the spring. During pipeline construction, movement of bulk freight into the construction region north of Ft. Simpson would be restricted by the conditions at Ft. Simpson. But actual construction in the northern regions would be able to proceed under "winter conditions" for 2-3 weeks after operations in southern areas have ceased.

In the past, winter road use has been restricted both in the fall and spring more by ice bridge build-up and deterioration than by the condition of the winter roads. (This topic will be discussed further in the Ice Bridges section of this report). If, however, snow roads or ice roads are constructed to withstand greater vehicle frequency and heavier loads than heretofore, this time difference could be closer, due to the relatively longer time it would take to construct a "processed" snow road. On the other hand, the better quality winter road could
have a longer usage time in the spring.

C. Vegetative Cover

Vegetative cover does not affect the trafficability of winter roads, other than possibly in the construction of a new route. During clearing of heavily forested areas, D-8's or similar vehicles are normally used to shear off the shallow rooted trees, and then the debris is windrowed similar to the current practice along seismic lines. The one objective of the operator of such heavy equipment should be to leave the peat and moss cover in tact, so that the natural insulation of the permafrost is not lost. Unless this is done, terrain degradation might severely hamper the use of the winter road along the affected portion, and great expense could be incurred in remedying the damage. It would be wise, in future, if more concern could be shown for forested areas during the planning of alignments for winter roads.

Rare and endangered species of vegetation do not appear to be of concern, and will not affect the use or alignment of winter roads. It is doubtful if any vegetative species would be eliminated by this or any other activity associated with pipeline construction.

D. Snow Drifting

Drifting snow is the most critical factor in limiting the use of winter roads. However, it is possible that in winters where snowfall is minimal, drifting snow could be utilized to advantage for building
up a snow road to the depth required to protect the delicate terrain.

Snow fences are traditionally the method most widely used to control snow drifting. The Russians (Bzalobzheskiy, Komarov) have studied snow drifting extensively; and snow fences have received considerable attention. Komarov (NRC TT-1094) gives a good description of the physical factors affecting snow accumulation:

"1. The quantity of snow deposited out of a snow-wind flow when the wind velocity is decreased depends on the difference between at least the cube of the initial and final velocities; consequently a relatively small decrease in wind velocity facilitates the deposition of a substantial quantity of snow. For example, if the wind velocity is reduced by the factor of two, the total snow flux is reduced by more than a factor of eight.

2. Snow is deposited at barriers when there is a very small decrease in wind velocity due to the barrier and is observed when the wind velocity away from the barrier is more than 5-6 m/sec, i.e. snow deposition is unavoidable with any decrease in wind velocity.

3. The greatest quantity of snow is deposited beyond the initial decrease in velocity, although the decrease may be small, with further decrease in wind velocity by succeeding barriers, for example, the second and third rows of fences, the quantity of snow deposited decreases.

On the basis of these results one can make a number of practical suggestions to increase the efficiency of snow control measures.
1. In designing single-row fences there is no need to try to reduce the wind velocity beyond the fence to the zero point. It is completely sufficient to create a situation in which the wind velocity would be reduced to 3 - 4 m/sec, i.e. a velocity at which there would be no noticeable snow migration.

2. In constructing multiple fences, such as a series of parallel barriers as well as the planting of forest strips, the design at the present time is to have each row of fence operating independently and reducing wind velocity as much as possible (up to 80 - 85%) of that over the open fields. From an analysis of the rules governing snow transfer and deposition it follows that the most effective operation of a multiple-row fence would occur if the snow-wind flux would fall under the joint influence of all the rows of the fence. From this it would be expedient to build each succeeding row of fence with an increase in open space between, but designed so that the velocity of the wind would be reduced evenly, and beyond the last row it should not exceed 3 - 4 m/sec, at which snow transfer is not observed.

3. As regards retaining snow on the fields by means of mobile fences, it should be noted that with grid-type fences one should try to have 20-25% density in the framework and built to a height of 1 m. With such dimensions a wide, flat snow cover is formed reaching the height of the fence and extending away about 25 to 30 times the height of the fence. This is the most favourable arrangement as far as distribution of snow on the field is concerned. Let us recall that at the present time in protecting railroads the fences usually have 25 - 50% density, which form short, high walls or drifts. Having a more open type of grid work for the fence not only facilitates a more rational distribution of snow on the fields but also reduces the expenditure of material and labour.

4. Since the length of the snow-collecting area from which the snow is transferred to the fence is limited, snow retention as a measure of combatting snowdrifting can be effective on the fields adjacent to the roads up to a width of 2 - 3 km, i.e. the area over which the snow may be transferred."

Schneider (1962) also provides an excellent description of measures to combat snow drifting, and gives two general concepts:
1. Installations at which the snow is blown over or past the place to be protected.

A. The flattening off of the slopes of cuts;

B. The raising of the roadway to a height where it will be swept by the wind;

C. Erection of fence-like structures or walls which guide the wind so that it sweeps over the object to be kept clear and carries the snow with it (guide walls, baffles);

D. Parapets which guide the wind and the snow over the object.

2. Installations which cause the drifting snow to be deposited before it reaches the object:

E. Rows of trees and hedges;

F. The erection of snow fences;

G. The widening of cuts;

H. Makeshift devices;
   1. Snow walls made from blocks of snow;
   2. Snow dykes;
   3. Earth dykes;
   4. Walls of fir and pine branches, reeds.

It is obvious from these descriptions that many of these control measures are impractical from the point of view of winter roads in the Arctic. Nevertheless, some of the methods (such as raising the roadway, erection of snow fences and the use of snow dikes) may find some use. In forested areas the correct placement of windrowed trees removed from the right-of-way might be used to great advantage as a snow accumulation or snow clearing mechanism.
E. Drainage and Icings

Drainage has been recognized as one of the most important factors (Crawford and Johnston, Sprague, Dynamic North Books I and II) to be taken into account in the planning of roads in the north. Three references directly associate a drainage problem to winter roads. Lewellen and Brown (1969) describe a situation whereby a snow road, constructed in the winter of 1963-64, was effective in temporarily damming the run-off waters, which caused extensive thermal erosion. Another reference describes how the melting of a build-up snow road on a hillside caused thermal erosion due to the concentrated meltwater. The third reference is that of Hernandez (Appendix "A") and relates to an exposed ice wedge.

In the winter, "icings" of the roadway are the major consequence of poor drainage. Icings are sheets, terraces, domes and cones of ice, sometimes up to twenty feet thick, and in some instances covering thousands of acres (Hake, 1943). Gardner (1961), Hake (1943), and Thompson (1966) give detailed accounts of this most serious problem of the Alaskan Highway. Because it is nearly impossible to prevent icings, good winter road route location is imperative.

Groundwater flow in permafrost regions can be considerable. Brandon (1963) and Williams and Waller (1963) both give accounts of it, and how the groundwater flow can occur in the unfrozen materials above, within or below the permafrost. Springs can be formed with permafrost acting as the top confining layer. Because of this phenomena, icings
are more common on permanently constructed roads where the groundwater flow regime is cut-off from crossing the road, but groundwater flow continues due to the artesian condition. This is an ideal situation for "icing" to occur.

Both groundwater and drainage are important aspects that have to be considered in winter road operation. If drainage is necessary, several factors are worth noting. Arctic Engineering, (1955) gives some excellent points:

"SURFACE DRAINAGE. In planning for drainage of surface water, the following procedure is recommended.

(1) Reduce the possibility of fields of surface water by providing an adequate number of structures discharging into natural drains away from the road. Natural drains should preferably be on the low side of the roadway so that spring melt water from the icefield will not be required to pass through the drainage structures.

(2) Construct ditches to intercept sidehill drainage.

(3) Locate side ditches as far from the crown of the road as is practicable. The shoulder between the edge of the road and the ditch should be wide enough for storing snow.

(4) Use deep, narrow ditches in preference to wide, shallow ones. The thickness of surface ice will be the same for both, but the depth of the narrow ditch allows free flow of water for a longer period than does the shallow ditch.

(5) Locate drainage ditches and related facilities, when practicable, including haul roads on the side of the road least vulnerable to damage from construction activity. Disturbance of the ground during construction often results in an irreparable altering of the thermal regime.
(6) Provide adequate checks to prevent erosion in side ditches.

(7) Include in specifications the requirement that all excavations made near the roadbed, such as borrow pits, be drained.

(8) Make culvert sections deep and narrow rather than square. For ground drainage, deep, narrow sections are preferable.

SUBSURFACE DRAINAGE. In planning for drainage of subsurface water the following procedure is recommended.

(1) Anticipate the effect of cuts and fills on flows of ground water by providing for construction of French or other types of drains.

(2) Give special attention to drainage of road surfaces that are subject to heavy traffic and that may be particularly subject to frost boils during the spring thaw.

(3) Provide for thawing of underground drains and culverts that are susceptible to icing by installation of small pipes that can be connected to portable boilers when icing occurs.

SURFACE ICING. Because effluent ground-seepage icing frequently varies with the weather conditions and other factors, its control is more often a maintenance rather than a design problem. Sometimes, however, the possible formation can be forecast and preventive measures specified. As previously stated, it is preferable, when locating a line, to avoid areas that appear susceptible to seepage icing unless it seems practicable to prevent or control it.

It can be anticipated that drainage problems will affect winter road operations. However, it also appears that winter roads will not be affected by icings to the extent that permanent roads have been in the past.
F. Snow/Vehicle Trafficability

Nuttall and Thompson (Vol. I and II) and Wilson and Thompson (Vol. III) have extensively studied the snow-vehicle interaction. Vol. I gives a detailed description of the technique called the Nakaya "Roaring Bonfire". This gasoline-fired smoke-producing system simply etches the lines of stress (or stress bulb) upon the smooth vertically cut cross-section of the traffic lane. It allows one to locate, in the vertical section of the snow pack, the depth to which a certain vehicle is operating. Knowledge of the point when the pressure bulb reaches the ground level would be of interest in Arctic winter road studies, as it could indicate under what conditions depression of the frozen tundra might be expected.

Vol. II concentrated on the use of a shear vane and plate penetrometer to measure snow properties. Although further testing was recommended, some degree of disappointment in the results was indicated. Vol. III related to basic tests such as drawbar pull, slip, trim and sinkage of specific vehicles. This volume summarized the conclusions of all the tests described in the three volumes, which are given below:

1) The present vehicle mobility test procedure in snow is highly sensitive to depth of the snow pack and great care must be taken to record accurately the snow depth in which each reading of drawbar pull, slip, trim and sinkage is made in order that coherent results may be presented.
2) It is possible to obtain good traction either from the coarse-grained snows having high dynamic shearing resistance, found near the bottom of the pack, or from the fine-grained, low shearing resistance snows near the top of the pack. In the latter case, sufficient track area must be provided to ensure that the sinkage and so the motion resistance is very low and that use is made of the small cohesive component of the snow's shear strength.

3) Valid measurements of mechanical and physical properties of the snow pack can be of great assistance in the interpretation of vehicle test data.

4) The Nakaya "Roaring Bonfire" Technique can be of great assistance in interpretation of vehicle performance data through providing a physical picture of the location in the vertical section of the snow pack in which the vehicle is operating at any given time.

5) The results of comparative vehicle tests have been shown to be of no value in the solution of vehicle design problems in relation to vehicle mobility in snow although they may be of interim interest to the vehicle designer. Quantitative evaluation of changes in vehicle mobility resulting from design changes can only be made on the basis of absolute test results obtained by a group of procedures of the types demonstrated in the three volumes of this report.

Diamond's (1956) studies of the trafficability of snow related mainly to off-road vehicles. It was found that some difference in performance results with the use of certain types of grousers attached to the vehicle track or half-track. Matthews et al (1955) studied the trafficability of Alaskan silts, with some of the results being pertinent to winter roads and winter road planning. Their findings were summarized as follows:

1. It appears that vegetation is a guide to trafficability. Since birch trees grow on well-drained soil, black spruce in swamps, and spruce, alder, aspen, and willow where drainage is poor, the presence or absence of the above trees indicates soil moisture and, hence, the trafficability.
2. Because they have not been compacted by the clearing process, virgin soils have cone indices substantially lower than do cleared and cultivated soils. Although remolding tests were not made, it is expected that the trafficability of virgin soils will be very much lower than that of cleared and cultivated soils.

3. Trafficability on tops of hills is somewhat lower than it is on the surrounding hillside.

4. No useful correlation was found between trafficability and the engineering properties of the silts.

5. No correlation existed between the contoured cone index readings and topographic map contours or the soil map. However, both types of maps possess information very useful to a trafficability study.

Ager (1966) found that the "Rammsonde" seems to be the preferable method for measuring the trafficability of snow. This fact is very important as most tests on snow roads were conducted much earlier (in the 1950's), when the Rammsonde was used extensively.

Mellor (1963) studied the trafficability of many vehicles, but primarily under off-road conditions. It was found that vehicles tended to bog down in deep snow after several passes along the same track.

Knight reported on the U.S. Army trafficability tests in 1965, where a wide variety of indices were compared with vehicle trafficability.
Tests were based on a "go" or "no-go" basis rather than by any environmental considerations. Tests showed that snow trafficability depended on snow type, wetness, depth and strength. In muskeg, the strength and depth to the frozen layer are the most significant factors.

In summary, trafficability of snow vehicles has concentrated on off-road vehicles, unless the trafficability tests were conducted as part of snow-road compaction tests. For this reason, the section of this report on snow road construction is the most applicable discussion relating to the trafficability of winter roads. More specifically, hardness readings as indicated by density or Rammsonde readings are potentially the only available method to quantify the trafficability of winter roads.
Vehicles and Loads

It is difficult to specify specifically the limits to which a certain winter road can sustain a particular vehicle, partly due to the wide range of variation within the three basic winter road classifications. In general, however, some concept of the traffic limits can be presented.

(a) Winter Trails

Winter trails are generally used only by tracked vehicles. An exception is the use of wheeled vehicles, but with the stipulation that towing is generally required continuously or intermittently, usually by tracked vehicles. Due to the uncertainty of travel, vehicles often travel in "tractor trains". Arctic Engineering (1955), by the U.S. Navy lists a typical tractor train composition:

(1) One each weasel (train foreman) equipped with plywood cab and gyro compass.

(2) One each Class IV tractor equipped with Balderson cable-operated snowplow and Hyster towing winch.

(3) Four each bald-faced D-8 tractors equipped with Hyster towing winches.

(4) One each D-8 tractor equipped with Le Tourneau cable dozer and Hyster towing winch.

(5) One 10-24-ft. trail-type sleeper wanigan mounted on No. 9 Michler freighting sled, containing 50-watt radio transmitter and receiver.

(6) One 8- x 24-ft trail-type galley mounted on Michler No. 9 sled.

(7) One 8-x12-ft trail type shop mounted on Michler go-devil, containing a Hobart 300-amp gasoline engine welder, a Witte 8-kw 110/220-v 3-phase 60-cycle diesel-electric generator set, a Herman-Nelson heater, a 2-hp electric centrifugal train fuel pump, and miscellaneous tools, spare parts, and equipment.
(8) One fuel tanker (4 each T-6 pontoons mounted on Michler No. 9 sled).

(9) One each 8 x 12 ft. Michler (go-devil).

(10) Thirteen each Michler No. 9, 8 x 24 ft. flat-bed cargo sleds.

(11) Two each Michler No. 9, 8 x 36 ft. flat-bed cargo sleds.

(12) One each Michler No. 9, 8 x 24 ft. boxed flat-bed cargo sled.

(13) One each 18 x 36 ft. trail drag.

MacFarlane (1969) gives a very good account of the specifications of tracked vehicles now finding common use for muskeg travel. Many of these vehicles are in common use for snow trail travel and reference to this excellent description is recommended for a reader not familiar with the available tracked vehicles.

The Pipeline and Gas Journal (1972) gives the specifications of the Rolligon, which was used extensively on the snow trail from Fairbanks to the North Slope of Alaska. Success in gaining over land access to the North Slope of Alaska makes this vehicle particularly noteworthy.

Canadian Petroleum (1969) describes the most successful answers to transport problems across muskeg as being tracked vehicles that are designed to reduce ground pressures to something in the same order as a man walking (2.6 psi) or even lower. The Flex-Track-Nodwell
People are reported to have three suitable vehicles: a four-track, 12-ton payload transport that exerts a ground pressure of 2.6 psi when fully loaded; an FN400 model with a rated capacity of 20 tons; and an FN600 with a capacity of 30 tons; both the latter exert a ground pressure of less than 4 psi.

Canadian Petroleum (1971) reported on the Otaco sled, which can reduce ground pressures to 4 psi with a load of 30 tons. A description is given of a tractor train powered by a Foremost Husky-8, which has been used on the Mackenzie Delta to pull 3 Otaco sleds with a payload of over 100 tons. This vehicle averaged seven miles per hour over a 60 mile route. By pulling two extra sleds, this combination is believed to be capable of a payload in the order of 170 tons, and can operate at \(-60^\circ\text{F}\). This would allow Arctic transportation at a rate of 1000 ton miles per hour.

Oilweek (1970) also gives a good account of low pressure tracked vehicles. Confidence is illustrated that the future of tracked vehicles is assured, but further development is suggested.

The common characteristic of all these vehicles that appears to make them suitable for snow trail transport is their low ground pressure when loaded.
In general, tracked vehicles should have little problem travelling a properly constructed snow road. This requires that the density of the surface layer should be at least 0.55 gm/c.c. or greater; alternatively, a Ram reading of 350-450 must exist consistently over the roadway.

The Canadian-U.S. Compaction Trials included traffic-tire tests on a portion of an aircraft runway which was constructed in a similar manner to a snow road. The compacted snow was fourteen inches deep and had a density of 0.55 gm/c.c. The muskeg underlayer was frozen to a depth of eighteen inches. Twenty-four test lanes were staked out and three vehicle types with various tire treads were tested. Since this data is very significant, the results of these tests are presented in Table I in its entirety. Several conclusions can be drawn from these test results:

1. All lanes were trafficable after 20 passes;
2. Lanes traversed with sand tires inflated to the high or low pressure consistently improved with traffic.
3. Sand, commercial and military lugged tires, in that order, are preferable.

The sand tires utilized in these tests appear to be large-diameter, smooth tires, with parallel grooves running around the periphery.

A relatively simple test for trafficability (described as a means for assuring the above measure of success) was observed: if a small eight inch bread knife cannot be thrust by a 200 pound man into the snow road, the road is probably trafficable. (This author suggests a somewhat safer hand tool should be developed for this purpose).
### TABLE I

**THE FOLLOWING SUMMARIZED DATA SHEET IS SELF-EXPLANATORY**

Vehicle Speeds... 10 mph.  
4 Wheel Drive Used on all Vehicles Throughout the Tests.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Lane No.</th>
<th>Type Tires</th>
<th>Tire Pressure</th>
<th>No. Passes</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 x 6</td>
<td>1</td>
<td>Sand</td>
<td>35 Front</td>
<td>35 Rear</td>
<td>90% of ruts less than 1&quot; in depth. 10% of ruts ranged from 1&quot; to 2&quot; in depth. Snow surface apparently improved with increase of passes.</td>
</tr>
<tr>
<td>2 1/2 Ton Reo</td>
<td>2</td>
<td>Military</td>
<td>45 Front</td>
<td>80 Rear</td>
<td>50% of ruts 2&quot; to 5&quot; in depth. 50% of ruts 1&quot; to 2&quot; in depth.</td>
</tr>
<tr>
<td>60 cwt Ford</td>
<td>3</td>
<td>Sand</td>
<td>15 Front</td>
<td>15 Rear</td>
<td>85% of ruts less than 1&quot; in depth. 15% of ruts 1&quot; to 1 1/2&quot; in depth.</td>
</tr>
<tr>
<td>6 x 6</td>
<td>4</td>
<td>Sand</td>
<td>35 Front</td>
<td>35 Rear</td>
<td>85% of ruts less than 1&quot; in depth. 15% of ruts ranged from 1&quot; to 2&quot; in depth. Snow surface apparently improved with increase of passes.</td>
</tr>
<tr>
<td>2 1/2 Ton Reo</td>
<td>5</td>
<td>Military</td>
<td>45 Front</td>
<td>80 Rear</td>
<td>60% of ruts 2&quot; to 5&quot; in depth. 40% of ruts 1&quot; to 2&quot; in depth.</td>
</tr>
<tr>
<td>6 x 6</td>
<td>6</td>
<td>Sand</td>
<td>15 Front</td>
<td>15 Rear</td>
<td>85% of ruts less than 1&quot; in depth. 20% of ruts 1&quot; to 1 1/2&quot; in depth.</td>
</tr>
<tr>
<td>2 1/2 Ton Reo</td>
<td>7</td>
<td>Military</td>
<td>35 Front</td>
<td>50 Rear</td>
<td>60% of ruts 1&quot; to 2&quot; in depth. 40% of ruts 2&quot; to 4&quot; in depth.</td>
</tr>
<tr>
<td>4 x 4</td>
<td>8</td>
<td>Commercial</td>
<td>35 Front</td>
<td>35 Rear</td>
<td>90% of ruts 1&quot; to 2&quot; in depth. 10% of ruts 2&quot; to 4&quot; in depth. Ruts did not appear to deepen after 15th pass.</td>
</tr>
<tr>
<td>6 x 6</td>
<td>9</td>
<td>Commercial</td>
<td>35 Front</td>
<td>35 Rear</td>
<td>Similar to lane 8</td>
</tr>
<tr>
<td>Vehicle</td>
<td>Lane No.</td>
<td>Type</td>
<td>Tire Pressure</td>
<td>No. Passes</td>
<td>Remarks</td>
</tr>
<tr>
<td>---------------</td>
<td>----------</td>
<td>----------</td>
<td>---------------</td>
<td>------------</td>
<td>-------------------------------------------------------------------------</td>
</tr>
<tr>
<td>4 x 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60 cwt Ford</td>
<td>10</td>
<td>Military</td>
<td>35 Front</td>
<td>50 Rear</td>
<td>Similar to lane 7</td>
</tr>
<tr>
<td>6 x 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 1/2 Ton Int.</td>
<td>11</td>
<td>Commercial</td>
<td>15 Front</td>
<td>15 Rear</td>
<td>Average depth of ruts was 2&quot;. No tire penetration greater than 3&quot;.</td>
</tr>
<tr>
<td>4 x 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60 cwt Ford</td>
<td>12</td>
<td>Commercial</td>
<td>45 Front</td>
<td>80 Rear</td>
<td>Average depth of ruts 1 1/2&quot;. No tire penetration deeper than 1&quot;.</td>
</tr>
<tr>
<td>4 x 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60 cwt Ford</td>
<td>13</td>
<td>Commercial</td>
<td>35 Front</td>
<td>50 Rear</td>
<td>Average depth of ruts 1&quot;. No tire penetration deeper than 1 1/2&quot;.</td>
</tr>
<tr>
<td>6 x 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 1/2 Ton Int.</td>
<td>14</td>
<td>Commercial</td>
<td>15 Front</td>
<td>15 Rear</td>
<td>Average depth of ruts 1&quot;. No tire penetration deeper than 1 1/2&quot;.</td>
</tr>
<tr>
<td>4 x 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60 cwt Ford</td>
<td>15</td>
<td>Commercial</td>
<td>45 Front</td>
<td>80 Rear</td>
<td>Similar to lane 12</td>
</tr>
<tr>
<td>6 x 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 1/2 Ton Reo</td>
<td>16</td>
<td>Military</td>
<td>15 Front</td>
<td>15 Rear</td>
<td>Average depth of ruts was 2&quot;. No tire penetration greater than 4&quot;.</td>
</tr>
<tr>
<td>6 x 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 1/2 Ton Reo</td>
<td>17</td>
<td>Military</td>
<td>35 Front</td>
<td>35 Rear</td>
<td>Average depth of ruts was 1&quot;. No tire penetration greater than 2&quot;.</td>
</tr>
<tr>
<td>4 x 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60 cwt Ford</td>
<td>18</td>
<td>Commercial</td>
<td>35 Front</td>
<td>50 Rear</td>
<td>50% of ruts 2&quot; to 5&quot; in depth. 50% of ruts 1&quot; to 2&quot; in depth. Ruts well compacted upon completion of test.</td>
</tr>
<tr>
<td>6 x 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 1/2 Ton Reo</td>
<td>19</td>
<td>Military</td>
<td>15 Front</td>
<td>15 Rear</td>
<td>Similar to lane 16</td>
</tr>
</tbody>
</table>
### TABLE I (Cont'd)

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Lane No.</th>
<th>Type</th>
<th>Tire Pressure</th>
<th>No. Tires</th>
<th>Passes</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 x 6</td>
<td>20</td>
<td>Military</td>
<td>35 Front</td>
<td>20</td>
<td></td>
<td>Average depth of ruts was 1&quot;. No tire penetration greater than 2&quot;.</td>
</tr>
<tr>
<td>2 1/2 Ton Reo</td>
<td>20</td>
<td>Military</td>
<td>35 Rear</td>
<td>20</td>
<td></td>
<td>Ruts were well compacted after 20 passes.</td>
</tr>
<tr>
<td>6 x 6</td>
<td>21 &amp; 22</td>
<td>Military</td>
<td>35 Front</td>
<td>20</td>
<td></td>
<td>Average depth of ruts approximately 1&quot;. No tire penetration greater than 2&quot;. Ruts well compacted.</td>
</tr>
<tr>
<td>2 1/2 Ton Int.</td>
<td>24</td>
<td>Military</td>
<td>15 Front</td>
<td>20</td>
<td></td>
<td>Average tire penetration was 2&quot; with no ruts deeper than 3 1/2&quot;.</td>
</tr>
</tbody>
</table>
As reported by the joint Canadian-U.S. Compaction Trials, heavy rollers will compact snow in two or three passes to 0.54 gms/c.c. irrespective of type. From this point there has to be a decrease in voids to bring an increase in density to 0.60 gms/c.c. This can be done by the addition of 10.4% by weight of water or, in 12" of snow already compacted to 0.54 gms/c.c., the addition of 3.3 lbs of water per sq. foot. For a 20-foot road width, this is approximately equivalent to 35,000 gallons per mile. Except for special maintenance or unique conditions, the hauling of water is a very inefficient method of obtaining ice roads.

The impracticability of hauling water in Arctic conditions and also the scarcity of this resource in many regions in the winter probably accounts for the majority of ice road research being conducted by the use of heated pulvimixers (P.V.). On this basis the minimum processing required for a road which can definitely carry heavy traffic is:

1) 2 passes very heavy roller Density approaching 0.54-0.55 gms/cc
2) 5 passes P.V. with heater 10% moisture added
3) 1 pass of very heavy roller Density increased to 0.56 - 0.60 gms/cc
(22,000 lbs. and above)

Fuel consumption per hour for the above combinations are as follows:

2 passes roller with D-7 or TD-18A at 4.7 gals/hr = 9.4
5 passes heater and P.V. at 42.9 gals/hr = 214.5 *
2 passes roller with D-7 at 4.7 gals/hr = 9.4
(175 gals kerosene. 58.3 diesel fuel) 233.3 gals/hr

* Consumption for snow at 19°F.
Further tests conducted by the same authority revealed some very significant findings, which are presented in Table II in summary form. This table shows the percentage of lanes, laid by each method, that were able to carry traffic:

**TABLE II**

<table>
<thead>
<tr>
<th>Method</th>
<th>Percentage of lanes placed by method indicated which carried traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulvimixer with heat &amp; rollers</td>
<td>82%</td>
</tr>
<tr>
<td>Rollers (segmented &amp; rubber tires) alone</td>
<td>61%</td>
</tr>
<tr>
<td>Pulvimixers without heat and with rollers</td>
<td>56%</td>
</tr>
<tr>
<td>Pulvimixers alone with heat</td>
<td>7%</td>
</tr>
<tr>
<td>Pulvimixers alone without heat</td>
<td>12.5%</td>
</tr>
</tbody>
</table>

The above analysis is of course again without regard to ambient air temperature, temperature of processing, period of age hardening or hardened snow temperature.

From the table, it can be seen that with pulvimixers (with or without heat), and under wide ambient air temperature fluctuations, it is almost impossible to produce a good road which will carry traffic without the use of heavy rollers. However, if the criteria laid down by the directive for traffic tests are disregarded and rutting of the road accepted, additional and continued traffic will probably further compact such roads so that after a period of time they become very hard. This actually occurred at Goose Bay and Kapuskasing.

This same source indicates that:

"The sequence of operations for the construction of roads, if undertaken, be:

(a) **Construction**

1. Breaking pass if snow is above 36" depth
2. 1 or more passes of a heavy roller (22000 lb) if necessary to attain density of 0.53 gms/cc
3. 5 Passes of heater pulvimixer (2.56 mil BTUs/hr, to attain density 0.55 - 0.56 gms/cc and 10% moisture content.
4. 2 Passes of heavy roller

(b) **Improvement** - Several passes of heavy drag to improve and smooth surface.

(c) **Maintenance** - Drag or roll or if possible use high speed plow or blower."
Traffic tests were conducted on a mile stretch of ice road constructed in this manner. These tests indicated that after 25 passes by vehicles with weights ranging from 1 1/2 to 20 tons no damage was done to the road even with normal tire pressures (ranging from 35 - 65 psi). Results were so good that tests were not conducted at low tire pressures. During later testing of the same road, in which 74 passes were made by the same vehicles, observers agreed that although some ruts occurred the road was generally better than before testing.

Moser, in Vol. 1 of the Symposium on Cold Regions Engineering (1971) gives a good description of high strength snow roads. Construction rates of up to 1 mile per day per 6-man crew have been achieved, but new techniques are expected to increase this to 1 1/2 miles per day with a 4-man crew. This is in the context of Antarctica experience.

Texas Eastern Transmission Corporation (See Bliss Appendix "A") has supplied the only available information on the maximum volume of traffic that could be expected along a particular pipeline spread. This information indicates that the maximum tire pressure of vehicles would be 50 psi, the maximum load would be about 60 tons, and the total maximum volume of traffic would be in the order of 36,000 passes.
Military experience indicates that it is possible for winter roads to withstand a tire pressure of 50 psi and heavier loads than 60 tons have already been transported on winter roads (Canadian Petroleum Roessingh, Perrin).

The most heavily trafficked snow road referred to in the literature was one constructed during the U.S.-Canadian Joint Snow Compaction Trials at Churchill. Over 22,000 miles were compiled over a 4.6 mile section with a range of vehicles all loaded to capacity. This is equivalent to approximately 5,000 passes, which is considerably less than the estimated volume of traffic associated with pipeline construction. On the other hand, the road tested was a snow road constructed by the compaction (drag) technique only. With better construction techniques, considerable improvements in the maximum possible number of passes could be expected.

The above figures indicate that one significant piece of research should be completed immediately; that is an answer must be found to the question: "Can the best possible constructed snow or ice road (in terms of hardness) sustain the volume of traffic and loads anticipated for pipeline construction?" This would entail the careful construction of a single lane of ice road in a loop, so that repeated loadings (passes) by selected vehicles could be accomplished.
A logging road of special interest was described in the joint Canadian-U.S. Compaction Trials. The comments related to terrain, construction and trafficking make this description worthy of quotation:

Of all logging roads studied in the Kapuskasing area, only one was really worthy of comment. This road, built by a logging Contractor to the Pulp and Paper Co., was exceptionally smooth and hard. Located twenty miles West of Kapuskasing, it ran North from the Trans Canada highway into the bush for twelve miles to a river crossing where the contractor's main camp was located. In common with all roads built in this vicinity, curves and hills were the exception except in the first two miles where some fairly rugged topography, with a relief of 80-90 feet, was encountered.

The methods used in processing this road were found to differ from the Paper Company's practice. The jobber starts his road earlier in the season which although adds to the initial cost is offset by the superior surface and therefore higher traffic density obtained in the winter when trucking starts.

Construction:

In the early stages of winter, as soon as there is 2-3 in. of snow on the right of way, a light D-2 tractor makes one pass over the road. The road, used every winter, is clear of brush and stumps, and, is impassable in the summer. This initial pass of the D-2 tractor brings water to the surface in the soft spots which mixed with the layer of snow, brings about early penetration of the frost into the subgrade. A day later, or as soon as the frost has penetrated 1" -2" into the muskeg or soil, an extremely light and crude wooden drag is pulled over the road by the tractor until it is planed smooth. Two or even more passes of the drag are necessary.

Following this a tank sled is hauled over the road and approximately 0.1 gal/sq. ft. of lake water is sprayed on the road. A total of four passes are made creating a layer of 1 - 2 inches of frozen snow and water. According to men who have prepared these surfaces, the higher the air temperature, provided it remains below the freezing point, the better are the results from the road processed in this manner. After watering, the muskeg or soil is then allowed to freeze to a depth of five inches. Traffic is then allowed on the road. As soon as the early winter snows commence the road is continuously dragged smooth with the same wooden drag used in the beginning, loaded with about a ton of logs. In maintaining the road, at anytime, when the snowfall exceeds more than two inches, it is removed immediately by a V shaped "battle ship" plow mounted on a 3 ton GMC truck. Immediately following the use of the plow the road is again dragged to even out the surface. Should a snowfall occur while hauling is being carried on, the drag is hooked on the back of a loaded outgoing truck and detached from the truck at the entrance of the road. Returning trucks pick up the drag and take it back. In this manner the road is continuous-
ly maintained during a snowfall. In the Kapuskasing area such snowfalls seldom exceed five inches and therefore usually constitute no problem.

A typical cross section of this road is shown:

![Cross Section Diagram]

Density of the upper three inches of snow or the pavement averaged .52 gms/cc and was only three inches thick. Average Ramsonde hardness of this layer was 627. According to this year's findings this road could carry vehicular traffic of all types.

This road was continuously used by loaded pulpwood trucks, usually 3 ton GMCs carrying up to four cords of wood. At least twenty-five loads per day were taken out, the average weight of truck and load being about 15 tons. Total number of vehicles passing over the road per day was usually above sixty and included trucks and cars.

Of special interest was its unusually smooth surface. It was in fact stated that independent truckers would haul for this jobber in preference to taking shorter hauls, since high speeds were possible. This gave a greater return to the trucker. A jeep and a station wagon were able to traverse the road at speeds between 35 - 40 mph without trouble or discomfort to the passengers.

Of all the logging haul roads around Kapuskasing this was the smoothest and best. The success of this road appeared to be through what might be described as maintenance "discipline". The jobber kept strict control of his trucks. No lugged tires or tractors were allowed on the road, and trucks were not allowed to haul whenever the snowfall exceeded two inches. As a result the surface was always in superlative condition and it was stated that more wood was hauled over this jobber's road than any other in the area.

This was the ideal winter road, however, it must be noted that despite the low cost to build and maintain it, $1500.00 throughout the winter, its success was based on:
a) Early start in winter.
b) Continuous dragging.
c) Maintenance and trucking discipline.

Only under the conditions of static warfare would these conditions be militarily acceptable. The main interest in this study however, is in the use of snow and ice as a pavement. It is certain that if a pavement of this nature (See figure on previous page) can be placed on a firm subgrade, military vehicles could use winter roads at higher speeds than normally employed.
H. Maintenance

Maintenance of roads has been achieved consistently according to the literature by plowing, then dragging or rolling of the original roadway. A typical maintenance procedure covering the roadbed once with each unit is given as:

1 TD - 18A towing a timber drag
1 TD - 14A towing an 8 ft./3900 lb. corrugated roller
1 TD - 18A towing a 10 ft./7880 lb. corrugated roller.

In the Northwest Arctic region of concern, maintenance has been carried out by drags, or by blading only. Rollers have not been recorded as being used extensively in the area.

Arctic Engineering (1955) gives the most detailed coverage of maintenance procedures for roads and storage areas. The technology of snow removal in arctic areas probably has progressed considerably since then, although no specific reference to such has been found. Therefore, the Arctic Engineering procedures are presented here:

"SNOW REMOVAL. Complete removal of snow is required in regions where climatic conditions do not permit compaction or where snowfall is in excess of that which can be compacted. Light snowfalls are removed with angle dozers, tractor-mounted one-way blades, truck-mounted plows and rotary snowplows. Drifts are usually opened by tractors or trucks with V-blades or by a rotary snowplow. An effective cutter for high drifts is a rotary consisting of 3 horizontal light spiral blades, mounted one above the other. The action is similar to that of a disk harrow turned vertically. V-blades on wheeled vehicles are generally ineffective in packed and crusted snow. Large crawler tractors operating as bulldozers in parallel, tandem, or echelon should be used under such conditions. Dozers are quite effective in pulling down steep snowbanks so that rotary
plows can operate. The efficiency of displacement plows decreases rapidly as new windrows increase in depth. In general, rotary plows or blowers should be used to remove windrows over 10 inches high.

(a) Roads. Snow should be removed from the road surface as soon as possible after it falls. Equipment should, when practicable, be stored along the roads and, with its operators, should be ready to move promptly when a snowstorm occurs. Sections of the road subject to drifting should be patrolled in windy weather with drags or plows. Two and one-half to five-ton trucks with one-way blades are best adapted for clearing moderate depths of snow on long stretches of roads. The usually operate at from 15 to 25 mph. For heavier snowfalls or to widen traffic lanes, heavy 4-wheel drive special-purpose displacement plows are best, although standard 5-to 10-ton trucks equipped with straight V-blades are used on many highway networks. Standard equipment operates usually on heavy drifts at about 15 mph. Special-purpose equipment should be designed for 20 to 30 mph. V-shaped plows are more effective than other types in breaking through heavy drifts. Either V-shaped or straight-blade plows equipped with side wings are used to push the snow beyond the shoulder line and to provide room for additional snow storage. Abrasives for better traction and as ballast are usually carried by plowing trucks. Tractors are sometimes required for heavy snowfalls and deep drifts. Motorized graders are satisfactory for light snow.

(b) Bases. Snow removal from storage and service areas, driveways, and parking lots can be economically handled by truck or caterpillar-mounted straight blades and V-blades to accumulate and windrow the snow. The windrow is then loaded into dump trucks by snow blowers or snow loaders. Available in many types. Certain types of conveyor or front-end loaders are effective, but all available types are not suitable for advanced base use. Carryall scrapers are often used to remove snow from around buildings and from parking and material storage areas. Material piles should be so spaced that carryall scrapers can remove snow that drifts around them. In areas where the snow is dry and crystalline, snow should be disposed of in flat spoil piles on the downwind side of the camp area. Whenever possible, advantage should be taken of high wind to blow snow clear of operating areas. Often winds of even 10 to 20 mph are sufficient to blow light snow long distances. Constant operation of drags during periods of moderate winds prevents snow drifting on traffic lanes. In many areas rotary brushes have been effective in keeping loading platforms clear of snow. Several types of brushes and sweepers are available as standard equipment, but tests have indicated that all types are not suitable for advanced base use."

114
ICE BRIDGES

The topic of ice bridges (artificially thickened ice for river crossings) has received an abundance of attention in the literature. Analysis of this data gives this author the impression that technologically, ice bridges are the most advanced and positive aspect of a winter road.

A. Construction Methods

In the past, winter road construction and the construction of ice bridges has utilized "corduroy"; that is, trees that have been trimmed and laid parallel across the traffic lane. This practice is still common in many parts of Canada. However, in the Arctic this practice is less common, partly due to the non-existence of suitable timber. Use of timber in river crossings is permissible, subject to the following provision of the Territorial Lands Act for river crossings.

"Every operator shall
(a) When constructing a crossing of any waters
   (i) take all practicable precautions to avoid disturbing the adjacent ground surface or vegetation, and
   (ii) choose a location for the crossing that causes the least disturbance to the shores, banks and bed of the waters;

(b) When abandoning a crossing of waters
   (i) remove all debris and fill used in constructing the crossing, and
   (ii) restore the shores, banks and bed of the waters, as far as is practicable, to their previous condition; and

(c) When abandoning a crossing built on ice, remove all logs, timber or debris used in the construction of the crossing."
The tendency in the construction of arctic river crossings in the Mackenzie Valley and Delta areas has been to eliminate timber, and to construct ice bridges in the following manner. First a snow dike is built on both sides of the right of way by windrowing snow with light vehicles or snow blowers. In this manner snow is completely removed from the ice surface. These dikes are iced, or if snow is lacking, loos are used to confine the area. A hole is then cut in the ice, into which an intake line of a pump is inserted, and pumping of the "diked" area begins. This is completed by moving the pumps until the complete area is flooded with 1" or 2" of water. The water is allowed to freeze solidly, after which the ice bridge is built up to a one or two foot thickness in 1" or 2" lifts. Approaches are usually built of compacted snow frozen into place.

Carson (1955 and 1958) describes the construction of an ice bridge using timber in the Yukon Territory. Maintenance procedures to extend the use of the bridges into late spring utilized sawdust. This procedure is not acceptable by modern standards. (See section on Environmental Aspects).

Arctic Construction (1962) gives a good description of ice bridge construction with timber-reinforced approaches; some type of reinforced approach or built-up ice approaches will be required at many river crossings in the Arctic, since river banks are potentially one of the most serious terrain damage problems. The NRC (1958) Technical Memorandum No. 56 on the bearing strength of ice discusses ice bridges;
most specifically it mentions speed reductions required for vehicles, and also the fact that 36" of ice is required to carry 40 tons. Vehicle drowning and salvage is also discussed in some detail. A plot is presented of ice thickness versus load range.

B. **Equipment**

The equipment required for the construction of an ice bridge includes the following:

- Snow clearing or snow blowing equipment.
- Pump (4" or 6" is generally used).
- Timbers to act as dikes in the event that there is no snow.
- Caterpillar tractor for constructing approaches.
- Drags or rollers for maintenance purposes.

C. **Capacity**

The capacity of ice bridges depends on many factors, but the most important criterion used to date is ice thickness. In general, this is taken to be the thickness of solid, clear or blue ice, and does not include slush ice, or frozen snow.
Gold gives an excellent graphical presentation of failure load versus ice thickness, maximum load observed versus ice thickness, and calculated effective ice thickness versus given loads. An inspection of this data suggests that a curve given by \( P = 0.025 h^2 \) (where \( P \) is the allowable load in tons, and \( h \) is the effective ice thickness in inches) envelopes all the data, so that failure would have an extremely low probability of occurrence. This formula is based strictly on ice thickness, and therefore the additional conditions listed below should be checked:

1) The ice responds elastically, which means in practice that the load must be travelling at a speed greater than about 1 mile/hr.
2) The speed of the load is sufficiently slower than the speed of the hydro-dynamic disturbance set up in the water so that no resonant wave is formed in the ice cover. In practice this limits the upper speed of a vehicle to between 5 and 10 miles/hr. depending on the depth of the water and the thickness of the ice.
3) The ice is of good quality.
4) The thickness of the white ice can be taken into account when calculating the effective ice thickness. In most mathematical approaches, two inches of white ice is assumed to be as effective as one inch of good "blue" ice.
5) There are no cracks which pass right through the ice cover.

Nevel (1965 and 1970) gives a theoretical analysis of ice bridges in terms of bridge dimensions, ice properties, and ice quality in regard to concentrated and distributed loads. The 1970 analysis shows the critical velocity of travel on an ice cover to be related to water depth and ice thickness. From the graphical presentation of results this general comment can be made: for an ice bridge over...
water more than 5 feet deep, a velocity below 7 mph. assures no
danger from the standpoint of critical velocity.

Lofquist (1951) gives an estimate of bearing capacity for some
specific conditions of static loads.

Kumarov (1960) gives some Russian experience for estimating safe
loads for ice bridge transportation. The formula \( h = 10\sqrt{P} \) cm. or
\( P = \frac{h^2}{100} \) tons (metric) is quoted. Since a metric ton is 2200 lbs.,
this formula reduces to \( P = 0.07h^2 \) where "P" is in tons and "h" is in
inches. (This exact formula also has been suggested by Gold).
However, the safer formula \( P = 0.025h^2 \) appears to be more acceptable
on the basis of very conservative design.

Kumarov further classifies ice as to quality and suggests the factors
required to increase or decrease acceptable loads under various ice
conditions.

Vehicle speed, temperature, quality of cover, snow cover and static
loads are all cited as factors affecting bearing capacity. This dis-
cussion ends by noting that failures have been recorded even at \( P = 0.025h^2 \)
where \( P \) is in tons and \( h \) is in inches. On this basis, the previous
suggestion of limiting loads by this formula is warranted.

Stevens and Tizzard give results of tests on an ice sheet. Their test results
indicated a 36,250 lb. load as being safe on 28 inches of ice. This is
slightly below the value of 40,000 lbs. predicted by the limiting formula
The Dynamic North (Book II, 1956) gives a section summarizing the problem of wave generation by moving vehicles. This section of the report is reproduced here in its entirety:

"EFFECTS OF MOVING LOADS. Russian investigators have observed the possibility of danger from development of resonance in waves created in the ice sheet under moving loads and have actually encountered conditions in which several machines in motion and passing each other in both directions set up such wave action that the ice broke (6). They have reported that such occurrence becomes especially dangerous when the machines are traveling at speeds corresponding to those of the propagation of the ice waves and that in such a case a single vehicle can produce sufficiently strong resonant vibrations to cause it to break.

The Russians have prepared rules for speed and spacing of vehicles to avoid this effect. On ice about 24 inches thick, over water of the order of 16 to 33 feet deep, the Russians have found that at speeds between 3 and 9 miles per hour a depression of the ice under the vehicle moves at the same speed as the vehicle. At speeds above about 12 miles per hour, wave vibrations are formed which spread far to the sides of the path, at speeds which on this lake were found to be 19 to 25 miles per hour. They concluded that on this lake initial speeds of about either 15 or 25 miles per hour should be maintained and that speeds intermediate between these rates should be avoided. Overtaking of one machine by another should also be avoided, and spacing between vehicles varying from 200 feet to 650 feet and more were recommended, depending on the speed of movement and the strength of the ice. Particular caution was advised near shores where complex wave effects may occur.

Repetition of loading under extensive operations causes ice to become weakened. It is reported that one reason for this is the progressive deepening of temperature cracks under the flexing action of heavy traffic. Under such conditions, a desirable procedure is to provide sufficient area, or alternate routes, so as to permit frequent changes in traffic lanes.
It is also reported that ice will break up much more readily under vehicles with low-speed motors than under those with high-speed motors, because of the differences in frequency and intensity of vibrations transmitted to the ice. Traveling parallel to major cracks must be avoided.

D. Maintenance

In general, ice bridges require minimal maintenance. Snow clearing or snow blowing and dragging of the surface to remove rutting may be required periodically. Ice thickness should also be checked periodically to ensure that the ice is not eroding from the bottom.

E. Travel Season

The travel season of ice bridges is extremely important in the operation of winter roads, since an ice bridge can often be the last component of a winter road to be constructed in the fall and the first to deteriorate in the spring. Obviously the dates of opening and closing of an ice bridge, which establishes the travel season, is in some way related to freeze-up and break-up dates. Many references (Allen (1964), Allen and Cudbird (1971), MacKay (1961, 1962, and 1964)) contain material dealing specifically with the Mackenzie River, and freeze-up and break-up dates of rivers in the Mackenzie District. Allen's references in some cases give the date of freeze-up and break-up in terms of dates "safe for travel."
The present author has attempted to correlate these so-called "safe for travel" dates with various parameters derived from daily mean temperatures at weather stations closely corresponding to the ice observation stations. The method of Bilello (1963), which had considerable success in predicting ice from shore to shore on the Mackenzie River at Ft. Good Hope, was adapted in order to estimate safe for travel dates, which were compared with recorded dates. The results were discouraging. However, the fact that good correspondence of results existed for the ice formation data, but not for "ice safe for travel" data, leads this author to conclude that the data for "ice safe for travel" may be suspect. Certainly the date for complete ice cover (freeze-over) at a specific location would be a much more reliable observation. On this basis, it is suggested that ice thickness measurements near ice bridge locations be obtained in order to allow a more theoretical analysis of travel season to be attempted. At present, the mean date of opening or closing is as reliable as any other parameter.

The importance of even a one- or two-week notice accurate to \( \pm 3 \) days would be significant in terms of a construction project of the magnitude of an arctic pipeline.

The prediction of the first "date of safe crossing" in the fall is not as critical as the final date at spring break-up. If haul vehicles
are notified of the date that construction of an ice bridge begins, then the ice bridge constructor can probably give the most reliable date (estimated to be \( \pm 1 \) day with 7 days notice) for the first crossing of various tonnage vehicles. Therefore the length of advance warning would need to be the loading time plus the travel time from Edmonton to the first critical crossing, which is at Ft. Simpson. This is estimated to be about three days.

An item of importance that has been calculated from data uncovered by the literature review is the fact that continuous snow cover at the southern region of concern (Ft. Simpson) occurs on November 1 \( \pm 12 \) days (Std. Deviation). On the other hand, the earliest opening on record of the ice bridge at Fort Simpson is November 16, which occurred in 1969. Statistically, the ice bridge at Fort Simpson opens on December 3, with a standard deviation of 3 days. Thus the probability that the ice bridge would be completed when there is no snow cover in the area is less than 3%. In the spring, the ice bridge is removed on the average by April 12 \( \pm 4 \) days (Std. Deviation) whereas the snow cover is lost on the average on April 30 \( \pm 12 \) days. On this basis the probability that the ice bridge is usable after the snow cover is lost is approximately 13%. These calculations stress the importance of ice bridges to the winter road travel season. (The statistics are based on the assumption of normal distributions for both break-up and freeze-up dates about their mean, and also for snow cover and loss dates about their mean).
Break-up dates appear to be the most critical dates from an ice bridge construction point of view. In the past, closing of ice bridges has been on the basis of a predetermined (sometimes average) date of closure. This fact alone would indicate why difficulty is encountered in attempting to correlate ice bridge closure dates with daily mean temperature data.

The collection of some data on ice thickness at various times of the winter for critical ice bridge locations appears warranted. Such data would possibly permit waiving of the impending date of closure of an ice bridge. On the other hand, experience indicates that ice bridges deteriorate from the bottom upwards, probably due mostly to water temperature increases. This points to the need for periodical field measurement of ice thickness, which in turn could possibly mean that weight restrictions might have to be imposed for late spring use of ice bridges. It would, however, permit maximum use of winter roads.
One observation that has become quite apparent in the present study is the sequence of development of various aspects of importance in relation to winter roads. In the early 1950's, concern was basically of a fundamental nature relating to snow as a construction material. Later in that decade compaction and processing techniques became dominant. In the early 1960's, theoretical considerations gained precedence, but, by the middle of that decade, environmental evils in the north were becoming apparent (as in most other regions of North America) and since that time at least some references to the environmental aspects of winter roads appear in the literature.

However, environmental damage or terrain degradation is not a unique process that began in 1964 or 1965; rather, these dates merely indicate the recent consideration man has had for his environment. Although the "science" of environmental damage and terrain degradation is relatively new, many of the related sciences, and available engineering and technology, should make this subject one of the fastest advancing frontiers of knowledge of record. In the next few pages, a few of the topics concerning environmental and terrain degradation aspects relating to winter roads will be discussed with reference to pertinent literature.
A. Planning

In the past, planning of winter roads has been sadly lacking; in most cases it has been non-existent except from the viewpoint of the operator of the road, and sometimes from the viewpoint of the operator of the bulldozer. Not to imply that our American neighbours are behind in their planning effort for winter roads. The TAPS road is utilized as an example here because it is the most documented road (Lotspeich, Turner, Reyes, Engineering News-Record (1964) and Contractors and Engineers Magazine (1969)), up to the present, that stresses the lack of environmental consideration and planning.

Lotspeich (1971) implies that costs of the Livengood to the Yukon River road were doubled "due to unforeseen difficulties that should have come to light by intensive reconnaissance." This entire article dwells on the advantages and merits of route selections; furthermore, it stresses points to be considered such as water, drainage, recreation, minerals and timber, stream crossings, flood potential, seepage areas, advantages of high ground, wildlife, spawning grounds and aesthetics.
Savage (1964) and Vulis (1970) also discuss the planning and location of winter roads, and of highways. The paper by Vulis appears particularly pertinent to the analysis of winter road quality, and average velocity and intensity of traffic. Unfortunately, only the abstract has been translated from Russian, and consequently no actual figures are available.

Savage comments on the necessity of complete pre-planning before undertaking northern field work. Passive construction is required, which means disturbing the existing thermal regime as little as possible. This generally means retaining the vegetative cover, to avoid uncontrolled stripping which can result in large settlements and turn the terrain into a quagmire. Maintaining the existing drainage patterns as much as possible also is cited as being very important. Icings are discussed in relation to drainage, and control by the use of dual staggered culverts has had some success south of Hay River on the Mackenzie Highway. As is usually the case, this article is written in the context of permanent highway planning and design. Of particular interest is the description of methods utilized for highway location:

"Because placing and maintaining large survey parties at northern locations is costly, every effort is made to do as much of the preliminary engineering as possible before the main party moves into the field. R.C.A.F. air photo coverage is available for much of the North. When the general location for a proposed new highway has been established, air photo mosaics are prepared, a detailed stereoscopic examination is conducted and an approximate route selected."
Alternate locations are also indicated. An interpretation report is prepared for the guidance of the field engineers.

A location engineer then makes a complete aerial reconnaissance of the route with a light aircraft or helicopter. If terrain permits, he lands at a number of points to check or supplement information supplied. On the basis of this reconnaissance, a final route is selected and route report is augmented with the observations of the reconnaissance engineer. Depending upon the complexity of the location, scarcity of good construction materials, etc., a decision may be made at this point to arrange for low level photography and a further route refinement. If possible, an 8 to 10 foot wide line should be cleared along the approximate route before the low level flying, since this will prove of considerable benefit to the interpreter and will also provide access for the location party.

Wherever possible, arrangements are made to bulldoze this base line before the main location group moves into the project. The bulldozer is guided by a location engineer. There there are few landmarks, the location engineer frequently employs a light aircraft with two-way radio contact to put the bulldozer on line. As part of this same operation, the bulldozer builds small airstrips, provides access to lakes, checks gravel pits and places temporary fills across streams. It is possible to average as much as 5 miles of line per day with this technique. Once the proposed line has been cleared, the main location group moves in with trucks or track vehicles to complete the detailed work of location without being delayed for line clearing. Aside from the economy, this method simplifies servicing problems and makes it possible to take maximum advantage of the short season suitable for location work.

Where the tree cover is not too heavy and there are a number of small lakes, the bulldozed line is eliminated; two or three location groups are placed in light fly camps and leapfrogged along the line with float planes. In all cases, the exact method of location is adapted to terrain and weather conditions."
In relation to this type of planning and route location, Hawley (1971) gives a detailed account of multi-disciplinary complaints of environmental damage compiled on an inspection trip of a Task Force on Northern Roads. Besides the detailed documented occurrences of environmental damage along various northern roads, of particular interest is the personal philosophy and assessment contained in his conclusions:

"The inspection trip has shown that there are many undesirable practices presently employed in the northern roads program when viewed from other viewpoints. Destructive effects to wildlife are predominantly the calamitous alteration and elimination of wildlife habitat. Most of the damage by roads to wildlife and wildlife habitat, aquatic and terrestrial, is caused by soil erosion and the deposition of erosional debris. Although we hear a great deal about damage to fish and other animals by sewage and industrial wastes, it is unlikely they affect streams to anything like the degree that sedimentation does (Graham 1947). Damage to, and loss of soil is irreparable since soil cannot be replaced during the time span in which we operate. Soil and water are vital to wildlife. Tacks and Whyte (1956) state that roads are more damaged by erosion than by traffic. The high loss of material from the road surface, shoulders and ditches; pointed out earlier; require large mounts of money to replace. In deterring erosional losses through the establishment of stable vegetation, maintenance costs are also greatly lessened since there is no need to continuously cultivate, mow, and eradicate vegetation. The stability of roadside banks, cuts and fills plus the elimination of damage by flash flood also reduces maintenance costs and protects structures from damage. It is likely that most of the reclamation costs would be recovered by reduced maintenance costs."
In my opinion, the exercise has amply proven that several disciplines must be involved in planning road construction programs which, by their nature, have such a huge effect on the environment. I have suggested that the group be composed of a highway design engineer, a social economist, an ecological based landscape architect and a soil and water conservation biologist.

I believe personnel within D.P.W. should be trained to an awareness of the reasons and intent for the considerations of the other disciplines so that they can advise, direct and control operations at the field level. However, I am of the firm belief that the planning and control group should be multi-agency as well as multi-discipline.

Damage repair and reclamation will entail a great deal of effort if the government program is truly to be above approach. These facts are of serious concern and remedial or preventative measures should be initiated immediately on those projects now in progress. I refer specifically to the Dempster Highway. I have received many personal informal complaints of the conduct of that job from private, government and oil company personnel (the latter complain they are asked to restrict activities that the government does routinely). The Task Force discussed the possibility of using the stretch of the Dempster Highway from Fort Macpherson to the Yukon border as a pilot project of the multi-discipline planning group. I urge that the entire highway be subjected to such scrutiny (even though the location portion and most design has been completed) to reduce criticism and bring it as close as possible to the ideal.

In the conduct of the planning of route selection, design and construction, it will be impossible to use the computer program set up for road engineering (Ridge, 1961) since many of the other values are intangibles and they cannot be equated to cost-production figures used by the engineers. Until a suitable program is devised, I suggest the transparent overlay technique of McHarg (1969) be adapted for use.

In conclusion, I urge that the multi-discipline planning (advisory) group be formed immediately and that its standards of excellence be set higher than those the Land Use Regulations would force them to use. The government would then not only be above reproach but would be setting an admirable example."
Inasmuch as the previous two authors' discussions relate to permanent roads, one fact can be clearly deduced from the literature - that is, the amount of planning currently going into the selection of winter road route location is even less than that for permanent roads. The need for better planning for northern roads of all types is essential because it is the prime method through which environmental damage can be minimized.
B. Soils Classification

As part of the planning effort, a good soils classification system is required. Linell and Kaplan, Brown, MacKay, Andersland and Redsforth have done extensive work on northern soils classifications. However, complete coverage of the Arctic regions in terms of soils maps will be impossible for years to come. For this reason, route selection as related to soil classification will by necessity continue to be on a reconnaissance basis, with route location changing only to avoid "impossible conditions".

A more immediate and beneficial concern at present is a terrain classification system. There is a need to relate the severity of winter road terrain degradation to terrain type and, more important, to plan the least damaging type of winter road for various terrain types. Field observations will be necessary to accomplish this objective. To date, field observations have concentrated completely on the negative aspects of winter road use. It now appears to be more advantageous, especially from the user's point of view, to concentrate on terrain types, elevations, grades, vegetation, and the type of winter road that results in minimal or even negligible terrain damage. Planning must incorporate the most advantageous terrain for winter travel; it is doubtful that sufficient information is available to do this at present, except in the most obvious cases.
Hurwitz (Oct. 1970) has made some pertinent remarks in relation to terrain type characteristics and phenomena, the following extract, which is taken from the summary, is written in the context of pipeline construction:

"An examination of the terrain to be traversed gave rise to the following principal conclusions:

1. In the areas north of Norman Wells, the regression of permafrost beneath cleared lines is not as severe as surface conditions indicate. This is particularly true when the surface is examined only from the air. On the average, the permafrost table on seismic lines and winter roads is only some one to two feet lower than in adjacent terrain.

2. Areas which are cleared by bulldozer have a wet, sloppy appearance initially but dry up and ingrow with time, although the character of the vegetation differs from the original. Coarse grasses replace the moss, while deciduous trees grow into areas where coniferous trees were once present.

3. Ice saturated silts, which predominate in the northern reaches of the proposed line, represent potentially dangerous soil conditions when they are found on slopes. Erosion or mud flow may occur on even the most gentle slope when permafrost regression takes place in these soils.

4. Undisturbed riverbanks are for the most part stable. But when a slide or slump does develop, whether by natural means or as a result of a man-made disturbance, it is usually massive. The slumps continue to enlarge as newly exposed permafrost melts and we could not predict when a state of equilibrium would be reached. There would appear to be no way to resist or stop the ground movement once it has started.

The need for careful investigation of river crossing points is indicated."
In a November, 1970 report of the same study, Hurwitz makes the following remarks:

"The reconnaissance survey has shown ice-saturated silts to be the predominant soil type in the valleys of the Yukon Territory and in the Peel Plateau and northern Mackenzie Valley in the Northwest Territories. Massive lenses of excess ice, and wedges of ice in polygon formations, were also found in the test holes."

It is through this type of information (that is, basic subsurface field data) that adequate planning of winter road location can be accomplished and problem areas avoided. As mentioned previously, it is fully realized that in the vast area of concern, such work must be on a reconnaissance basis of a pre-chosen preliminary route. However, adverse conditions indicated by such surveys should have profound influence on the final location of such a route.
C. **Terrain Damage**

Numerous articles document the occurrence of terrain degradation caused by vehicles operating in the North. As previously noted, very few cases are directly attributable to winter road use; by far the most damage is directly associated with summer travel. Excellent literary and pictorial examples, both from a research and industrial activity, are given by Hok (1969) and Burt (1971). In most cases where severe damage occurred, excessive removal of the vegetative mat, which exposed the mineral soil, resulted in excessive permafrost regression due to decreased albedo. Peyton (1970) has discussed this phenomena in detail. The practice of removing the vegetative mat has ceased, except for the odd case caused primarily through ignorance or carelessness.

Hok shows pictures of a bladed winter trail of the 1968-69 season taken the following summer. The trail is very obvious over the entire portion visible in the picture (estimated to be in the order of two miles). Water is ponded intermittently, and it appears that regression will continue. Hok also shows the remnants of a "packed" winter trail of about 20 years of age. Hok observes that:

"Some evidence of a packed-snow road will remain for many years. Usually the lasting effects are not as pronounced as those resulting from exposure of the surface to direct contact with heavy vehicles. However, where slopes or other obstacles to travel promote surface disruption (e.g. Toolik River disturbance), the effects may duplicate those of summer travel."
The differences evident the following summer, resulting from winter road use over various terrain types, again points to the need for good planning of winter road locations.

Burts' study was of a concentrated research nature where ten 1000 ft. test strips were laid out, and various vehicles were tested on each strip. Although these tests were made during the summer, the conclusions included the following remarks:

"In all the test areas it is becoming quite obvious that these tracks will not affect the depth of thaw or the permafrost. Healing or complete restoration of tundra in other areas of the Arctic, observed in separate studies, gives good reason for optimism in the use of low ground pressure vehicles.

At this time no controlled tests have been conducted on sloping terrain. Various research projects, however, are now being considered to cover this and other problem areas. Present speculation is that perhaps use of low ground pressure vehicles will not disturb vegetation enough to permit erosion.

The aim of these tests is to establish a sound basis for decision making on summer travel across the tundra. At least two matters must be determined before such can be done:

1. Levels of permissible disturbance must be established for different areas (wild life preserves, parks, oil lease zones, forests, etc.).

2. Sufficient tests must be run, including the use of actual working conditions as experiments for correlation, with tests, to determine what restrictions on vehicle type and work are required to keep disturbances to a specified level in different areas."
As mentioned by the above author, these tests were conducted on level terrain. It is suggested that in future terrain damage studies should be attempted more by monitoring winter roads in use under natural conditions than on specially constructed test strips. The results would be more general, and relative response of various terrain types to winter road use would become apparent.

Some statements occur in the literature so frequently that no attempt is made here to document each source. Falling into this category are statements relating to the travel season of winter roads, and the importance of retaining the vegetative cover. The first case is typified by the work of Bliss and Wein (1970) who comment that to limit terrain degradation on winter roads it is necessary to prevent their use too early in the fall and too late in the spring. This early and late season use is the most commonly expressed cause of terrain degradation in the literature. However, no indication whatsoever is given by any reference as to what constitutes "too early" or "too late". This omission limits the present study in view of its terms of reference: the basic objectives of minimizing terrain degradation and maximizing the travel season are in direct conflict. At present, the only means of gauging whether it is "too early" or "too late" is by observing terrain degradation: then it is indeed too late.

Only one possibility exists to resolve the dilemma described above. The Rammonsonde or density indicators of snow or ice road hardness can possibly be related to field observations of "too early" or "too late". The consistency and reliability of the hardness readings indicated
throughout the literature gives reason for optimism that this difficulty
can be resolved through research by field observations.

In regard to vegetative cover removal, Hernandez (1972) contains a
very typical statement:

"The 1965 summer line was the most affected because of the
bulldozing to the side of the vegetated layer."

Hernandez also concluded that summer disturbance is much more detrimental
than winter disturbance to all plant communities sampled. This latter
principle has generally been accepted as true throughout the literature
survey.

Brown, Richard and Vietor (1969) comment in their conclusions of a
study of the effect of disturbance on permafrost terrain that:

"The results of our 1969 summer observations re-emphasize
the importance of the surface layer in preserving perma-
frost terrain and provide data which demonstrate the magni-
tude of changes which occur in a single summer following
natural or man-made changes. Essentially, any disturbance
which eliminates or greatly reduces plant growth will result
in an increased thaw. If the vegetative cover is physically
damaged and mineral soil is exposed the increased thaw will be
accompanied by erosion. A twofold increase in thaw after
shearing the tundra vegetation was observed on carefully
controlled experimental plots. The same increase was observed
on mulched plots. Removal of vegetation by fire also results
in an increased thaw. These increases are caused by the ab-
sorption of more energy into the soil through the darker sur-
face cover. Establishment of new vegetative growth following
damage will undoubtedly slow the rate of permafrost degrada-
tion and as shown by a recent Soviet report may result in the
aggradation of permafrost. It is recommended that all vege-
tation or restoration studies of tundra measure thaw penetration
under revegetated and controlled unvegetated sites to determine
the magnitude of these differences. The difference will undoubt-
edly vary based on geographic and local conditions (i.e. Copper
River Basin vs North Slope; valley bottoms vs north-facing slopes)."
Kevan (1971) describes an 11 year case history of vehicle tracks on the high Arctic tundra (Ellesmere Island). He reports that along the most heavily trafficked route (even with vehicles of less than 4000 lbs.), plants were entirely absent. He adds that insulation should be provided over ice wedges to ease road maintenance and avoid mud-holes. Although vehicle tracks are lasting, at least for eleven years, he suggests that such would not occur if travel was restricted to the winter period, and that better vehicle tracks should be designed to protect the vegetation from scouring.

Porkhaev and Sadowskii (1959) assure us that the Russians have found retention of the surface vegetation to be advantageous. They state that:

"The preservation of vegetation in the foundation of the embankment is imperative when constructing according to the method of preserving a frozen subgrade. While improving the thermal insulation properties of the embankment foundation, vegetation also interferes with the penetration of fines into the body of an embankment made of coarse material. In addition, the presence of vegetation under an embankment reduces heaving. Thus, according to the data of K.M. Krasnov (1944), a road with permafrost in its subgrade constructed in Kolyma in 1937 over a hillocky area (cemetery mounds) was subjected to exclusively strong heaving in those stretches where the vegetation layer had been removed and the cemetery mounds levelled. Heaving was less intense in areas where the cemetery mounds were preserved, even though the vegetation had been removed, and there was no heaving at all in those stretches of the road where the mounds were left untouched and the vegetation was not removed."

Although the above experience is written in the context of permanent roads, again some information applicable to winter roads is apparent. It suggests that in areas where preservation of the frozen subgrade
is desired, it is imperative to preserve the vegetation. Furthermore, it suggests that bulldozing off the mounds to level the terrain for winter trails is not wise; and for this reason it is suggested that (from a permafrost regression aspect) built-up snow or ice roads may be better than levelling the terrain to a suitable smoothness.

Murrmann and Reed (1972) discuss the relation of military facilities to environmental stress in cold regions. In particular, reference is made specifically to terrain degradation resulting from a winter road:

"Although virtually every disturbance will have a long term effect on the permafrost regime, immediate effects result from catastrophic perturbations such as those generally related to construction where the soil surface layer is pulverized or removed and ice-rich soil below becomes exposed to direct radiation of the sun and the effects of runoff waters. An example of permafrost degradation from this type of activity is shown in Figure 6 (not included in this report) which shows what was a winter road in central Alaska constructed by simply bulldozing away trees and surface vegetation. Late spring traffic initiated erosion during the spring runoff period which was followed by accelerated thaw and additional erosion during the late summer rains. As a consequence of permafrost degradation and surface erosion, a difference of as much as three meters in relief of the local terrain occurred in one summer season."

The noteworthy point of this quotation is that "late spring traffic initiated erosion." In other words, many terrain damage problems can be avoided by restricting winter road use in the early fall and late spring. It appears that an early date of closure of winter roads is necessary. After that date, or even before it if the situation demands, operations should be conducted on a day-to-day basis. Once the road cannot be travelled in the daytime, the sites should be
abandoned with any final travel over winter roads being done at night.

Kerfoot (1972) did an excellent study of winter road disturbance of terrain in the northern area of concern. Of particular interest was the description of the construction method of an "ice road", as built by Gulf Oil Company. The account is presented below:

"The first stage in the construction of the Gulf winter road involved using a tracked vehicle to drag a beam along the proposed route to fill in most of the depressions in the ground surface with snow, and create a relatively smooth surface. Flat-tracked vehicles, with water tanks mounted on the back, were then used to spray water on the surface of the road, and this procedure was repeated several times until a layer of ice was developed which was capable of supporting a similar water truck mounted on wheels. This vehicle was then used to spray additional quantities of water on the road surface until the layer of ice was strong enough to support the heavier wheeled vehicles used to transport the drilling rig. Throughout the earlier part of the winter, a route was selected which followed the areas of higher ground and detours were made around the major water bodies. Later in the winter, as the thickness of the ice increased, many of these detours were abandoned in favour of more direct routes across lakes."

One other aspect of Kerfoot's study that is significant was the evaluation of a summer seismic program with respect to terrain damage. Kerfoot mentions the results of this study as part of his summary and conclusions, which are presented here:

"In interpreting these comments, it is imperative to remember that the limited sample sizes, the inability to establish the pre-disturbance terrain conditions with any real degree of accuracy, and the almost total absence of any vital information regarding the operating conditions and amounts and types of vehicular traffic involved, seriously limit the usefulness of some of the conclusions."
The investigations of the sites of winter road operations show that the destruction of the vegetation cover and surface microrelief forms has produced a predictable increase in the thaw depths and ground temperatures beneath the disturbed areas as compared to the adjacent undisturbed terrain. This obliteration of the surface microrelief has also led to more uniformity in the thaw penetrations in the damaged areas, and if the recovery process is to include the development of these features, this will involve a much longer time period than that required to re-establish a continuous vegetation cover. The field observations suggest that the ice road method of construction is much more effective than the snow packing technique in limiting the level of terrain disturbance, but additional research is necessary to determine more precisely the number of years that the same access route should be used. Data from the quadrat studies in the Shingle Point area indicate that, in comparison to the undisturbed terrain, the re-use of the road produced a relative increase in the thickness of the active layer of almost 27 per cent, which compares with an increase of slightly less than 21 per cent in the winter road which was used for only one year's operations. This difference, of less than 6 per cent, may be too insignificant to warrant a consideration of the restriction of the use of an access route to only one year, but it remains to be seen whether Dr. Lambert's vegetation studies reveal any more appreciable differences. In terms of the general appearance of the two winter roads at Shingle Point, however, there is no doubt that these access routes should not be used for more than two years' operations. The extreme form of damage exhibited by the winter road at Sitidgi Creek demonstrates what can happen when the surface organic layer is finally destroyed to a point where pronounced thermokarst subsidence is initiated. The sequence of events associated with the activities of the resource exploration industry in the Sitidgi Creek area, particularly as related to the crossing of the open water of the creek in winter, also indicates that there is a need for improvements in the planning procedures used to select the routes for the winter roads.

The investigations of summer seismic lines, from one to nine years old, and those made during an actual summer seismic programme demonstrate conclusively that, in certain areas at least, and with the adoption of suitable operational techniques, the terrain disturbances associated with these operations need not result in any serious damage to the tundra. Indeed, the negligible amount of terrain disturbance revealed in the 1971
seismic operations suggests that there are in fact certain merits in scheduling summer programmes. Most of the disruption of the ground surface was in fact due to a compression of the organic layer and this ability of the terrain to undergo slight deformation in response to the weight of the vehicles may produce less damage than the abrasive effects of vehicles on the same terrain when it is frozen solid. Similarly, the supple nature of the vegetative cover, and the shrub layer in particular, in the summer allows it to withstand the passages of vehicles with fewer adverse effects than in the winter months. The on-site investigations also confirmed that, for the most part, the real problem with respect to cross-tundra movements in the summer thaw period is the maximum number of vehicle passes that the ground surface can tolerate before the degree of disturbance begins to exceed acceptable levels. Even with the use of a stationary base camp, an excessive number of vehicle passes along the same route is possible and, unless additional future research indicates otherwise, it appears that no more than two of the heavier vehicles (e.g. drill rigs or recording unit) should be encouraged to follow the same tracks.

The terrain disturbances associated with the 1970-71 winter seismic operations of Elf Oil Exploration and Production Canada Limited, and Deminex (Canada) Limited, on Banks Island are negligible. The minimal nature of the disturbance reflects a combination of factors including (a) the efficiency of each company's operations, (b) the careful selection of routes for both the seismic lines and the winter roads, and (c) the continued presence of a local resident during the actual operations. However, closer scrutiny is apparently necessary in certain aspects of the operations, particularly with respect to a curtailment of any unnecessary movements of vehicles over the tundra, the filling in of shot holes and garbage disposal.

The following tentative recommendations are made with regard to the application of, and future research into, the Land Use Regulations as applied to the operations of the resources exploration industry in the tundra regions of far northern Canada.

1. Winter roads, constructed by using conventional snow packing techniques, should not be used for more than two consecutive winters' operations.
2. The ice road method of building winter roads results in less damage to the terrain than the snow packing method of construction, and a wider adoption of this method should be encouraged in general, and particularly when there is a scant snow cover or where it is definitely intended to use the same access route for two consecutive years.

3. There is a need to consider more thoroughly the section of the Land Use Regulations which encourages vehicle operators to follow existing lines, trails or rights-of-way wherever possible. In most cases the accentuated damage along the old line is much more severe than the level of disturbance that would be incurred in following a new route across previously undisturbed terrain.

4. The extreme form of damage associated with the late passage of vehicles along the Gulf ice road indicates that there is also a need for a stricter control, through the issuance of specific permits, of all cross-tundra movements of vehicles. The rights of individual companies to restrict the movements of other companies along routes for which they have the prime responsibility should also be firmly established.

5. If the Land Use Regulations are to have any real meaning, severe penalties must be levied against any blatant violations of these regulations.

6. Summer seismic operations in the Mackenzie Delta area need not result in any serious damage to the terrain, but no summer seismic work should be permitted on any recently burnt-over areas of the tundra.

7. The revegetation of any disturbed areas, resulting from summer seismic operations, will probably be enhanced if the work is performed during the early part of the summer (e.g. late June and July), thereby facilitating some recovery of the vegetation during the remainder of the summer, rather than in the following year.

8. The level of disturbance associated with summer seismic operations is intimately related to the number of heavier vehicles moving along the same route, and rather than encourage a concentration of such traffic within a 33-foot width of the tundra, it would appear to be advisable to promote a dispersion of this vehicular activity.
9. On-site research, conducted during actual operations, provides the only means of recording the precise nature and extent of the terrain disturbance; the causal factors involved, and the collection of data that can be applied immediately to minimize the damage to the tundra in future land use operations. The advantages of this method of study are such that a concerted effort should be made to seek the further co-operation of the resource exploration industry in promoting this type of research as much as possible.

10. Where 'after-the-event' or 'post-morten' investigations of terrain disturbances are the only feasible method of study, there is an immediate and compelling need to establish a comprehensive data bank system which should include exact maps of the operations, and details of the numbers and types of vehicles used, number of passes and tonnage involved, as well as any relevant information (e.g. depth of snow cover) pertaining to the operating conditions under which the work was performed."

The recommendations of Bliss and Wein (1972) from the ALUR program are very significant to the winter road study and are presented here in part:

"(1) The landscape units identified show such a wide diversity of characteristics that the specific area must be known to predict the response to a given disturbance. Land use officers and future researchers should be aware of these differences.

(2) In the High Arctic the lowland areas with relatively lush vegetation are a relatively small proportion of the landscape but are extremely important biologically and should be protected whenever possible.

(3) Winter seismic operations should be conducted using "mushroom shoes" on the crawler tractor blade to prevent disrupting the ground surface. This results in little modification of the plant surface and increased depth of the active layer."
(4) Extreme caution should be exercised in the use of summer seismic operations in the Low Arctic. In the High Arctic the polar deserts once dried out in the summer may permit operations with little biological damage.

(5) On winter roads travel in early fall and late spring can be detrimental. Fall damage can occur when the surface has frozen but a thawed layer remains below. In the Low Arctic, keep to the lowland communities and waterways where possible. Frozen saturated soils protect underground plant parts and provide a solid roadway whereas upland shrubs are broken back to ground level.

(6) Choose winter road routes, drill sites and landing strips in summer when it is possible to locate coarse textured materials and less sensitive areas. Wherever possible aerial photographs should be used in aiding these decisions.
Of particular interest from Bliss and Weins study are the following two observations:

"The data presented show that one cannot generalize for the Arctic as a whole regarding the summer impact of seismic activity, winter roads, natural and artificial reseeding success, and the impact of surface disturbance on plant cover and depth of the active layer. Neither can one accurately predict in advance the influence of surface disturbance, seeding response, and required fertilizer levels in upland and lowland sites within a few acres or hectares."

"Winter snow roads destroy nearly all of the above ground plant parts in upland areas dominated by shrubs. Re-sprouting from underground parts occurs to only a limited degree. In lowland areas where sedges predominate re-sprouting from underground parts is common and in summer show little effect of the winter operation."

Lambert (1972) also did botanical work in the Mackenzie Delta area, which was very closely related to the work of Kerfoot previously presented. Although this work is from a different viewpoint than Kerfoot, their conclusions are so similar that Lambert's recommendations are not included here.

In consideration of the work of Bliss and Wein in comparison to that of Kerfoot, and Lambert, two direct conflicts of opinion appear:

(1) Bliss and Wein appear to favor continued use of the same right-of-way from year to year for winter roads, whereas Kerfoot suggests only one year's use of a right-of-way, and possibly two years' use under favorable conditions.
(2) Bliss and Wein propose winter road planning should take advantage of low, wet areas, where vegetation is more abundant and can recover more readily, whereas Kerfoot has observed that planning should take advantage of high ground. Kerfoot's basis for this observation is given below:

"The Elf Oil Company winter road from the staging area at Johnson Point to the site of the seismic operations is approximately 45 miles in length. The amount of care and thought involved in the selection of the route, to follow as much of the higher ground as possible, is reflected in the negligible disturbance along the route and the consequent difficulty in tracing it from the air. The only major exception to this pattern occurred where the winter road intersected the most easterly of the north-south seismic lines. Here, an inordinate number of separate tracks made it difficult to establish the real position of the road. The trace of the road also seemed to be more prominent where the route involved an oblique traverse of a slope. This can possibly be attributed to the fact that in such locations the weight of the vehicle is unevenly distributed on the tracks. This problem can possibly be alleviated in the routing of subsequent winter roads (and seismic lines) by following paths which run directly up or down a slope wherever the gradient permits.

The Deminex winter road from the staging area at Herbert Point was almost impossible to detect over much of its length, indicating negligible disturbance of the terrain."

As part of the ALUR program Radforth (1972) observed terrain disturbance from off-road vehicles. Of particular interest is a graph which showed conclusively from observation that vehicle weight is definitely related to permafrost recession depth and/or disturbance levels. This is significant in relation to winter roads in the area of concern, in that it points out the need to transport very heavy loads during the winter period.
D. River Crossings

River crossings are not particularly a problem in connection with winter road use. More important, however, are the approaches to ice bridges -- and these have not been discussed to this point.

Approaches to ice bridges offer one of the most acute terrain degradation problems. This is particularly evident when one considers the mud flows and siltation that potentially could result from permafrost regression and thermal erosion in such close proximity to a river.

Due to the nature of stream bed cross-sections, most approaches to the river banks are on slopes, which require extra power for vehicles to ascend. On any sloping ground, the slippage due to traction difficulties results in wear and tear on a road to the extent that the snow pack is removed, the vegetative cover is disturbed, and mineral soil is exposed. On south-facing slopes, this is potentially the first area for which restrictions should be imposed. However, because the rest of the road is still trafficable, use of the road continues, and terrain damage often results. It is suggested that many instances of such degradation need not occur if active, rather than passive, maintenance procedures are practised. In addition, properly designed and compacted and/or processed approaches should be incorporated into the winter road when it is initially constructed. If this procedure does not avert most approach problems, other methods such as pre-cast concrete ramps or timber ramps should be investigated.
E. Admixtures

The use of admixtures in connection with winter roads has already been mentioned in the use of chemicals for snow melting in processing techniques (US-Canadian Snow Compaction Trials). This same report discussed testing of sawdust as a snow admixture material for strength and insulative capabilities, as have several other reports (CRREL Special Report 60, US Naval Civil Engineering Laboratory, GERA 961, 1964, Kingery and Moser). Although some success has been achieved by the use of admixtures, it is recommended that the use of such materials be completely disallowed in practice until they have been thoroughly tested and approved.

The use of sawdust is presently allowed for special purposes (i.e. under drill rigs) where there is no danger of surface drainage or flooding. Land Use Authorities indicate a dislike of the use of sawdust, primarily for the consideration of fish as reported by LeBel.
F. Indirect Environment Aspects

Several factors indirectly related to winter roads could have some effect on the environment. Included in this group are forest fires, vehicle exhaust, and oil and gas spills.

Although forest fires are not probable from the viewpoint of winter road use per se, nevertheless they do open up new access by man to northern areas. In the Fort Simpson area particularly, and in any populated are in general, this can increase the probability of summer forest fires. Winter forest fires are possible, but are necessarily started by camp fires or other concentrated heat sources. Such fires are usually small, although they have been known to smoulder in the moss and vegetation layer and to break out later during conditions more conducive to forest fires. On the other hand, Hurwitz (1970) documented a case where a forest fire was limited from spreading by a man-made feature (the Canol Road). In general, however, construction workers should be made aware that winter forest fires are possible, and that negligence in this regard is not acceptable.

Vehicle exhaust has been cited (Salmi, 1969) as being significant in northern regions (Finland). Although no environmental degradation was cited, some plant species could be sensitive to fumes in the Arctic region. Of particular note, Salmi found that:
"The investigation indicated that ash and lead are distributed most evenly on open bogs, the amount decreasing with distance from the road. Forest, individual trees and snow fences prevent the effective spread of ash and lead. Variations in the distribution of woods and open bogs thus cause variations in the spread of ash and lead. This may be influenced by air currents caused by trees. In particular, petrol fumes containing lead float in woods so that notable amounts of lead occur far from the roads."

In relation to this, Schofield and Hamilton (1970) stated that:

"Most plants are damaged by small amounts of toxic substances in the atmosphere that cause no apparent damage to human beings and most other animals. Certain plants, however, such as mosses and lichens, are far more sensitive to atmospheric toxicants than others. All but a very few lichen species are sensitive to even small amounts of toxicants. Among lichens, fruticose (shrubby) species are more sensitive than either crustose (encrusted) or foliose (leaflike) forms."

They further mention pollution particles as potential water and ice fog nuclei during inversions. Winds in some regions would eliminate this effect. In conclusion, they state:

"It is clear that there will be times when oil companies will have to curtail fuel consumption in order to protect the environment. This will become increasingly so with further oil-field development in Alaska. Even under the most favorable atmospheric conditions, there will be little leeway for flaring of gas or accidental burning of sulfur-bearing hydrocarbons. Arctic oil field development should include a thorough study of pollution effects on lichens to determine the extent to which our interpretation of the data is borne out by actual conditions in the field."

Inasmuch as these latter statements refer to massive fuel consumption, this topic may be insignificant in terms of winter road use. However, to be aware of this potential problem is considered noteworthy.
Oil and gas spills could have immense effect on localized areas along winter roads, primarily through collision or accident. It is recognized that it is impossible to avoid such occurrences; it is suggested, however, that snow which is saturated with oil or gas from spills should be collected and disposed of in an area of limited drainage, such as a confined borrow area. In relation to minor spills around construction vehicles, as one author stated: "This is due to carelessness and ignorance."

Many aspects of winter roads have implications with regard to wildlife and fish. However, in all cases where wildlife have been mentioned in relation to winter roads, the problem is not unique to this particular source. For instance, any roads (including winter roads) give game hunters access to new areas. Excellent reference to this is supplied by Williams Bros. Canada Ltd. in their study of the Porcupine Caribou Herd.

Ice bridges pose the only unique problem in regard to fish. Other than damage to fish, and possibly bottom damage to the river, due to the removal of ice bridges by blasting, no real problem is anticipated for fish from winter road use. In small creeks and streams, where fish inhabit and migrate in winter, it will be important not to freeze the streams to the bottom.
There is evidence that sawdust can lodge in the gills of fish. For this reason, it is recommended that sawdust or admixtures of any sort not be used arbitrarily on or near rivers.
G. Revegetation, Erosion and Siltation

It has been established that the loss of vegetable cover is primarily responsible for thermal erosion in relation to winter roads. As indicated by Hill (1971), the existence of permafrost (which might be impervious to water) causes a lack of drainage which often results in an excess of surface water even though the arctic is characterized by low precipitation. Whenever an excess of surface water exists the potential for more thermal erosion, excess water, erosion and siltation results.

Hawley has documented a presentable argument on this subject in relation to northern roads:

"Illustrations of speed, cost and engineering expediency considerations were in evidence everywhere but little attempt to preserve wildlife habitat was seen. All attention and effort was apparently devoted to building and maintaining a flat, straight, high-speed roadbed.

Firstly, damage to wildlife habitat is, generally, far more disastrous than direct destruction of individual animals since animals reproduce rapidly but habitat does not (Egler, 1958). Wildlife habitat is directly dependent on the land, land use and land conservation (Graham, 1947). One of the most harmful effects on the land is erosion which not only reduces the amount and productivity of soil but pollutes, destroys and depletes our water resources (Jacks and Whyte, 1956). Therefore good soil and water conservation is inseparable from sound wildlife conservation (Cottam, 1958). Soil erodibility is a man made factor since no undisturbed mature soil exhibits appreciable erodibility or it would have disappeared (sic). Road and
highway construction and maintenance subject the soil to great disturbances and accelerated erosion is a common and appreciable complement of them (Diseker and Richardson, 1961; Graham, 1947; Jacks and Whyte, 1956; Kraebel, 1936; McCardle, 1960). Erosion and sedimentation were observed almost constantly during this inspection trip and only minor effort to prevent it was noted and then generally as a direct protection of the structure itself. Since the accelerated erosion at the road right-of-way will likely be self increasing and self expanding, it will more and more adversely affect an area enormously large and far removed from the initial disturbance site (Graham, 1947)."

Revegetation of denuded areas has for years been common practice for erosion control of engineered earth structures. In the context of the arctic environment, however, little information is documented beyond that of Bliss and Wein, 1970, 1971 and 1972, Lambert (1972) and Hernandez (1972). This work is very pertinent to winter road revegetation. Aesthetically, several authors in the literature have referred to the fact that winter road alignments are often visible from the air for years after abandonment. This in itself seems to be generally acceptable, even if one species is predominant along the right-of-way, so long as no thermal erosion, subsidence or siltation results. It is probable that revegetation of abandoned winter roads can be realized through planting of natural or imported species, and that considerable degradation of the terrain can be avoided by this means.

Brown and West (1970) have also referred to track disturbance, revegetation, and erosion and siltation. In regard to revegetation
they stated:

"Disturbances by surface vehicles are basically of two types. One type, less apparent than the other, is the passage over the tundra which causes the compression of the standing vegetation (live, and especially dead) to a layer a few centimeters thick directly above the wet moss and organic interface. Such areas are seen in subsequent years as "green belts" stretching over the tundra. They appear to be increased plant growth but this may be an illusion caused by the removal of contrasting brown and tan standing dead material due to increased rate of decomposition. The effects of these disturbances are certainly evident in the plant canopy where air temperatures, wind, and light penetration are altered. This type of disturbance commonly results from traffic over a tundra with shallow snow cover. Even snowmobiles may produce this effect. As the number of passes increases over the snow-covered trail the effects can grade into those of the second type of track disturbance.

The second and more destructive type of disturbance results from physical disruption of the vegetative and soil organic layer. This drastically changes the thermal balance with the vegetation and soil, and increased soil thaw occurs. These tracks typically result in depressions over melting ice wedges and soils and tundra which are more wet. The degree of thawing and consequent subsidence depends upon the amount and type of ice contained in the permafrost beneath the track. Melting of ice wedges results in small ponds. If the track is on a slope or intercepts a drainage channel, it is susceptible to erosion, as is dramatically indicated by the effects seen on the research sites at Barrow."

After discussion of some specific aspects of their research program they stated that:

"In conclusion, track disturbance resulted in very definite alterations of the vegetation, soil and soil solution such that biological activity and primary production was stimulated. This does not mean that the disturbance was good, however, for if much of a slope gradient existed there likely would have been severe and detrimental soil erosion. The results do
give an indication that controlled physical disturbance of the surface vegetation and peat layer might be used to stimulate more vigorous vegetative growth with beneficial results. However, these conclusions must be tempered until complete analysis of samples and data have been accomplished."

It should be noted that most of these observations appear to be on tracks from off-road vehicles. Therefore, the results can possibly only be related to winter trails on tundra. In this context, also, the mention of "shallow snow cover" makes the observed results difficult to assess.

The Roberts-Pichette (1972) Annotated Bibliography of Permafrost Vegetation-Wildlife Landform Relationships has recently become available. This is the most comprehensive literature survey available on the subjects indicated by its title. Hence, the authors' answer to eight specific questions, as well as some general remarks, are presented here in total:

"General Impressions from the Literature

The overall impression one gains from the more recent literature is that, if reasonable care is taken, the arctic tundra and other communities are not nearly as sensitive to damage as once thought. Since fine-grained soils are apparently always wet they are subject to severe frost disturbance if the vegetation mat is broken and the thermal balance is altered. On well-drained soils, scars resulting from disturbance may be visible for many years or decades, even though revegetated quite quickly. Very little information has been obtained on the result of stream bed and bank disturbance at stream crossings and what effects gravel removal or extra silt loads may have on fish or other aquatic populations.
Another aspect of concern is the possibility of change in drainage patterns due to the often unpredictable enlargement of temporary ponds, lakes or drainage channels created over permafrost, especially if massive ground ice or icy sediments are present in or near the banks. The siting of pumping stations becomes of major concern, especially if large quantities of water vapour or other chemical emissions are produced. The nature of the meteorological conditions are such that ice fogs and local deposition of exhaust chemicals could be excessive especially if pumping stations are sited in valleys. Some workers are concerned with the effects of noise, especially on the caribou.

There seems to be little doubt that a pipeline can be built through the Mackenzie corridor, with all its attendant facilities, without major disruption to the land-based animals and plants and to the land itself, provided appropriate (and usually expensive) precautions are taken.

Some Specific Questions

The contract specified certain questions on which to concentrate. Insofar as it has been possible to find the answers from the available literature, the results follow:

**Question 1:** To what extent does vegetation and raw humus protect the ground from thermal erosion?

Wet silty and clayey soils are the ones most subject to frost action while well-drained soils are not greatly disturbed by it. The former soils support the heavy organic matter and vegetation mats, while the latter are likely to have a much thinner (and often shrubby) vegetation mat.

The important insulating layers are the ground vegetation (particularly mosses and lichens) and the underlying peat. There are reports that the removal of trees and shrubs, provided the ground vegetation mat is not broken, has no adverse effect on the underlying permafrost. Preliminary North American experiments and some work from the USSR indicates that perhaps the peat layers themselves are the most important insulators and that the living bryophyte and lichen mat can be removed with only a small increase to
the depth of the permafrost table. Work in North America, Europe and the USSR has indicated the feasibility of building roads, runways, buildings, etc., after a gravel pad has been placed over an unbroken vegetation mat. For heated buildings, of course, a ventilation area between the floor and the gravel pad is necessary to preserve the thermal balance.

Question 2: Of what value are the vegetation types as indicators of permafrost?

No general answer can be given. All workers consider a thorough knowledge of the local area imperative before reliance can be placed in vegetation types as indicators of permafrost. In the zone of discontinuous and sporadic permafrost it appears that certain vegetation patterns—heights of trees, absence of certain species, particular combinations of species, wetness of area, etc., can all be used as evidence for the presence or absence of permafrost in a given area, but a set of criteria for one locality cannot necessarily be transferred to another. The scalloped banks of rivers and the presence of thaw lakes and sinks are also indicators of permafrost. In the areas of continuous permafrost, there is no way of predicting the presence, amount, or depth of massive ground ice from vegetation or other surface patterns. In clay and silty soils the quantity of water in the form of ice crystals and/or massive ground ice, may be very great.

Question 3: What are some specific unfavourable (or favourable) effects or removing or disturbing vegetation on sites underlain by permafrost?

Unfavourable effects basically are the initiation of thermokarst (melting of ice below the soil surface) in its various forms, producing extensive slumping, mud flows, slides, hummocky terrain, thaw lakes, etc. The amount and type depends on the water content of the soil. In very wet areas quagmires may be the result. On the other hand, the favorable effects (depending on land-use requirements) can be important, again depending on the site. The lowering of the permafrost table allows better plant growth, deeper rooting and more volume for root growth. In local home gardens or agricultural stations, in the continuous permafrost zones of the world, lowering of the permafrost table has led to
important crop increases. Again, the ice content of the soil determines whether or not hummocky terrain will develop, as has happened at some agricultural stations. Special ground preparations in areas of permafrost have allowed USGS investigators to plant trees further north in the tundra than has previously been possible.

Evidence seems to be accumulating that the total removal of the ground moss mat, particularly sphagnum moss mats, and underlying peat, is extremely important in the satisfactory regeneration of white and black spruce where they occur on permafrost, and in the establishment and maintenance of a conventionally productive forest. Fire, which is so disastrous to communities with reindeer lichen mats, appears to be the main initiator of succession on soils suitable for forests (i.e. not those soils which are thin and stony, very wet, or composed or raw humus over bedrock). Evidence points to fire (completely removing humus and exposing mineral soil) or occasional flooding (on alluvial bars) as preventing the invasion of sphagnum mosses under softwoods, with the consequent rise in the permafrost table and eventual stagnation of the forest. It is important to recognize that reindeer lichen sites are not necessarily those that support sphagnum, though the two are frequently interfingered.

Question 4: What plant succession can be expected following disturbance of given vegetation types?

This question has not yet been fully answered. In general, it appears that the severity, area and time of the disturbance determines the general succession. On lightly disturbed tundra, such as produced by tracked vehicles making one or two passes, sedge communities regenerate rapidly from undamaged underground parts; shrub tundra recovery is slower from sprouts. In both types, invasion from surrounding undisturbed areas begins fairly quickly. In severely disturbed areas, a whole-new succession cycle may be initiated, once thermokarst development has ceased, from invading species rare or uncommon on surrounding undisturbed sites. Where disturbance is continuous, e.g., gullying and flow-sliding, revegetation may be inhibited or prevented. After fire or flooding, various successions may be initiated, depending on the availability of seed, the site, and the severity of damage.
Question 5: How rapidly will various conditions recover from the type of disturbances which are likely to occur during pipeline construction?

Again, very little information is available though it is accumulating. Certain grasses can be seeded, which grow very rapidly, with good soil stabilization but they do not develop an insulating mat as do the bryophytes, and this insulating mat is very important for permanency. Willows and alders have also been used, but so far no results have been reported. Severely disturbed permafrost areas of fine-grained soils with high ice content will be very slow to recover but with reasonable precaution and effort, drastic disturbance of such sites should not occur.

Further problems are likely to occur if revegetation above a buried, hot pipeline is projected. Use of gravel berms and gravel insulation over the pipeline will result in excess aridity of the fill which may prevent eventual revegetation with native species. Many of the grasses presently under trial appear to be attractive food sources for rodents and large herbivorous mammals, and the rights-of-way appear to be used by migrating caribou. Thus, stabilization by exotic grasses may be very precarious.

There is still some controversy over the effects of winter damage caused by the construction and use of temporary ice, packed snow, and graded winter roads on sedge communities and on shrub communities. The former two winter-road types appear to be less damaging than the latter provided (1) the active layer is frozen to the permafrost before construction, and (2) the roads are not used after thaw sets in. The ice roads appear to be least damaging, since the method of construction preserves the microtopography in hummocky terrain. All methods of construction may cause damage because of the retarded growth of species under packed snow or ice. On the other hand, shrubs appear to be much more subject to severe damage in winter because of their brittle nature when frozen. In the high arctic at least, there is evidence that summer use of vehicles on the upland shrub-tundra is not destructive, as the shrubs are very resilient.
Question 6: Are some vegetation types more sensitive to disturbance than others?

Generally speaking, shrub and lichen communities are more sensitive to disturbance than grass and sedge communities if recovery rate is indicative of sensitivity. The former communities have very slow growth rates and are therefore slower than grasses and sedges to recover. However, the severity and season of the damage are usually more important in determining the rate of recovery than the vegetation type.

Question 7: How can an adequate insulating mat of vegetation be preserved during construction, or, if disturbed, replaced following construction?

In general, a gravel pad over the insulating unbroken vegetation mat appears the best principle. Failing this, winter activities are generally less harmful than summer ones - though this does not necessarily apply in areas of well-drained soils with a deep permafrost table. Adequate precautions should be taken with tracked vehicles: they should not climb slopes at a steep angle, preferably they should not use grouser bars which can be very damaging, and the loads should be carefully calculated for the type of terrain over which they are crossing. Suggestions have been made that temporary winter roads should only be used one (or two) seasons and that every following season a new parallel road be used - the reason: less harm will occur to any particular right-of-way if it is only used one season. However, there is always the criticism that aesthetic problems are created even though recovery and regrowth of the vegetation is rapid. This is a matter of scale! In certain types of terrain, some evidence is accumulating that corridors only should be used, without construction of a road.

In answering the question on how to replace a vegetation mat following construction, several ideas have been put forward (see also question 5). As yet there has not been very much experimentation, but pressed peat mats, wood chips, fibre and bark may be used as insulating material and may have considerable merit especially as a rooting medium. All of these have a good water holding capacity, but aridity may still be a problem over a buried hot pipeline. Another solution may be the use of bitumen or polystyrene under pressure to obtain temporary or semi-permanent stabilization. The use of riprap and wire grids may be the only solution under some circumstances.
Question 8: Of what influence is the wildlife on the arctic habitat and to what degree will pipeline construction disturb their activities?

The native animal populations of the arctic and subarctic may have considerable influence on the vegetation and land. The activities of microtine rodents are vital for the health of the tundra. Their four-year cycles allow a buildup and utilization of vital soil nutrients. The larger animals do not have a very great effect on the tundra, except where they have been herded together under situations controlled by man. Caribou trails crisscross the tundra but these apparently cause no extensive damage. Certain water fowl and the caribou can congregate at the edge of water bodies and do local, perhaps temporary damage to the vegetation. How important this is in the total picture is uncertain, but it does not appear to be very great. Burrowing and den-producing animals choose well-drained sites and have considerable effect in further lowering the permafrost table and allowing abundant growth of species often rare in the adjacent tundra. There appears to be more information on this subject in USSR literature than in North American. The pingos and palsas in the tundra can be important denning sites of fox or mink, observation posts for birds, and also the habitat for a particular species of vole. Evidence of the disruption of caribou migration trails by pipeline, seismic lines, power line rights-of-way, etc. does not appear to be accumulating. In fact there is some evidence that the caribou will use rights-of-way where possible in their migration and some companies appear more concerned about damage that the caribou may do to the pipeline, rather than problems the pipeline may cause the caribou.

It will probably be necessary to impose strict regulations for the control of fire arms and thus of hunting in the Far North since the populations of large mammals will become more and more vulnerable to human interference.

Studies which should provide more complete answers to many of the foregoing questions are currently under way in the North and are the particular concern of both the ALUR programme and the Environmental Protection Board. Time is required before more definitive answers can be found for revegetation problems because of the slow growth of northern species, but temporary solutions are being tested which may provide the necessary stop gap."
In general, there is nothing with which the present author would disagree in the answers to these questions by Dr. Roberts-Pichette. In fact, the appraisal of the situation exhibited in her answers are excellent. The only critique of the appraisals are in the form of two omissions, which in the first case has probably been assumed to be obvious. Nevertheless, added comments are given below.

In answer to Question 3 on the adverse affects of removing or disturbing vegetation in permafrost areas, it should be noted that the underlying adverse effect of the unfavourable ones cited is the initiation of erosion and siltation. Hawley has documented the implications of this occurrence, which relates to the destruction of fish and wildlife habitats.

In answer to Question 7, where comments are made on the route selection of winter roads, the opinions of Bliss have not been given equal consideration. Like Bliss, this author believes that continued use on a given right-of-way has merit over limiting use to one or two years. The reasons for this opinion are:

a. The majority of damage occurs in the first year.

b. Aesthetically, abandoned winter roads will probably be obvious for several years, regardless of the length of time of use, and for this reason confining the areal extent appears prudent.
c. If revegetation is necessary, a confined area will limit the effort and expense. and d. Maintenance and concern confined to one right-of-way will be more appealing to the user, resulting in a more concentrated and complete post construction rejuvenation of the area.

Regardless of one's philosophy in regard to the latter question, the comments of Bliss should be included for completeness.
H. Remedial Measures

Most of the environmental problems associated with winter roads will not be apparent until early spring or summer. For this reason, inspection of winter roads should be carried out during this period. As is now customary on at least some winter roads, a particular company is responsible for the winter roads that it constructs. While it is obvious that it is expedient to have one company or agency responsible for a winter road, if that company does not want to be responsible for the carelessness of others, it must police its roads. On a project of the magnitude of the one at hand, co-operation in the use and maintenance of winter roads must exist.

If damage to the terrain is observed, such damage should be reported to the Land Use Officials so that remedial procedures can be initiated immediately. Remedial procedures must be carried out in co-operation between government and industry in an atmosphere of trust and concern. The situation must not develop where it is expedient or rewarding for contractors to bury their mistakes. The danger in this is that terrain degradation or permafrost regression may be impeded only temporarily. For this reason, remedial measures must be well planned and designed, so that future degradation is eliminated.
The one remedial procedure currently used in cases of ground subsidence, gullying or thermal erosion, is to "fill" the depression or scar with granular material. In effect, the insulative capacity of the vegetative or mineral layer is simply replaced by the insulation of the granular material. Numerous references are available for thermal calculations to insure proper design of such remedial measures.

Revegetative measures are used in conjunction with the above procedure, or in isolation. Such measures require that the fill, or in the case of shallow scars, the depression, be covered with suitable top soil and seeded with native or imported seed. Bliss and Wein (1972) give more detailed information on this subject.

One other possible remedial procedure should be mentioned. In areas where terrain degradation has occurred, but access over the same area must be provided even under adverse conditions, the use of artificial insulation should be considered. As has been noted previously in this report, several researchers have tested various materials, but more in relation to permanent roads. However, under adverse conditions, a permanent road section may be required over troublesome areas as a remedial procedure. The bibliography gives several direct references on this subject.
As has been the conclusion of many sections of this report, averting and anticipating problems through good planning can eliminate many problems that would have required remedial procedures. Nonetheless, it is very probable that ample opportunity will arise to attempt the few remedial measures that presently exist.
ALTERNATIVE MODES OF TRANSPORTATION

The alternatives to winter roads vary considerably depending upon the use, origin and destination of such roads. The most obvious alternative is the semi-permanent or permanent road. In the Mackenzie Valley, it seems that a permanent Mackenzie Valley Highway will shortly be a reality, whereas railroads will not have expanded beyond Hay River, NWT. Winter roads will still serve a purpose, but will probably be expanded as laterals more than north-south transportation links.

In the past, air travel, air freight, and barge freight have offered alternative means of transportation to winter roads, and they will continue to function as such in specific areas and particular times of the year. Off-road vehicles also will have a special function as described below.

A. Off-Road Vehicles

Off-road vehicles are basically of two types: tracked vehicles and hovercraft. Tracked vehicles have been discussed extensively in relation to winter road travel throughout this report, and hence will be mentioned only briefly here. Under normal winter snow conditions in the Mackenzie Valley, they would experience little difficulty manoeuvring, provided good judgment is exercised by their operators. A snow depth of 8 inches will usually insure virtually no damage to
the terrain, provided a few inches of frozen tundra or muskeg exists beneath the snow. Any terrain damage resulting from tracked vehicles would most likely stem from off-road travel too early in the fall or too late in the spring.

Many papers have been prepared describing the success and failures of hovercraft in northern terrain (Hughes (1961), Cooner (1965), Cooner and Starr (1966), Canada Defence Research Board (1966), Pennie (1967), Oilweek (v.20, no.41, 1969), Walker (1969), Oilweek (v.21, no.16, 1970), Liston (1971), Petroleum Engineer International (v.32, no. 7, 1971) and others). Although a full range of hovercraft is described by these papers, only brief comments on those with unique features will be mentioned here.

Petroleum Engineer International describes the Act 100 hovercraft produced in Calgary, which can haul a 100 ton payload across essentially any level terrain. The gross weight of this vehicle is 250 tons. Since the vehicle is towed, ground contact support is required only for the lead vehicle. In operation, ground pressures beneath the Act 100 less than 1.0 psi could be expected. Such a vehicle could be of considerable value under ideal load and terrain conditions. However, it has operating limitations on sloping ground.

Cooper (1965) indicates that, as of 1965, running costs of hovercraft were similar to those for small aircraft. Furthermore, he indicates
that "routes" would be required if hovercraft are to be competitive. Others also imply the necessity for routes, particularly since hovercraft have ground clearance limitations.

Cooper and Starr (1967) indicate that hovercrafts exert ground pressures considerably less than 1.0 psi but greater than 0.2 psi. This feature alone makes hovercraft suitable for operation over many northern terrain types in both summer and winter, and almost definitely assures a place for hovercraft in future northern development work.

The consensus of the literature, however, seems to be that hovercraft are still in the development stage, although its obvious advantages as a low ground pressure vehicle give good reason for optimism that it will see considerable use in the future. At present, it is doubtful whether hovercraft will see general use on northern construction projects.

B. Cost Comparisons

Many transportation decisions in northern construction will undoubtedly be based on economics. For this reason, some general remarks on relative costs are justified.

The Royal Commission Inquiry into Northern Transportation, Province of Manitoba, 1969, gives some information of interest:
"The impact on transportation costs through upgrading of existing tractor roads to wheeled vehicle routes is indicated in the following cost comparisons. The costs of a tractor train are between 40¢ and a $1.00 per ton-mile depending on the characteristics of the route. The cost by air exceeds 70¢ per ton mile. If winter roads for wheeled vehicles were available the costs would range between 7.5¢ and 9¢ per ton-mile."

Wilson (1970), while comparing costs of transporting steel from Pittsburg to Prudhoe Bay, indicates typical barge costs from Hay River to Prudhoe Bay would be $90.00 to $100.00 a ton. This is roughly equivalent to 7¢ a ton-mile. For comparison, exact air freight costs cannot be calculated from the data presented; however, there are indications that air freight costs are probably twice as high as the barge costs.

The North of 60 Prospectus (1971), published by the Department of Indian Affairs and Northern Development, gives excellent references to transportation facilities. It indicates that Mackenzie River barge rates are 4¢ a ton-mile, and that freight rates in the Territories can be expected to be 20-50% higher than rates for southern Canada.

Petroleum Engineer (1970) also gives cost comparisons, and these correspond closely to those of Wilson (1970) above. Wilson notes, however, that cost comparisons are very elusive for the North Slope. He says that it is not only necessary to compare the mode of transportation but also the timing, the cost of material at the originating point, and the length of term of the commitment.
In summary, exact estimates of transportation costs in the north are elusive. In many cases, considerations other than cost may well influence the mode of transportation to be used for a specific task. Hence, cost may not be the primary factor in selecting transportation methods.

It has been mentioned before in this report, but it bears repeating here:

"Winter roads will be competitive with other modes of transportation economically, but particularly with permanent roads, so long as the need for transportation in the area is anticipated for only a few years."

This observation can be deduced from Russian experience as presented in the abstract of work by Shtyrev and Shein (1966). They stated that:

"a 200 km year-around road costs 100,000 and 2000 rubles/km to construct and maintain respectively as against 30,000 and 1000 rubles/km for a winter road of the same length."

This seems to indicate that Russian winter roads are competitive on a strictly economic basis, so long as their use is not expected to exceed three years. A deduction such as this is important when considering winter roads, particularly in relation to borrow areas, etc., where the use of access roads normally will be for a limited time.
APPENDIX "A" - INTERVIEWS

Introduction

The content of this Appendix is a record of the conversation and reply to questions from numerous individuals who have had experience with some aspect of winter roads. Notes were hand taken during the interviews, and, therefore, the answers presented here have been expanded to convey the tone and bulk of the conversation.

Each participant since the interview has reviewed the script, and all misquotes and errors have hopefully been eliminated. Also, permission to include the interviews of those presented herein has been granted by the individuals.

The reader is reminded that many of the answers are personal opinions, and for this reason the names, title, firm, and a brief description of the participant's association with winter roads is given. It is believed that this information will help to put the interview in its proper context.

The interviews are presented chronologically:

1. Mr. Tom Sigfusson, Sigfusson Transportation Company Ltd., Winnipeg, Manitoba.

The main operator of winter roads in northern Manitoba. Extensive experience in constructing, maintaining and operating miles of winter roads to supply remote villages.

2. Mr. Jim Riley, BACM, Winnipeg, Manitoba.

Experience in constructing, maintaining and operating winter roads required for construction projects in northern Manitoba.

3. Mr. Don Propp and Mr. Ivan Bishko, Northern Geophysical, Calgary, Alberta.

Northern Geophysical has constructed, maintained and operated several winter roads necessitated during winter work in the Mackenzie Valley area.
4. Mr. Dale Fickenger,
Vice-President,
PanCana Industries Ltd.,
Calgary, Alberta.

The construction division of PanCana Industries, Baines Bros. Construction, has been engaged in construction of winter roads used for access by the petroleum industry for over twenty years. Currently they operate and maintain a winter road through the Mackenzie Valley from Fort Simpson to Inuvik, N.W.T. under a federal lease.

5. Mr. A.G. Turnock,
Field Operations Supervisor,
Imperial Oil Ltd.,
Edmonton, Alberta.

Extensive experience with winter roads gained through construction, maintenance and operation of access roads required by exploration drilling crews, etc. Some experience recently with winter roads through the Mackenzie Delta.

6. Mr. R.G. (Bob) Wilson,
Field Services,
Imperial Oil Ltd.,
Edmonton, Alberta.

Experience with winter road operations through Field Services supervision.

7. Mr. Doug Readman,
Driver,
Tower Trucking,
Edmonton, Alberta.

Only experience on winter roads is from a driver's viewpoint of the Fort Simpson to Inuvik winter road.

8. Dr. Larry Bliss,
Professor of Botany,
University of Alberta,
Edmonton, Alberta.

Experience gained through travel and terrain degradation observations during extensive research efforts throughout the Mackenzie Valley region.
9. Mr. Helios Hernandez,
Research Associate,
University of Alberta,
Edmonton, Alberta.

Experience gained during the summers of 1970 and 1971 through study of natural plant recolonization of surficial disturbance in the Tuktoyaktuk Peninsula region, N.W.T. In relation to Dr. L.C. Bliss's research program, the study involved sampling several sections of winter roads used to move and supply drilling rigs. Other sections of winter roads were examined in the summer of 1972.

10. Mr. Ted Boodle and Mr. Hugh Taylor,
Resource Management Officer and Assistant Resource Management Officer, respectively,
Department of Forestry,
Hay River, N.W.T.

Mr. Boodle has had extensive experience in winter road observations in relation to Land Use Regulations in the lower Mackenzie Valley and Delta area. Mr. Boodle who has recently been transferred to Hay River, and Mr. Taylor have both travelled and made observations in the Hay River area.

11. Mr. Richard Silbeston,
Cat Operator
Goodzeck Construction,
Hay River, N.W.T.

Only notable experience with winter road was on trip from Fort Simpson to Inuvik in 1971. Also, operated Cat in Inuvik area until spring.
Q. Which ground conditions are the worst for operating a winter road?

A. Small creeks with vegetation are the worst areas because snow hangs in the vegetation, insulates, and prevents freezing of the water.

Q. What about permafrost areas?

A. These areas are used to advantage, as they give a firm base early.

Q. How do you handle the small creek problem?

A. If no vegetation, snow and water freeze with no particular problem. Normally we tramp the vegetation with a Nodwell or M7, which tends to eliminate the problem.

Q. How do you know when to begin operations in the fall?

A. It normally takes a real cold snap to give us the depth of freeze required. That is, -30 degrees F to -40 degrees F below. Zero temperature just isn't much help. For this reason it is usually Christmas or the New Year.
before we get going. It seems you can depend on it being cold then.

Usually we use a probe to check out the first run over, and on ice we would cut through to check the thickness.

Q. Do you have any rule of thumb for ice thickness and carrying capacity?

A. Two feet of ice is good for 20 tons, and 30" will carry almost anything, at least 30 tons. Vibration such as a D-9 is one of the worst types of load.

Q. How else do you aid getting started in the fall?

A. The first step is to scrape the snow off the surface to get the frost in when it comes. This operation starts early in December. River crossings are also a key to starting. The lead vehicle normally carries the equipment, a small pump, and flooding is accomplished that way.

Q. In the spring, what normally restricts traffic first?

A. Hills get mucky first. Hills of clay are first to go in the spring.
Q. How long can you operate after initial melting in the spring?
A. Normally the road is good for a week after initial melting. If it rains, a day or two can stop progress. You can operate in the spring for a while by stopping in the day and travelling at night as long as you're getting frost at night.

Q. Do you haul any snow for the road grade?
A. No. Normally we haul snow only to fill holes.

Q. Do you ever use corduroy?
A. Yes. Over bogs as much as a quarter mile in length, and also at small river crossings.

Q. What about drainage?
A. Corduroy has a minimum disruption of drainage, even on the small river crossings. The problem with corduroy is that its expensive and hard work.

Q. What about culverts?
A. We use some used culverts, normally for shallow rivers, and they usually don't get washed out. We tie the culverts to rock by cable, so we can retrieve them if they do wash out.
Q. What about environmentalists; do they give you any trouble?
A. No. We haven't been bothered.

Q. Would you say that there is much damage?
A. There is some at river crossings when ruts are formed perpendicular to the stream. Gullying does occur in the ruts.

Also, there is definite depressions in the road after a few years of use and water stands during the summer.

Q. Can you give us some idea of costs for various roads?
A. Rule of thumb for year-to-year maintenance is $500.00 per mile. However, a Cat and sled can get by for $100.00 per mile.

Q. What would be the average cost for a new snow road?
A. I really don't know. On the average I would estimate $1,000.00 per mile in that country. Bush is expensive; it could run up to $3,000.00 per mile. That is just an estimate.

End of interview
How does the authority decide when to open an ice bridge?

A. Normally, he drills holes to test the thickness.

When to close the ice bridge?

A. The road is usually gone first.

How would you suggest the procedure be improved?

A. Nothing needs to be done as far as the ice bridges are concerned.

Is there any winter condition on record where an ice bridge had to be shut down?

A. No, at present 50 to 60 ton loads are transported on several tires, and it could be more.

Is there a law against use of corduroy in ice bridges?

A. None that I know of, and it's used regardless, and even government personnel drive on it.
Q. Against the use of sawdust?
A. I have never seen it used.

Q. How much notice could the ice bridge contractor give for the date of opening and how accurate would it be? For the closing?
A. Usually about 10 days. If you get an early fast thaw, you can really beat up a road.

Q. What do you look for in a river cross-section for approaches and exits from an ice bridge?
A. Mainly look for no white water; a gently sloping stretch is best.

Q. What is the maximum possible weight that can be transported across an ice bridge, if any?
A. You wouldn't want to take a chance with a valuable piece of machinery like a turbine.

Q. Describe the sequence of events in the construction of an ice bridge.
A. We lay two parallel timbers in natural state, and use ice and snow to form dykes. Small trees are laid perpendicular, and cemented together with snow and water. We repeat this
for two or three layers and end up with a $1\frac{1}{2}$ or 2 foot thick bridge.

Q. Describe the maintenance procedures.
A. None.

Q. What research do you visualize as necessary to extend the use of ice bridges?
A. None.

Q. What controls the date of road opening?
A. Soft tracks can make it earlier, but it is usually December 1 before we move north of '55. If it freezes before it snows you're in business. About 6" of snow is right for a truck road. Pickup can go 25 to 30 miles per hour.

Q. The date of road closing?
A. The north bank of a river usually goes first.

Q. Which ground conditions are worst for operating a winter road?
A. Open swamp.
Q. What about permafrost areas?
A. We like permafrost - you get operating earlier, but we do rut it up pretty good.

Q. How do you handle crossing small creeks?
A. If they're over three feet we sometimes use culverts, but normally we doze in timber so we don't block the flow, and then we cover with moss and snow.

Q. Do you have rule of thumb for ice thickness and carrying capacity?
A. We like 18" for a D-6. We just count the blue ice, as slush ice isn't worth anything.

Q. In the spring what normally restricts traffic first?
A. The north approach to an ice bridge normally does.

Q. How long can you operate after initial breakup in the spring?
A. We continue until the bogging down gets too bad.
Q. Do you haul any snow for road grade?
A. None. Snow is usually high on each side.

Q. Do you use corduroy for any condition on the winter road?
A. Just in some bogs.

Q. What about drainage?
A. Drainage is no real problem. The odd creek will fool you, as the crossing will ice up with a slope, and you're forced to put a culvert in. It pays to put culverts in right at the start.

Q. Do you use culverts?
A. Yes.

Q. Have you had any criticism from conservationists or environmentalists?
A. No.

Q. Do you feel there is a need for them to be involved?
A. Yes, they are going to get involved.
Q. Would you say there is much damage?

A. Yes, but what is the difference. Rain tends to level it out.

Gullying does occur on some clay and silt slopes.

Q. If so, where mainly?

A. Hillsides are the worst.

Q. Is continued use from year to year better than a new alignment each year?

A. Generally continued use is better. There is no apparent difference year after year, and less damage because the drivers get to know the road.

Q. Do you have any traffic survey figures, gross load, and axle or wheel load data for the winter road?

A. I doubt if any were ever taken.

Q. Over the two or three years of service, have you noticed any progressive type problems associated with winter roads?

A. No.

Q. Does any type of land use official, conservationalist or whatever make a final run over the winter road in the spring, or not? In the fall?

A. None, whatsoever.
Q. Can you give me some idea of the terrain damage from the winter roads with which you are experienced?

A. Beyond the treeline there is very little healing capacity. For this reason, in general it is possible to use wheeled vehicles south of Fort Norman, but necessary to use tracked vehicles north of Fort Norman. Stream crossings often cause the most problem.

Q. I'm of the opinion that to extend the use of winter roads, it would be more beneficial to concentrate on extending the spring date of closure, rather than the fall date of opening. Do you agree?

A. From our standpoint it is just as hectic and important to get started in the fall.

Q. Does the Department of Lands and Forests ever inspect your winter roads?

A. Yes, they often fly over the route to check for damage, often daily.
Q. Are the land use people reasonable to deal with?
A. Yes, the Authority is quite reasonable at present.

Q. On the main toll winter road, how do you make out?
A. Usually we can travel from Fort Simpson to Norman Wells in 30 hours. With tracked equipment, you average three or four miles per hour.

Q. Do you notice much difference in springtime of use between say Fort Simpson and Norman Wells?
A. Yes, there is about three weeks between Simpson and Inuvik. Say if Simpson is April 5, Fort Norman will be April 15, and Inuvik about May 1 for the spring last day of use of the winter road. We find a date is good for closure in the spring. You know how long you've got to get your work done, so you get it done and get out.

Q. Do you have any general suggestions about winter road use?
A. It is important to leave the peat intact. That's where you can get into trouble.
Q. How does the authority decide when to open an ice bridge?

A. No authorization is required for opening of an ice bridge. The construction consists of flooding the river permitting it to freeze, increasing the thickness of the ice until an adequate thickness has been reached to accommodate the anticipated traffic weight.

Q. When to close the ice bridge?

A. Ice bridges are usually closed due to the deteriorating condition of the road which is served by the ice bridge. In some cases flooding becomes sufficiently severe to destroy the bridge.

Q. How would you suggest the procedure be improved?

A. I am sure the method of construction can be improved, however, the present system seems to meet the requirements except for the length of time required for the construction.

Q. Is there any winter condition on record where an ice bridge had to be shut down?
A. Not that I can recall, however late fall flooding or early spring flooding on the river could cause the bridge to break up or become unserviceable due to the water cover.

Q. Is there a law against use of corduroy in ice bridges?
A. Not that I am aware of presently.

Q. Against the use of sawdust?
A. It is of no use to us anyway.

Q. How much notice could the ice bridge contractor give for the date of opening, and how accurate would it be?
A. Probably five to ten days on the Mackenzie River. You can depend on crossing at Fort Simpson around the first of January.

Q. What do you look for in a river cross-section for approaches and exits from an ice bridge?
A. Grade is the biggest concern. It is best to put it in when the river is low, and of course we look for a narrow section in the river.

Q. What is the maximum possible weight that can be transported across an ice bridge, if any?
Q. Describe the sequence of events in the construction of an ice bridge.
A. Usually parallel snow dykes are built the length of the crossing. Then 6" or 4" pumps are used to put an inch or two of water on, and the pumps are moved along the length.

Q. Describe the maintenance procedures.
A. Nothing necessary, except snow removal.

Q. What research do you visualize as necessary to extend the use of ice bridges?
A. None.

Q. What controls the date of road opening?
A. A good freeze in the south. In the permafrost area, there is less trouble since the cold comes into the active layer from bottom and top.

Q. The date of road closing?
A. We deal directly with the Forestry and Environmental people on a day-to-day basis. The field conditions determine when it is shutdown time. Runoff from creeks sometimes determines cutoff date. All factors are considered to determine closure.

Q. How do you handle crossing small creeks?
A. We flood and make ice bridges.

Q. Do you have a rule of thumb for ice thickness and carrying capacity?
A. Eighteen inches of clear ice will carry a fair load. Twenty-four inches is normally required.

Q. How else do you aid getting started in the fall?
A. We stockpile along the river bank. We work between the incoming rivers between the ice bridges. We need an all-weather road to achieve all-weather service, to eliminate isolation, to achieve all-weather emergency sickness relief, and probably most important all-weather access in case of pipeline rupture.

Q. How much sooner could the main winter road be opened if you started in the north and worked south?
A. This is already taken advantage of, since staging areas are all along the river.

Q. In the spring what normally restricts traffic first?
A. Flooding creeks.

Q. How long can you operate after initial breakup in the spring?
A. No operating after water starts running.

Q. Do you haul any snow for road grade?
A. No. We just use dozer or drag to fill in low places.

Q. Do you use any special equipment?
A. It's too expensive to use rollers.

Q. Do you use corduroy for any condition on the winter road?
A. We haven't had to use any in the north. Clear ice leaves no residue.
Q. What about drainage?
A. This is one reason we don't use corduroy.

Q. Do you use culverts?
A. No, not on winter roads.

Q. Have you had any criticism from conservationists or environmentalists?
A. None, whatsoever. We do not quarrel with them, but rather try to work with them.

Q. Do you feel there is a need for them to be involved?
A. Yes! Some people would take advantage of the situation.

Q. Would you say there is much damage?
A. Let me put it this way; there is no real damage, and certainly nothing that is progressive. However, there can be no progress without some effect.

Q. If so, where mainly?
A. I can't really give you a good example of damage. They can even replace the turf now on the pipeline right-of-way, so that should give some indication.
Q. Is continued use from year to year better than a new alignment each year?
A. There is no indication of year-to-year build-up of damage.

Q. What are the costs for a new road under various conditions?
A. First year, there are opening costs and maintenance costs, whereas in later years there is just maintenance.

Q. What would be the yearly reopening and maintenance cost?
A. I can't release that information.

Q. Am I in the ball park at $600.00 per mile?
A. You're not too far out.

Q. Do you have any traffic survey figures, gross load, and axle or wheel load data for the winter road?
A. Only available through DIAND.

Q. Over the two or three years of service, have you noticed any progressive type problems associated with winter roads?
A. No.
Q. Does any type of land use official, conservationist or whatever make a final run over the winter road in the spring, or not? In the fall?

A. Yes, they patrol the roads now more frequently by air.

Q. In your opinion what constitutes the most probable detrimental effect to the arctic environment from winter road use? (Please rank if more than one)

A. Technology of winter roads has advanced so that there is no real detrimental effect.

Q. Are you aware of any research programs with regard to winter roads over the last couple of years?

A. No, I think we have satisfactory solutions now.

Q. Are you aware of any problems that tend to be self-perpetuating rather than self-healing in relation to winter roads?

A. None.

Q. What research do you visualize as necessary to extend the use or usefulness of winter roads?
I would like to see the development of a modular construction of bridges for river crossings.

Q. Are you aware of Bailey bridges?
A. Yes, but they are limited to short spans.

Q. Do you know the capacity of Bailey bridges?
A. No, but the Department of National Defence should give you that information.
Q. How does the authority decide when to open an ice bridge?

A. On the basis of quality and thickness. Generally we use 48" for a D-7 Cat, and 54" for a D-8 Cat. Throughout the Mackenzie Delta we have a general rule that until year end we use the tundra, but after year end when the ice is good we go out of our way to travel on ice covers.

Q. When to close the ice bridge?

A. Whenever the ice starts rotting. If there is water under the snow the operators get squeesy about travelling. The thing some people don't realize is the ice melts from the bottom and even if it turns cold you can still be losing ice. After April 20, even if it turns cold you should be out.

Q. How would you suggest the procedure be improved?

A. I don't know.

Q. Is there any winter condition on record where an ice bridge had to be shut down?

A. None.
Q. Is there a law against use of corduroy in ice bridges?
A. We are not convinced corduroy does any good. Logs placed vertical and frozen in place that give bearing capacity on the bottom have been reported to help.

Q. Against the use of sawdust?
A. We use sawdust under pads for rigs. We have our own chipping machine for summer use.

Q. How much notice could the ice bridge contractor give for the date of opening, and how accurate would it be?
A. If you can demonstrate that you are not going to break through, then you can cross.

Q. What do you look for in a river cross-section for approaches and exits from an ice bridge?
A. We look for minimum work, no cuts, or look for natural cuts. We avoid bramble bush in the Delta as it won't come back but is replaced by grasses.

Q. What is the maximum possible weight that can be transported across an ice bridge, if any?
A. One hundred tons on eight wheels, or at least 70 to 80 tons is possible. Rig loads are in the order of 30 tons maximum, plus truck.

Q. Describe the sequence of events in the construction of an ice bridge.

A. In the Delta area we have found that we can make ice as fast by keeping the snow off as we can by flooding. In fact, at two sites four miles apart, we got the same results with no flooding and with one inch lifts of flooding. With no flooding three inches of ice and hand snowplowers were used to get started.

Q. Describe the maintenance procedures.

A. Constant use is best, and snowplowing where needed.

Q. What research do you visualize as necessary to extend the use of ice bridges?

A. Some bearing capacity work is necessary, but we have had trouble on thicker ice when we've had success on thinner ice. Obviously an ice quality factor is involved. Also, we should determine if clean, fresh water makes
a better ice bridge than dirty fresh water. It has been found that a dirt fill over 18" of ice could carry the equivalent of 36" of ice. Normally 54" of ice is required to land a Hercules aircraft.

Q. What controls the date of road opening?
A. At least one and one-half inches of frozen tundra and eight inches of snow pretty well assures travel. If there isn't eight inches of snow, we grade it onto the road. Also, if there isn't eight inches of snow, a greater depth of freeze on the tundra suffices. In this case it is trial and error, with demonstrations in the field and the land use people make a judgment call.

Q. The date of road closing?
A. Normally the ice bridges go first. If there are no ice bridges, the approaches to lakes facing south give trouble first. April 20th approximately.

Q. Which ground conditions are worst for operating a winter road?
A. Hilly country in general due to no cutting being desirable, and secondly the springs and numerous creeks.

Q. What about permafrost areas?
A. Silt flats are no problem. High country tundra with its hummocky areas is very rough and hard on equipment.

Q. How do you handle crossing small creeks?
A. We fill them up with snow, but remove them before spring. We sometimes use gravel in place of snow, but removal is still necessary.

Q. Do you have a rule of thumb for ice thickness and carrying capacity?
A. We have a chart that we have had prepared. In general, 24" is required for an Otter landing, 54" for an Electra or Herc, and 54" will take about 100 tons. (The chart indicates 92 tons).

Q. In the spring what normally restricts traffic first?
A. Ice crossings usually.

Q. How long can you operate after initial breakup in the spring?
A. Just guessing, but possibly a couple of weeks after initial melting starts on the surface.

Q. Do you haul any snow for road grades?
A. We just move it by maintainer if less than eight inches of snow, but this is a function of the ground. If we see a bare spot on the road, we cover it. With accumulation of snow, we tend to build it up rather than grade it down. This has evolved in last three years.

Q. If so, how do you collect it?
A. We use patrols, snowplows, snowblowers, and even V-blades on loaders.

Q. What is the rest of the procedure?
A. We normally just pack it with tracked vehicles, or a 953 Kenworth which has a tire 27" wide and $5\frac{1}{2}$ feet high.

Q. Do you use corduroy for any condition on the winter road?
A. No.
Q. What about drainage?
A. This is no problem in the Delta area, and not even at Norman Wells in my experience.

Q. Do you use culverts?
A. Yes, if we are building a road to a staging area which will be used as a summer access road, but there are not very many of these. Also, some are used for access to tank farms, etc.

Q. Have you had any criticism from conservationists or environmentalists?
A. Not really, Imperial tries to be one of the best for following the rules.

Q. Do you feel there is a need for them to be involved?
A. Yes, they serve a function.

Q. Would you say there is much damage?
A. Yes, a few companies get away with some things that our management would not let us away with ourselves.

Q. If so, where mainly?
A. Drilling without adequate site preparation. We watch our seismic and sub-contractors closely. No seismic work with wheeled vehicles is allowed.

Q. Is continued use from year to year better than a new alignment each year?

A. My opinion is you're better on one route. However, even among the land use people there is disagreement. With flat tracks or low pressure vehicles one pass, then move from place to place is best. This avoids tramping into the ground.

Q. What are the costs for a new road under various conditions?

A. Same from year to year, since all crossings are removed.

Q. What would be the yearly reopening and maintenance cost?

A. Approximately $2,000.00 per mile on tundra and $1,000.00 per mile on ice.

Q. Do you have any traffic survey figures, gross load, and axle or wheel load data for the winter road?

A. No.
Q. Over the two or three years of service, have you noticed any progressive type problems associated with winter roads?

A. No, road cuts seem to get better year by year. There is no real difference environmentally. The first year about seven miles per hour is possible on a new road, 12 miles per hour the second year and 20 miles per hour thereafter, using big trucks.

Q. Does any type of land use official, conservationalist or whatever make a final run over the winter road in the spring, or not? In the fall?

A. Yes, they're out there periodically all the time. We stop work when told to stop. For about a week we operate on 24-hour notice, which gives us time to get the house in order.

Q. In your opinion what constitutes the most probable detrimental effect to the arctic environment from winter road use? (Please rank if more than one).

A. After five years I would bet you couldn't find where we drilled the way we operate now. Even to find the previous year's road we have to use air photos, maps, and surveyors.
Q. Are you aware of any research programs with regard to winter roads over the last couple of years?
A. Yes, sprinkling and heating, but with little satisfaction.

Q. Are you aware of any problems that tend to be self-perpetuating rather than self-healing in relation to winter roads?
A. No, I haven't witnessed any.

Q. What rare species (flora or fauna) do you visualize as needing general attention?
A. I don't know of any.

Q. Are most or all rare species known and identifiable that might be affected?
A. One thing the Government doesn't want destroyed is pingos.

Q. Describe the maintenance procedures.
A. Mainly snowplowing after storms. The built-up sections remain clear. Road patrols are used a lot.

Q. What research do you visualize as necessary to extend the use or usefulness of winter roads?
A. One operational problem that needs attention is the quality of snow. Snow will simply not pack. We can make a road on which you could drive 60 miles per hour, but the first truck would punch through.
Q. Mr. Wilson, I have talked to Mr. Turnock of your staff, but could I have your opinion of research needs related to winter roads?

A. It would be good to know the possible loads versus ice thickness for various qualities of ice. If we could cut this finer with 100% confidence, it would be a big help.

Also, some sort of statistical modelling of storms and optional equipment for snow removal for various conditions would be helpful. Capabilities of machines on a miles per machine day basis would also be helpful.

Knowledge about the mechanics of snowplowing to minimize snow drifting would be beneficial. Also for ice roads, the ice thickness and carrying capability should be established.
CONVERSATION WITH DOUG READMAN, DRIVER FOR TOWER TRUCKING, EDMONTON, ALBERTA, ON SEPTEMBER 20, 1972

Q. I understand you have driven the winter road from Fort Simpson to Inuvik?

A. Yes, I have.

Q. What did you think of it from a driver's standpoint?

A. It is slow going, probably 10 miles per hour. You require a good truck and tire chains.

Q. Did you have much trouble?

A. I would advise travelling in pairs, and take a tow truck or Cat. Even the tow truck couldn't get up a hill on the south side of Norman Wells. The first trip is the worst, and load distribution is important. We also had trouble at Saline River, breaking through and getting stuck in holes. When it blows it is very difficult to keep open.

Q. Any other comments?

A. Take lots of food and travel in pairs. It would be wise to take a Cat with you.
Q. What about the worst sections?

A. The road is better between Fort Simpson and River Between Two Mountains. North of there it gets bad.

Q. How could it be improved?

A. Mainly by cutting down the hills, which could speed things up.

Q. What about more traffic, would it help?

A. No, more traffic would cut it up more.

Q. Did small creeks give you any problem?

A. Just one between Fort Norman and Norman Wells.

Q. Do you have any other comments?

A. Just watch the weather and the load distribution.
CONVERSATION AND REPLY TO QUESTIONNAIRE ON WINTER ROADS BY DR. LARRY BLISS, BOTANY DEPARTMENT, UNIVERSITY OF ALBERTA, ON SEPTEMBER 20, 1972

Q. How should an authority decide when to open an ice bridge?
A. A calendar date is no good; it should be flexible.

Q. How would you suggest to improve the procedure?
A. Probing is probably good enough. Do this at stream crossings and southern exposures.

Q. Is there a particular area that is most easily damaged?
A. Well the forested areas are more self-healing, but then they see more use.

Q. Have you seen any areas on the main toll road where you would say there was terrain damage?
A. Yes, 15 to 20 miles north of Norman Wells.

Q. Is it repairable?
A. Yes, it would be irreparable only if it were on massive ice.
Q. What controls the date of road opening?
A. Usually a totally frozen active layer. Rick Haag (Bliss's graduate student) is trying to correlate freeze depth to degree days or some such parameter for Norman Wells and Tuk.

Q. What controls the date of road closing?
A. It should be a visual inspection.

Q. What ground conditions are worst for operating a winter road?
A. Impounded areas adjacent to a stream with poor drainage.

Q. How else could you aid getting started in the fall?
A. Possibly by using snow fences to keep a bare surface to get a faster surface freeze. Also, snow fences could collect snow if it could be used for grade.

Q. How long can you operate after initial breakup in the spring?
A. Only by using a gravel buildup, could you extend past breakup.
Q. Would you say there is much damage over the main toll road?
A. Over a 50 miles stretch that I travelled, generally there was less damage than I had anticipated.

Q. Where did the damage occur?
A. Mainly at river crossings caused by rutting.

Q. Is continued use from year to year better than a new alignment each year?
A. Yes.

Q. Why?
A. In forest and tundra the damage is areal, so restrict it to one alignment, no wider than necessary. If the peat thickness is maintained, little damage occurs.

Q. Do you have any traffic figures?
A. Yes, only what Gas Arctic Systems released which is estimated traffic only.

Q. Over two or three years of service have you noticed any progressive type problems, associated with winter roads?
A. Yes, near Tuk after two years of use, near the crest of a hill where turning of vehicles occurred, the surface got churned and thinned until it melted out, caved in, collected snow, which increased melt, which increased erosion, resulting in a bigger hole. The process was hopefully nullified by backfilling the hole with material this past summer.

Q. In your opinion what constitutes the most probable detrimental effect to the Arctic environment?
A. As described above, melt outs caused by removal of insulation.

Q. Are you aware of research programs related to winter roads over the last couple of years?
A. Yes, our energy budget study and a revegetation study.

Q. Are you aware of any problems that may be self-perpetuating?
A. Most problems will eventually stabilize, but depressions and spring melt water cause a nasty problem.

Q. Do rare species concern you?
A. Not so much concern with plants. The wildlife people have a greater concern here.

Q. What research do you visualize as necessary to extend use or usefulness of winter roads?

A. I would like to see a winter road section really mucked up to see what restoration could be effected. Also, I would like to see methods of achieving an iced surface on roads.

Q. Do you have any information with regard to expected traffic volumes or frequency along the pipeline right-of-way or winter roads?

A. The only available information is that of an estimate of the number of construction trips required for one winter's construction season on the North Slope (Spread No. 1). This tabulation (attached) gives a breakdown by construction operation, the average number of trips, and the maximum number of trips.
### 48" GAS ARCTIC SPREAD NO. 1

**REvised Traffic Count Estimate for First Year of Construction**

<table>
<thead>
<tr>
<th>OPERATION</th>
<th>NO.</th>
<th>TYPE OF EQUIPMENT</th>
<th>WEIGHT (LBS.)</th>
<th>TRIPS</th>
<th>MAX.</th>
<th>LOADING (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade</td>
<td>6</td>
<td>Dump Trucks</td>
<td></td>
<td>60</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Scrapers</td>
<td></td>
<td>100</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>D-8</td>
<td>70,000</td>
<td>24</td>
<td>32</td>
<td>13.5</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>D-9</td>
<td>84,000</td>
<td>20</td>
<td>20</td>
<td>12.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Motor Patrol</td>
<td>24,000</td>
<td>144</td>
<td>260</td>
<td>37.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3/4 Ton Pick-Up</td>
<td>5,000</td>
<td>420</td>
<td>500</td>
<td>17.0</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Bus</td>
<td>10,100</td>
<td>210</td>
<td>210</td>
<td>13.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Sub-Total Grade</strong></td>
<td></td>
<td><strong>978</strong></td>
<td><strong>1,302</strong></td>
<td></td>
</tr>
<tr>
<td>Trenching</td>
<td>2</td>
<td>TA-77</td>
<td>62,000</td>
<td>2</td>
<td>2</td>
<td>13.0</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>320-Ditching Mach.</td>
<td>48,000</td>
<td>1</td>
<td>1</td>
<td>17.0</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1 Yd. Backhoe</td>
<td>71,200</td>
<td>5</td>
<td>5</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>27 D. Backhoe</td>
<td>110,000</td>
<td>6</td>
<td>6</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Bus</td>
<td>10,100</td>
<td>120</td>
<td>120</td>
<td>13.2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3/4 Ton Pick-Up</td>
<td>5,000</td>
<td>420</td>
<td>600</td>
<td>17.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>D-8</td>
<td>70,000</td>
<td>2</td>
<td>2</td>
<td>13.5</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>Air Tracts</td>
<td>8,300</td>
<td>20</td>
<td>20</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>600 CFM</td>
<td>9,600</td>
<td>20</td>
<td>20</td>
<td>25.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Sub-Total Trench</strong></td>
<td></td>
<td><strong>596</strong></td>
<td><strong>776</strong></td>
<td></td>
</tr>
<tr>
<td>OPERATION</td>
<td>NO.</td>
<td>TYPE OF EQUIPMENT</td>
<td>WEIGHT (LBS.)</td>
<td>TRIPS AVERAGE</td>
<td>TRIPS MAX.</td>
<td>LOADING (PSI)</td>
</tr>
<tr>
<td>--------------</td>
<td>-----</td>
<td>----------------------</td>
<td>---------------</td>
<td>---------------</td>
<td>------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Stringing</td>
<td>20</td>
<td>Trucks, Empty</td>
<td>29,000</td>
<td>2400</td>
<td>2400</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>Trucks, Loaded</td>
<td>78,760</td>
<td>2400</td>
<td>2400</td>
<td>42.0</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Trucks, Empty (Regular)</td>
<td>29,000</td>
<td>790</td>
<td>1580</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Trucks, Loaded</td>
<td>78,760</td>
<td>790</td>
<td>1580</td>
<td>42.0</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>25 T. Crane</td>
<td>66,760</td>
<td>1</td>
<td>1</td>
<td>12.2</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>583</td>
<td>85,000</td>
<td>1</td>
<td>1</td>
<td>12.2</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>3/4 Ton Pick-Up</td>
<td>5,000</td>
<td>240</td>
<td>300</td>
<td>17.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tow Cat</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>SUB-TOTAL STRINGING</td>
<td></td>
<td>6623</td>
<td>8265</td>
<td></td>
</tr>
<tr>
<td>Bending</td>
<td>1</td>
<td>583</td>
<td>85,000</td>
<td>3</td>
<td>3</td>
<td>12.2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>572</td>
<td>61,000</td>
<td>6</td>
<td>6</td>
<td>11.4</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Bending Machine</td>
<td>60,000</td>
<td>1</td>
<td>1</td>
<td>14.8</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Bus</td>
<td>7,500</td>
<td>140</td>
<td>180</td>
<td>13.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SUB-TOTAL BENDING</td>
<td></td>
<td>150</td>
<td>190</td>
<td></td>
</tr>
<tr>
<td>Pipe Gang</td>
<td>2</td>
<td>572</td>
<td>61,000</td>
<td>4</td>
<td>4</td>
<td>11.4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Quads</td>
<td>65,000</td>
<td>2</td>
<td>2</td>
<td>12.2</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Bus</td>
<td>10,100</td>
<td>210</td>
<td>210</td>
<td>10.1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Buffer</td>
<td>7,000</td>
<td>1</td>
<td>1</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>3/4 Ton Pick-Up</td>
<td>5,000</td>
<td>210</td>
<td>300</td>
<td>17.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SUB-TOTAL PIPE GANG</td>
<td></td>
<td>427</td>
<td>517</td>
<td></td>
</tr>
<tr>
<td>OPERATION</td>
<td>NO.</td>
<td>TYPE OF EQUIPMENT</td>
<td>WEIGHT (LBS.)</td>
<td>TRIPS AVERAGE</td>
<td>TRIPS MAX.</td>
<td>LOADING (PSI)</td>
</tr>
<tr>
<td>------------</td>
<td>-----</td>
<td>-------------------</td>
<td>---------------</td>
<td>---------------</td>
<td>------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Welding</td>
<td>45</td>
<td>300 Amp</td>
<td>3,200</td>
<td>45</td>
<td>45</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>D-4</td>
<td>31,600</td>
<td>90</td>
<td>180</td>
<td>10.1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Bus</td>
<td>10,100</td>
<td>210</td>
<td>300</td>
<td>13.2</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>3/4 Ton Pick-Up</td>
<td>6,000</td>
<td>210</td>
<td>300</td>
<td>17.0</td>
</tr>
<tr>
<td><strong>SUB-TOTAL WELDING</strong></td>
<td></td>
<td></td>
<td></td>
<td>555</td>
<td>825</td>
<td></td>
</tr>
<tr>
<td>Coating &amp;</td>
<td>8</td>
<td>594</td>
<td>121,000</td>
<td>24</td>
<td>24</td>
<td>14.4</td>
</tr>
<tr>
<td>Lowering In</td>
<td>2</td>
<td>D-8 Tow Cat</td>
<td>70,000</td>
<td>6</td>
<td>6</td>
<td>13.5</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Bus</td>
<td>10,000</td>
<td>210</td>
<td>300</td>
<td>13.2</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>3/4 Ton Pick-Up</td>
<td>5,000</td>
<td>210</td>
<td>300</td>
<td>17.0</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Heated Truck</td>
<td>20,000</td>
<td>4</td>
<td>6</td>
<td>30.4</td>
</tr>
<tr>
<td><strong>SUB-TOTAL COATING &amp; LOWERING IN</strong></td>
<td></td>
<td></td>
<td></td>
<td>454</td>
<td>636</td>
<td></td>
</tr>
<tr>
<td>Tie-Ins</td>
<td>4</td>
<td>594</td>
<td>121,000</td>
<td>4</td>
<td>4</td>
<td>14.4</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Nodwell</td>
<td>7,000</td>
<td>1</td>
<td>4</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Bus</td>
<td>10,100</td>
<td>210</td>
<td>300</td>
<td>13.2</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>3/4 Ton Pick-Up</td>
<td>6,000</td>
<td>210</td>
<td>300</td>
<td>17.0</td>
</tr>
<tr>
<td><strong>SUB-TOTAL TIE-IN</strong></td>
<td></td>
<td></td>
<td></td>
<td>425</td>
<td>608</td>
<td></td>
</tr>
<tr>
<td>OPERATION</td>
<td>NO.</td>
<td>TYPE OF EQUIPMENT</td>
<td>WEIGHT (LBS.)</td>
<td>TRIPS</td>
<td>MAX.</td>
<td>LOADING (PSI)</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>-----</td>
<td>-------------------</td>
<td>---------------</td>
<td>--------</td>
<td>------</td>
<td>---------------</td>
</tr>
<tr>
<td>Backfill, Padding and Clean-Up</td>
<td>5</td>
<td>D-8</td>
<td>70,700</td>
<td>15</td>
<td>30</td>
<td>13.5</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Grade</td>
<td>56,600</td>
<td>4</td>
<td>8</td>
<td>37.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1 1/2 Yd. Clam</td>
<td>93,100</td>
<td>2</td>
<td>2</td>
<td>11.2</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>977</td>
<td>977</td>
<td>15</td>
<td>30</td>
<td>11.2</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>Dump Truck</td>
<td>32,800</td>
<td>66</td>
<td>132</td>
<td>50.5</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Bus</td>
<td>10,100</td>
<td>420</td>
<td>580</td>
<td>13.2</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>3/4 Ton Truck</td>
<td>6,000</td>
<td>420</td>
<td>580</td>
<td>17.0</td>
</tr>
<tr>
<td>SUB-TOTAL BACKFILL, PADDING &amp; CLEAN-UP</td>
<td></td>
<td></td>
<td></td>
<td>942</td>
<td>1,362</td>
<td></td>
</tr>
<tr>
<td>Testing &amp; Tie-In</td>
<td>4</td>
<td>594</td>
<td>121,000</td>
<td>4</td>
<td>4</td>
<td>14.4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>D-8</td>
<td>70,700</td>
<td>2</td>
<td>2</td>
<td>12.2</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1 1/2 Yd. Clam</td>
<td>93,100</td>
<td>1</td>
<td>1</td>
<td>11.2</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Bus</td>
<td>10,100</td>
<td>210</td>
<td>300</td>
<td>13.2</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>3/4 Ton Truck</td>
<td>6,000</td>
<td>210</td>
<td>300</td>
<td>17.0</td>
</tr>
<tr>
<td>SUB-TOTAL TESTING &amp; TIE-IN</td>
<td></td>
<td></td>
<td></td>
<td>427</td>
<td>607</td>
<td></td>
</tr>
</tbody>
</table>
## Revised Traffic Count Estimate for First Year of Construction

### TYPE OF WEIGHT TRIPS LOADING

<table>
<thead>
<tr>
<th>OPERATION</th>
<th>NO.</th>
<th>EQUIPMENT</th>
<th>WEIGHT (LBS.)</th>
<th>TRIPS AVERAGE</th>
<th>TRIPS MAX.</th>
<th>LOADING (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camp, Supplies, etc.</td>
<td>2</td>
<td>Low Boys</td>
<td>119,000</td>
<td>280</td>
<td>300</td>
<td>50.0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Hi Boys</td>
<td>70,000</td>
<td>800</td>
<td>850</td>
<td>43.7</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>5 Ton Lube</td>
<td>42,800</td>
<td>440</td>
<td>540</td>
<td>32.0</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>5 Ton Fuel</td>
<td>38,900</td>
<td>440</td>
<td>540</td>
<td>29.0</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>5 Ton Winch Tr.</td>
<td>20,200</td>
<td>2100</td>
<td>2400</td>
<td>30.4</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>5 Ton Skid</td>
<td>22,000</td>
<td>210</td>
<td>300</td>
<td>33.8</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>3/4 Ton Pick-Up</td>
<td>5,000</td>
<td>2100</td>
<td>2400</td>
<td>17.0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Nodwell</td>
<td>10,000</td>
<td>840</td>
<td>1000</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>Mechanic Truck</td>
<td>6,000</td>
<td>4000</td>
<td>5000</td>
<td>16.0</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Power Wagon</td>
<td>7,000</td>
<td>840</td>
<td>1000</td>
<td>12.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Camp Move-ins</td>
<td></td>
<td>560</td>
<td>625</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>SUB-TOTAL CAMP, ETC.</strong></td>
<td></td>
<td>12,610</td>
<td>14,955</td>
<td></td>
</tr>
</tbody>
</table>

| Inspection                 | 10  | Company                        | 5,000         | 2200          | 3000        | 17.0          |
|                            | 10  | Government                     | 5,000         | 2200          | 3000        | 17.0          |

**SUB-TOTAL INSPECTION**

| GRAND TOTAL                |     |                               | 28,587        | 36,043        |             |               |
Q. What controls the date of road opening?
A. I would say "freeze-up" in general. I would recommend travel only when the ground is solidly frozen; that is, so all the layer that has thawed during the summer is once again frozen.

Q. What controls the date of road closing?
A. In general "thaw"; that is, eliminate traffic before surficial thaw begins again so that damage is minimized by preventing churning up of the surface.

Q. Would you say there is much damage? If so, where mainly?
A. In general, other than an aesthetic effect, it appears that damage is greatly reduced if operations are carried out only during the periods when the ground is solidly frozen. In upland tundra areas of the Tuktoyaktuk Peninsula if the dwarf shrubs and above ground vegetation are removed without removing the peat layer little damage usually
results. The most susceptible areas in upland regions appear to be at the crest of hills where the peat layer can be worn away as vehicles come over the top. Revegetation by native species, though slow, does occur. In low, wet areas of the summer little winter damage occurs since the area appears to be protected by ice.

Q. In your opinion what constitutes the most probable detrimental effect to the Arctic environment from winter road use?

A. Up to now, it would appear that with proper management; that is, no early fall or late spring traffic, the greatest effect is from the removal of vegetation. Although the thaw depth is increased, if the peat can be left intact the increase in thaw depth is in the order of 25%. Natural revegetation by sedges, grasses and other species does occur.

Q. Are you aware of any problems that tend to be self-perpetuating rather than self-healing in relation to winter roads?

A. No, other than the one case at Tuktoyaktuk, where an ice wedge was exposed in 1971. It melted causing a
depression which accumulated snow in winter and resulted in more erosion from melt water the following spring. This depression was filled in during the past summer in an attempt to see if it could be stabilized in this manner.
Q. How does the authority decide when to open an ice bridge?
A. Ice bridges are industries' problem. Land use and preservation of the environment is our concern. Industry has to determine whether or not ice thickness is suitable to support their equipment.

Q. When to close the ice bridges?
A. Usually it is a matter of the last man out, ripping the ice bridge out, usually with a bulldozer equipped with a ripper tooth.

Q. How would you suggest the procedure be improved?
A. No timber should be used. Use pure ice for ice bridges, and then use a ripper to take them out. At present a lot of bank damage results during removal of ice bridges.

Q. Is there any winter condition on record where an ice bridge had to be shut down?
A. No. Ice bridges must be removed before spring break up so as to not obstruct the natural flow of the stream.
Q. Is there a law against use of corduroy in ice bridges?
A. Yes, in the Fisheries Act. In fact, there is a stiff fine associated with it. No material is to be left in the stream.

Q. Against the use of sawdust?
A. Sawdust can be used under rigs where no drainage is near. We allow it, but we don't like to see it used. Sawdust and wood shavings are harmful to fish and other marine life.

Q. What do you look for in a river cross-section for approaches and exits from an ice bridge?
A. Gently sloping approaches are best. If, however, this type of approach is not possible snow fill with a sway-back is practical. Here again, removal is demanded before spring and this presents a problem, especially any damage to the banks by equipment.

Q. Describe the sequence of events in the construction of an ice bridge.
A. We are mostly interested in the approaches and here we recommend iced snow for the grades.
Q. What research do you visualize as necessary to extend the use of ice bridges?

A. A method to aid removal of snow fills and ice bridges at rivers or streams. Fast and efficient removal would extend the use, as we could wait until the last minute if we know they could be taken out effectively.

Q. What controls the date of road opening?

A. Freeze depth controls. At Inuvik 4" or 5" of frozen tundra as indicated by probing, or 1½" of frozen tundra with 8" of snow cover will usually permit traffic. However, the final decision is made by us in the field.

At Hay River, November 15 is approximately the date of commencement of operations such as seismic and well drilling and movement on access roads.

Q. The date of road closing?

A. This is tied into a shutdown date. However, last year we allowed traffic past the tentative shutdown date since winter conditions and cold weather persisted into late spring. With 4" of snow left, we noticed the Nodwells and Bombardiers breaking through the snow. When you
see this, it's time to close the road. No rutting of the lichen resulted in this case. The snow in late spring begins to crystalize and when the water content of the snow reaches approximately 40% their machinery begins to break through.

Q. Which ground conditions are worst for operating a winter road?
A. Once there is a layer of hard packed snow on frozen tundra it doesn't matter much. Cat blades that are built up in height to control snow being pushed over top causes damage due to the extra ton or so of weight. The existing runner ski, or mushroom shoes should be widened to account for the extra weight so that cutting through to the soil or tundra below will not occur.

Q. How do you handle crossing small creeks?
A. Snow fills with swaybacks are the most common and these fills must be removed if possible to do so.

Q. Do you have a rule of thumb for ice thickness and carrying capacity?
A. Yes, 4" is usually required on a river before a man can safely go out to test the ice thickness.

Q. How else do you aid getting started in the fall?
A. Wide rubber tires with 2" of frost can be used in some areas if no snow is on the ground. As far as seismic operations, probes on the geophones of the line recorders would tend to lessen the surface disturbance because the probe could penetrate the snow cover left on the line. Many companies insist that the geophones be set directly on the bared tundra or soil in order to get suitable records, and in these cases the lines or a strip along one edge of the line has to be completely cleared of snow. Also, by not using Cats in the field except to draw the camp.

Q. In the spring what normally restricts traffic first?
A. The road itself on level land, but in general south exposures and river crossings is where the snow melts or softens up, allowing machinery to break through first.

Q. How long can you operate after initial breakup in the spring?
A. If water is lying on the road, you shouldn't be on it. Dark patches in the snow indicate a saturated condition, and the road should be shut down immediately. Night operation only can extend the exploration season. This past winter after the road was closed, the adjacent snow-plowed banks were flattened for a road surface for a few days use on a water haul road from a lake (water supply) to a well drilling site.

Q. Do they haul any snow for road grades?
A. They normally just blade it into the centre. If not frozen, hand labour has been used to shovel snow into centre.

Q. Do you use corduroy for any condition on the winter road?
A. None.

Q. What about drainage?
A. Swaybacks in stream and creek fills are a must. The drainage problem can be serious if these are not put in place because with a level fill the water backs up and floods out beyond the stream banks sometimes causing an erosion problem.
Q. Do you use culverts?
A. Not much, at least I haven't seen any in use in the Inuvik area.

Q. Have you had any criticism from conservationists or environmentalists?
A. Some of the large oil company environmentalists are more critical of the operations than the land use people. Even within government there is a wide range of opinion in constructing and methods of removal of creek and stream fills.

Q. Would you say there is much damage?
A. There was at one time, but it was not extensive. Now there is very little to speak of, in fact, north of Inuvik it is very difficult to follow their seismic lines.

Q. If so, where mainly?
A. South of Tuk there is some damage. A summer seismic operation about 1963 resulted in considerable slumping of the permafrost. Over a long period of time, that is, a number of years of use, there is damage to the vegetation and the trail turns brown. Also, too little
snow (less than 4") will allow considerably more
winter kill of the vegetation (mosses, lichens, etc.)

Q. Is continued use from year to year better than a new
alignment each year?
A. If brown marks of tracks left after one year, stay to
the one alignment. In summer operations, if they must
work at that time, vary tracks over a \(\frac{1}{2}\) mile wide
corridor.

Q. Why or why not?
A. If it kills the vegetation in one year, then why destroy
more than one strip.

Q. Do you have any traffic survey figures, gross load, and
axle or wheel load data for the winter road?
A. Yes, in the Inuvik office of the Forestry Service, Land
Use Office.

Q. Have you noticed any progressive type problems
associated with winter roads?
A. On the Western Electronic Road (Fort Simpson - Inuvik)
some hills where cuts existed there is slumping on some
hills, none on others. It would be a good research project to determine why slumping should occur on some slopes and not on others.

Q. Does any type of land use official, conservationalist or whatever make a final run over the winter road in the spring, or not? In the fall?
A. Yes, in the spring. Final inspections are done after the snow has gone. In the fall, it is not always done.

Q. In your opinion what constitutes the most probable detrimental effect to the arctic environment from winter road use? (Please rank if more than one).
A. Moss compaction or rutting due to too early use of road in fall and too late of use in spring.

Q. Are you aware of any research programs with regard to winter roads over the last couple of years?
A. Yes, that of Dr. Kerfoot and Dr. Lambert.

Q. Are you aware of any problems that tend to be self-perpetuating rather than self-healing in relation to winter roads?
A. Not specifically related to winter roads. However, problems relating to human waste disposal and soap effects on northern waters should be looked into soon. Fuel spillage is a straightforward case of carelessness.

Q. Describe the maintenance procedures of winter roads.

A. Normally they just snowplow on ice roads of streams and lakes. On land snow is compacted in place to prevent vehicles from running directly on the moss or soil surface.

Q. What research do you visualize as necessary to extend the use or usefulness of winter roads?

A. The one real problem is the efficient removal of snow fills and ice bridges. Revegetation of areas where winter kill of vegetation has occurred may have to be instituted in the future.
CONVERSATION WITH GOODZECK CONSTRUCTION, CAT OPERATOR, AT HAY RIVER, N.W.T. ON SEPTEMBER 21, 1972

Q. I understand you have travelled the main winter road up to Inuvik.
A. Yes, last year we did.

Q. How did things go in general?
A. Well, its pretty bad in places. We took a Cat along and we would never have made some of the hills without it. Along the route we had to unload the Cat off the lowbed four or five times in order to pull us up the hills.

Q. Did creek or river crossings give you any problem?
A. Just one that I can remember.

Q. Do you have any suggestions to improve winter roads?
A. Just make sure you take a Cat along. You can make it back down without a Cat, at least we did it. I stayed up with the Cat to work around Inuvik.

Q. Is there much damage due to Cats in that area?
A. I couldn't really say, as I was mainly hauling with ours.