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Summit Station Skiway Review

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Abstract: Summit Station, located at the peak of the Greenland ice cap, is a scientific research station maintained by the National Science Foundation. Transportation to and from the station, for the delivery of personnel and materials, is by skied airplanes or by annual traverse. To support aircraft, the station staff uses heavy equipment to maintain a 5120.6×61.0 m ($16,800 \times 200$ ft) skiway. When the station is open for the summer season, from mid-April through August, the skiway sees regular use. This report defines procedures and identifies equipment to strengthen and smooth the skiway surface. Effective skiway maintenance has the potential to help reduce the overall skiway maintenance time, decrease the number of slides per flight period, increase ACLs, and reduce the need for Jet Assisted Take-Offs (JATO). All are important reductions to preserve the clean air and clean snow science done at the station.

We reviewed the available equipment on station and current skiway construction and maintenance procedures. Furthermore, measurements of skiway strength and snow density of the skiway were made. Based on these findings, we provide recommendations for modifying current equipment, future purchases, and establishment of standard operating procedures (SOPs) for future construction and maintenance efforts.

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Preface

This study was conducted as part of Engineering for Polar Operations, Logistics and Research (EPOLAR).

The work was performed by Margaret A. Knuth, Terry Melendy, and Amy M. Burzynski (Force Projection and Sustainment Branch, Dr. Edel Cortez, Chief), US Army Engineer Research and Development Center/Cold Regions Research and Engineering Laboratory (ERDC/CRREL). At the time of publication, Jennifer Mercer was the program manager for EPOLAR. Dr. Justin Berman was Chief of the Research and Engineering Division of ERDC/CRREL. The Deputy Director of ERDC/CRREL was Dr. Lance Hansen, and the Director was Dr. Robert Davis. COL Kevin J. Wilson was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

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Unit Conversion Factors

Multiply	By	To Obtain
degrees Fahrenheit	$(F-32)/1.8$	degrees Celsius
feet	0.3048	meters
horsepower (550 foot-pounds force per second)	745.6999	watts
inches	0.0254	meters
miles (US statute)	1,609.347	meters
miles per hour	0.44704	meters per second
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms
square inches	6.4516 E-04	square meters

1 Introduction

Summit Station, located at the peak of the Greenland ice cap (approximately 3200.4 m [10,500 ft] elevation), is a scientific research station maintained by the National Science Foundation's Office of Polar Programs. The station supports a variety of scientific research, including year-round measurements of the atmosphere, ice core drilling, and ground-based validation of satellite measurements.

Transportation to and from the station, for the delivery of personnel and materials, is by skied airplanes (currently Twin Otters and LC-130s) or by annual traverse. To support aircraft, the station staff maintains a 5120.6 × 61.0 m (16,800 × 200 ft) skiway. When the station is open, from mid-April through August, the skiway regularly sees three to four LC-130 flights per month. The Air National Guard (ANG) operates the LC-130s.

The allowable cargo load (ACL) for the skied aircraft and the number of attempts at takeoff, or slides, depends on the skiway condition (primarily strength and surface roughness) throughout the season. To maintain a high ACL and to reduce the number of slides, the skiway should be strong, smooth, and level. Heavy equipment operators (HEOs) maintain the skiway using available equipment on-site. At this time, none of the implements in the inventory are well suited for compacting the snow or leveling the skiway surface. A high-quality skiway allows for a higher ACL (i.e., more cargo, fuel, and personnel per flight). It is also important at Summit, where much of the science requires clean air or snow, that the planes be able to take off on the first attempt so that they emit less soot.

The goal of this project is to define procedures and to identify equipment to strengthen and smooth the skiway surface. Effective skiway maintenance has the potential to help reduce the overall skiway maintenance time, decrease the number of slides per flight period, increase ACLs, and reduce the need for Jet Assisted Take-Offs (JATO). In this effort, we reviewed the equipment available on station and the current skiway construction and maintenance procedures. We made measurements of skiway strength and snow density and also tracked skiway maintenance to determine if there was systematic correlation between skiway performance and maintenance. Based on these findings, we provide recommendations for

modifying current equipment, making future purchases, and establishing standard operating procedures (SOPs) for future construction and maintenance efforts.

2 Current Equipment

2.1 Prime movers

Two vehicles are used for the construction and maintenance of the skiway: a Tucker SnoCat (Fig. 1) and, until 2012, a Case Quadtrac (Fig. 2). However, in the summer of 2012, the Case Quadtrac was switched with a traverse vehicle; a Case Magnum series tractor (Fig. 3). Both are adequate for the job, and the move was primarily made for standardization of traverse equipment rather than for operational issues at Summit. See Table 1 for the vehicles' specifications.



Figure 1. Tucker SnoCat at Summit Station, June 2011.



Figure 2. 485 Case Quadtrac at Summit Station, June 2011.



Figure 3. Case Magnum at Summit Station, May 2012.

Table 1. Specifications of the Summit Station prime movers (Lever and Weale 2011, Lever 2011).

	Horsepower (HP)	Weight (lb)	Ground Pressure (psi)
Tucker SnoCat	140	14,600	1.8
Case Quadtrac	485	69,500	6.6
Case Magnum	335	36,280	6.3 (front)/4.5(rear)

2.2 Implements

The following implements are currently on station at Summit: two drags, a Maxey Groomer, and a newly constructed harrow (Fig. 4). The small and large drags are 4.9 and 7.3 m (16 and 24 ft) wide, respectively, and are used for surface smoothing and for clearing snow from the skiway. The Maxey Idaho Special Groomer, or Maxey Groomer, is 3.1 m (10 ft) wide with a height controlled cutting edge, 0.9-m (3-ft) diameter drum roller, and a drag pan. The Maxey Groomer is intended to reduce the runway roughness by smoothing the high points out of the skiway. The most recent addition to the implements at Summit is a 4.9-m (16-ft) wide harrow with eleven 45.7-cm (18-in.) long teeth. The harrow was constructed on station, from salvaged steel, and was built to disaggregate the snow prior to compaction efforts.

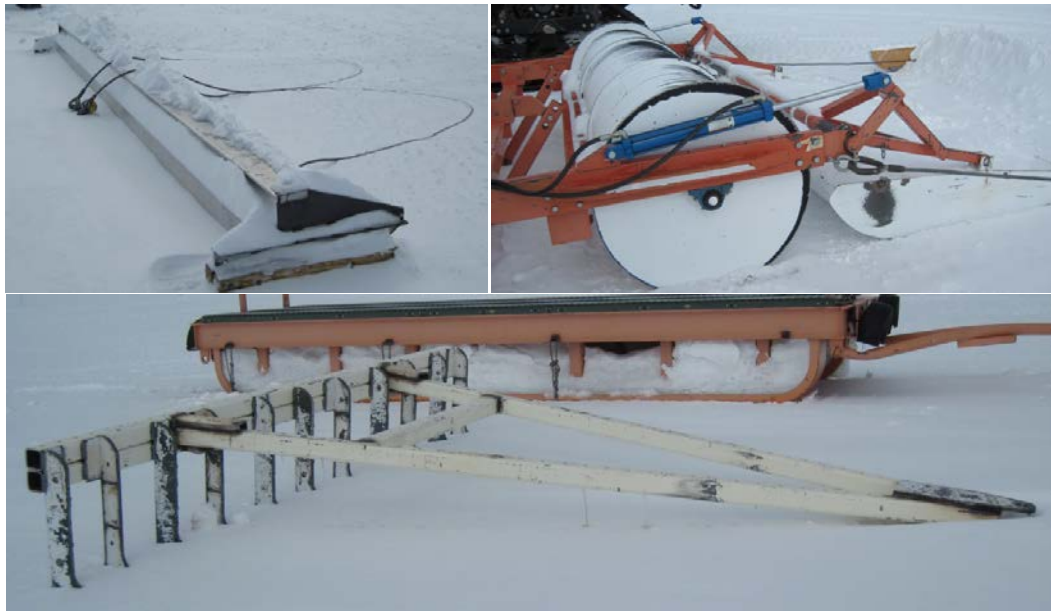


Figure 4. Current equipment at Summit Station: large drag (top left), Maxey Groomer showing roller and pan (top right), and harrow (bottom).

At the start of this study, there were no implements on station capable of effectively compacting the snow surface. Compaction efforts to date had consisted of track packing with the Case tractor. With either Case, owing to the low ground pressure, this was not very effective for increasing the strength of the skiway.

However, a 60 × 60 Icon Rolling Packer (1.5 m [60 in.] width and diameter with an empty weight of 6450 kg [14,220 lb]), commonly called a sheepfoot, was delivered to the station via traverse during the summer of 2012 (Fig. 5). The sheepfoot is a two drum configuration with 7.63 × 7.63-cm teeth that are 23 cm long. Appendix A provides a historical review of skiway construction and maintenance equipment.



Figure 5. Sheepfoot roller similar to the one delivered to Summit Station in 2012.

2.3 Equipment modifications and new implements

After review of the current inventory of equipment at Summit Station and of the historical testing of equipment for skiway construction and maintenance, we recommend several equipment modifications and one purchase.

First, we suggest modifying the harrow to tear up the surface no more than 15.2 cm. Either cut down its existing 45.7 cm teeth or build skis to lift the teeth up higher off the ground. There is no equipment at Summit (even with the addition of the sheepfoot roller) that is able to re-compact to 46 cm. If the teeth are not cut down, this tool could actually do more harm than good and should be removed from the station. Other ways to increase the harrow's effectiveness include increasing the number of tines and potentially adding weight to the entire unit.

Next, adapt the large drag to create an angled implement that is more capable of moving snow from one side of the skiway to the other. Currently there is no implement on station able to move snow effectively. Installing eyehooks on the drag and using the existing cable to change the pulling angle would easily achieve this.

Install D-rings or eye-hooks on the new sheepfoot to allow pulling the sheepfoot and drag in combination.

Last, we strongly recommend purchasing a land plane (e.g., Fig. 6) capable of removing the oscillations that can occur on the skiway throughout the season. There are off-the-shelf products that would work with little modification or, to cover a larger area in a single pass, are capable of being easily adapted to include wings. These "wings," as described in Appendix A to

extend the reach of the land plane, can even be removed, making transportation up to Summit possible in an LC-130.



Figure 6. Art's Way land plane being used in McMurdo, Antarctica.

3 Skiway Observations and Evaluation

We made a series of skiway observations to relate current practice to skiway performance. Additionally, we evaluated a test compaction method to determine its usefulness for enhancing runway performance. We documented the snow strength with a Rammsonde Cone Penetrometer and determined the density by extracting cores from the skiway surface with a Kovacs corer and then weighing slices of the core.

CRREL machined a Rammsonde Cone Penetrometer and delivered it to Summit during the Phase III turnover in February 2011 so that it would be available for testing during spring skiway construction. Appendix B provides background information about the instrument and instructions for use. Guidelines called for testing, at least once per week, at consistent locations on the skiway. Testing was completed on the centerline at three locations along the skiway: (A) 0.61 km (2000 ft) from the south end, (B) the middle of the skiway, and (C) 0.61 km (2000 ft) from the north end of the skiway. Station staff, who were trained in taking the measurements, did the testing. Guidelines also recommended that station personnel track skiway construction and maintenance over the course of the season.

We took additional strength and density measurements while at Summit during flight period 4, 9–13 June 2011. During that time, we discussed current maintenance practices with the Station Manager, trained staff on proper use of the Rammsonde Cone Penetrometer, inspected current equipment, and conducted a track packing experiment with the Case Quadtrac.

3.1 Track packing experiment

This test evaluated the strength gained on the skiway by track packing with the Case Quadtrac. The Case was chosen because its ground pressure is about 6 times higher than the Tucker and, therefore, compacts better, by comparison. However, with a ground pressure of only 6.3 psi, it is still not as effective at compaction as equipment like a sheepsfoot roller or weight carts.

We completed testing on a small section between 0.61 and 0.67 km (2000 and 2200 ft) remaining from the southern end of the skiway (Fig. 7). Prior

to track packing, we took strength measurements for the entire area with the Rammsonde Cone Penetrometer. Immediately following those tests, the Heavy Equipment Operators (HEOs) track packed the site at approximately 4 mph, with packing occurring along the length of the skiway (Fig. 8). Day two, approximately 24 hours after the first track packing, we characterized the strength of the entire area again. Following that effort, the HEO track packed half of the original area with packing oriented perpendicular to the length of the skiway. On day three, approximately 24 hours after the second compaction cycle, we again completed strength testing over the entire area.

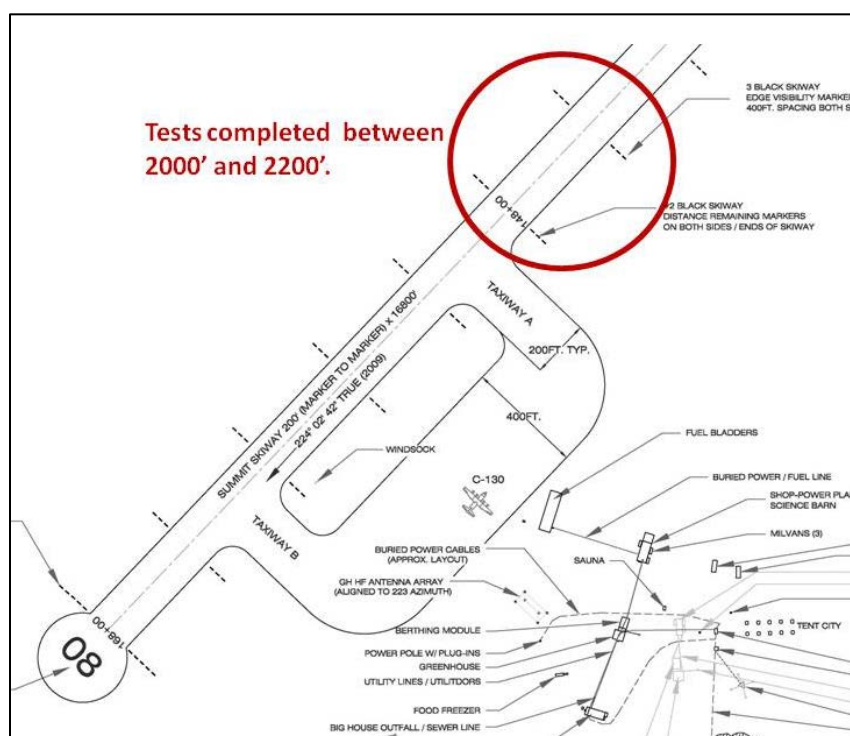


Figure 7. Summit Station map showing skiway and location of track pack testing. (Adapted from 2009 Summit Camp Layout map.)

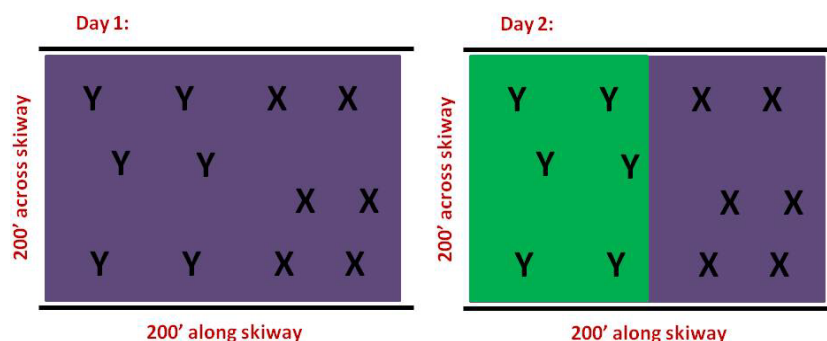


Figure 8. Test plan for track pack testing. Y and X indicate the locations of strength tests. Day one track packing was completed in the purple zone and day two in the green zone only.

Figure 9 shows the progressive changes in strength over the course of this test. The graphic on the left shows the initial strength of the test area. One sees some variability between the two sections (X and Y), but their strengths were roughly the same. The center graph, approximately 24 hours after compaction, shows the immediate increase in strength. Note that the track packing has only influenced about the top 10–15 cm of the skiway surface. The rightmost graph shows a sharp decrease in strength in about the top 5 cm for both sides, although they had different treatments.

During this test, the temperatures recorded at Summit by the NOAA Earth System Research Laboratory (ESRL) (at 1.8 m above ground level) were among the highest recorded at the station all summer (Fig. 10). In particular, temperatures remained relatively high, even in the evenings; and on 12 June, the overnight low was only -15°C .

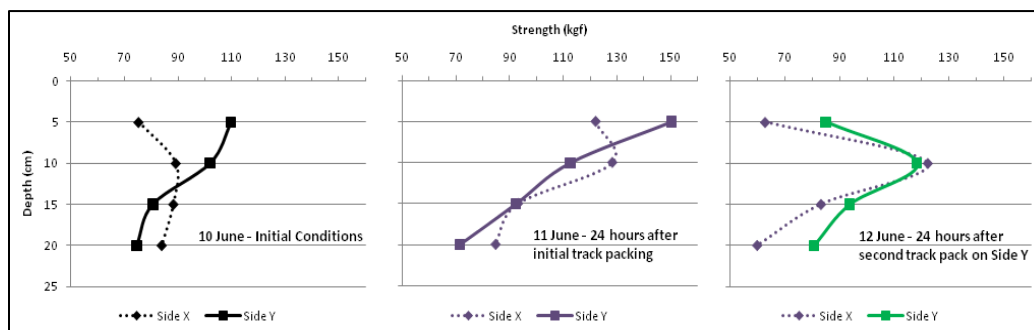


Figure 9. Averaged strength results for track packing experiment.

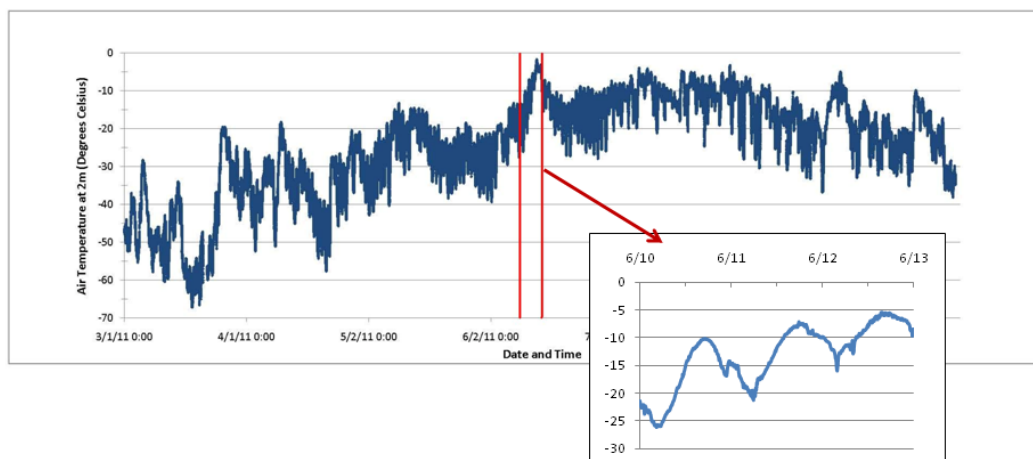


Figure 10. Air temperature data from NOAA's ESRL station. The zoomed portion reflects the timing of the track pack testing during flight period 4.

3.2 Density

On 10 June, we collected single cores down to approximately 61 cm from locations A, B, and C along the length of the skiway using a Kovacs core barrel 10.2 cm in diameter. As shown in Figure 11, the density profiles are similar at each location down to 15 cm, but location A has a consistently higher density throughout the rest of the profile. These densities are similar in magnitude to those found at McMurdo Station during the first season (2009) of skiway construction at Pegasus Airfield (Haehnel et al. 2013) but consistently lower than densities of processed snow roads in the McMurdo area (Shoop et al. 2010). This indicates that there is near surface compaction of the new snow, but deeper down (> 15 cm) the snow is likely unaffected by current surface operations.

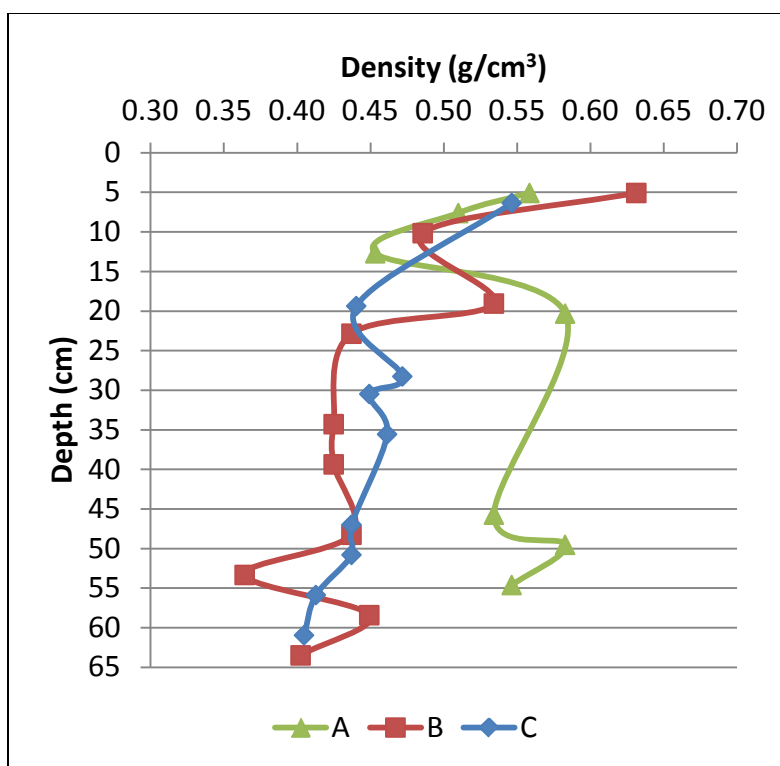


Figure 11. Density of the Summit skiway calculated from cores taken 10 June 2011.

3.3 Seasonal strength

Station staff took strength measurements at regular locations about once a week throughout the summer season, from the end of March through September (data were not collected in May). Early season results show generally low strengths in the upper 20 cm but then large peaks in strength at depths greater than approximately 40 cm (Fig. 12). Based on data from the Bamboo Forest for 2008–2011 (McConnell 2011), the average snow accumulation from August to March is 40–60 cm (Fig. 13); so it appears that this strength at depth is the previous season's snow that has sintered to form strong bonds, likely during the previous season's operation of the skiway and temperature induced sintering during the intervening winter.

Figure 14 shows strength results for the summer season, broken into depth layers. These results show a general increase in strength that is most pronounced in the top 10 cm. This data set also shows a sharp increase in strength at the end of the season, which correlates to the decreasing temperatures starting in the middle of August.

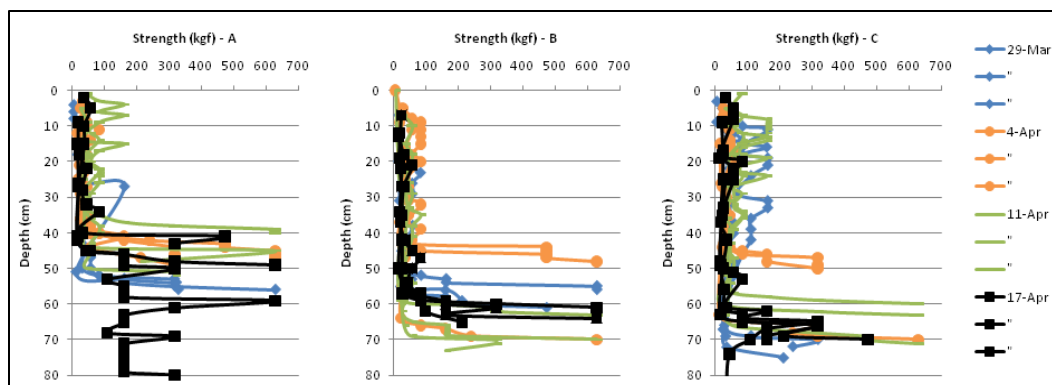


Figure 12. Early season skiway strengths.

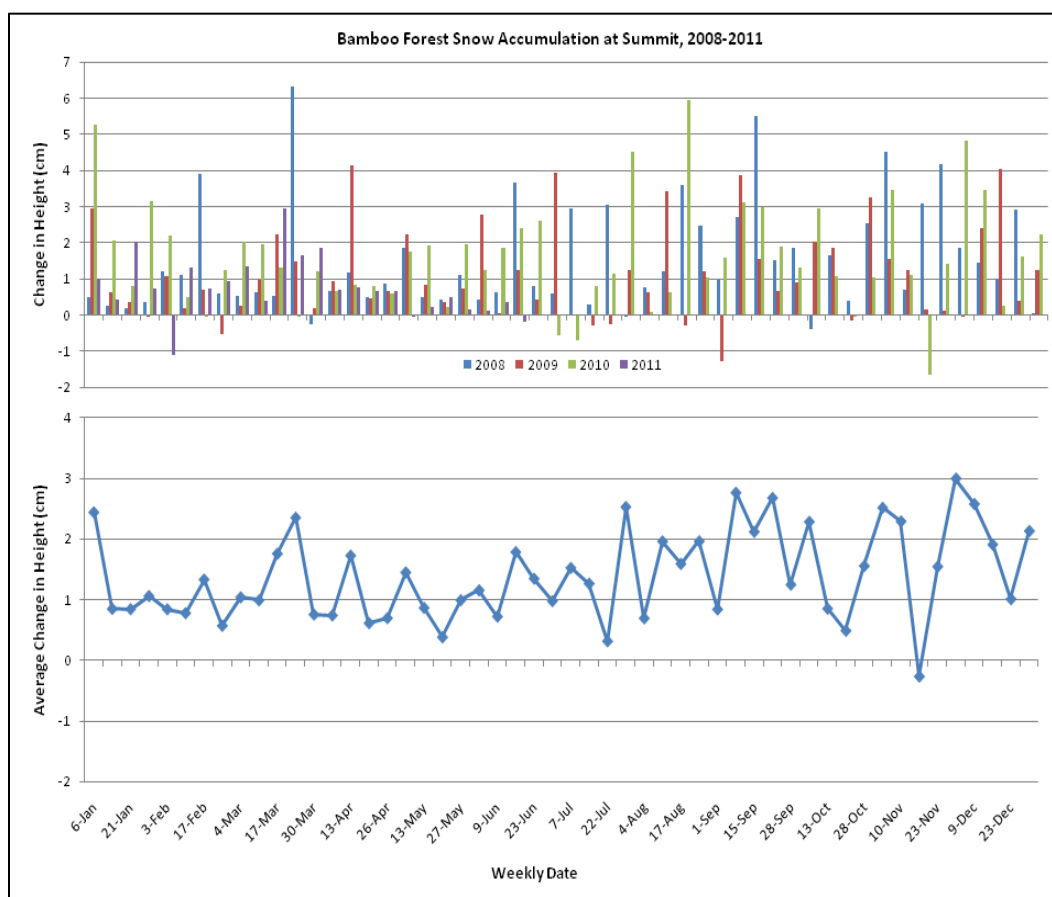


Figure 13. Snow accumulation at Summit Station in the Bamboo Forest (data from McConnell 2011).

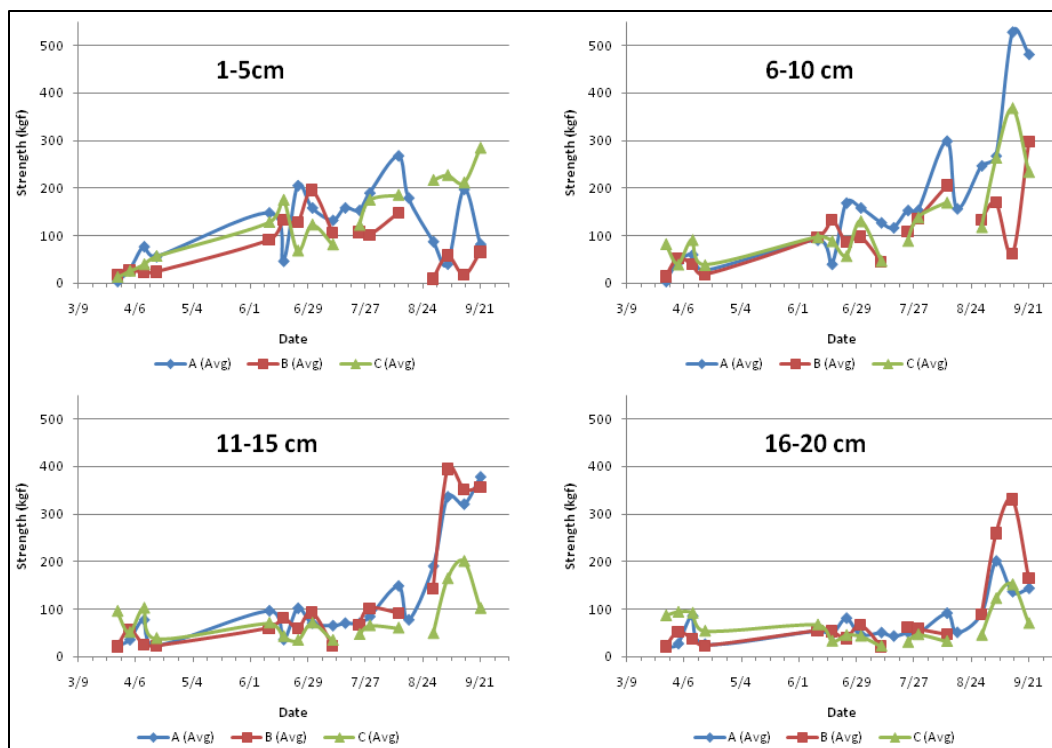


Figure 14. Strength of Summit skiway throughout the 2011 summer season. The data are broken into depth layers in 5-cm increments.

The maximum strengths measured in late summer (typically 300–400 kgf) are noticeably lower than the strengths of 600–700 kgf measured at 40+ cm in April (Fig. 12). This supports the idea that further strengthening of the snow occurs during the winter months when high temperature gradients promote temperature induced bond growth (Kamata et al. 1999, Kaempfer and Schneebeli 2007).

4 Maintenance Records and SOP Development

Maintenance records acquired were from the weekly log kept by the Station Manager. These logs provided information on the type of maintenance and the rough location of effort. Exact equipment (Tucker with Idaho groomer or Case tractor with drag) is not always clear from these records. However, they do provide enough information to see the general tempo of grooming on and around the skiway (Fig. 15). The records list 59 skiway construction and maintenance efforts and 25 skiway related (taxiway, cargo line, etc.) grooming efforts. In Figure 15, these are plotted along with known storm events (as per notations in the same station weekly log) and LC-130 takeoff information from station staff.

These records show that grooming typically took place closely following storm events, which is important for maintaining the strength of the skiway. However, with this level of detail, it is unclear if the increased number of slides for the LC-130s is related to maintenance or increasing temperatures, though it is probably a combination of both. To further correlate maintenance, strength, and flight success, the maintenance records need to provide greater detail of maintenance efforts. We recommend keeping digital maintenance records for consistency in descriptions and ease of data processing (an example template is provided in Appendix C). In the future, with better record keeping, maintenance efforts may be correlated with the strength data and snow accumulation information (vs. generic storm event dates) to provide a complete picture of skiway strength through the season.

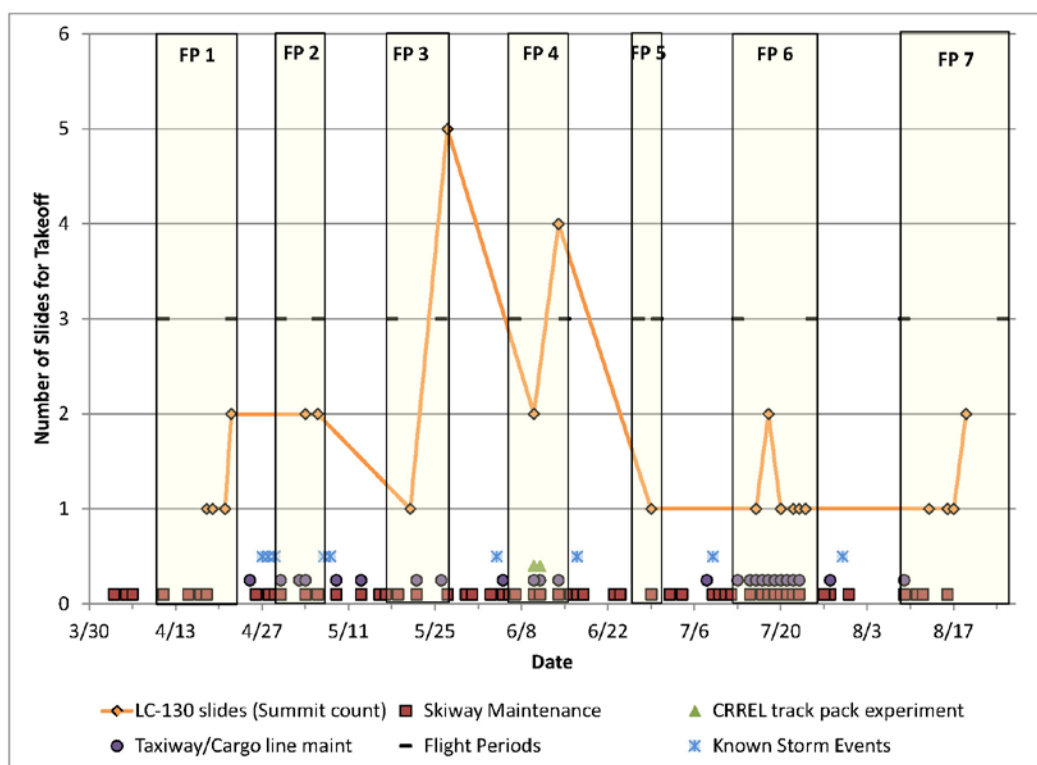


Figure 15. Timeline of flights, skiway maintenance and known storm events. The y-axis primarily indicates the number of slides needed for LC-130 takeoff.

The maintenance records, as well as interviews while on site with station personnel and emails and telecons with contract staff, were the bases of development of an SOP. This SOP for skiway construction and maintenance at Summit Station is meant to standardize processes as station management and heavy equipment operators vary from year to year. In its draft form (Appendix D) it also provides guidance with varying pieces of equipment on station. As the station adds new equipment, ideally it will be tested and the SOP will be updated and refined.

5 Flight Mission Summaries

At the conclusion of each mission to Summit, the LC-130 flight crew prepares a mission summary. These summaries contain a variety of information, including cargo and fuel loads, landing and takeoff weights, and number of takeoff slides. Most importantly, they often contain comments on skiway conditions from the flight crew's perspective. Comments from the 2011 summer season included, "three takeoff slides required due to fresh snow on skiway, 2–3 inches," "went long to get airborne," and "severe undulations in skiway." This is all important information to relay to the Station Manager so that work can be completed to fix these issues, if possible, before the next flight. These same comments determine the ACL for the next flights, so one poor experience could affect station operations for several weeks. Unfortunately, the issue of "rollers," or undulations, in the skiway is difficult for the station staff to address with the current equipment on station. A skilled and careful operator can help to ensure that these undulations do not occur during the season, yet when they are present they are very difficult to remove.

Additionally, slide counts provided by the Air National Guard occasionally differ from the log kept by the station. If number of slides is used as a metric of skiway performance in the future, it would be helpful to find the differences between the two accounting practices.

6 Recommendations

Effective skiway maintenance has the potential to help reduce the overall equipment use, decrease the number of repeated take-off attempts (or slides) per flight period, increase allowable cargo loads (ACLs), and reduce the need for Jet Assisted Take-Offs. With this in mind, Appendix D provides a draft standard operating procedure (SOP) for construction and maintenance. We developed this draft in conjunction with station personnel and contract staff. This SOP will assist in standardizing the work process for continuity between the seasons or during a season when one heavy equipment operator builds the skiway and a different one later maintains it. While we will have to test and update the methods and total time to complete these steps after working with station staff and heavy equipment operators, this SOP defines a process from which each operator, station manager, and higher management can work.

In addition to drafting an SOP, after reviewing the equipment on station, we suggest the following modifications and new purchases as detailed in Section 2.3. In italics are updates on recommendations at the time of final report publication:

- The harrow should be modified to tear up the surface no more than 15.2 cm. (*Skis were added in the spring of 2012.*)
- The large drag could be adapted to create an angled implement that is more capable of moving snow from one side of the skiway to the other. D-rings or eye-hooks should be installed on the new sheepsfoot so that the sheepsfoot and drag can be pulled in combination. (*Completed summer of 2012.*)
- We strongly recommend purchasing a land plane capable of removing the oscillations that can occur on the skiway throughout the season. (*Purchased summer of 2012; currently being transported to Greenland.*)

Skiway construction and maintenance at Summit Station has been successful because of the dedicated staff. With standardized construction and maintenance procedures and updated equipment, skiway performance should continue to improve. A smooth, strong skiway will cause less wear and tear on ANG planes, thereby reducing aircraft maintenance costs. Ad-

ditionally, reducing the number of slides will result in lower fuel consumption and emissions levels, important to the clean air and clean snow science research at Summit.

Looking forward, as new implements are modified or purchased a thorough field test should be completed. This would include training, as needed, with the operators and testing the level of compaction or smoothness the new implement is able to produce on the skiway. To date, this has been completed with the sheepsfoot and compaction results and an updated SOP are in progress.

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Appendix A: Historical Review of Snow Runway Construction

Machinery and building processes for the construction and maintenance of snow runways have evolved over time. This Appendix documents the evolution of construction methods and equipment pertaining to snow runways, also called skiways.

From the 1990s to the present, construction techniques for skiways have varied between the polar regions because of the availability of equipment and personnel. At McMurdo Station, Antarctica, the skiway is constructed via compaction with weight carts early in the season and maintained with drags and gooses for smoothing and leveling the rest of the season. Daily flights during the austral summer provide some level of compaction as well.

Early Navy efforts

In 1942, British Prime Minister Churchill directed research to study the feasibility of landing airplanes on bodies of water using large quantities of wood pulp and frozen water (pykrete). The hope was that this would create a surface hard and large enough for landing in remote areas. This design had many problems, including requiring 19.4 ha (48 acres) of water and 1.8 million metric tons (2 million tons) of pykrete to construct the landing areas large enough to be highly visible from a distance. In 1947, the US Navy's Operation Highjump led to extensive research in polar snow and ice cap airfield design and construction. Moser (1962) discusses the first documented polar runway, built on the Ross Ice Shelf in 1947. This initial effort proved to be more efficient than building floating runways on large bodies of water.

The construction procedure developed by the Navy and documented by Moser (1962) aimed to have repeated flights using R4D aircraft on skis (Fig. A1). There was only one documented procedure during construction consisting of depth-processing (cutting the surface down to approximately 0.3 m) followed by compressive compaction. The Navy further modified this procedure by processing to double the original depth (for a resulting depth of approximately 0.61 m) by a) using smooth drummed rollers

towed behind a low ground pressure tractor, b) leveling with snow planes, and c) repeating the process in 0.3 m lifts. Cold sink times between each procedure were approximately 12 to 24 hours. Double depth processing intends to achieve higher surface strength through layers of compacted material (Moser 1962).



Figure A1. R4D aircraft on skis. (Photo taken from US Navy, www.bluejacket.com.)

Double depth processing was successful in creating a snow pavement strong enough to support the taxiing of R4D aircraft on skis but was not strong enough for wheeled R4D planes. The ultimate strength resulting from this method is not available because the testing equipment was not dependable.

In 1953, the Navy conducted tests on the Greenland ice cap. This was a repeat test of the work described above from 1947. In the Greenland tests, a bulldozer compacted (using the tracks) and graded (by back dragging with the blade) in both the single and double depth processing methods. The single depth process had a measured density of 0.46 g/cm^3 , and the double depth process had a density of 0.51 g/cm^3 . Though not a big difference, the double depth process resulted in a higher density to greater depth. The single depth process was not capable of supporting wheeled C-47 traffic; the double depth sections were.

In addition, these tests led to implementing a wheel-mounted leaning grader (or plane) (Fig. A2) to contend with wind-created snow drifts. This hand-operated leaning grader had the ability to cut down oscillations in the runway surface and was able to move snow in either direction across the skiway. This type of plane was eventually upgraded to have skis instead of wheels, a cab to shield the operator from the environment, and a longer frame to increase the effectiveness of cutting out oscillations. An example of the land plane updated by the Navy in 1960 is the Model 40 snow plane (Fig. A3). This type of plane incorporated hydraulics to control the blade height and was primarily used for fine surface leveling on the runways in

Antarctica. Its structural inability to withstand the stress of cutting and pushing snow with a full blade limited its use as a surface leveling tool.

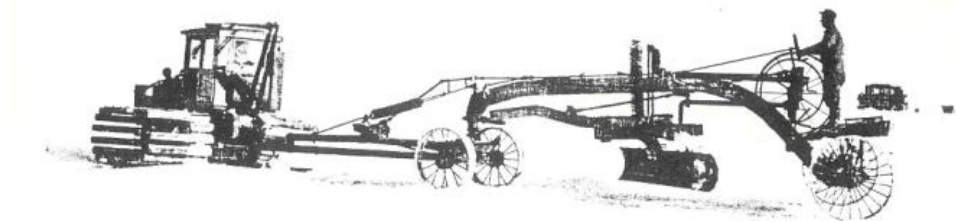


Figure A2. Leaning wheel grader (Abele 1990).

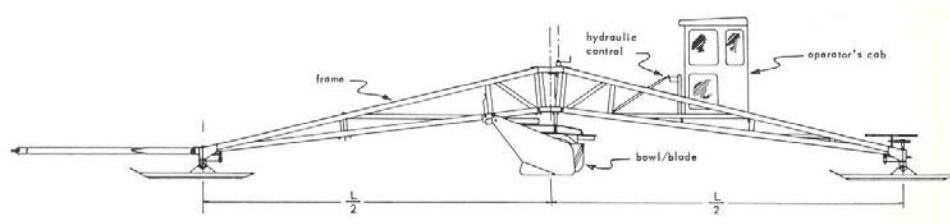


Figure A3. Model 40 snow plane (Moser 1961).

Further Navy research led to the development of a snow roller and a snow mixer to aid in compaction and snow processing techniques. The roller was used for pre-compaction and compaction activities to improve the overall strength of the skiways. The mixer was based on Russian research that combined a power driven earth pulverizing roller with a compacting roller (Fig. A4). The snow mixer had the ability to complete snow disaggregation and compaction in one pass, cutting down on the total number of passes required.



Figure A4. Navy Model 42 Snow Pulvimixer being towed by a tractor (Camm 1961).

Annual construction of skiways in Antarctica started in 1957 with Operation Deep Freeze at Byrd and South Pole Stations and ran until 1962. (During this time McMurdo had a runway constructed on ice, which is why it is not discussed further here.) With no standard operating procedure

(SOP), the construction and maintenance of these two skiways varied, depending on the crew and equipment available. A lack of guidance and of knowledge of skiway construction led to using a variety of mixing, grading, and compacting equipment, yielding a wide range of results and unknown skiway reliability.

Early Army efforts

Following Operation Highjump and the first snow field runway tests in Greenland, the US Naval Civil Engineering Laboratory and the US Army Snow, Ice and Permafrost Research Establishment (SIPRE), later combined and called the US Army Cold Regions Research and Engineering Laboratory (CRREL), were tasked with testing and determining optimal construction equipment for future dry (no water added) skiway construction. The type of testing that took place fell into three categories: compaction, disaggregation, and leveling and smoothing.

Compaction

Compaction was tested with various methods, including sheepsfoot rollers, drum rollers, pneumatic-tire carts, corrugated rollers, and vibratory compaction. The sheepsfoot was initially included but was dropped from testing in many cases because of its poor weight-to-diameter ratio and inconsistent compaction. The results were similar to compacting in sand, with more displacement of material than compaction (Wuori 1959). However, a later study concluded that an increase in density resulted when pre-compacting with a sheepsfoot roller was followed by a more effective and consistent compaction tool (i.e., smooth roller, vibratory plate compactor, etc.) (Wuori 1960). The sheepsfoot roller in these tests ranged from 1814.4 to 2268.0 kg (4000 to 5000 lb), and the smooth drum rollers weighed 3628.7 to 9979.0 kg (8000 to 22,000 lb) (Fig. A5). In subsequent testing, the sheepsfoot was modified to be more effective at compacting by increasing its surface contact area. This modification consisted of removing the teeth and plates from the roller and effectively turning it into a smooth drum roller (Fig. A6). Drum rollers with consistent ground pressure per square inch were determined to be most effective for base course compaction efforts (compaction event after pre-compaction effort). Further modifications included corrugated rollers, which, at the time, could be made to greater widths and were less expensive than some other available options. There is no measured compaction difference between a corrugated roller and a smooth drum roller.

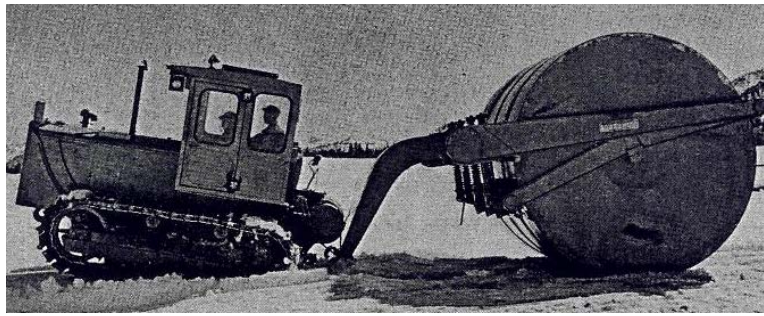


Figure A5. 3.1-m (10-ft) diameter roller (Camm 1961).

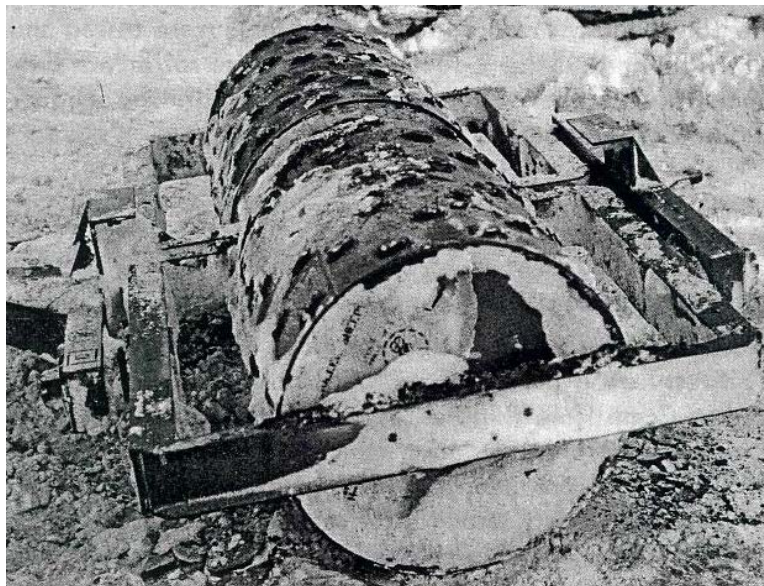


Figure A6. Sheepfoot modified to be more effective by cutting down the original teeth (Camm 1961).

The pneumatic-tire cart (Fig. A7) consisted of as many as 13 independent turning tires with the ability to compact uniformly across a surface. This type of equipment was best suited for deep compaction because of the high bearing pressure and the kneading action created at depths up to 15.2 cm (6 in.) (Camm 1961). The weights of these implements range from 11.8 to 20.0 metric tons (13 to 22 tons), making them ideal for compacting efforts, producing a ground pressure from 1585.8 to 2137.4 kPa (230 to 310 psi).

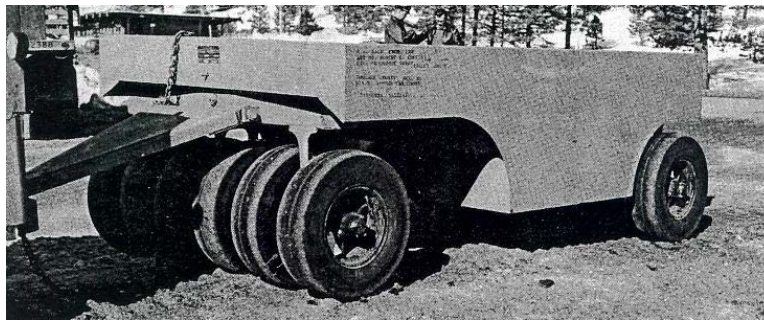


Figure A7. 11.8-metric-ton (13-ton) pneumatic tire cart (Camm 1961).

Testing with vibratory compaction (Fig A8) showed good results; however, those results varied with temperature. Vibratory compaction that immediately followed snow disaggregation (for these tests a rotary mixer was used; further disaggregation techniques are described below) provided higher bearing capacity than either the roller or pneumatic compaction efforts at low temperatures. As snow temperatures neared the melting point, compaction from drum rollers and pneumatic-tire trailers resulted in higher density increases compared to vibratory compaction (Wuori 1959).



Figure A8. Vibratory Compactor.

Disaggregation

Kragelskii (1945) documented the use of a harrow (Fig. A9) for snow processing. The harrow was effective in disrupting the surface of snow but lacked the ability to efficiently process snow at depths greater than 30.5 cm (12 in.). By 1958, rotary snow plows were being developed and tested (Fig. A10). The snowblast was a tractor mounted rotary snow plow with back casting chutes that had the ability to process snow at depths of 1.06 m. The chutes allowed the disaggregated snow placed behind the machine to be immediately compacted. The original design was intended for use in the Swiss Alps and was first tested on the Greenland ice cap during 1958 and 1959 (Jackovich and Wuori 1963).

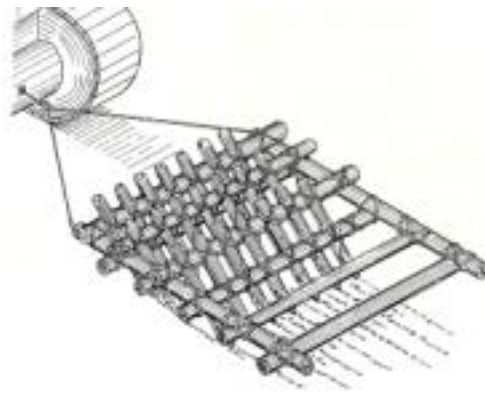


Figure A9. Snow Harrow (Abele 1990).



Figure A10. Snowblast plow (Jackovich 1963).

The Peter snow miller was an experimental rotary snow blower used during the late 1950s and into the 1960s (Fig. A11). The Peter miller, unlike other versions, was a dedicated piece of equipment (i.e., no interchanging the tractor with other implements). Other iterations of snow blowers consisted of tractors mounted with rotary blades that could be removed. Testing these machines proved disaggregation to be effective in increasing the ultimate strength of a skiway because the Peter miller and snowblaster were capable of producing an average snow grain size of 0.6 mm. This was less than previous efforts with the Navy's pulvimixer (described previously in *Early Navy Efforts*), which produced an average snow grain size of 0.9 mm (Abele 1990). The smaller grain size increased the rate of age-hardening and associated resultant strength.

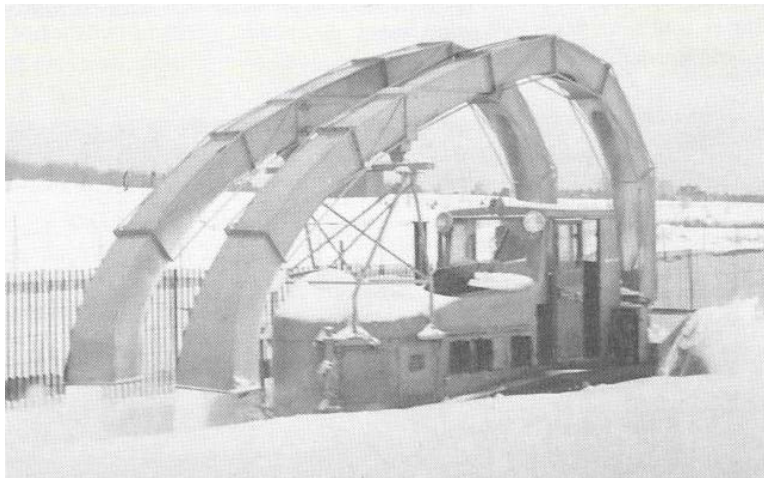


Figure A11. Peter miller (Abele 1990).

Leveling and smoothing

Surface smoothing operations, or finishing drags, remove surface irregularities commonly seen after constructing new runways or after drifting events. The first drags were wood with metal faces (Fig. A12). Its narrow width limited its effectiveness such that it took many passes to smooth a skiway (Camm 1960). Later iterations of this type of drag were composed of three attached drags with rounded contact faces to reduce friction. The drags were constructed completely out of steel and had approximately 1283.7 kg (2830 lb) of bearing pressure to increase the effective area and lower maintenance time (Fig. A13).

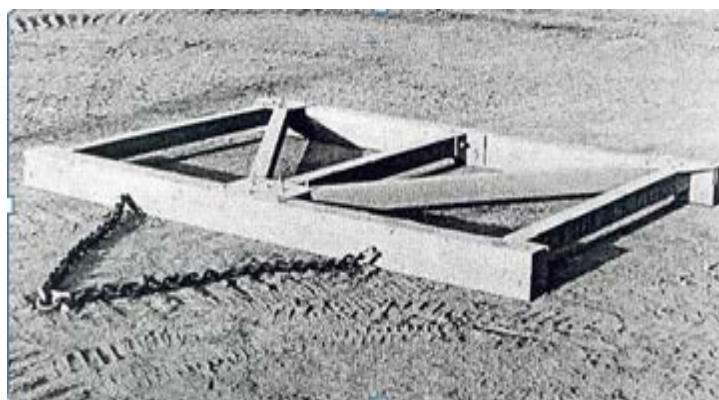


Figure A12. Drag built for Operation Deep Freeze 1 in 1955 (Camm 1960).

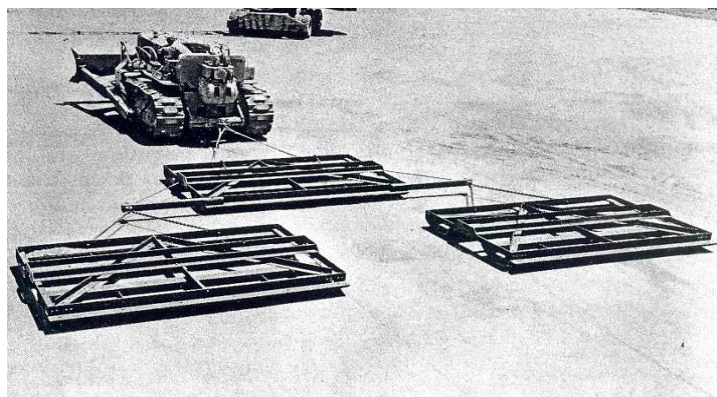


Figure A13. Prototype drag designed to be gang towed (Camm 1960).

Modified techniques

Snow processing from the 1940s through the early 1970s assumed the availability of specialized machines, such as the mixers and road builders, on-site to construct skiways, which is not the case in some of the remote locations where research is currently performed around the world. Procedures were formed in 1973 to guide Army units and field groups on rudimentary tools and the process required to create high strength skiways (Clark et al. 1973). The procedure required one or two tractors, depending on availability, and consisted of disaggregation, compaction, grading, compacting a final time, and a final grade (Fig. A14).

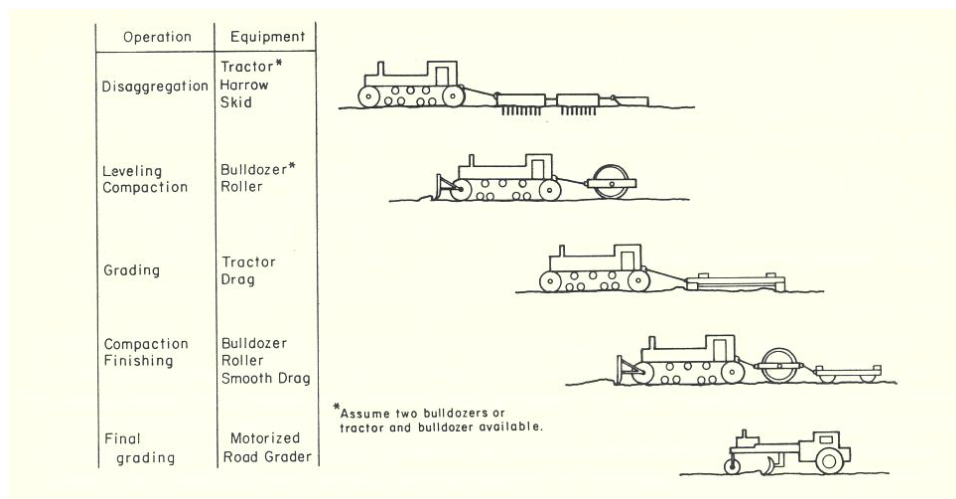


Figure A14. Schematic of operation sequence (Clark 1972).

The equipment for these procedures was designed to be constructed out of basic materials commonly found in most base camp operations, such as culvert piping, metal piping, 2 × 4s, 208.2-L (55-gal.) drums, and chain.

The disadvantage to this approach was the increased number of passes with tractors necessary to achieve similar results associated with larger, heavier equipment. The construction time associated with this method increased as well because of prolonged set times between events and the additional passes on the skiway.

In the 1970s, the Rammsonde Cone Penetrometer, or “Ram,” was determined to be best suited for measuring snow strength. The Ram’s ability to measure strength with relation to depth made it possible to compare snow layers. A variant of this tool is used today to determine skiway and road-way strength (Fig. A15).



Figure A15. Left: Rammsonde penetrometer in 1973 (Clark et al. 1973). Right: Rammsonde use in 2009.

Hybrid systems

Hybrid systems combining disaggregation, compaction, and leveling were created and tested at Camp Century and McMurdo Station. An example of this type of machine is the Gurries Road Builder, which is pulled by a tractor or bull dozer (Fig. A16). The snow road builder combined a land plane with a harrow, a mixer, and plate compaction. The weight of this machine was in the range of 19958.0 kg (44,000 lb), providing sufficient weight for compaction efforts with the added benefit of vibration from an onboard engine to operate components, creating an early form of vibratory compaction (Abele 1964). CRREL researchers tested this technology in Antarctica and Greenland and proved that it created a hard, level snow surface but with higher associated costs for equipment and maintenance (Abele 1968).

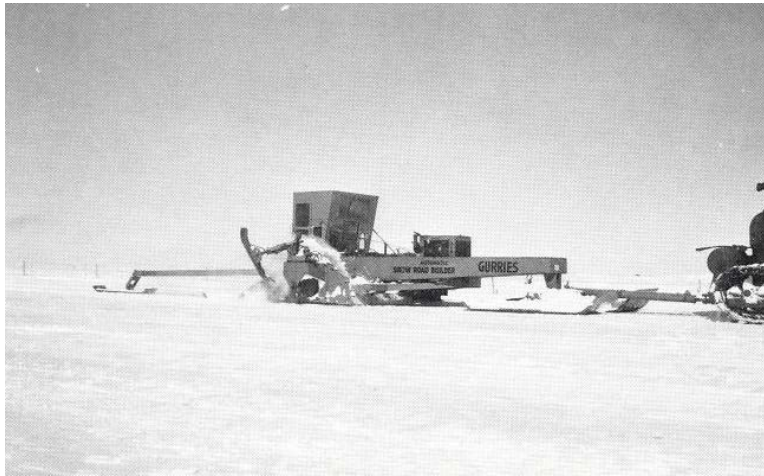


Figure A16. Gurries Snow Road Builder (Abele 1990).

In 1979, the USSR designed a thermo-vibrating snow compactor (Volkova 1979) that was twice as fuel efficient as in previous attempts (unsuccessful efforts from the 1950s are outlined in Bender 1956). This Soviet model combined heat from a blower at the mixing stage and then vibratory plate compaction (Fig. A17). The process of using heat to aid in compacting the snow proved to be high in maintenance and build time. Other issues included freezing hoses and needing a slow rate of movement to allow the snow to adequately mix and melt.

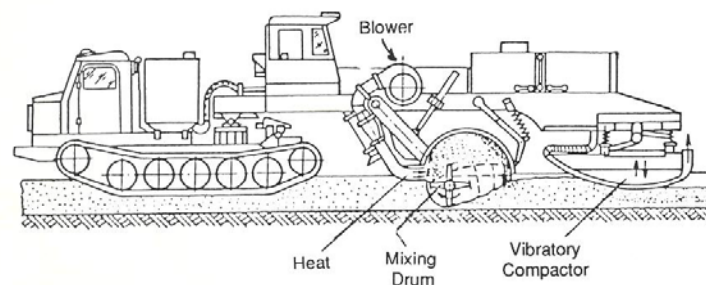


Figure A17. Soviet thermo-vibrating snow compactor (Volkova 1979).

During the early 1990s, a plan to improve logistics at the South Pole, using C-141s, was proposed (Abele 1990). The proposed construction method included building an additional 0.6 m of depth on top of the existing runway. This would be completed by building two 0.3 m lifts with disaggregation via rotary mixers, followed by compaction from tractors, vibrators, and rollers. The skiway would have to sit for a year in between lifts to cold soak and increase strength. After these 2 years, to achieve the required bearing capacity, the surface layer would then have to be heat treated or landing mats would have to be installed on top of the lifts. Installing mats

would create a high maintenance stress on the runway crew but would allow for the airfield to support larger aircraft without the extended set time associated with heat processing.

Key equipment for state-of-the-art construction

Agricultural implements have often been linked to the fundamental designs of snow processing equipment (e.g., harrows or plows, graders, and tractors). Advancements in agricultural equipment have led to better suited snow implements in both portability and production. As described above, key equipment should provide disaggregation, compaction, and leveling.

Disaggregation can range from rotary mixers and millers to harrows. The harrow shown in Figure A18 can be up to 12.2 m wide. It has folding wings to aid in transportation and has the ability to control depth of snow displacement. The ability to control the depth of snow disruption is key to building a high bearing capacity skiway. Because of the extra time, maintenance, and cost associated with mixing techniques, a harrow is the chosen tool for remote locations such as in Greenland.



Figure A18. Folding harrow (Remlinger Manufacturing).

Compaction should be completed by either a smooth drummed roller or pneumatic tire cart completing multiple passes. Compaction from vibratory methods is effective but is more temperature dependent and needs higher maintenance than the two recommended methods.

Leveling should be completed with either a goose or land plane. A drag is effective for smoothing a skiway and clearing snow drifts but is unable to eliminate oscillations, which can damage aircraft landing gear. Land planes are capable of cutting down the high points in oscillations but are often large and may require on-site assembly because of transportation restrictions (Fig. A19). Goose implements used in McMurdo are effective for smoothing and leveling but are limited by their width and inability to remove oscillations, increasing the amount of passes that have to be completed to cover a skiway.

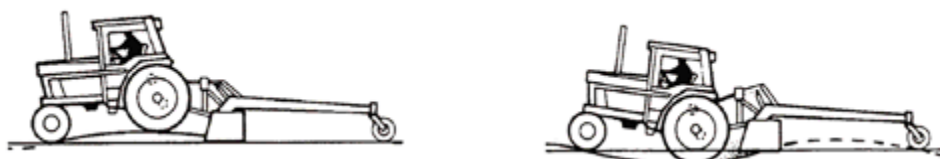


Figure A19. Example of how a land plane works (Image from Art's Way Manufacturing).

A new style land plane, shown in Figure A20, is capable of cutting out oscillations, can be constructed up to 12.2 m wide, and can be folded to one third of its total width for ease of transportation.



Figure A20. Example of a folding land plane (Art's Way Manufacturing).

Equipment currently being tested by CRREL and Keweenaw Research Center includes a snow miller (Fig. A21) capable of smoothing, milling, and vibratory plate compacting in one pass. This particular miller is different from versions in the past; it is smaller and does not require an on-board operator outside of the tractor cab. This technology is being tested at McMurdo and shows promise for future construction techniques.



Figure A21. Snow miller (Keweenaw Research Center).

Appendix B: Rammsonde Instructions

Background

The US Army and others adapted the Rammsonde Cone Penetrometer, or Ram, from an instrument originally used in the Swiss Alps. It is widely used for estimating avalanche danger and for determining allowable wheel loads on artificially compacted snow pavements. The device is a cone penetrometer consisting of a hollow, 2-cm (0.79-inch) diameter aluminum shaft with a 60° conical tip, a guide rod, and a drop hammer. At Summit Station, working in processed snow, a smaller Rammsonde cone should be used. The small cone has a 30° tip, while the larger cone is more blunt with a 60° tip. The guide rod, inserted into the top of the shaft, guides the drop hammer. The Rammsonde hardness number (*R*) is an index which indicates snow's resistance (in kilograms force, kgf) to vertical penetration of a metal cone of given dimensions. The hardness reading at any depth represents the mean hardness through that depth and the previous reading.

To obtain penetration force, the hammer is raised by hand to a certain height which is read in centimeters on the guide rod and then dropped freely. The centimeter scale on the shaft indicates the penetration depth. The resistance to penetration (hardness) of the snow can be determined by observing either the amount of penetration after each hammer drop or the number of hammer drops (blows) necessary to obtain a certain penetration. In relatively hard, homogenous snow, it is usually more convenient to determine the number of blows needed to penetrate through some predetermined depth increment. Recording the number of hammer blows after each 5-cm depth increment is convenient and commonly used. In layered and new, soft snow, the more satisfactory procedure is to observe the amount of penetration after each hammer blow. The Rammsonde kit contains two drop hammers, 1 and 2 kg. A combination of one of the hammer weights and a drop height ranging from 0 to 50 cm usually allows a suitable rate of penetration. Rates between 1 cm per five hammer blows and 5 cm per one hammer blow achieve good results in a wide variety of snow conditions.

The Ram hardness (for a 30° cone) is computed from the following equation:

$$R = 1.56 \times (Whn/x + W + Q) \quad (B1)$$

where:

R = Ram hardness number (kgf)
 W = weight of drop hammer (kg)
 h = height of drop (cm)
 n = number of hammer blows
 x = penetration after n blows (cm)
 Q = weight of penetrometer (kg).

Inventory

- Penetrometer with 30° cone
- 1-m penetrometer extension
- guide rod
- 1-kg weight
- 2-kg weight



Figure B1. Rammsonde Cone Penetrometer shown with 1-m extension, guide rod, and drop weights.

Assembly



Figure B2. Connect the guide rod (left) to the main shaft of penetrometer (right).



Figure B3. Pick a weight and slide it down the guide rod (left).
Unless the skiway is very hard, use the 1 kg weight.

Procedure

1. Set the cone end of the penetrometer on the snow surface being tested. At the start of the test, the widest part of the cone should be flush with the snow surface.
2. Depending on the snow surface being tested, choose a weight (i.e., heavy weight for firm snow; light weight for weak, virgin snow).
3. Raise the weight so that the bottom of the weight is aligned with the appropriate height from which you want to drop. (Again, this will depend on the strength of the snow and will take some experience and “feel” for drop heights and weights.)
4. Hold the penetrometer as straight as possible, and drop the weight.
5. In soft snow, record the penetration with each blow (i.e., if you are at the lowest weight and lowest drop height and it still penetrates 4 cm). Otherwise, record the number of blows it takes to reach 5 cm, then 10 cm, and so on. These are called blow sets. DO NOT change weights or drop heights in the middle of a blow set.
6. For each blow set (be it one or many drops), record the drop height (h), the number of hammer blows (n), and the penetration after n blows (d).
7. Normally, you would continue blows until you reach refusal (nominally 10 blows with less than 2.5 cm penetration using the heavy weight and the largest drop height). At Summit, I suggest going to 50 cm.
8. NOTE: If there is fresh snow and you set the penetrometer down and it is already reading 3 cm, then note that in the log as $n = 0$, $d = 3$.

Example field entry

DATE: _____ TIME: _____ WEIGHT: _____
LOCATION: _____ NAME: _____

n	d	h
5	5	50
6	10	50
3	16	50
6	20	40
11	25	40
7	30	50
6	35	50
2	43	50
2	45	30
8	50	30



Figure B4. Example of two people taking penetrometer measurements. One is dropping the weight and guiding the penetrometer and the other is taking notes.

Appendix C: Database for maintenance operations¹

The screenshot shows the SummitSkiwayMaintenanceForm_v1.xlsm spreadsheet in Microsoft Excel. The form is designed with yellow input fields for data entry. The data is organized as follows:

Row	Field	Value
1	Please enter data in yellow fields	
3	Operator Name	TJ
4	Date:	1/27/2012
5	Start Time	0800
6	Stop Time	1700
7	Primary Vehicle:	Case
8	If Other:	
11	Towed:	Maxi Groomer + Sm. Drag
12	If Other:	
15	Location	Skiway
16	If Other:	
19	Reason for work	Flight w/in 24 hours
20	If Other:	
23	Comments:	

A 'Save' button is located in the center of the form, spanning rows 11 to 14 and columns F to H.

¹ Image only. File "SummitSkiwayMaintenanceForm_v1.xlsm" available upon request.

Appendix D: DRAFT Standard Operating Procedure for Summit Skiway

2012 Season—Available equipment: harrow, Maxey groomer, drag, sheepsfoot (post construction).

Construction procedure

All efforts should start at one flag line and work progressively across the skiway.

1. Raise skiway markers as early as possible in the spring to reduce skiway drifting.
2. Using the modified harrow, drag the skiway, with no overlap, to a maximum depth of 6 in. This will equal 14 passes. At a suggested speed of 8 mph, this will take 6 hours.
3. Track compact the skiway (pulling the large drag behind) as soon as possible after disaggregation (Step 2) using the Case tractor. The track paths should not overlap and should cover the full width of the skiway. This will take 33 passes; at a suggested speed of 5 mph, this will take 21 hours.
4. Drag the skiway with the large drag, overlapping each pass by one-third the width of the blade (8 ft with the 24-ft drag). This will equal 13 passes each round. Without a land plane, this may need to be completed multiple times to limit oscillations (“rollers”). At the suggested speed of 8 mph, this will take 5 hours each round. Let the skiway sit for 48 hours after compaction to allow it to sinter.

Total construction time will take approximately 32 hours or 4–5 working days.

Surface maintenance procedure

Drag the skiway with the large drag, overlapping each pass by one-third the width of the blade (8 ft with the 24-ft drag). This will equal 13 passes each round. With the lack of a land plane, this may need to be completed multiple times to limit oscillations. At the suggested speed of 8 mph, this will take 5 hours each round. This should take place

- As soon as possible after a snow event or drifting.
- No more than 24 hours before the expected arrival of a plane.
- If ruts are found during the post flight skiway check.

Note: Alternate patterns can be used when dragging, particularly when needed for greater visibility for aircraft.

Total maintenance time will take 5 hours or 0.5 days.

Strength maintenance procedure

Strength measurements should be taken weekly at consistent locations (three minimum) along the skiway. When the skiway Rammsonde average strength in the 5–10 cm layer drops below 150 kgf, the following strength building procedure should immediately be completed unless:

- There is less than 1 week before a planes arrival.
- The air temperature is greater than 14°F (–10°C) for the previous 24 hours.

Otherwise, proceed with the following:

1. Compact the skiway with the sheepsfoot (pulling the large drag behind). With no overlap between passes, this will equal 17 passes. At the suggested speed of 5 mph, this will take 11 hours. The equipment should not be stopped in the middle of a pass, only at the ends of the skiway.
2. Immediately after compaction, drag the skiway with the large drag, overlapping each pass by one-third the width of the blade (8 ft with the 24-ft drag). This will equal 13 passes each round. With the lack of a land plane, this may need to be done multiple times to limit oscillations. At the suggested speed of 8 mph, this will take 5 hours each round. Let the skiway sit for 48 hours after dragging to allow it to settle.

Total maintenance time will take 16 hours or 2 days.

2013 Season—Available equipment: harrow, Maxey groomer, drag, sheepfoot

Construction procedure

All efforts should start at one flag line and work progressively across the skiway.

1. Raise skiway markers as early as possible in the spring to reduce skiway drifting.
2. Using the modified harrow, drag the skiway, with no overlap, to a maximum depth of 6 in. This will equal 14 passes. At a suggested speed of 8 mph, this will take 6 hours.
3. Compact the skiway with the sheepfoot (pulling the large drag behind) as soon as possible after the disaggregation effort (Step 2). Overlap 6 ft each pass because of the gap between the drums. This will equal 33 passes. At the suggested speed of 5 mph, this will take 21 hours. The equipment should not be stopped in the middle of a pass, only at the ends of the skiway.
4. Immediately after compaction, drag the skiway with the large drag, overlapping each pass by one-third the width of the blade (8 ft with the 24-ft drag). This will equal 13 passes. With the lack of a land plane type implement, this may need to be completed multiple times to limit oscillations. At the suggested speed of 8 mph, this will take 5 hours each round. Let the skiway sit for 48 hours after dragging to allow it to sinter.

Total construction time will take approximately 32 hours or 4–5 working days.

Surface maintenance procedure

Drag the skiway with the large drag, overlapping each pass by one-third the width of the blade (8 ft with the 24-ft drag). This will equal 13 passes each round. With the lack of a land plane type implement, this may need to be done multiple times to limit oscillations. At the suggested speed of 8 mph, this will take 5 hours each round. This should take place

- As soon as possible after a snow event or drifting.
- No more than 24 hours before the expected arrival of a plane.
- If ruts are found during the post flight skiway check.

Note: Alternate patterns can be done when dragging, particularly when needed for greater visibility for aircraft.

Total maintenance time will take 5 hours or 0.5 day.

Strength maintenance procedure

Strength measurements should be taken weekly at consistent locations (three minimum) along the skiway. When the skiway Rammsonde average strength in the 5–10 cm layer drops below 150 kgf, the following strength building procedure should immediately be completed unless:

- There is less than 1 week before a planes arrival.
- The air temperature is greater than 14°F (–10°C) for the previous 24 hours.

Otherwise, proceed with the following:

1. Compact the skiway with the sheepsfoot (pulling the large drag behind). With no overlap between passes, this will equal 17 passes. At the suggested speed of 5 mph, this will take 11 hours. The equipment should not be stopped in the middle of a pass, only at the ends of the skiway.
2. Immediately after compaction, drag the skiway with the large drag overlapping each pass by one-third the width of the blade (8 ft with the 24-ft drag). This will equal 13 passes. With the lack of a land plane type implement, this may need to be completed multiple times to limit oscillations. At the suggested speed of 8 mph, this will take 5 hours each round. Let the skiway sit for 48 hours after dragging to allow it to sinter.

Total maintenance time will take 16 hours or 2 days.

Future Seasons—Available equipment: harrow, drag, sheepsfoot, land plane.

Construction procedure

All efforts should start at one flag line and work progressively across the skiway.

1. Raise skiway markers as early as possible in the spring to reduce skiway drifting.
2. Using the modified harrow, drag the skiway, with no overlap, to a maximum depth of 6 in. This will equal 14 passes. At a suggested speed of 8 mph, this will take 6 hours.
3. Compact the skiway with the sheepsfoot (pulling the large drag behind) as soon as possible after the disaggregation effort (Step 2). Overlap 6 ft each pass because of the gap between the drums. This will equal 33 passes. At the suggested speed of 5 mph, this will take 21 hours. The equipment should not be stopped in the middle of a pass, only at the ends of the skiway.
4. Drag the skiway with the large drag, with no overlap, immediately after compaction. This will equal nine passes. At the suggested speed of 8 mph, this will take 4 hours. Let the skiway sit for 48 hours after dragging event to allow it to sinter.
5. Plane the skiway, with a 24–40 ft wide land plane, with limited overlap in each pass to minimize wind rows. This will remove oscillations in the skiway. This will equal five–eight passes. At a suggested speed of 8 mph, this will take 2–4 hours.

Total construction time will take approximately 35 hours or 4 working days.

Surface maintenance procedure

1. If oscillations are present, it may be necessary to use the land plane. It is important to overlap each pass enough to minimize wind rows. This will require five–eight passes with limited overlap. At a suggested speed of 8 mph, this will take 2–4 hours. If there are no oscillations, skip to Step 2.
2. Drag the skiway with the large drag, with no overlap. This will equal nine passes each round. At the suggested speed of 8 mph, this will take 4 hours each round. This should take place:
 - As soon as possible after a snow event or drifting.
 - No more than 24 hours before the expected arrival of a plane.
 - If ruts are found during the post flight skiway check.

Note: Alternate patterns can be done when dragging, particularly when needed for greater visibility for aircraft.

Total maintenance time (drag and plane) will take approximately 6–8 hours.

Strength maintenance procedure

As described for previous seasons.

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14. ABSTRACT Summit Station, located at the peak of the Greenland ice cap, is a scientific research station maintained by the National Science Foundation. Transportation to and from the station, for the delivery of personnel and materials, is by skied airplanes or by annual traverse. To support aircraft, the station staff uses heavy equipment to maintain a 5120.6 × 61.0 m (16,800 × 200 ft) skiway. When the station is open for the summer season, from mid-April through August, the skiway sees regular use. This report defines procedures and identifies equipment to strengthen and smooth the skiway surface. Effective skiway maintenance has the potential to help reduce the overall skiway maintenance time, decrease the number of slides per flight period, increase ACLs, and reduce the need for Jet Assisted Take-Offs (JATO). All are important reductions to preserve the clean air and clean snow science done at the station. We reviewed the available equipment on station and current skiway construction and maintenance procedures. Furthermore, measurements of skiway strength and snow density of the skiway were made. Based on these findings, we provide recommendations for modifying current equipment, future purchases, and establishment of standard operating procedures (SOPs) for future construction and maintenance efforts.					
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