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Evaluation of a New SnowPaver at McMurdo Station, Antarctica

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Abstract

The snow roads at McMurdo Station are the primary transportation corridors to the surrounding airfields. However, during warm spells, deteriorating road conditions can seriously limit payloads for all types of vehicles. The Cold Regions Research and Engineering Laboratory (CRREL) has studied the construction and maintenance of the snow roads and teamed with the Keweenaw Research Center (KRC) and the National Science Foundation (NSF) to assess the feasibility of using a new SnowPaver to build snow roads in Antarctica. KRC built the SnowPaver, a single unit consisting of leveling blades, a milling unit, and a vibratory plate compactor, and shipped it to McMurdo in November 2010. In McMurdo, the SnowPaver constructed snow pavement sections that were monitored for performance based on snow-road strength and vehicle rutting. The SnowPaver was also used for reworking and compacting old and slushy snow during the height of the warm season. In November 2012, the power unit was upgraded; and snow roads built with the improved SnowPaver were 5 to 7 times stronger than the unprocessed road and 3 to 4.6 times stronger than the Pegasus Road. An economic analysis showed the SnowPaver would pay for itself in 1 to 5 years, depending on the usage.

Contents

Abstract ii

Illustrations v

Preface vii

Acronyms and Abbreviations viii

Unit Conversion Factors x

1 Introduction 1

1.1 Issue 1
1.2 Background 2

2 SnowPaver Background 4

2.1 History of snow-processing research 4
2.2 Evolution of the milling groomer (SnowPaver) 5
2.3 KRC-Ebert SnowPaver 9

3 2010 Antarctic Test Program 11

3.1 Test section construction 13
3.1.1 Pegasus Test Road C *13*
3.1.2 LDB soft snow test section *16*
3.1.3 Pegasus Road soft snow test section (Mile Post 4) *16*
3.2 Snow strength and density measurements 18
3.2.1 Rammsonde Snow Penetrometer *19*
3.2.2 Clegg Impact Hammer *19*
3.3 Vehicle trafficking tests 20
3.3.1 Trafficking vehicle *21*
3.3.2 Test section performance indicators *21*
3.3.3 Vehicle trafficking tests *22*

4 2010 Data and Testing Analysis 24

4.1 Snow strength and density monitoring 24
4.2 Vehicle trafficking tests 28
4.2.1 Soft snow test sections *28*
4.2.2 Pegasus Road Test Lane C *34*

5 Initial SnowPaver Capability (2010–2011) Summary and Recommendations 35

6 2012 Upgrade and Evaluation 38

6.1 Power unit upgrade and performance testing 38
6.2 Assessment by the McMurdo heavy-equipment operators 42

7 Economic Considerations....................44

8 Summary and Recommendations....................48

9 References....................51

Appendix A: 2012–2013 Upgraded SnowPaver Operation....................54

Appendix B: 2012 SnowPaver Upgrade and Testing....................78

Appendix C: McMurdo Personnel Comments....................102

Report Documentation Page (SF 298)....................109

Illustrations

Figures

1 Map of McMurdo Station road and airfield system ... 1

2 KRC first-generation SnowPaver ... 8

3 Elements of the KRC SnowPaver: overview (top), miller (bottom left), and variable vibrating plate compactor (bottom right) ... 10

4 KRC SnowPaver groomer being unloaded at McMurdo Station, November 2010 ... 11

5 SnowPaver groomer, McMurdo Station (2010) ... 12

6 SnowPaver configured for McMurdo snow-road use (2010) ... 12

7 Map detail of SnowPaver test sections ... 13

8 The first pass of SnowPaver on Pegasus Test Road C ... 15

9 Fully groomed Pegasus Test Road C, 16 November 2010 ... 15

10 Pegasus Road soft snow test section at Mile Post 4. Lane C is the snow road SnowPaver test section ... 17

11 SnowPaver operating in untracked (soft) snow ... 18

12 Rammsonde snow hardness profiling measurement ... 19

13 Clegg Impact Hammer measuring road surface strength ... 20

14 Ford E350 Van ... 21

15 We measured rut depth from the original snow surface to the deepest part of the rut ... 22

16 We measured from the undisturbed snow surface the height of the pile on the side of the rut (typical from Shoop et al. 2014) ... 22

17 Rammsonde measurement from the LDB soft snow test section and adjacent area. Note the strong layer from the 2009 snow road at a depth of 40 to 50 cm (15 to 20 in.) ... 24

18 Density profile from the SnowPaver test sections. The dense layer at 40 to 70 cm (15 to 28 in.) depth is likely from the prior year melt surface or snow-road surface ... 25

19 Strength measurements (Rammsonde average for top 15 cm [6 in.]) for the Pegasus Road lanes. Listed across the top of the graph are the associated maintenance activities ... 26

20 Strength profiles for Pegasus Road lanes ... 26

21 Strength comparison of LDB and Pegasus soft snow test sections ... 27

22 Surface CBR strength comparison of Pegasus Road lanes and Pegasus Test Road C ... 28

23 Rutting photos for LDB soft snow test section showing no or minimal impact after 15 passes ... 29

24 Rutting photos for LDB soft snow test section. Ruts in portion of test section subjected to vehicle bouncing ... 29

25 Rutting photos for LDB soft snow test section. Area of deep rutting after 15 passes, with rut edges cutting vertically (40 cm [16 in]) into the snow pavement 30

26 The curve at the north exit of the LDB soft snow test section shows very little impact even after 40 kph (25 mph) and the increased shear forces from turning 30

27 After one pass, LDB soft snow test section showing no rutting, just tread imprints 31

28 After four passes, LDB soft snow test section still has no appreciable rut depth, just tread imprints 31

29 The van bounced through wavy portion of LDB soft snow test section closest to LDB 32

30 Example of significant rutting caused by bouncing 32

31 LDB soft snow control section after 15 passes (plus numerous passes from other vehicles) with no appreciable rutting....................33

32 Comparison of rut depths on SnowPaver test sections after 26 passes of the E350 Van near Mile Post 4 on the Pegasus Road and soft snow (floating pavement) test section 34

33 The SnowPaver being used at the Scott Base Transition during the height of the melt season (left). The surface was immediately available for van traffic (right)................37

34 The SnowPaver with the new power-pack upgrade being tested at McMurdo Station, November 2012....................38

35 Ice shelf road layout, test site, and strength measurement locations....................39

36 Rammsonde values at the Short Cut Road and at MP 6 (November 2012). Also see discussion of Figure B4 in Appendix B....................41

37 Maximum strength from each Rammsonde profile before and after SnowPaver use on the Short Cut Road and nearby at MP 6 of Pegasus Road for comparison (November 2012)....................42

Tables

1 Comparison of SnowPaver processed-snow strengths one half hour after processing. The highest strengths are achieved by fine milling 9

2 Pegasus Test Road C events....................14

3 LDB soft snow test section events....................16

4 Pegasus Road soft snow test section events 17

5 Operating cost assumptions....................44

6 Comparison of existing maintenance methods to the SnowPaver operations for cost per mile....................45

7 Cost savings and ROI for the 10 ft and the 16 ft SnowPaver used on the snow roads for an estimated 150 miles per season (50 ft wide lane) 46

8 Cost comparison of existing methods and the SnowPaver operation for one full grooming of the Pegasus skiway (McMurdo) and the Summit skiway (Greenland)............46

Preface

This study was conducted for National Science Foundation (NSF), U.S. Antarctic Program, Division of Polar Programs (PLR), under Engineering for Polar Operations, Logistics, and Research (EPOLAR) EP-ANT-12-15, “Snow Roads and Transportation.” The technical monitor was George Blaisdell, Chief Program Manager, NSF-PLR, U.S. Antarctic Program.

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Acronyms and Abbreviations

AIL	Antarctic Infrastructure and Logistics
ANG	Air National Guard
bb	Ball Bearing
BISP	Black Island/South Pole
CBR	California Bearing Ratio
Clegg	Clegg Impact Hammer
CRREL	U.S. Army Cold Regions Research and Engineering Laboratory
EPOLAR	Engineering for Polar Operations, Logistics and Research
ERDC	Engineer Research and Development Center
GEO	Directorate of Geosciences
HMW	High Molecular Weight
kgf	Kilograms Force
kph	Kilometers per Hour
KRC	Keweenaw Research Center
LDB	Long Duration Balloon
LLL	Land Locomotion Laboratory
MI-DNR	Michigan Department of Natural Resources
MP	Mile Post
NSF	National Science Foundation
PLR	Division of Polar Programs
PTO	Power Take Off

R	Rammsonde Hardness Number
ROI	Return on Investment
RPSC	Raytheon Polar Service Company
SIPR	Snow Ice and Permafrost Research
TACOM	Tank and Automotive Command
USAP	United States Antarctic Program
USDA	United States Department of Agriculture
VMF	Vehicle Maintenance Facility
WISSARD	Whillans Ice Stream Subglacial Access Research Drilling

Unit Conversion Factors

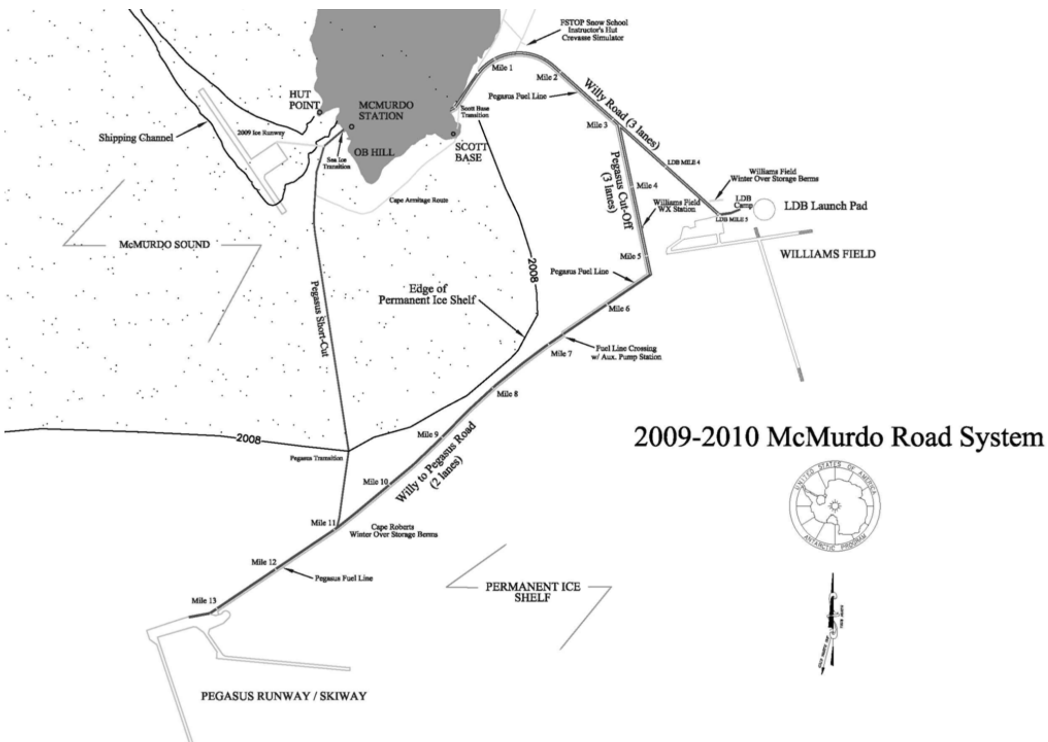
Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
degrees (angle)	0.01745329	radians
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters
horsepower (550 foot-pounds force per second)	745.6999	watts
inches	0.0254	meters
miles (U.S. statute)	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

1 Introduction

1.1 Issue

Ground vehicles at McMurdo Station, Antarctica, use approximately 32 km (20 miles) of snow roads connecting the station and its airfields (Figure 1). For the past several years, the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) has been researching how to effectively improve construction and maintenance of the snow roads to lower labor and equipment hour requirements and to improve the performance and durability of the snow-road surfaces at McMurdo Station.

Figure 1. Map of McMurdo Station road and airfield system.



Moreover, McMurdo Station may be experiencing higher summer temperatures due to a range of regional climatic influences (Shoop et al. 2010; Weatherly and Helble 2012; Hardy 2014). Higher temperatures and more extreme temperature fluctuations can severely reduce the road strength, compounding snow-road construction and maintenance challenges, and make the snow roads and other snow structures such as the Long Duration

Balloon (LDB) Pad more susceptible to failure. In some years, the snow roads fully support wheeled traffic for the entire summer season; and in other years the snow is too soft. The cost of snow-road failure is significant. In the worst case scenario, nearly all transport of personnel and supplies to and from aircraft servicing McMurdo, which is the largest Antarctic base and services international personnel from the trans-Antarctic mountains and beyond, must be via a few specialized vehicles or rotary wing aircraft.

1.2 Background

CRREL in Hanover, NH, previously studied the processes currently used to prepare and maintain the McMurdo Station snow roads. Researchers witnessed activities in December 2002–January 2003 and monitored existing snow-road strength, maintenance, and vehicle fleet operations. The report documenting this work, *Snow Roads at McMurdo Station, Antarctica* (Shoop et al. 2010), also contains a literature review of snow-road construction methods, background on snow compaction and age-hardening, and a summary of McMurdo's historic snow-road construction and maintenance guidelines developed by the U.S. Navy. The report concluded with recommendations to develop a modern snow-road construction and maintenance program. A second CRREL report also documented a survey of the entire McMurdo transportation system (Seman 2012).

Based on this previous work, CRREL performed a series of tests in December 2009 and January 2010 to evaluate the impact of different types of vehicles on the snow roads under various weather and road conditions. Shoop et al. (2013a) documents this work and Shoop et al. (2014) provides further detail. These reports describe several types of tests used to measure the impact of different vehicles on the snow roads and other prepared snow surfaces (i.e., the LDB Pad). They took initial strength measurements to characterize the test sites and drove test trafficking patterns with a standard McMurdo fleet operation's van. They then measured rut width and depth, the resulting snow pile height and width, and snow strength (taken in and between the vehicle tire tracks) to determine how vehicle and driving parameters, such as speed, acceleration, deceleration and turning radius, affect the snow-road surface.

We used the knowledge gained in that study to investigate a new piece of equipment, the SnowPaver, and the performance of snow-road test sections prepared with this equipment. The SnowPaver is a snow groomer that the Keweenaw Research Center (KRC), Michigan Technological University, developed in a joint venture with Ebert Welding Ltd. The SnowPaver equipment offers snow milling and vibratory compaction capabilities not currently available at McMurdo, with the additional advantage of completing the leveling, milling, and compaction all in one pass of the equipment. Ideally, this would save numerous labor and equipment hours over the current techniques of leveling, smoothing, and compacting the surface, which use a different implement for each process. Alger et al. (2011) discuss the initial SnowPaver development, and Shoop et al. (2013b) assesses SnowPaver use in Antarctica and the performance of the initial test sections. As a result of these tests, we decided to upgrade the power source for the SnowPaver to a self-contained unit mounted on the paver itself; and the SnowPaver was then used for additional test section construction.

This report presents the evolution of the SnowPaver and the basis of its design, its deployment to Antarctica, and the testing undertaken to characterize the performance of test sections that the SnowPaver prepared after it arrived at McMurdo Station in November of 2010 and after it was upgraded in November 2012. Appendix A provides an operation manual for the final version of the SnowPaver, and Appendix B documents the design, deployment, and initial use of the upgraded SnowPaver.

2 SnowPaver Background

2.1 History of snow-processing research

Over the past fifty years, snow mechanics research has enabled the construction of snow roads and runways in deep snow. Studies by CRREL (Wuori 1960, 1963) have shown that milling or disaggregating snow and then compacting it greatly enhances the metamorphism of snow. Studies made by CRREL in the 1960s (Abele and Wuori 1962; Abele 1963; Wuori 1963) and further work in the 1970s indicate that a mixture of mechanically milled snow, having grain sizes of one to several millimeters in diameter and compacted to a density of 0.55 g/cc (34 lb/ft^3), hardens to approximately one-half its ultimate strength, or roughly 690 kPa (100 psi) (unconfined strength) in two to three days. The resulting surfaces, if thick enough, can support heavy-wheeled aircraft and other vehicles.

More recent research at Michigan Technological University's KRC indicated that a mixture of very finely milled snow, 1 mm (0.04 in.) or less in size, compacted to a density of 0.55 g/cc (34 lb/ft^3) or higher, hardens very rapidly (within one hour) to produce a durable pavement (Alger 1993a). Because of this, it is important to mill the snow as finely as possible before compaction to ensure rapid hardening through sintering of an increased number of grain contacts even though the energy requirements for this milling process may be high.

Additionally, when considering snow roads or pavements, not all snow is new or fresh. Under traffic and with time and temperature, snow can change to a coarse, cohesionless mixture of kinetic snow (also known as corn snow, sugar snow, depth hoar, and even bb [ball bearing] snow). Vehicle traffic rapidly deteriorates these old or soft snow surfaces to cause large bumps, ruts, moguls, and potholes. The action of tires and tracks also helps to accelerate the formation of large, non-active crystals on the snow pavement. To cause this type of snow to bond and form a hard, durable surface, it must be mixed with new snow or finely milled to a powdery material to promote bonding and hardening.

Further, when snow is milled, it behaves as a fine granular material, and vibratory compaction is then quite effective. Previous studies at CRREL

(Wuori 1965) have shown that at lower temperatures (less than −10°C [14°F]), higher vibration frequencies, above 1000 hits per minute, are more effective for snow compaction, while at temperatures close to 0°C (32°F), lower frequencies, 300 hits per minute or less, are best. In either case, compaction must happen immediately after milling, before bonding or sintering takes place. This process forms a snow layer that has a high density and a larger number of contact points, thus promoting the sintering process.

More recent studies at KRC have shown that a mixture of finely milled snow and a percentage (50% or less) of larger crystals can bond together to form a snow pavement matrix. In simple terms, this process is similar to crushing washed gravel to a consistency that resembles road gravel. This is a mix of the original gravel particles and smaller particles from sand size to silt and clay sized particles. These types of mixes work well for soil roads and even better for snow as the strong bonds created in the mix increase the strength considerably (Alger 2003).

2.2 Evolution of the milling groomer (SnowPaver)

From the late 1950s through the early 1980s, there was great interest within the U.S. Government and specifically in the U.S. Armed Forces to maximize vehicle mobility and logistics in snowy terrains. During this period, CRREL and KRC and their predecessors SIPR (Snow, Ice and Permafrost Research) and LLL at TACOM (Land Locomotion Laboratory at Tank and Automotive Command), performed numerous research studies to improve vehicle designs to maximize snow mobility.

At the same time, a number of efforts addressed modifying the terrain to improve mobility of existing vehicle platforms. For Arctic and Antarctic regions, these investigations included snow. The mechanisms that create a strong matrix of bonded snow particles were becoming better understood, and the search for mechanical means to make pavements out of snow continued.

In areas where existing vehicles and drive configurations became immobilized, mechanical manipulation of the snow was used to make stronger pavements so vehicles could move and aircraft could land. Researchers evaluated a number of different concepts. These included rotary snow blowers, mixers, heaters and melters, compactors, and vibrators. Through this research, it became evident that strong snow roads and runways could be developed, but the mechanical development of these pavements was difficult and costly.

In the late 1980s, both the National Science Foundation, Division of Polar Programs (NSF-PLR), and the Michigan Department of Natural Resources (MI-DNR) approached KRC with a similar problem. NSF was interested in enhancing vehicle mobility (including landing wheeled aircraft) in Antarctica. MI-DNR was searching for cost-effective methods to produce more durable surfaces on snowmobile trails. Both of these inquiries helped further the studies of processing snow to manipulate strength.

One of the first studies at KRC involved using a portable hammer mill, like those used to crush stone, to grind large snow crystals into smaller, more active crystals (more surface area). This method showed some promise; and using the results of the study, KRC constructed a second-generation hammer mill device (Alger 1993b). This unit was a tow-behind trailer with a 1.2 m (4 ft) wide, 30.5 cm (12 in.) diameter hammer mill preceded by a number of different leveling devices, including blades and discs. The trailered implement consisted of the leveling blades, followed by the drum, then a compaction roller, and eventually a drag pan. The research team found several interesting results when using this unit. First, the power required to turn the hammer mill in even a 1.2 m (4 ft) wide unit was excessive. Second, the snow produced by the unit was not ground up sufficiently. A third result showed that at the higher grooming speeds, over 16 kph (10 mph), needed for snowmobile trail grooming, the compacting roller did not work well and, in fact, created its own set of bumps. Further testing at that time involved a walk-behind vibrating plate compactor. The results showed a vibratory plate was useful to further densify the snow beyond densities from roller compaction alone.

Concurrent with the hammer mill studies, Alger (1993a) performed lab studies to determine the ultimate grain sizes for rapid bonding and ultimate strength. These studies showed that a mix of finely milled crystals and sizes, including unmilled grains, created a strong matrix pavement. This result was encouraging because it negated the need to mill the entire snow mass to a fine powder.

The results of the first hammer mill tests indicated that another method would be needed to achieve the desired snow properties. With this in mind, KRC devised a miller drum with properties similar to the present SnowPaver miller. The first of these units was 0.6 m (2 ft) wide and mounted in a stationary unit at KRC. Ice samples were mechanically pushed through the unit, and it turned solid ice into a mass of snow-like crystals. The first drum consisted of cutting bars that were welded to the inner drum. However, ice tended to fill the space between the cutters, clogging the drum and resulting in an ineffective, smooth drum of ice. This instigated the next design incorporating loose cutter bars that vibrated the snow particles out of the space between bars, eliminating the icing problem.

After testing the small prototype drum, KRC designed and fabricated a 2.4 m (8 ft) wide tow-behind groomer for MI-DNR (Alger 1994). This unit was very similar to the present SnowPaver configuration and had a built-in vibrating pan. During the groomer development process, it became evident that the load on the pan should be maximized to increase snow density even further. Contemporary commercial drags carried pan pressures of 10 kPa (1.5 psi) or less, and the new SnowPaver pressure was increased to 20 kPa (3 psi).

KRC performed a number of tests on snowmobile trails using this unit towed by a Caterpillar Challenger tractor. The results were encouraging; and with the funding from a second U.S. Department of Agriculture (USDA) project, KRC designed and fabricated the next prototype SnowPaver, including a built in tractor unit, from September to November 1998 (Figure 2) (Alger and Gruenberg 2002; Alger 2003).

Figure 2. KRC first-generation SnowPaver.

This KRC first-generation SnowPaver consisted of a 2.44 m (8 ft) transversely mounted drum with 45 cutting bars mounted on its periphery. The drum was powered by a 300 hp diesel engine and rotated at up to 1000 rpm. Following the drum was a leveling blade and a vibratory compactor. This SnowPaver was self-propelled and designed to operate at forward speeds of 8.0 to 12.9 kph (5 to 8 mph).

The prototype was run in several different modes to compare the resulting snow surfaces. The miller drum could turn in the normal forward direction, with the top of the drum moving in the direction of travel, or in reverse. This resulted in two different snow surfaces behind the miller. The normal direction caused the snow to come off the drum and be thrown, or impacted, onto the surface. The reverse drum rotation shot the snow up into the air, where it then fell to the surface, resulting in a more fluffy snow surface. The unit was also run with and without the compactor operating. Table 1 presents some of the snow density and strength obtained with this prototype and by other milling equipment (Wuori et al. 1999; Alger et al. 1999).

Table 1. Comparison of SnowPaver processed-snow strengths one half hour after processing. The highest strengths are achieved by fine milling.

Snow Description	Typical Density (g/cc)	Rammsonde Hardness	Unconfined Compressive Strength
Fine milled only (miller in reverse) (half hour after processing)	0.42	50	240 kPa (35 psi)
Fine milled only (miller normal) (half hour after processing)	0.5	80	310 kPa (45 psi)
Fine milled (miller normal) and compacted (half hour after processing)	0.58 to 0.68	240 to 480	520 to 760 kPa (75 to 110 psi)
Coarse milled and compacted (half hour after processing)	0.55 to 0.58	100	345 kPa (50 psi)
Coarse milled and compacted (half hour after processing)	0.55 to 0.58	200 to 300	480 to 620 kPa (70 to 90 psi)
Ice (for comparison)	0.86	>1000	1100 kPa (160 psi)

2.3 KRC-Ebert SnowPaver

The development of the current KRC-Ebert SnowPaver configuration began in 2003 and was based on the findings from the prior work. Ebert Welding and KRC incorporated a snow miller and a vibrating pan into a Sur-Trac drag to accomplish smoothing, grading, milling, and compaction with one piece of equipment (Figure 3).

The KRC-Ebert SnowPaver, commonly called the *SnowPaver*, first smoothes the snow surface with drag knives that cut out high spots and aggressively move the snow through the drag to break it down into smaller chunks. A transverse mounted miller follows the drag to cut the snow into fine crystals. After the smoothing, mixing, and cutting process is completed, the snow passes under a vibrating plate compactor. The vibration frequency of the compactor can be manually tuned to optimize the snow compaction based on temperature. Although this tuning is largely based on subject matter expertise, Wuori (1965) provides some guidance and states that high frequencies work best at temperatures lower than −10°C (14°F). In late winter 2004, tests using this machine on fresh snow and snowmobile trails in Houghton, MI, resulted in snow with compressive strengths ranging from 340 to 690 kPa (50 to 100 psi) immediately after passage through fresh snow and over 1380 kPa (200 psi) after use on previously established trails (Alger 2004). The first production unit of the SnowPaver was deployed in northern Ontario, Canada.

Figure 3. Elements of the KRC SnowPaver: overview (top), miller (bottom left), and variable vibrating plate compactor (bottom right).

3 2010 Antarctic Test Program

The SnowPaver arrived at McMurdo station on 6 November 2010 (Figures 4 and 5). There, Russ Alger of KRC prepared the unit for operation under tow by a Challenger tractor (Figure 6). Although the unit was intended to attach to a tractor with a power take off (PTO), which would fully power the groomer, none were available; so we made adjustments to run the SnowPaver off the Challenger's hydraulic system.

Once the SnowPaver reconfiguration was operational, we began test-section construction (Figure 6). The work constructing the test sections served to (1) refine the SnowPaver operating configuration, (2) check the hose and lever configuration, and (3) develop the procedures for construction and maintenance of McMurdo snow pavements using the SnowPaver. This also included setting the operating positions for the components of the unit—the miller, drag, pan, and wheels—which were adjusted for optimum operation for the broadest set of conditions encountered at McMurdo.

Figure 4. KRC SnowPaver groomer being unloaded at McMurdo Station, November 2010.

Figure 5. SnowPaver groomer, McMurdo Station (2010).

Figure 6. SnowPaver configured for McMurdo snow-road use (2010).

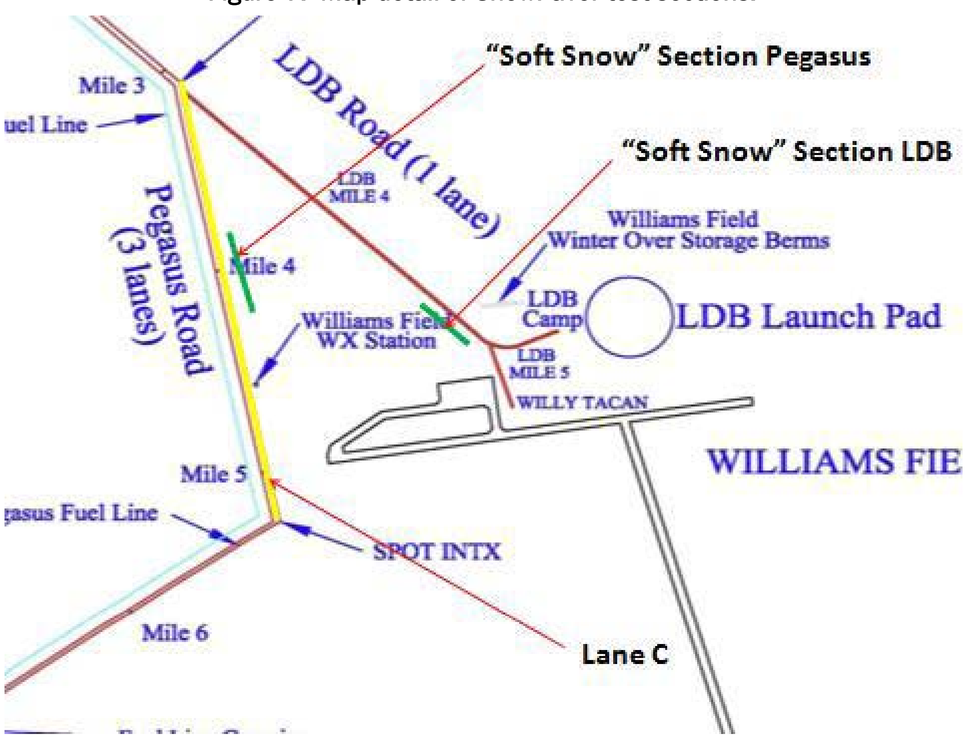
3.1 Test section construction

Once the SnowPaver was operational in its new configuration three test sections were constructed (Figure 7):

- Pegasus Test Road C (Lane C of existing Pegasus Road)
- LDB soft snow test section (virgin-snow test section parallel to the LDB road)
- Pegasus Road soft snow test section (virgin-snow test section parallel to the Pegasus Road).

This chapter discusses the construction, trafficking, and performance of the test sections (also in Alger 2010; Shoop et al. 2013b). We monitored the performance of the three test sections by using density, strength, and temperature measurements; visual assessments; maintenance tracking; and vehicle impact testing.

Figure 7. Map detail of SnowPaver test sections.



3.1.1 Pegasus Test Road C

The Pegasus Test Road C test section comprises Lane C of the existing Pegasus Road between the LDB intersection (Mile Post [MP] 3) and the

SPoT intersection (Mile Post 7), highlighted in yellow on Figure 7. The SnowPaver prepared the lane surface on 15 November and maintained it until trafficking tests were completed in late December 2010. Afterward, the lane was opened to normal vehicle traffic.

The test section was paved using six passes at 8.2 kph (5.1 mph), covering the entire surface once. Both the miller and the vibrator were on for all passes. Each pass overlapped by approximately 30 cm (12 in.). The SnowPaver made another five passes the following day, 15 November, with both the miller and vibrator running, as before. Table 2 lists the activities on Pegasus Test Road C. Figures 8 and 9 show the beginning and end result of the test-section construction.

Table 2. Pegasus Test Road C events.

Date	Event
8 Nov. 2010	Rammsonde, Clegg, and temperatures on all lanes
12 Nov. 2010	Weight cart (2 widths) on east side of lane
13 Nov. 2010	Closed to traffic
15 Nov. 2010	SnowPaver initial use, miller engaged—six passes at 5 mph
16 Nov. 2010	SnowPaver, miller engaged—five passes at 5 mph
16 Nov. 2010	Rammsonde and temperatures on all lanes
23 Nov. 2010	Rammsonde and temperatures on all lanes
3 Dec. 2010	Rammsonde and temperatures on all lanes (at MP 3.2, 4, and 5)
8 Dec. 2010	Rammsonde, Clegg, and temperatures on all lanes
11 Dec. 2010	Rammsonde, Clegg, and temperatures on all lanes

Figure 8. The first pass of SnowPaver on Pegasus Test Road C.

Figure 9. Fully groomed Pegasus Test Road C, 16 November 2010.

3.1.2 LDB soft snow test section

The LDB soft snow test section was parallel to and approximately 30.5 m (100 ft) from the LDB Road (Figure 7). The test section was approximately 7.6 m (25 ft, 2.5 SnowPaver widths) wide and 152.5 m (500 ft) long. Russ Alger constructed the test section on 12 November 2010. He first vibrated the entire section with three passes and then milled and vibrated three more passes. The SnowPaver made a second set of passes on the LDB soft snow test section on 22 November 2010. Table 3 lists the activities on the LDB soft snow test section.

Table 3. LDB soft snow test section events.

Date	Event
12 Nov. 2010	Initial test lane construction with the SnowPaver
15 Nov. 2010	One pass with the Challenger—zero sinkage, not even cleat!
18 Nov. 2010	One pass with the 4-door Ford 350—No sinkage
18 Nov. 2010	Rammsonde: two on the centerline, two on virgin snow
22 Nov. 2012	Constructed on and off ramps for use in vehicle trafficking tests
29 Nov. 2010	Two passes with the SnowPaver, two with the drag
3 Dec. 2010	Tried to go onto test section with the fleet operations truck, but sank into the ramp
6 Dec. 2010	One pass with Mattrack—no sinkage except in drift (up to 6 in.)
6 Dec. 2010	Rammsonde, Clegg, and temperature measurements near the center of the test section and Rammsonde on virgin snow 20 ft from the test section for comparison
7 Dec. 2010	Two passes each with the Mattrack and the Delta Flipper—sinkage only in drifted areas
8 Dec. 2010	Rammsonde, Clegg, and temperatures
11 Dec. 2010	Rammsonde, Clegg, and temperatures

3.1.3 Pegasus Road soft snow test section (Mile Post 4)

We initially constructed the Pegasus soft snow test section on 16 November 2010 in the undisturbed snow 30.5 m (100 ft) off the adjacent Pegasus Road near MP 4. The test section was approximately 152.5 m (500 ft) long, and was prepared by traveling over the entire length with four overlapping passes with the SnowPaver drag body all the way up (all weight of the unit on the pan) at about 6.6 kph (4.1 mph). We then completed a second set of overlapping passes using the miller and with the pan vibrator on. A third set of passes was completed over the whole surface of the test section, and the ramps were constructed on 22 November.

The Pegasus soft snow test section included an on-ramp to allow vehicles onto the section and a turn-around at the other end (Figure 10). During the trafficking tests, this configuration allowed trafficking and monitoring of the soft snow section and across all the four lanes of Pegasus Road, including the Pegasus Test Road C, for each lap of the vehicle.

Table 4 lists the activities on the Pegasus soft snow test section. Figure 11 shows the operation of the SnowPaver at the beginning of construction of the test section.

Figure 10. Pegasus Road soft snow test section at Mile Post 4. Lane C is the snow road SnowPaver test section.

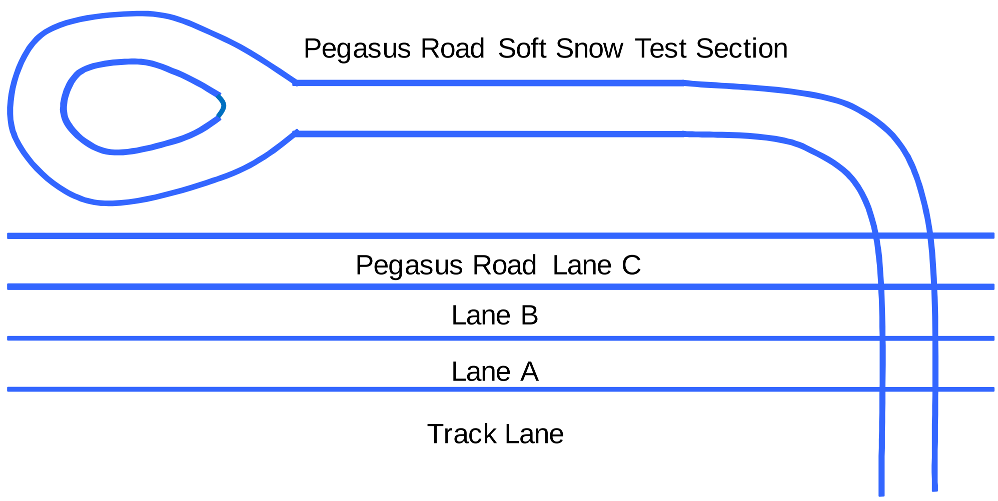


Table 4. Pegasus Road soft snow test section events.

Date	Event
16 Nov. 2010	Initial construction of the test section (2 passes over the full width) (Russ, KRC)
17 Nov. 2010	8 more passes with the paver (Russ, KRC)
18 Nov. 2010	Rammsonde: 4 on the centerline, 3 in virgin snow (Russ, KRC)
22 Nov. 2010	Paver over entire the surface and fixed ramps (Russ, KRC)
1 Dec. 2010	4 passes over the section using the paver without miller (Kristy, RPSC)
7 Dec. 2010	2 passes each with the Mattrack and the Delta—no sinkage aside from drifts
7 Dec. 2010	Rammsonde, Clegg, and temperatures
8 Dec. 2010	Rammsonde, Clegg, and temperatures
11 Dec. 2010	Rammsonde, Clegg, and temperatures

Figure 11. SnowPaver operating in untracked (soft) snow.

3.2 Snow strength and density measurements

A Rammsonde Snow Penetrometer and a Clegg Impact Hammer (Clegg) were used to characterize the strength of the test sections prepared or maintained by the SnowPaver and to monitor the impact of the vehicles on the snow strength after trafficking. We used the Rammsonde Snow Penetrometer (Abele 1990) to measure a strength profile over time and the average strength value for different depth snow layers. The Clegg (Shoop et al 2012) allowed us to measure the integrated strength of the road surface over time to determine if the vehicle traffic changed the snow either through compaction or by weakening through breaking the bonds of the prepared snow surface. Snow strength was measured after the vehicle maneuvers by using the Clegg both in and between the ruts of the vehicle tire tracks. Shoop et al. (2010) contains a discussion of the strength test procedures as applied in the McMurdo snow-road studies, and the nuances of using the Clegg on snow is given in Shoop et al (2012).

Core samples were collected at each test section and then cut into sections to calculate the density profile for each snow pavement.

3.2.1 Rammsonde Snow Penetrometer

To determine strength relationships with allowable wheel loads on artificially compacted snow pavements, the U.S. Army adapted the Rammsonde (Figure 12) from an instrument originally used in the Swiss Alps for estimating avalanche danger. The Rammsonde used on snow roads and runways has a smaller cone* with a diameter of 2.4 cm (0.94 in.), a height of 3.9 cm (1.54 in.), a total length of 5 cm (1.97 in.), and a 60° conical tip. The smaller cone is more sensitive to snow strength in the range seen on snow roads and runways and is also easier to use (both to insert and to remove) on compacted snow surfaces. The Rammsonde hardness number, *R*, is an index that indicates the snow's resistance to vertical penetration (in kilograms force, kgf). The hardness reading is calculated from the number of hammer blows (drops) required to penetrate a measured distance. The penetration force is generated using a slide hammer of specific weight dropped from a measured height.

Figure 12. Rammsonde snow hardness profiling measurement.

3.2.2 Clegg Impact Hammer

The surface strength of the snow was measured using a Clegg Impact Hammer (AKA Clegg, Figure 13). Prior to the concurrent study of the

* A larger cone is often used for avalanche studies and has a diameter of 4 cm (1.57 in.) and a height of 3.5 cm (1.38 in.); the total length of the penetrometer cone element (to the beginning of the shaft) is 10 cm (3.94 in.).

snow-road construction, the Clegg had seldom been used on snow. The Clegg consists of a cylindrical mass hammer that is dropped within a guide tube from a set height. The standard Clegg uses a 4.5 kg (9.9 lb) hammer mass. In this testing program, we used two other hammer weights, the medium Clegg at 2.25 kg (5.0 lb) and the small Clegg at 0.5 kg (1.1 lb). Shoop et al. (2012) gives a detailed analysis of the use of the Clegg on snow and found that the medium 2.2 kg (5.0 lb) Clegg was the most suitable for characterizing the snow-road strength.

Figure 13. Clegg Impact Hammer measuring road surface strength.

The Clegg is equipped with an accelerometer that measures the peak deceleration on impact. For the snow roads and the SnowPaver study, we dropped the hammer five times at each location and took the average of the third to fifth drop as the strength values. Shoop et al. (2012) later found that using only three drops and reporting the third drop value is an adequate and easier method of measuring the snow-road surface strength.

3.3 Vehicle trafficking tests

One of the best methods to judge the capabilities of the SnowPaver test sections is to determine how they hold up with use. Thus, to quantify test section performance, a series of vehicle trafficking tests were performed with intermittent strength and rut monitoring.

3.3.1 Trafficking vehicle

The test vehicle used to traffic the SnowPaver test sections was the LDB Ford Van 215 (Figure 14). The van had Interco TRXUS M/T, 38.5 × 14.50 R 17 LT tires and the tire pressures were as follows:

Left Front = 75.8 kPa (11 psi)	Right Front = 75.8 kPa (11 psi)
Left Rear = 89.6 kPa (13 psi)	Right Rear = 82.7 kPa (12 psi)

Figure 14. Ford E350 Van.

3.3.2 Test section performance indicators

Using the untrafficked snow surface as the elevation datum, we measured the width and depth of the ruts from each tire track, left and right, with a straight edge cross piece and a meter stick or steel tape (Figure 15). We measured the adjacent pile heights and widths with a similar procedure (Figure 16). This type of testing and measurements was developed for snow in Shoop et al (2013b, 2014) based on measurements of vehicle disturbance on soil as described in Haugen (2002).

Figure 15. We measured rut depth from the original snow surface to the deepest part of the rut.

Figure 16. We measured from the undisturbed snow surface the height of the pile on the side of the rut (typical from Shoop et al. 2014).

3.3.3 Vehicle trafficking tests

We conducted trafficking tests on the LDB soft snow section on 14 December 2010. The course was driven in a loop moving from south to north along the test section and then returning along the LDB Road. The driver was to maintain a constant speed and to drive in the same tracks each pass. Passes 1 through 5 (low speed) caused very little impact, so we increased the target vehicle speed to 40 kph (25 mph) for the next 10 passes. The sequence of passes is listed below:

- passes 1 to 5, 24 kph (15 mph)
- passes 5 to 15, 40 kph (25 mph)

Surface damage and rutting were measured after passes 1, 5, 10, and 15.

We conducted a similar sequence of passes on the Pegasus Road soft snow test section and Pegasus Test Road C on 15 December 2010:

- passes 1 to 15, 24 kph (15 mph)
- passes 16 to 20, 32 kph (20 mph)
- passes 21 to 26, 40 kph (25 mph)

The driving course consisted of the entire soft snow test section and then crossed Lanes A, B, and C of the Pegasus Road near MP 4, turning around in the tracked vehicle lane. This allowed a good comparison of multiple surfaces by trafficking the (1) Pegasus soft snow test section; (2) Lane C SnowPaver test lane on the Pegasus Road; and (3) Lanes A and B of the Pegasus Road, as shown in Figure 10. Lanes A and B were subjected to the normal snow-road construction and maintenance procedures

4 2010 Data and Testing Analysis

4.1 Snow strength and density monitoring

The strength of the LDB soft snow section was measured at the center of the test section after the construction (Figure 17). Strength profiles taken on and off the test section showed a strong layer at a depth of 40 to 50 cm (15 to 20 in.) This could be the road surface or the surface melt (refrozen) from the prior summer. Figure 18 gives the density profiles of all three SnowPaver test sections. All cores showed a high density layer below 60 cm (23.6 in.) and near the surface. The LDB soft snow test section yielded the densest snow profile with density reaching 650 kg/m^3 at 40 to 50 cm (15 to 20 in.) depth (the snow surface from the prior summer) and nearly 600 kg/m^3 near the surface.

Figure 17. Rammsonde measurement from the LDB soft snow test section and adjacent area. Note the strong layer from the 2009 snow road at a depth of 40 to 50 cm (15 to 20 in.).

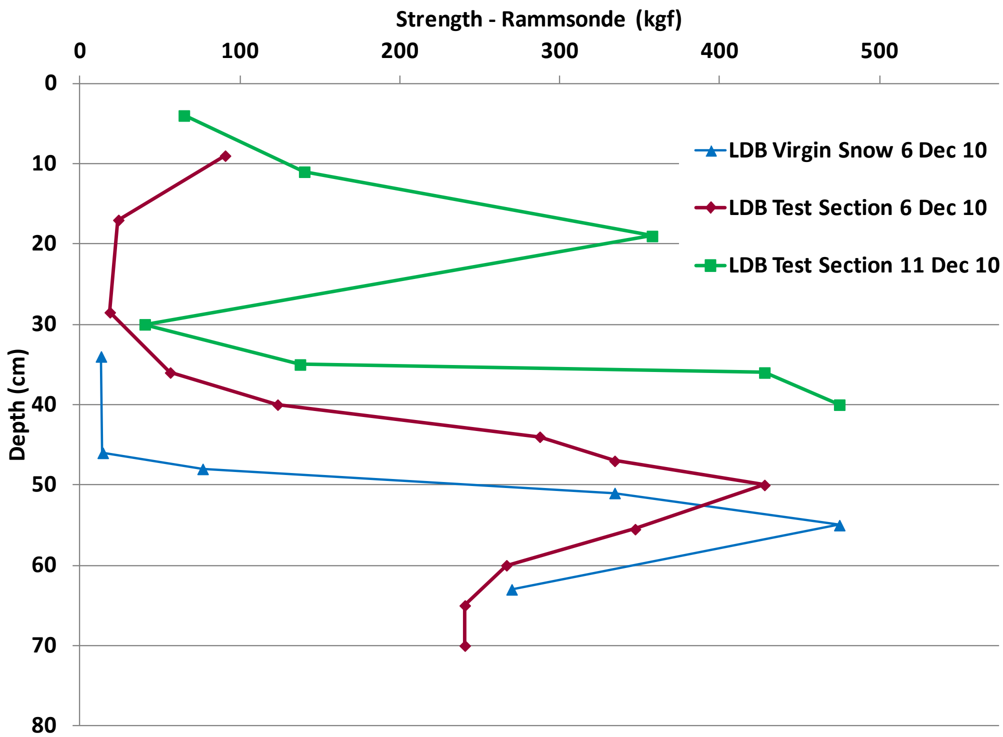


Figure 18. Density profile from the SnowPaver test sections. The dense layer at 40 to 70 cm (15 to 28 in.) depth is likely from the prior year melt surface or snow-road surface

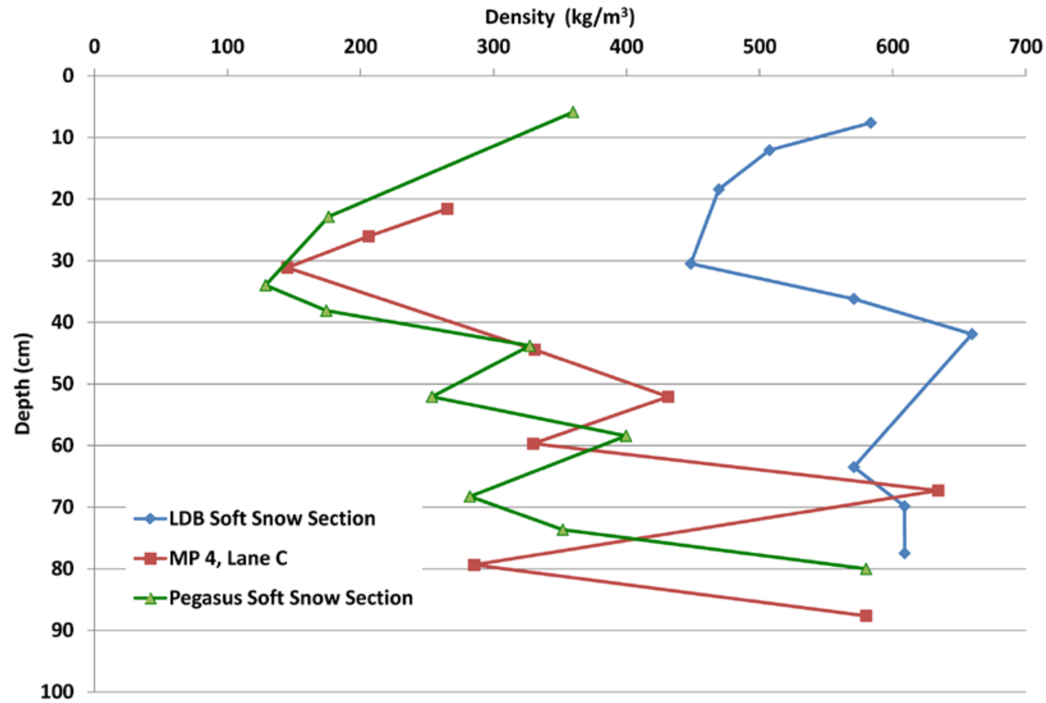


Figure 19 shows the strength of the Pegasus Test Road C test section over time along with the other lanes of Pegasus Road. The data along the top of the graph indicates when and what type of maintenance activities took place. The data at the bottom of the graph are the strength of the Pegasus Test Road C SnowPaver test section (Lane C) compared to the other road lanes (Lanes A, B, and the tracked vehicle lane). The strength values shown are the average of the Rammsonde profile for the top 15 cm (6 in.) of the snow, which is the snow layer exposed to the highest normal and shear stresses from vehicle traffic. Melendy et al. (2011) and Melendy and Shoop (forthcoming) discuss the impacts of the standard maintenance activities on snow strength.

Figure 20 compares the Rammsonde strength profiles of each lane on the day that the Pegasus Road soft snow test section was traffic tested. Both Figures 19 and 20 show the SnowPaver test lane section to have near-surface Rammsonde strength values that can be on the low side compared to the other lanes and were weakest in late December after a long period with no maintenance and above freezing temperatures (Figure 18).

Figure 19. Strength measurements (Rammsonde average for top 15 cm [6 in.]) for the Pegasus Road lanes. Listed across the top of the graph are the associated maintenance activities.

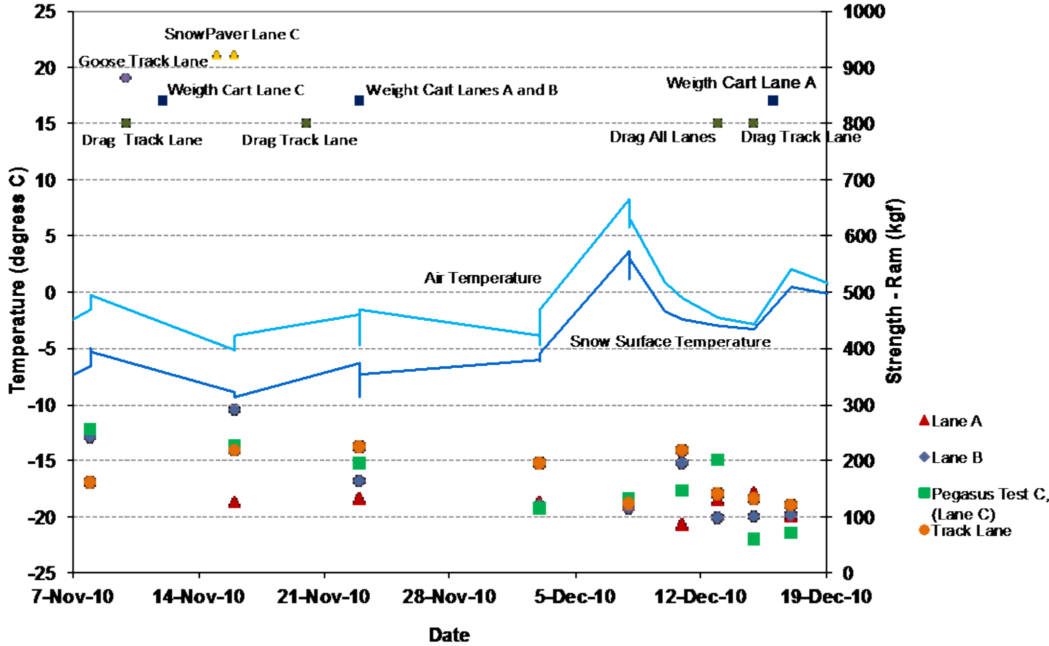
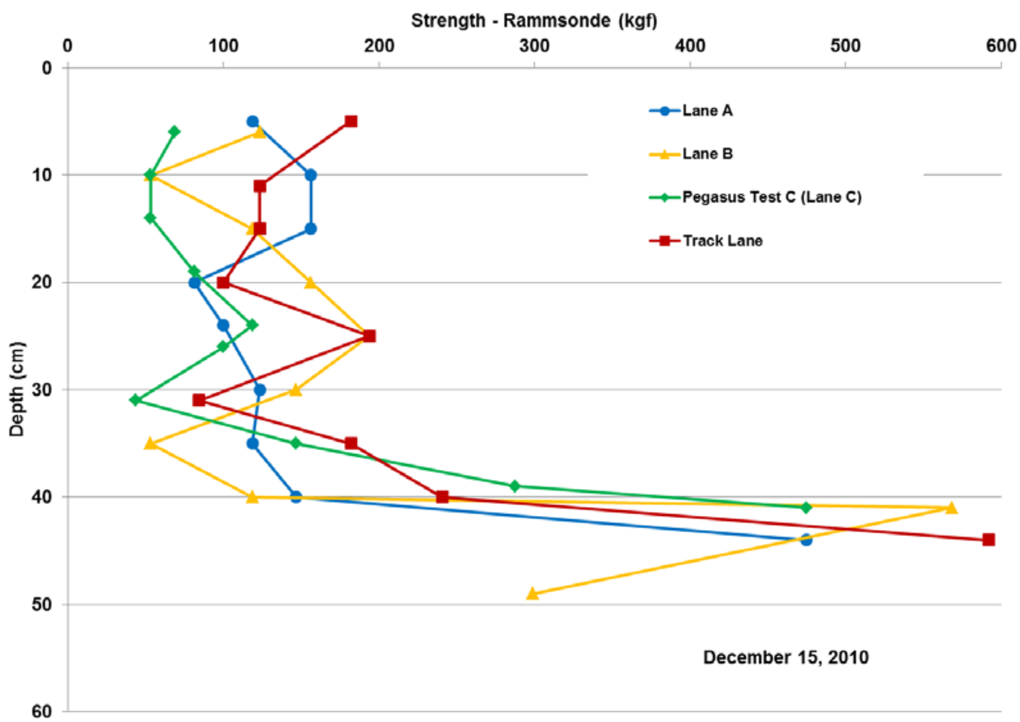


Figure 20. Strength profiles for Pegasus Road lanes.



The surface strength values are often better measured using a Clegg, however. The values from the Clegg can be converted to a standard strength measure, the California Bearing Ratio (CBR), as follows:

$$\%CBR = e^{[(10x - 14.936)/79.523]} \quad [1]$$

where x is the peak deceleration in Clegg units (Shoop et al. 2012).

Using the formula above to calculate the CBR, Figure 21 shows the strength of the two soft snow test sections (alongside the LDB and the Pegasus Roads) over time. Similarly, Figure 22 shows a time series comparison of Pegasus Road soft snow test section, Pegasus Road Test Lane C, and the other lanes of Pegasus Road (all near MP 4). Figure 22 shows the Pegasus Test Lane C to have strength comparable and sometimes higher than the other road lanes.

Figure 21. Strength comparison of LDB and Pegasus soft snow test sections.

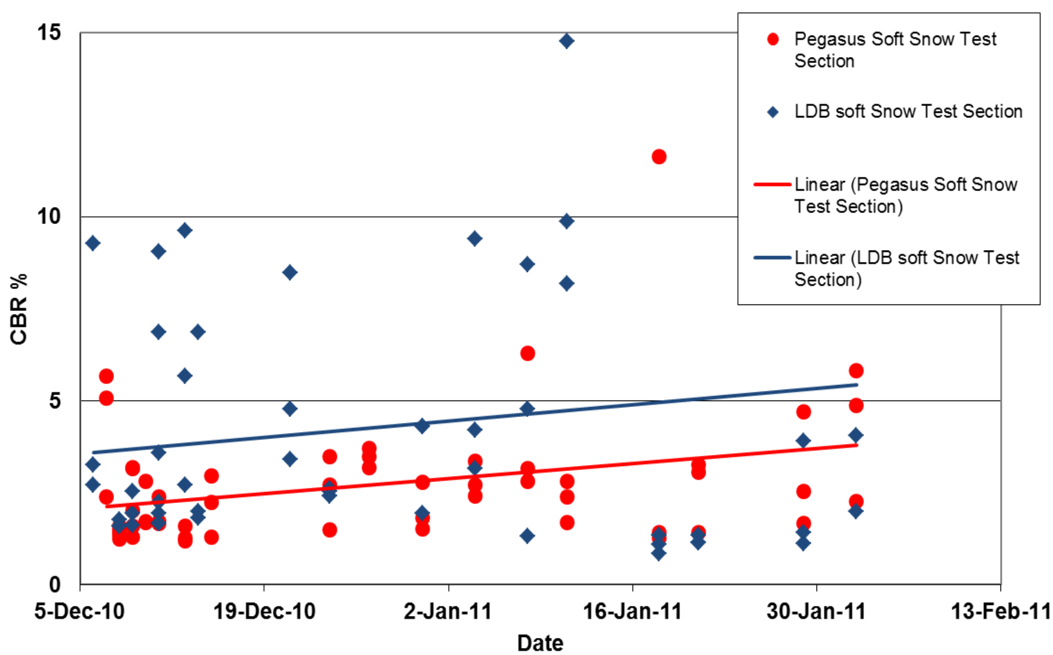
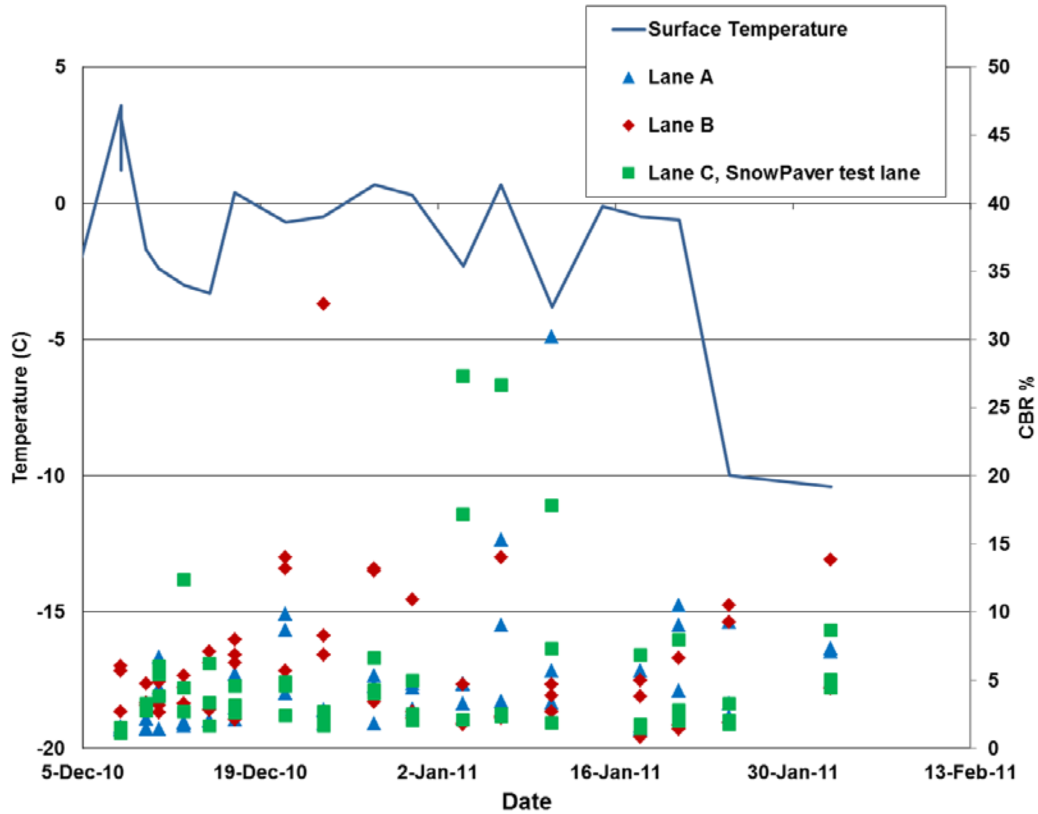


Figure 22. Surface CBR strength comparison of Pegasus Road lanes and Pegasus Test Road C.



4.2 Vehicle trafficking tests

4.2.1 Soft snow test sections

Rut dimensions and strength were measured during the vehicle trafficking tests after passes 1, 5, 10, and 15. We took the measurements in the areas of deepest ruts or bumps; and they are, therefore, skewed to the worst conditions. There was very little impact to the LDB soft snow test section surface during the first five passes of the test vehicle at 8 kph (5 mph) so we increased the speed to 40 kph (25 mph) for the subsequent 10 passes. Figures 23 through 31 show select pictures of the impact measurements.

During trafficking, areas with slight surface roughness caused the vehicle to bounce, resulting in progressively deeper ruts, reaching up to 40.6 cm (16 in.) in the worst areas (Figure 29). On the other hand, the curve at the north ramp exit showed very little impact after all passes (Figure 26). This was surprising as we expected the additional horizontal forces generated during turning to cause shearing damage. The turning forces were evidently much less than the damage caused by vehicle bounce where the high vertical load immediately crushed the snow bonds, allowing progressive damage with each pass.

The Pegasus soft snow test section had similar results where one poor area saw a maximum rut depth of 33.0 cm (13 in.) after 10 passes whereas the rest of the test section typically experienced zero to 6.35 cm (2.5 in.) ruts after 26 passes of the van.

Figure 23. Rutting photos for LDB soft snow test section showing no or minimal impact after 15 passes.

Figure 24. Rutting photos for LDB soft snow test section. Ruts in portion of test section subjected to vehicle bouncing.

Figure 25. Rutting photos for LDB soft snow test section. Area of deep rutting after 15 passes, with rut edges cutting vertically (40 cm [16 in]) into the snow pavement.

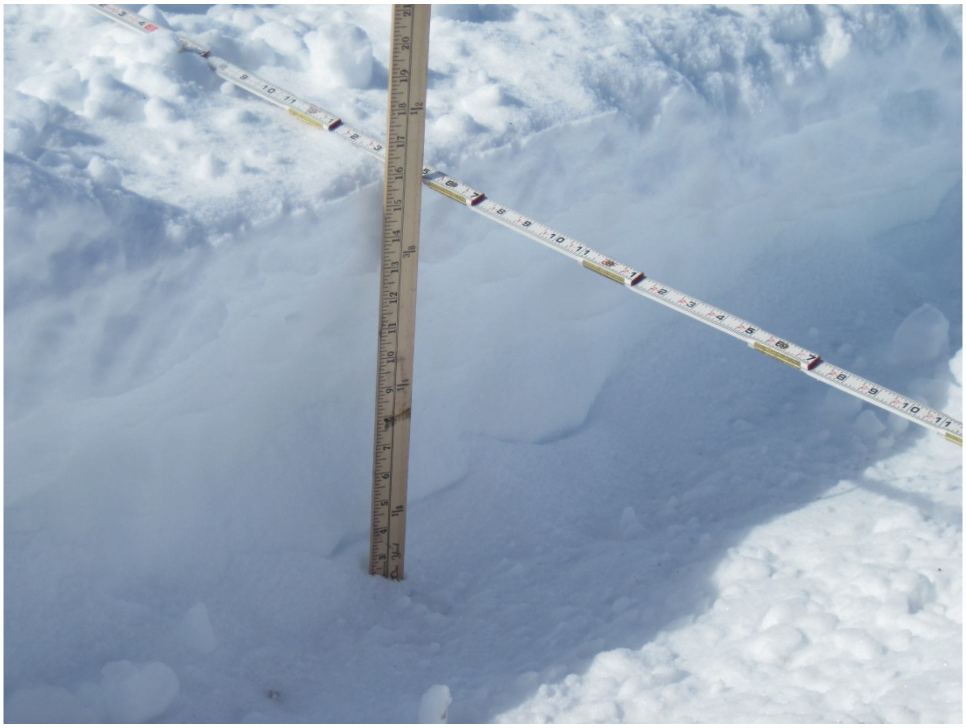


Figure 26. The curve at the north exit of the LDB soft snow test section shows very little impact even after 40 kph (25 mph) and the increased shear forces from turning.

Figure 27. After one pass, LDB soft snow test section showing no rutting, just tread imprints.

Figure 28. After four passes, LDB soft snow test section still has no appreciable rut depth, just tread imprints.

Figure 29. The van bounced through wavy portion of LDB soft snow test section closest to LDB.

Figure 30. Example of significant rutting caused by bouncing.

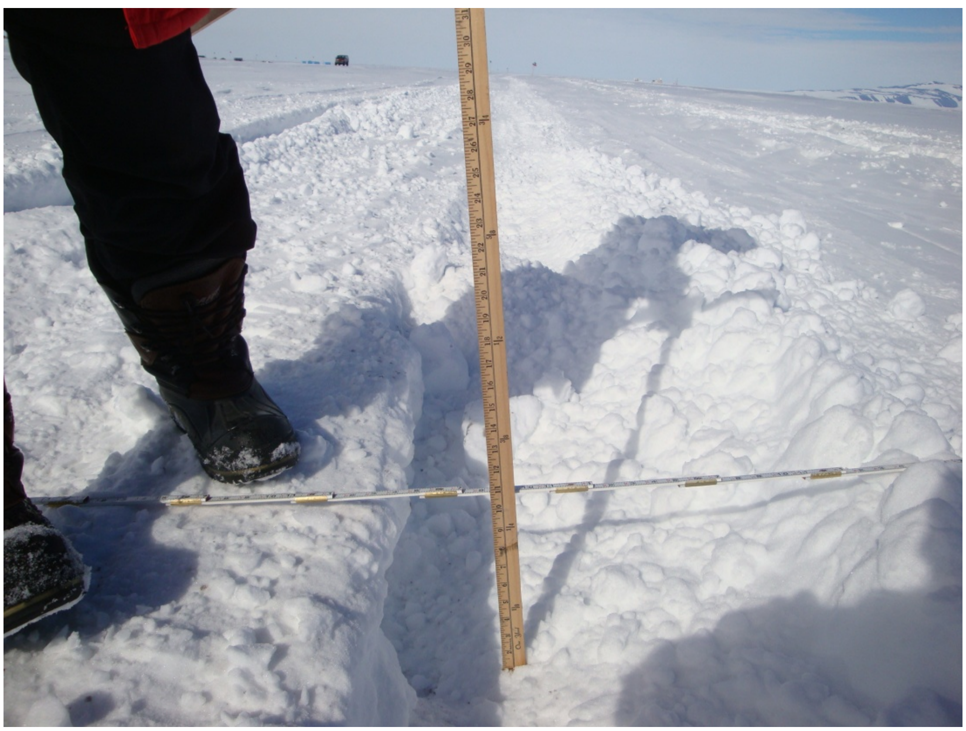
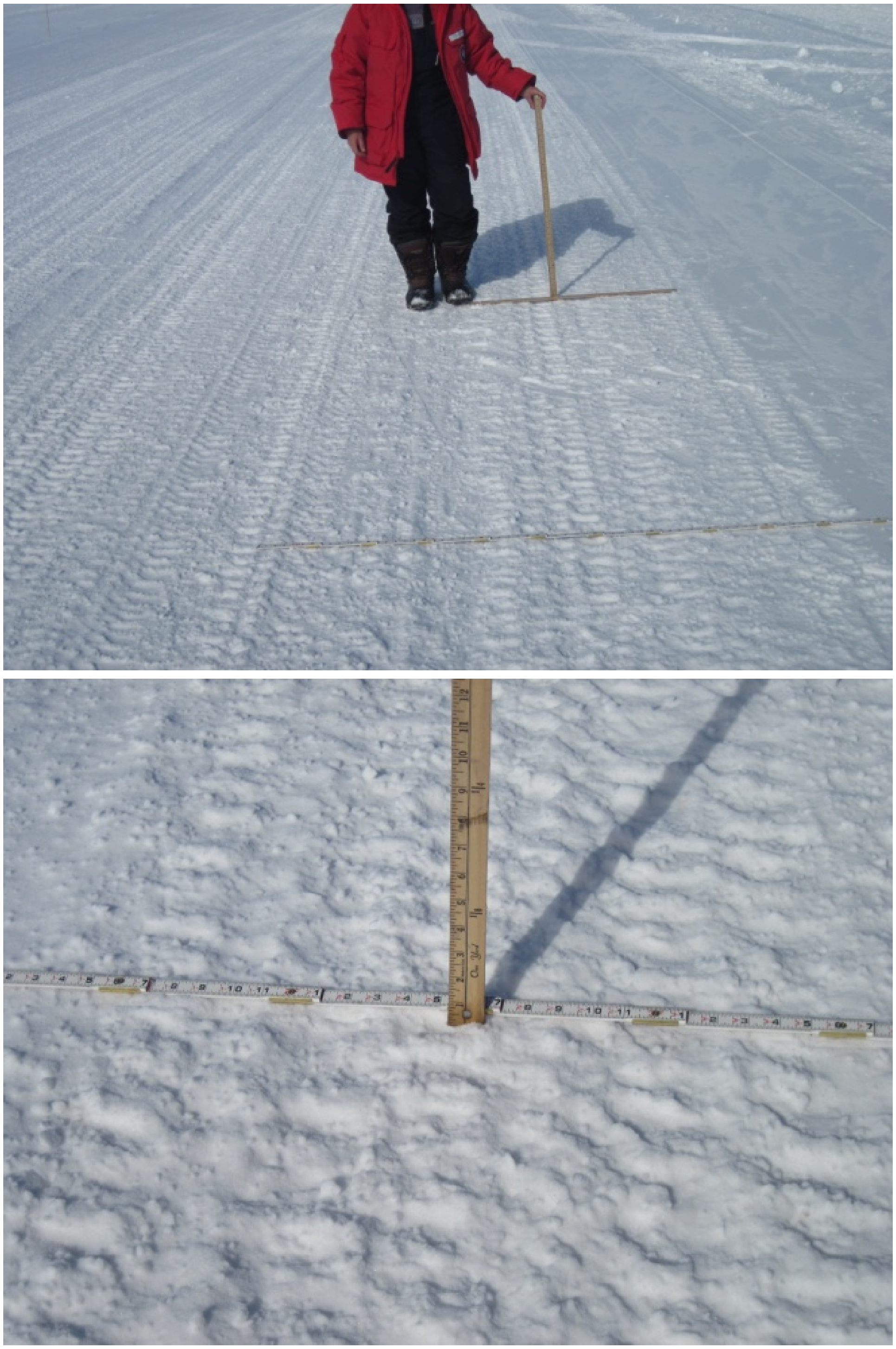


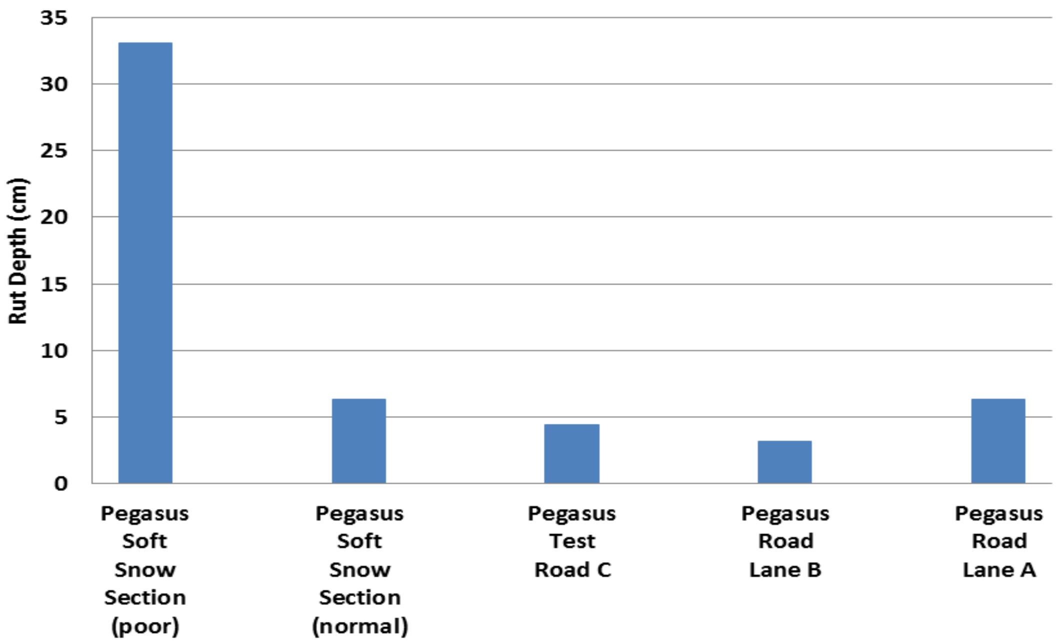
Figure 31. LDB soft snow control section after 15 passes (plus numerous passes from other vehicles) with no appreciable rutting.



4.2.2 Pegasus Road Test Lane C

Although the Pegasus Road Test Lane C was trafficked in only a limited area, the cross road driving pattern allowed a good comparison between the test lane and the other road lanes, all crossed during the same pass. Figure 32 shows a bar-chart comparison of the rutting across all portions of Pegasus Road and the Pegasus soft snow test section at MP 4 after all trafficking. The Pegasus Test Road C saw a maximum of 4.45 cm (1.75 in.) of rutting after 26 passes. Lanes A and B of Pegasus Road, which were not paved with the SnowPaver, had a maximum rut depth of 6.35 cm (2.5 in.) and 3.18 cm (1.25 in.), respectively. The SnowPaver test section performance is comparable to the other road lanes but was prepared using much less labor and maintenance.

Figure 32. Comparison of rut depths on SnowPaver test sections after 26 passes of the E350 Van near Mile Post 4 on the Pegasus Road and soft snow (floating pavement) test section.



5 Initial SnowPaver Capability (2010–2011) Summary and Recommendations

The McMurdo Station ice shelf crew has had limited equipment for surface compaction and currently has no equipment that can mill old, clumped, or windblown snow into fine particles that stimulate sintering. The SnowPaver, deployed to McMurdo in November of 2010, is unique in its ability to manipulate snow pack properties to enhance strength and to increase vehicle mobility on the snow roads. Its greatest benefits in this regard are that (1) it mills the snow to a small grain size to maximize the snow grain surface area; (2) the milling is immediately followed by compaction for maximum grain contact; (3) the high surface area and number of grain contacts provide the greatest number of sintering locations, which increases snow strength; and (4) the leveling, milling and compaction are completed in a single pass of the equipment, optimizing construction time. Ideally, the resultant snow surface is constructed faster and is equal to, and potentially stronger than, snow roads constructed using current methods.

Additionally, the SnowPaver is suitable for small repairs of weak areas that immobilize both wheeled and tracked vehicles. These areas can be quickly groomed to a hard surface that will support rubber-tired vehicles. The SnowPaver could also be useful for building snow pavements in deep snow. The miller and vibrator combination makes it possible to quickly build a single “floating” layer of strong snow, which can be built up with additional layers, in lifts, to form a more substantial snow pavement or foundation. Alternatively, the SnowPaver can be used to construct and groom a surface layer (wearing course) after base layer compaction using a sheepsfoot or pneumatic roller. This program tested a single lift layer, but optimizing construction methods for a full layered foundation is an area of potential future opportunity.

Once the SnowPaver was configured and operational, we constructed three test sections in November 2010 and took cores for density profiles shortly afterwards. Two of the test sections were built on soft (virgin) snow (LDB and Pegasus Road soft snow test sections), creating a floating pavement test section, and the third was a test lane using the SnowPaver for maintenance on the existing Pegasus Road (Pegasus Test Road C). From November 2010 to early February 2011, we monitored the test sections for surface strength (with the Clegg), strength profiles (with the Rammsonde), and temperature.

During December 2010, the test sections were also subjected to trafficking experiments using a passenger van typically driven on the snow roads. During trafficking, areas with slight surface roughness caused the vehicle to bounce, resulting in progressively worse (and severe) rutting in portions of the soft snow test sections. The remainder of the soft snow test sections and Pegasus Test Road C performed very well, even on curves (which increase the tire shear forces on the surface) and after many high-speed (40 kph [25 mph]) passes. The test sections were also found to have surface strength comparable to and sometimes greater than the strength on the other snow-road lanes.

The SnowPaver was also used for a variety of other more routine tasks during the 2010–2011 season:

- Repairing LDB pad blowouts (akin to giant potholes)
- Conducting normal snow-road maintenance and repair
- Grooming near the flags (the SnowPaver can get very close to and compact near the flags that mark the driving lanes)
- Repairing and maintaining the melting transition area where, in spite of the warm temperatures and melting snow, the SnowPaver surface was immediately used by the van fleet with minimal impact (Figure 33)
- Repairing a soft area of the Pegasus airfield apron

During the 2010–2011 season, the SnowPaver required only minor repairs and experienced no significant breakdowns, even with the modified engine, which left the miller underpowered and the SnowPaver unable to fully use both the compactor and the miller in all conditions.

Because the technology and experimental results looked promising, we recommended modifying the SnowPaver with a new power pack to bring the unit to full operating capability.

Figure 33. The SnowPaver being used at the Scott Base Transition during the height of the melt season (left). The surface was immediately available for van traffic (right).

6 2012 Upgrade and Evaluation

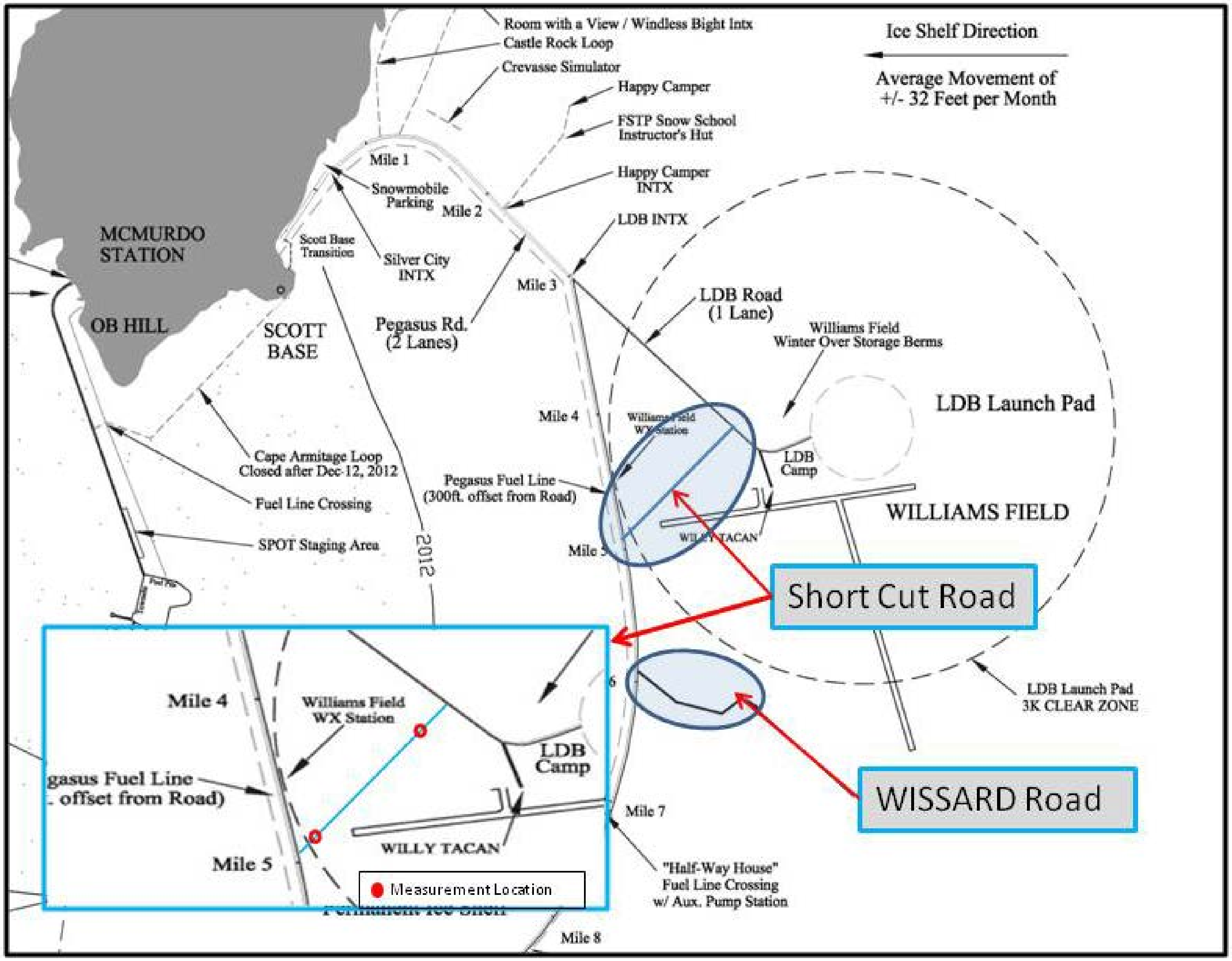
6.1 Power unit upgrade and performance testing

Based on the initial assessment, NSF funded a program to upgrade the SnowPaver. The upgrade consisted of a new motor with enough power for all of the paver functions to operate at the same time, independent of the tow vehicle. The new power pack enables the SnowPaver to be used with a wider range of tow vehicles. This was installed and tested at McMurdo during November 2012. Appendix A is the operations manual for this configuration of the SnowPaver. Figure 34 shows the upgraded SnowPaver. The upgrade was followed by limited testing at locations shown in

Figure 35.

Figure 34. The SnowPaver with the new power-pack upgrade being tested at McMurdo Station, November 2012.

Figure 35. Ice shelf road layout, test site, and strength measurement locations.



Appendix B provides the full report on the upgrade and initial testing performed by KRC, but one test section is of particular note for the exceptionally large strength increase. Figure 36 shows the strength profile on a road from the LDB town site to the Pegasus Road, an area (later called the Miracle Mile) previously compacted using a sheepsfoot roller. The sequence of events and strength measurements are as follows:

1. On November 15, we made a set of Rammsonde measurements (along the test road and on the Pegasus Road at MP 6). Subsequently, we used the SnowPaver on the test area with both the miller and the vibratory plate operating (one full coverage of the road in each direction). We then allowed the road to set up for 24 hours.

2. On November 16, we repeated this operation with the blades and vibrator only. The road had been covered with drift snow, and this snow was already fine-grained and did not need milling. This operation added a new snow layer of approximately 2 cm (0.8 in.) to the road.

3. On November 17, using the vibrator only, we again made two full coverages over the road, adding a snow layer of approximately 3 cm (1.2 in.). The Short Cut Road was not groomed with the paver after this.

4. During these days, a variety of vehicles used the test road and drags were pulled over it to cross over to the Pegasus Road during the normal operations on the McMurdo ice shelf.

5. On November 20, we made Rammsonde measurements at three locations along the Short Cut Road. The snow temperature at a depth of 5 cm (2 in.) was −9°C (16°F). Several inches of loose and drifting snow had accumulated after the road was processed by the SnowPaver three days before. Because of the soft surface layer, we did not take any Clegg measurements.

The Rammsonde strength measurements (Figure 36) show that there was a very hard layer present in the lane where the SnowPaver was used. This layer had strength of around 1000 R at a depth of 10 to 15 cm (4 to 6 in.), which is a significant increase over the original road surface and the strength of the Pegasus Road at MP 6. This layer was impenetrable with the Rammsonde. Excavation with an ice axe showed the layer to be 3 to 5 cm (1.2 to 2 in.) thick. To emphasize the impact that the SnowPaver had on the snow-road strength, a bar chart comparing the maximum strength values from the Rammsonde profiles is shown in Figure 37.

Figure 36. Rammsonde values at the Short Cut Road and at MP 6 (November 2012). Also see discussion of Figure B4 in Appendix B.

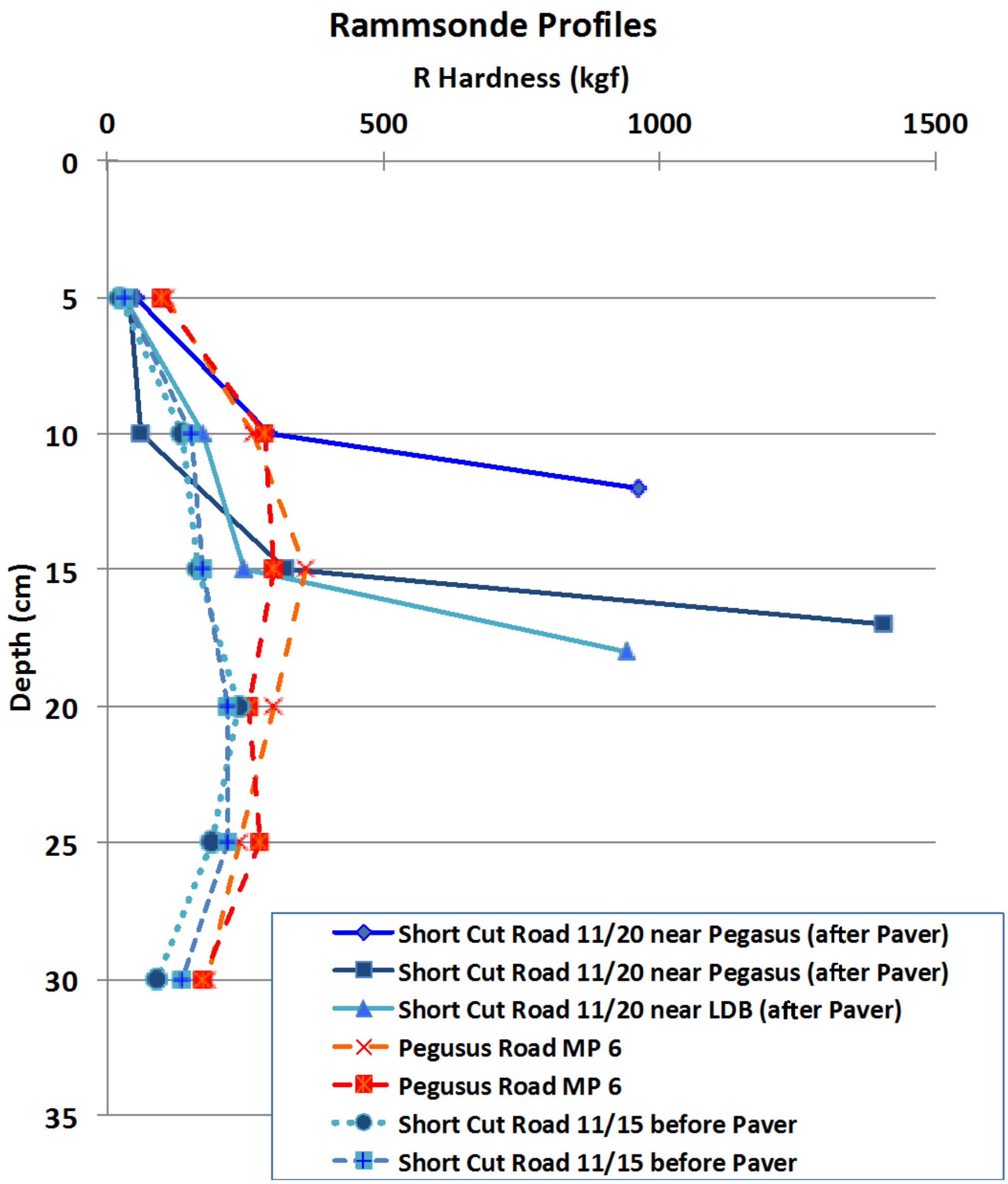
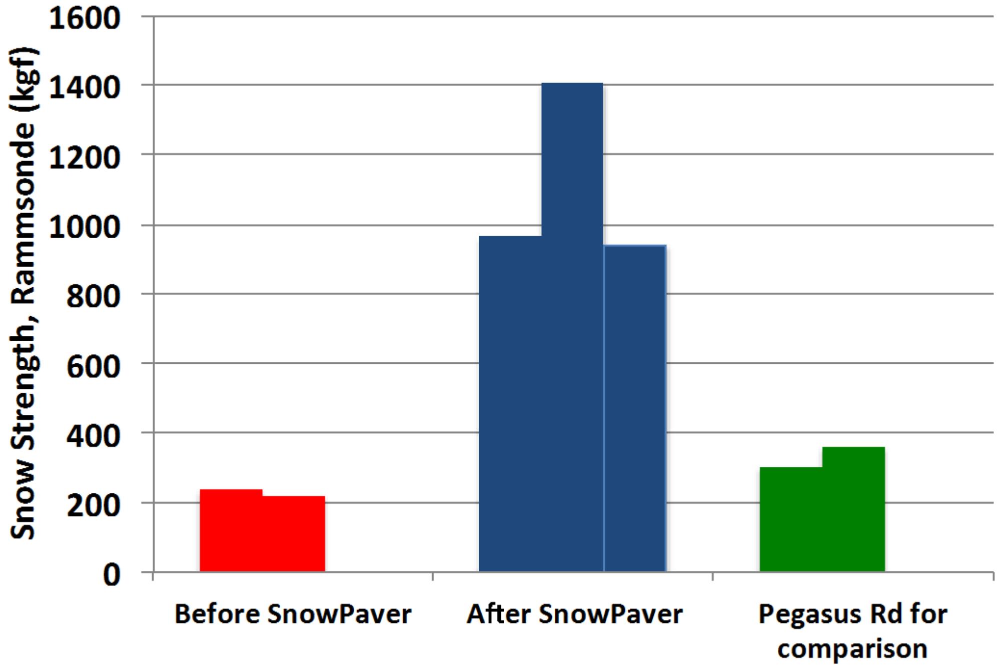


Figure 37. Maximum strength from each Rammsonde profile before and after SnowPaver use on the Short Cut Road and nearby at MP 6 of Pegasus Road for comparison (November 2012).



Budget constraints and reduced personnel deployments to McMurdo prevented further testing and longer-term monitoring of the SnowPaver's use and the long term performance of the test sections, but a formal test and monitoring plan should be considered in the future for a full characterization of the use and benefits of the equipment.

Additional positive results included the following:

- Produced a hard surface quickly
- Worked when some other items would not
- No similar capability available on station
- Could make strong pavement quickly (4 passes on Short Cut Road not passable by wheeled vehicles previously) but may need a subbase (with a sheepsfoot?)

6.2 Assessment by the McMurdo heavy-equipment operators

The SnowPaver's use during 2013 was not fully successful, however. Some of the fleet operations personnel had misgivings (outlined below), and the small size of the SnowPaver made it ineffective at smoothing drifts after wind storms. Appendix C gives the full comments solicited from the McMurdo personnel who used the SnowPaver during 2012 and 2013. However, some of the major concerns voiced by the McMurdo staff included the following:

- Miller tended to clog
- Hitch had several issues
- It had problems with deep drifts and slopes
- It may not actually fully replace other equipment
- It leaves windrows in several scenarios (we believe this has been corrected)
- Vibrator is under powered
- Control box is fragile
- It has the potential to be high maintenance

Most importantly, McMurdo staff who used the SnowPaver recommended a redesign for a larger version more suitable for use on roads and runways in Antarctica. Section 7, discusses this option and documents an economic analysis of the current 10 ft version and a larger 16 ft wide SnowPaver compared to methods currently used.

7 Economic Considerations

The economics of using the SnowPaver compared to existing methods used on the snow roads is not straight forward because no other milling or surface compaction capabilities currently exist at McMurdo. The grooming method that most closely represents an equivalent process to that of the SnowPaver is leveling or smoothing with a goose (a custom snow plane) towed by a Challenger, followed by surface compaction achieved by rolling the road with a smooth-tire Delta. With this in mind, we performed a simple economic analysis to compare the current available methods to two sizes of the SnowPaver. The three options compared were

1. the current maintenance methodology using the goose followed by compaction with a smooth-tire Delta,
2. the current 10 ft wide SnowPaver, and
3. a new 16 ft wide SnowPaver.

This analysis was performed and presented in English units, however, the unit choice does not affect the bottom line, expressed as a return on investment (ROI) presented at the end of the section.

Table 5 lists the assumptions we made to calculate the cost per mile. The capital equipment costs for the towing vehicle (prime mover) and the existing implements (goose or drag) are not included in the analysis.

Table 5. Operating cost assumptions.

Operating Costs	Rate	Rate Units
Operator	$1,432.00	$/week
Labor Boarding	$500.00	$/day
Challenger Maintenance	$10.00	$/hr
Delta Maintenance	$15.00	$/hr
SnowPaver Maintenance	$1.00	$/hr
Fuel	$4.70	$/gal.

To calculate a cost per mile, we must consider the width of the grooming vehicle and implement. In the case of the Delta, additional passes are needed to fill in between the wheel tracks to fully compact all parts of the lane. One coverage consists of several passes that fully cover a 50 ft wide lane. Table 6 lists the number of passes required for each option for a complete coverage of the 50 ft width. The costs above (Table 5) are then used to calculate the cost per mile, depending on the speed of the grooming vehicle. We chose two grooming speeds for comparison; 5 and 10 mph. These speeds span the range of grooming speeds typically considered for the ice shelf. Fuel consumption numbers for the equipment, also listed in Table 6, are general and are not specific to McMurdo operations but were considered reasonable estimates by the fleet operations manager.

Table 6. Comparison of existing maintenance methods to the SnowPaver operations for cost per mile.

Vehicle/ Implement	Fuel Consumption (gal./hr)	Grooming Width (ft)	Passes Needed (per 50 ft lane)	Time per Mile (Hours, at 5 and 10 mph)	Cost per Mile, 5 mph ($/mile)	Cost per Mile, 10 mph ($/mile)
Challenger with goose/drag	16	17	4	0.8/0.4	$108.69	$54.35
Delta	20	7.3	9	1.8/0.9	$287.40	$143.70
Challenger with 10 ft SnowPaver	18	10	6	1.2/0.6	$175.52	$87.76
Challenger with 16 Ft SnowPaver	19	16	4	0.8/0.4	$120.77	$60.39

To calculate an ROI, we first need to estimate how much the SnowPaver's use would replace the existing method. Using a conservative estimate that the SnowPaver would replace the processing on one lane of the 15 miles of snow road 10 times a year, we can then compare the savings for the 150 miles of snow road processed. This is a conservative estimate, and it is very likely the McMurdo staff would use the SnowPaver much more than this.

Table 7 gives the time estimated for an ROI based on a capital equipment cost for the SnowPaver of $37,034 for the 10 ft unit and $115,000 for the 16 ft unit. These numbers are largely controlled by the cost of fuel and labor, so the major economic advantage is the reduction in the number of passes needed for grooming and compacting the surface layer (now currently requiring both goose or drag and rolling the surface with a Delta). The bottom line is that either version of the SnowPaver would pay for itself in 1.1 to 5.6 years.

Table 7. Cost savings and ROI for the 10 ft and the 16 ft SnowPaver used on the snow roads for an estimated 150 miles per season (50 ft wide lane).

Vehicle/implement	Cost per mile	Savings per mile	Savings/season (150mi)	Payback (years)
At 5 mph grooming speed				
Challenger goose/drag + Delta	$396.09			
Challenger + 10' SnowPaver	$175.52	$220.57	$33,086.00	1.12
Challenger + 16 'SnowPaver	$120.77	$275.32	$41,298.00	2.78
At 10 mph grooming speed				
Challenger goose/drag + Delta	$198.05			
Challenger + 10' SnowPaver	$87.76	$110.29	$16,543.00	2.24
Challenger + 16 'SnowPaver	$60.39	$137.66	$20,649.00	5.57

Using the SnowPaver for runway construction and maintenance is also of interest; therefore, we calculated an ROI for 2 different runway dimensions:

- 10,000 × 200 ft dimensions of the Pegasus skiway at McMurdo Station and
- 16,400 × 200 ft dimensions of the skiway in Summit, Greenland.

Using the same operator, fuel usage, and cost estimates from Table 5 and assuming a grooming speed of 5 mph results in a cost savings of $1671 to $3420 per grooming event depending on the runway dimensions and SnowPaver width (Table 8).

Table 8. Cost comparison of existing methods and the SnowPaver operation for one full grooming of the Pegasus skiway (McMurdo) and the Summit skiway (Greenland).

Method	Passes for Full Coverage	Cost for Pegasus Skiway	Cost for Summit Skiway	SnowPaver Savings for Pegasus for One Full Grooming	SnowPaver Savings for Summit for One Full Grooming
Goose/drag with Challenger	16	$823	$1350		
Delta rolling compaction	36	$2177	$3570		
10 ft SnowPaver	24	$1329	$2181	$1671	$2739
16 ft SnowPaver	16	$915	$1500	$2085	$3420

Using the same capital cost for the SnowPavers, this results in an ROI after 13.5 to 55.5 grooming events, depending on the SnowPaver's width and the runway length. If the runway is groomed 20 times a season*, the ROI is between 1 and 3 years as follows:

- Pegasus: ROI after 22.2 groomings (1.1 years) for 10 ft SnowPaver
- Pegasus: ROI after 55.5 groomings (2.8 years) for 16 ft SnowPaver
- Summit: ROI after 13.5 groomings (0.7 years) for 10 ft SnowPaver
- Summit: ROI after 33.6 groomings (1.7 years) for 16 ft SnowPaver

In summary, the SnowPaver ROI is 1.1 to 5.6 years for use on 150 miles of snow roads and 0.7 to 2.8 years if used for just 20 runway groomings. If the SnowPaver is used on both roads and runways, the ROI is of course even smaller (better).

* Grooming estimates: Summit skiway is groomed 25 to 30 times per year, Pegasus 1 to 3 times per week for 4 months, and South Pole skiway is 12000 × 200 ft and is groomed 20 times per season.

8 Summary and Recommendations

The SnowPaver combines a cutting, leveling, milling, and vibratory compaction process all in one implement. It is designed to maximize the snow grain contacts for optimal sintering and to minimize labor and equipment operation hours. Prior to this project, no equipment of this type was available in the McMurdo inventory. Therefore, CRREL and KRC initiated a program to study the usefulness of a SnowPaver at McMurdo Station, Antarctica.

The SnowPaver arrived at McMurdo in November of 2010, and KRC subsequently modified it to operate without a PTO, leaving it underpowered. Even so, the SnowPaver was operational; and we constructed three tests sections in November 2010 and took cores for density profiles shortly afterward. Two of the test sections were built on soft (virgin) snow (LDB and Pegasus soft snow), and the third was a test lane using the SnowPaver for maintenance on Pegasus Road (Test Road C). From November 2010 to early February 2011, we monitored the test sections for surface strength (with a Clegg), strength profiles (with a Rammsonde), and temperatures. We found the test sections to have strength comparable to (sometimes greater and sometimes less than) the strength on the other snow-road lanes; however, the SnowPaver lanes were groomed less (even after storms) and also used less, making definitive conclusions problematic.

During December 2010, the test sections were subjected to trafficking experiments using a passenger van typically used on the snow roads. During trafficking tests, areas with slight surface roughness caused the vehicle to bounce, resulting in progressively more severe rutting in portions of the soft snow (floating pavement) test sections. However, the remainder of the test sections performed very well even at the higher vehicle speeds (40 kph [25 mph]), multiple passes, and on the curves, which experience increased tire shear forces.

During the 2010–2011 season, the SnowPaver was also used for a variety of other tasks, such as blowout repair, normal maintenance, repairs on melting snow at the Scott Base Transition, and repair of the Pegasus airfield apron. With minor maintenance, the SnowPaver was operated throughout the season. Because the technology shows promise for snow roads and for other snow construction needs and the experimental results were encouraging, we decided to add a power pack to bring the unit to full operating capability for further evaluation.

The upgraded motor on the SnowPaver was installed at McMurdo during November 2012, and the unit was immediately used for shakedown testing and roadway construction and maintenance. A test section of particular note was constructed over an area used as a shortcut road between LDB and the Pegasus Road (Figure 35), later renamed the Miracle Mile. Rammsonde strength measurements taken hours before the SnowPaver's use show a consistent strength profile with maximum values of less than 300 R. Several days following the SnowPaver use, and after some snowfall, the Rammsonde strength measurements indicated an exceptionally strong layer with multiple strength measurements recording values over **1000 R**. This is a significant increase over the original road strength (Figure 36).

Finally, the 10 ft SnowPaver dimensions and ruggedness were not ideal for Antarctic snow roads where a longer and wider unit could work better. McMurdo personnel sometimes need to use the goose to level the wind-blown surface after a storm, indicating a longer base for the leveling blades on the SnowPaver would be useful. Also, a wider unit would reduce the number of passes and time required to complete a road lane or runway. A 16 ft wide SnowPaver was considered to be wide enough to improve snow road or runway grooming and also would be transportable in an LC130 Hercules with minimal assembly. We, therefore, also consider the wider SnowPaver in the economic analysis in Section 7.

We completed a simple economic analysis comparing the current options for leveling and surface compaction with the two proposed sizes of the SnowPaver. The options considered were

1. current maintenance methodology using the goose followed by compaction with a smooth-tire Foremost Delta,
2. the current 10 ft wide SnowPaver, and
3. a new 16 ft wide SnowPaver.

Section 7 provides the full details and considerations of the economic analysis. The primary factors considered are related to the time required for grooming as reflected in operator labor, fuel usage, and equipment maintenance. We calculated an ROI for several scenarios for snow roads or runways (skiways). Using a capital cost estimate of $37,034 for the 10 ft SnowPaver and $115,000 for a 16 ft SnowPaver, the ROI can be summarized below:

- ROI for a 10 ft SnowPaver on snow roads is 1.12 to 2.24 years.
- ROI for a 16 ft SnowPaver on snow roads is 2.78 to 5.57 years.
- ROI for a 10 ft SnowPaver for runway is 1.1 to 1.7 years.
- ROI for a 16 ft SnowPaver for runways is 0.7 to 1.7 years.

The SnowPaver is a unique capability for building and maintaining durable snow roads, skiways, or foundations. Although it can be used alone, its advantages may truly lie with using it in combination with heavy compaction equipment or in building layered snow pavements.

We recommend several tasks to further develop the SnowPaver and to gain additional insight into building infrastructure with snow:

1. Monitor and quantify the *long-term* performance of SnowPaver test sections constructed under full hydraulic power (with milling and compaction units fully engaged).
2. Validate contributions of the milling portion of the unit (on and off) for different snow conditions.
3. Evaluate the SnowPaver for snow pavements (roads, foundations, pads, or skiways) constructed in successive layers.
4. Evaluate the SnowPaver's use in conjunction with other snow compaction and construction equipment, such as the sheepsfoot, weight cart, and dozer, for building a full-section snow pavement.
5. Use the knowledge gained above to incorporate the SnowPaver into a multi-step, multi-tool processing scheme and develop guidance for best use of each of the techniques (alone or in concert).
6. Document the resulting bearing capacity of the snow pavement and test performance limits using vehicle, aircraft, or equivalent loads.
7. Develop a maintenance and full life cycle schedule for the SnowPaver.

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Appendix A: 2012–2013 Upgraded SnowPaver Operation

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SnowPaver operation

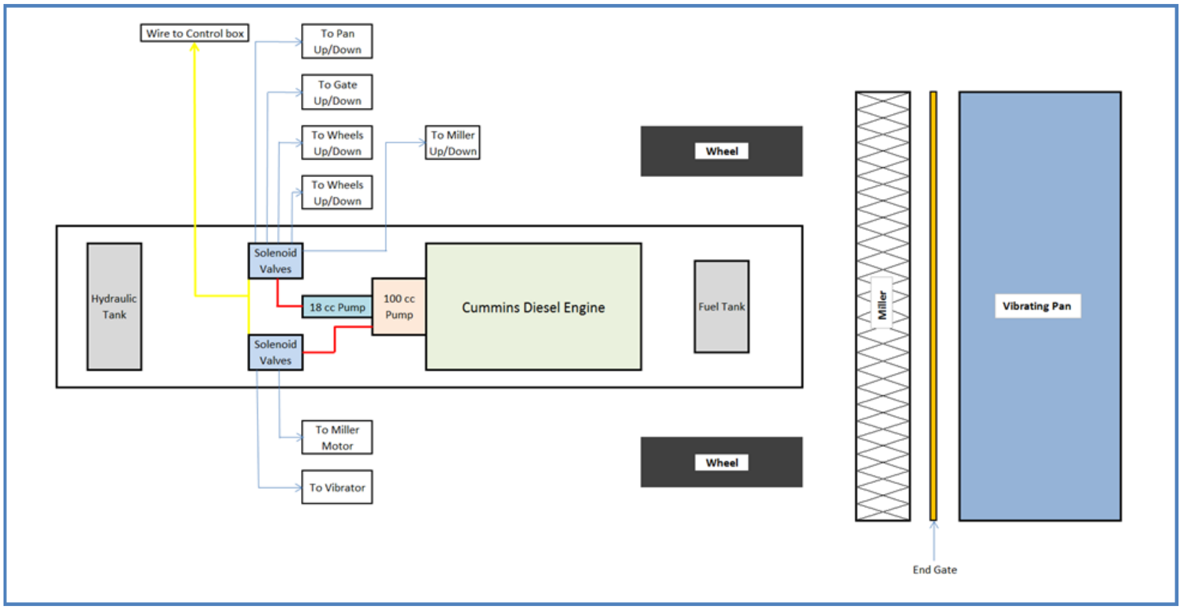
This manual is designed as an overview of the operation of the SnowPaver in the March 2013 configuration. There are two reports (Alger 2010, 2013) available that outline the progression of the SnowPaver between 2010 and 2013. These reports also contain testing and results using this equipment. Photo A1 is of the SnowPaver in its present (March 2013) configuration.

Photo A1. Upgraded SnowPaver in Antarctica, November 2012.

SnowPaver setup

In November 2012, a hydraulic power pack was installed on the SnowPaver to make it a self contained unit that could be towed with almost any tractor large enough to pull it. Alger (2013) outlines the installation of this power pack. The power pack consists of a diesel engine coupled to hydraulic pumps and valves that allow for operation of all of the functions of the SnowPaver from inside the cab of the tractor. Figure A1 is a schematic of the SnowPaver system. Each item in this schematic will be discussed in the following sections. A list of parts that make up the hydraulic power pack, as well as hydraulic and system schematics, is given at the end of this appendix.

Figure A1. Schematic of SnowPaver components.



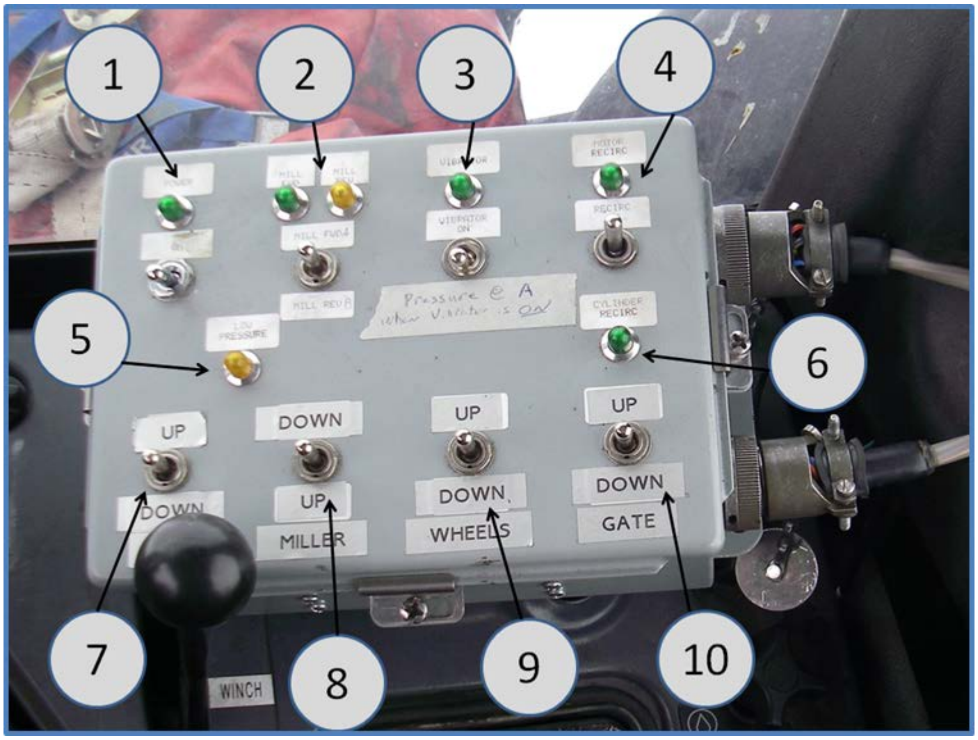
There are seven hydraulic functions on the SnowPaver. These are as follows:

- The 3-point hitch to raise and lower the front of the SnowPaver frame
- The motor that turns the miller drum
- Hydraulic cylinders that raise and lower the miller drum
- Hydraulic cylinders that raise and lower the vibrating pan
- Hydraulic cylinders that raise and lower the wheels for running off snow
- Power to the vibrator
- Hydraulic cylinders to raise and lower the end gate located just behind the miller drum

Photo A2 shows the control box that operates all of the functions except for the 3-point hitch (operated by tractor controls). The switches on this box control the functions, and indicator lights show when some functions are on or off. At present, the controls are connected to the SnowPaver with a double wire that must be threaded into the cab of the tow vehicle. In

Photo A2, the control box is mounted in a Challenger tractor. This vehicle has a port that can be used to route wires into the cab as shown. The control box is connected by two wires with two Military Standard connectors. These connectors are different sizes and can be connected only one way. When the SnowPaver is disconnected, the wire with connectors is pulled out of the cab of the vehicle and left coiled up on the paver.

Photo A2. SnowPaver control box.



The switches and lights on the box are laid out as follows (numbering corresponds to labels on Photo A2):

1. In the upper left corner of the box is a switch and light pair. This is the main power. This must be on for all of the other functions to work. It does not have to be on for the SnowPaver engine to run, however. This is a two position switch and is off down and on up. The green light indicates power is on.

2. Moving to the right across the top row, the second switch with two lights is the miller power switch. This switch is a three-position toggle with up, center, and down positions. Center is off. In this position, both lights will be off. Switching down from center runs the miller in reverse. In this position,

the yellow light is on. Switching up from center runs the miller in forward, which is the normal running direction. The green light will be on for this function.

3. The third switch to the right turns the vibrator on and off. It is a two position switch with down being off and up on. The green light above the switch will be on when the vibrator is running.

4. The top right switch and light control recirculation of fluid through the motor system. This switch is only needed when the system is being calibrated. It can be left off unless a calibration is needed. It is a two position switch, off and on; and the on light is green.

5. There is a yellow light in the middle on the left side of the control box. This light is a low oil pressure light. When it is on, the system should at least be monitored for problems. It can also come on when too many systems are on at once, but it usually indicates a system check is in order. It may also indicate an oil leak.

6. The green light in the middle on the right side indicates that the cylinder system is idling and is working properly. The four switches across the bottom control the up and down cylinders.

7. The furthest to the left controls the vibrating pan up and down. This is a three position toggle switch with automatic return to center, center being the off position. Pushing the switch up raises the pan, and down lowers it.

8. The second switch from the left controls the miller drum up and down. This is a three position toggle switch with automatic return to center, center being the off position. Pushing the switch up lowers the miller, and down raises it.

9. The third switch from the left controls the wheels up and down. This is another three-position toggle switch with automatic return to center, center being off. Pushing the switch up raises the wheel set, and down lowers them.

10. The switch on the bottom to the far right controls the end gate up and down. This is again a three-position toggle switch with automatic return to

center, center being off. Pushing the switch up raises the gate and down lowers it.

Three-point hitch

The front of the SnowPaver needed to be raised and lowered by some mechanism to adjust the cut depth during operation. To accomplish this using the Challenger tractor as a tow vehicle, a three-point hitch was built to fit the Challenger and was connected to the hydraulic lift mechanism on the back of tractor. The three-point hitch, as the name implies, connects to the Challenger in three places. It is used to raise and lower the front of the paver. Lowering the unit cuts more snow on the front cutting blades. On snow surfaces that are relatively smooth and on pre-existing road surfaces, it appears to be best to run with entire SnowPaver frame about level. This can vary, however, dependent on conditions. Adjustments are made to keep snow moving through the body of the paver without filling it or choking the system. The back of the paver is also raised and lowered (discussed further in the next sections) by the pan. When operating normally, the pan can be set to a point that the side of the paver is only slightly above the snow surface (about 2.5 cm [1 in.]); and the rest of the leveling adjustments can be made with the three-point hitch at the front of the SnowPaver. Photos A3, A4, and A5 are pictures of the hitch and connection points on a Challenger. Photo A6 shows the leveling blades in the SnowPaver body.

Photo A3. Three-point hitch on the Challenger.

Photo A4. Three-point hitch top connection.

Photo A5. Three-point hitch side connections.

Photo A6. Leveling and cutting blades.

Vibrating pan lift

Raising and lowering the vibrating pan raises and lowers the back end of the SnowPaver and adjusts the cut and how much snow passes out the back of the paver. It also raises and lowers the miller drum. If excessive snow builds up in the unit, raise the back end of the paver (lower the pan) and it will flow out. The pan can be raised too high and not be in contact with the snow. The pan needs to carry the weight of the back of the paver to work. It works best if a little daylight is visible out the side of the paver near the miller drum (again, about 2.5 cm [1 in.] up).

Raising both the front and rear of the paver is the best way to turn corners without leaving a wind row. It also works well for dead heading at higher speeds. The pan can be put all the way down to raise the back of the paver. Photo A7 shows one of the two pan lift cylinders (the vertical cylinder in the photo).

Photo A7. Pan lift cylinder.

Miller drum lift

The miller drum lift simply raises and lowers the miller system. It can be set at an efficient operating height and left there. This height is set by watching how the snow that is coming off of the blades is being milled and is passing through the system. If the miller keeps stalling, it means that too much snow is being pushed through the system. To fix this, the miller either needs to be lifted or the front and rear heights of the paver need to be raised. This can take some adjusting in the beginning but quickly gets set to a point where little additional adjustment is needed.

When the miller stalls, it is freed by raising the drum. If this does not work, the miller can be turned in reverse to clear the snow. This will be discussed further in the miller section to follow. Photo A8 is a picture of the miller lift cylinder.

Photo A8. Miller lift cylinder.

End gate

The end gate is located just behind the miller drum. It is a cutting blade that runs the full width of the SnowPaver. When it is all the way up, all of the snow passing through the miller passes under it. All the way down, it acts like a scraper and holds the snow in. During normal operation, it can be left all the way open. If the paver is used as a means to move snow from the side of the road, back onto it, the gate can be opened and closed to trap snow and dump it where it is desired. Photo A9 shows one of the two end gate lift cylinders.

Photo A9. End gate lift cylinder.

Wheels

The wheels are only needed when traveling off snow. Plug them in if needed and lower them down to travel. Leave them in the full up position for operation. Photo A10 shows the wheels in the up position used in normal operation.

Photo A10. Wheels in the up position.

Miller drum drive motor

The miller drum can spin in either direction. During normal operation, the top of the drum spins toward the front of the SnowPaver. This makes the snow slam down in front of the drum and sometimes forces it to get cut more than once. It is obvious when the drum turns the wrong way because snow will fly all over like a mini snow storm.

During operation, the drum height is monitored by looking out the back window of the tow vehicle to see how much snow is going into the miller. If none seems to be getting there, it does not hurt to lower the paver a little in the front to send more snow back. On a really hard surface, there may not be much snow going through the miller.

When too much snow gets into the miller, it can stall. To get it running again, raise the rear of the paver (lower the pan); and let the snow clear out of it. It will be difficult to run the miller efficiently if there is too much loose or fresh snow on the road. In this case, just leave it off and use only the vibrator. Once the snow is compacted, use the miller again.

Sometimes when the miller stalls, it is necessary to put it into reverse to get it cleared. This is OK; but when doing so, let the drum stop and come to rest for a few seconds before turning it the other way.

When parking for the night, always make sure snow is cleared out of the miller so it does not freeze up. Just turn it on either forward or reverse with the vehicle stopped to clear out the snow. The drum can be turned with a pry bar if it gets frozen. The pan should also be lifted when parking to keep it from freezing down. Photo A11 shows the motor that turns the miller, and Photo A12 is the miller drum showing the cutting teeth. These teeth should be inspected occasionally as they can get bent. This usually happens when something big like a rock is hit during operation, so this probably is not an issue in Antarctica.

Photo A11. Miller drive motor.

Photo A12. Miller drum and cutter bars.

Vibrator

The vibrator can be left on for all operations. It is best to turn it off when not moving. This system will always help to gain optimum compaction, especially in soft snow. It works best if the snow is not allowed to set up for long before vibrating it. The more weight there is on the pan, the better it works. For cases where compaction is important, turn off the miller and raise the rear of the paver all the way up, transferring weight to the pan. This is best if there is a lot of soft snow. Compact the soft snow once with the vibrator. Then go back and run the miller and vibrator over it a second time for best results. Operating on ice is ineffective and puts excessive force into the pan; just turn it off in surface-ice conditions.

As mentioned earlier, the vibrator motor is designed to run in only one direction. There is a directional control valve in it to keep it from running backwards. Photo A13 is a side view of the pan, and Photo A14 shows the location of the actual hydraulic vibrator. It is located inside a steel tube with a lid on it to keep snow out of the unit.

Photo A13. Vibrating pan.

Photo A14. Vibrator cover.

Other items

The manufacturer's manuals for the Cummins Diesel engine have been given to the Vehicle Maintenance Facility (VMF). The motor requires scheduled maintenance as laid out in those manuals.

There are all sorts of valves, hoses, and hydraulic motors on the system. They do not need to be adjusted under normal use.

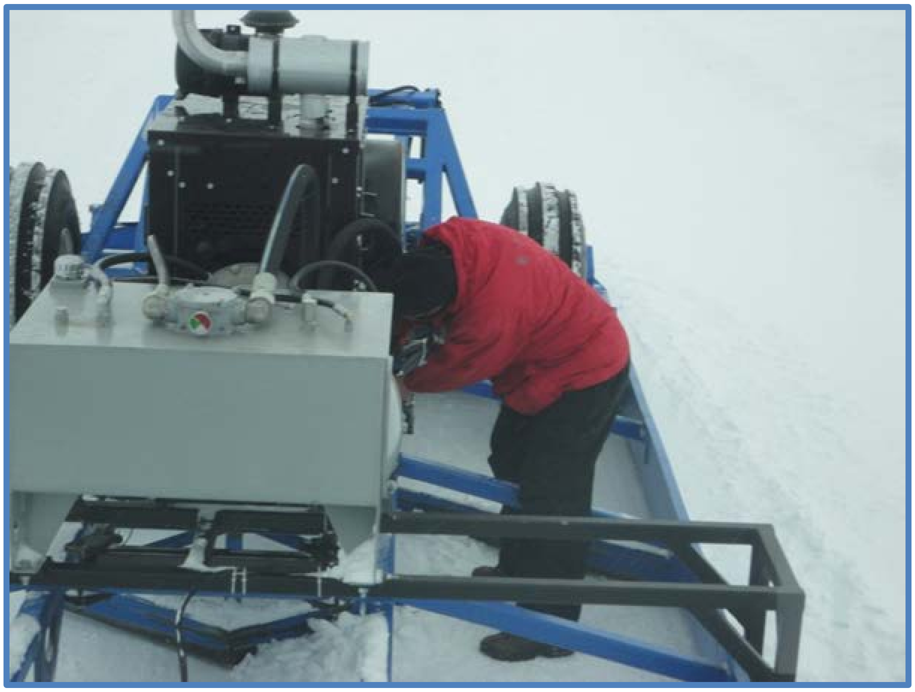
Fuel for the SnowPaver engine is diesel. A large fuel tank (approximately 200 L [50 gal.]) is located on the SnowPaver. To keep the weight of the entire system down, it is probably best to only fill it half full. Photo A15 shows this tank. Fuel usage will have to be monitored over the next season to determine fuel consumption.

Photo A15. Fuel tank.

Photo A16 shows the hydraulic reservoir for the system. This contains approximately 40 gal. (0.151 m^3 or 0.151.4 L) of low pour hydraulic fluid. It is not full because the oil tends to splash out of the breather a little when it is entirely full. There is an oil level gauge on the tank. It should be kept a little below the full mark. There is also a thermometer on the tank. While operating the system in McMurdo, the temperature of the oil stayed in a good operating range. This temperature should be monitored occasionally, however, especially when air temperatures are high. If the hydraulic fluid gets above 70°C (160°F), watch it carefully. At 80°C (180°F), the miller and vibrator should be turned off and the system put into an idle mode until the oil is allowed to cool. The oil used in this system is the standard low pour hydraulic oil used in Antarctica. Use the same rules for this oil as are used in other vehicle systems.

The oil filler cap is on top of the tank and there is a filter in the tank under the large cap on top of the tank. The oil being used is new (first used in November 2012) and should be clean. It might be appropriate to put a new filter (available from the VMF) in before the 2013–14 season and to inspect the filter that is taken out. This will give an idea of how much dirt has been collected by the filter and how long the new one should last. It should be OK almost indefinitely.

Photo A16. Hydraulic oil tank.



Starting the engine

The system has two block heaters and a battery box heater on the unit. These are located under the diesel engine, under the hydraulic tank, and around the battery. There is a single AC plug on the unit that runs these when it is plugged into shore power. To date, there has not been an issue starting it without being plugged in, even down to −30°C (−22°F).

Before starting, check the oil, make sure all of the system switches are off on the control box (Photo A2), check fuel level, and make sure everything (including yourself) is clear of moving parts.

The battery is charged by the system. It is used to start the motor and to run the valves and switches.

The controls for the motor are behind a small door on the starboard side of the motor as shown in Photos A17 and A18. Behind this door are the ignition switch, four gauges, a start light, and a “Permit Start” button. Oil pressure is normally above 50 psi (345 kPa) when running, voltage above 12 volts, and temperature around 93°C (200°F) when it is warmed up. The speed is controlled with a governor. The motor will idle low until a load is introduced (a component is used). Setting at about 1500 rpm seems to be a good place to start. It will run up to 2000 rpm under heavy load. The throttle is located on the side of the engine cover to the right of the control door. It is a threaded knob that raises and lowers the engine speed. It can probably just be set and left in one position.

There are starting instructions printed on the door. To start, turn the key to “On.” Push the “Permit Start” button, and the orange light will come on. Hold the button in until the light goes off, and continue to hold it in while cranking the motor over. Turn the key to the “Start” position to crank the motor. Keep cranking for as much as 30 seconds. If it fails to start, repeat the process.

Photo A17. Gauges and starting components.

Photo A18. Starting instructions.

General observations

The following are some general observations made during the configuration and the initial running of the SnowPaver:

- Cutting the loose surface snow with the miller blades helps to mix it up and to sinter.
- Make sure the pan is supporting at least some weight for compaction. Look for a little light out the back side of the drag (near the end gate hinge).
- Raise the rear of the drag (pan down) if too much snow piles up in it.
- Adjust cut depth with the front of the drag (raise the hitch point).
- A 16 kph (10 mph) speed seems to be a good. A little faster is OK but slow is better when trying to patch blowouts.
- The SnowPaver body can be lowered all the way down to move big volumes of snow like a scraper. The end gate could be totally closed when doing this also.
- Vibration is ALWAYS good. Putting all the weight on the pan by lifting the paver frame off the surface and vibrating is good, especially in soft snow.

- The miller is very useful, also, even if only a small amount of snow goes through it.
- Lifting the paver all the way up helps to avoid windrows on sharp turns.
- Grease the vibrator every 50 hours of operation or so. There are other grease fittings on the unit also that should be greased whenever the diesel motor is serviced.
- Adding layers of fresh snow on top of the previously groomed road will build a thicker pavement. This is good. Remember it takes a day or more for the sintering process to produce a strong pavement.

SnowPaver maintenance

The engine on the SnowPaver should have routine maintenance done on a schedule to be determined by fleet operations personnel at McMurdo. Whenever the unit is brought in for maintenance, the moving parts on the paver should be greased at all grease fittings. A walk around to look for broken or cracked welds would also be beneficial to avoid any major breaks. Hoses and couplings should be checked for leaks or seeps.

Before winter storage, the unit should be winterized in the same manner as other motors in McMurdo. The engine could be covered with a tarp if that is deemed appropriate. There is really no other maintenance needed for storage.

Parts list

KUNDINGER FLUID POWER
50 years 1961-2011

2441 Progress Ct
Neenah, WI 54956
Phone: 920-720-5000
Fax: 920-720-5010

QUOTATION

Order Number	
1149818	
Order Date	Page
9/22/2011 09:09:10	1 of 3

Quote Expires On9/29/2011

Bill To:
MICHIGAN TECH UNIVERSITY
ACCOUNTS PAYABLE
1400 TOWNSEND DRIVE
HOUGHTON, MI 49931-1295

906-487-2510
Attn: TRACY WOOD

Ship To:
MICHIGAN TECH UNIVERSITY
ACCOUNTS PAYABLE
1400 TOWNSEND DRIVE
HOUGHTON, MI 499311295

Requested By: Mr. RUSS ALGER

Customer ID: 101394

PO Number	*Ship Route*	*Taker*
Hydraulic Components		KVANEPEREN

Quantities Ordered	Allocated	Remaining	UOM / Unit Size	Disp.	Item ID / Item Description	Pricing UOM / Unit Size	Unit Price	Extended Price
1.00	0.00	1.00	EA / 1.0		PD100PS01SRS5AC00T00H0000 / 100 CC PISTON PUMP	EA / 1.0	3,237.8500	3,237.85
Required Date 9/23/2011								
1.00	0.00	1.00	EA / 1.0		PD018PS01SRS5AC00E1200000 / 18 CC PISTON PUMP	EA / 1.0	1,176.5600	1,176.56
Required Date 9/23/2011								
1.00	0.00	1.00	EA / 1.0		BVAL40NSS2VA / HIGH PRESSURE BALL VALVE	EA / 1.0	443.4650	443.47
Required Date 9/23/2011								
1.00	0.00	1.00	EA / 1.0		BVAL16SSS2VA / HIGH PRESSURE BALL VALVE	EA / 1.0	127.6550	127.66
Required Date 9/23/2011								
1.00	0.00	1.00	EA / 1.0		AD03HP052S/C / Aluminum Valve Manifold	EA / 1.0	335.0000	335.00
Required Date 9/23/2011								
1.00	0.00	1.00	EA / 1.0		AD08HP035S/C / Aluminum Valve Manifold	EA / 1.0	854.0000	854.00
Required Date 9/23/2011								
1.00	0.00	1.00	EA / 1.0		RAH101K30V / RELIEF VALVE	EA / 1.0	53.5000	53.50
Required Date 9/23/2011								

KUNDINGER FLUID POWER
2441 Progress Ct
Neenah, WI 54956
Phone: 920-720-5000
Fax: 920-720-5010

QUOTATION

Order Number	
1149818	
Order Date	Page
9/22/2011 09:09:10	2 of 3

Quote Expires On9/29/2011

Quantities Ordered	Allocated	Remaining	UOM Unit Size	Disp.	Item ID Item Description	Pricing UOM Unit Size	Unit Price	Extended Price
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1.00	0.00	1.00	EA 1.0		AD03D08VAAB Aluminum Valve Adaptor	EA 1.0	165.0000	165.00
Required Date	9/23/2011							
2.00	0.00	2.00	EA 1.0		D1VW009CVJC DIRECTIONAL CONTROL VALVE	EA 1.0	313.3900	626.78
Required Date	9/23/2011							
5.00	0.00	5.00	EA 1.0		D1VW004CVJC DIR CNTRL SOL OPER V	EA 1.0	313.9950	1,569.98
Required Date	9/23/2011							
1.00	0.00	1.00	EA 1.0		D61VW004C4VJC DIR CNTRL SOLENOID VALVE	EA 1.0	819.7750	819.78
Required Date	9/23/2011							
4.00	0.00	4.00	EA 1.0		CPOM2DDN MAN PILOT CHECK	EA 1.0	253.4950	1,013.98
Required Date	9/23/2011							
1.00	0.00	1.00	EA 1.0		BK227 BOLT KIT	EA 1.0	56.9850	56.99
Required Date	9/23/2011							
3.00	0.00	3.00	EA 1.0		BK209 BOLT KIT	EA 1.0	18.3400	55.02
Required Date	9/23/2011							
4.00	0.00	4.00	EA 1.0		BK243 BOLT KIT	EA 1.0	72.0500	288.20
Required Date	9/23/2011							
2.00	0.00	2.00	EA 1.0		N400S NEEDLE VALVE	EA 1.0	32.0650	64.13
Required Date	9/23/2011							
					15 WORK DAY LEAD			

QUOTATION

KUNDINGER FLUID POWER
50 years 1961-2011

2441 Progress Ct
Neenah, WI 54956
Phone: 920-720-5000
Fax: 920-720-5010

Order Number	
1149818	
Order Date	Page
9/22/2011 09:09:10	3 of 3

Quote Expires On9/29/2011

Quantities: Ordered	Allocated	Remaining	UOM / Unit Size	Disp.	Item ID / Item Description	Pricing UOM / Unit Size	Unit Price	Extended Price
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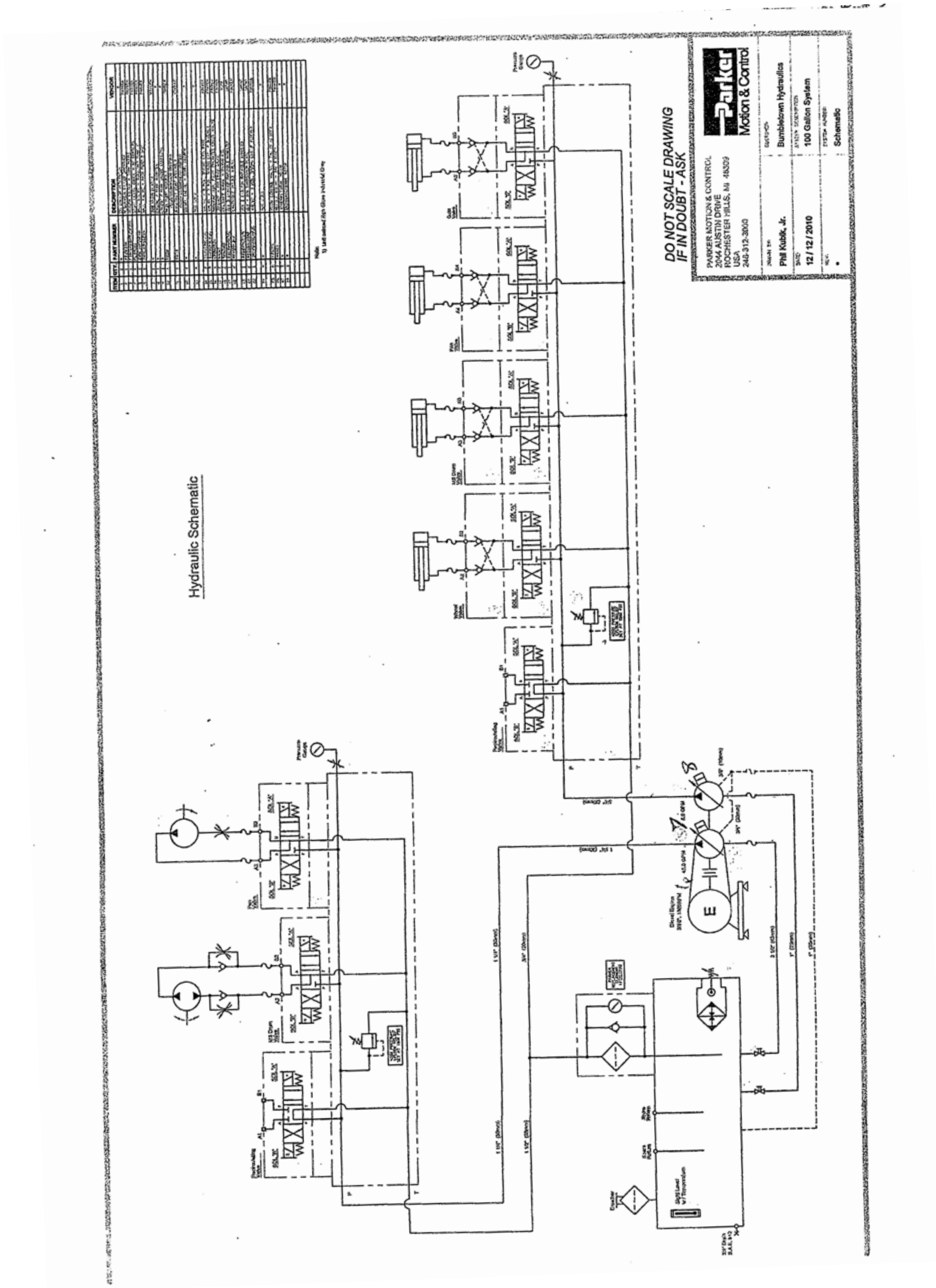
Required Date	9/23/2011							
1.00	0.00	1.00	EA / 1.0		N820S / NEEDLE VALVE	EA / 1.0	52.6350	52.64
Required Date	9/23/2011							
2.00	0.00	2.00	EA / 1.0		9767150 / 213.53-2.5(0-3000PSI)1/4LM	EA / 1.0	30.2000	60.40
Required Date	9/23/2011							

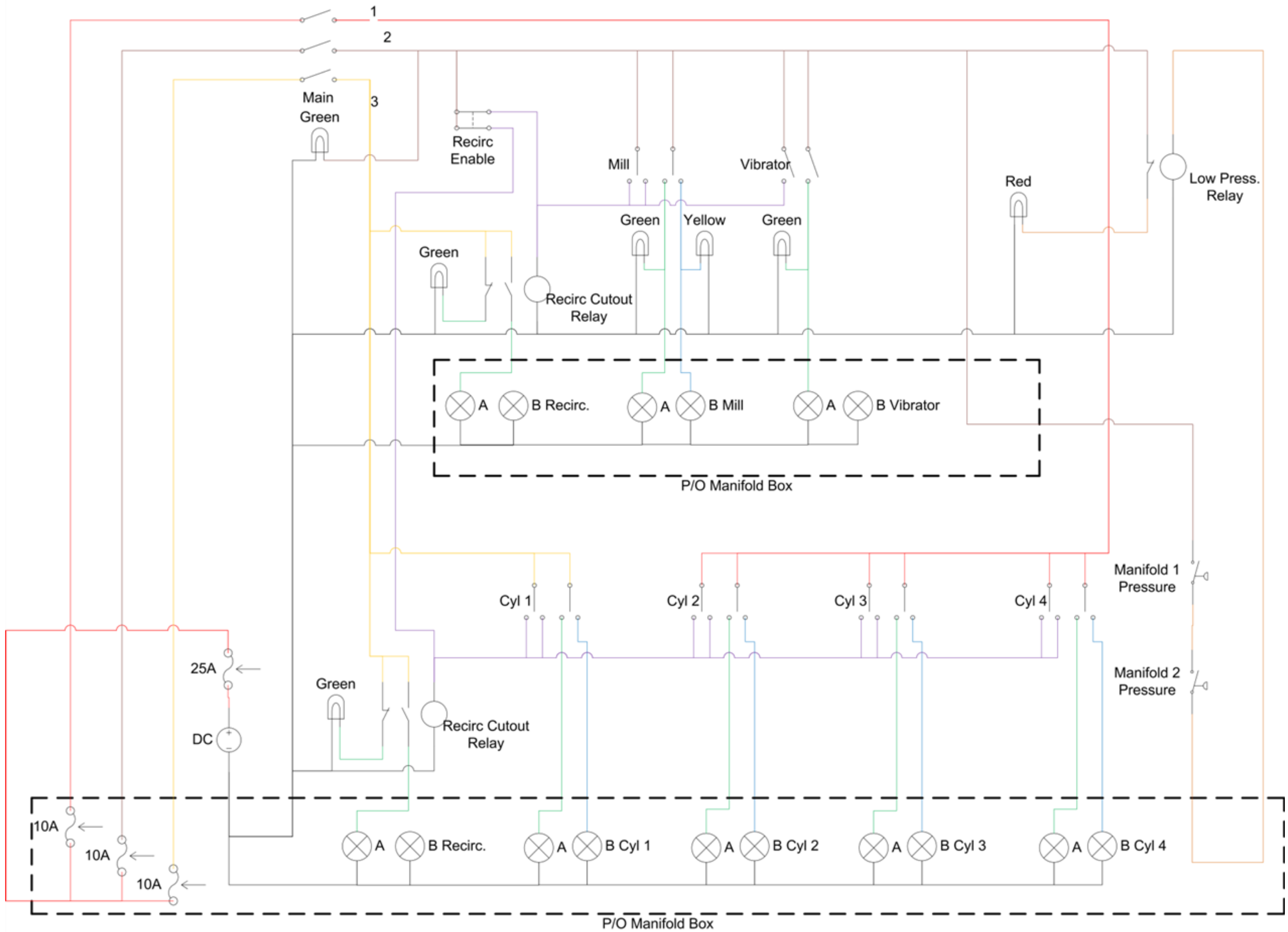
Total Lines: 20

SUB-TOTAL:	12,358.35
TAX:	0.00
AMOUNT TENDERED:	0.00
AMOUNT DUE:	**12,358.35**

Hydraulic and system schematics



Groomer Control Electrical Diagram



Appendix B: 2012 SnowPaver Upgrade and Testing

Russ Alger and Joel Kunnari, Keweenaw Research Center

Michigan Technological University. Houghton, MI

Introduction

CRREL contracted KRC under Contract # W913E5-11-C-0001 to continue testing and development of the snow processing technology known as the "Keweenaw SnowPaver." The first prototype unit was manufactured and shipped to McMurdo Station in October of 2010. Testing was performed in Antarctica on this piece of equipment, and required modifications were identified. A report is available that outlines this initial work (Alger 2010).

The SnowPaver was modified by adding a self-contained hydraulic power pack, which was built and shipped to McMurdo in October 2012. This unit was installed and tested in November 2012.

This appendix documents the development and manufacture of the power pack, the installation of the unit onto the SnowPaver, and subsequent testing performed with the upgraded paver at McMurdo Station during November of 2012.

Power-pack development

Testing during the 2010–2011 and 2011–2012 seasons at McMurdo showed that the SnowPaver equipment could be beneficial to the Antarctic programs in several different ways. The miller and compactor were capable of developing a snow pavement layer over soft snow. The SnowPaver also worked to smooth roads and runways, and hard snow pavements could be developed quite rapidly. This testing also pinpointed some shortfalls with the system. The largest issue in using the paver was that the tractors used to tow the paver did not have a power take off (PTO) or enough on-board hydraulic power to run the miller efficiently. With this knowledge, it was decided to design and build a self-contained hydraulic power pack to supply full power to the unit.

Using previous experience with the SnowPaver to estimate how much power it would take to turn the miller efficiently in operation, KRC designed a power pack. This unit was developed to make the paver a self-contained system, not only to run the miller, but also to operate all of the systems using this power pack and with the flip of a switch. There were seven system functions that needed to be powered: miller rotation, vibrator, miller (up/down), pan (up/down), gate (up/down), wheels (up/down), and front of paver (up/down). When the SnowPaver arrived in McMurdo in 2010, no PTO equipped vehicle was available. A Challenger tractor with four hydraulic connections was the best vehicle available to tow the SnowPaver.

Once the SnowPaver was hooked up to the hydraulics on the Challenger, only four of the SnowPaver functions could operate at a time. The lifting of the front of the paver is done by a three-point hitch (Photo B1) on the tractor. This uses one of the four hydraulic lines available. The other six functions shared the remaining three hydraulic connections. So, to operate the other systems, hoses needed to be plugged and unplugged on the tractor when one or more different functions were needed. This was very inefficient and made it difficult to adjust the operation of the unit.

Photo B1. Three-point hitch.

The new system was designed so that all of the components could be operated simultaneously. This was accomplished by configuring the hydraulics so that all of the individual components were connected and could be turned on and off by switches on a control box located in the cab of the tractor. This box was connected to the groomer by a wire running from the SnowPaver through the wire port on the tractor into the cab. In the future this may be accomplished wirelessly, but for now the wire was the easiest way to make the connection. Photo B2 shows the layout of the control box.

Photo B2. Control box.

The hydraulic power pack was designed to be mounted on the SnowPaver at McMurdo. This posed several interesting difficulties to the development of the unit. First, with the paver sitting in Antarctica, some of the dimensioning needed to be done remotely. This was accomplished fairly easily with emails back and forth with winter crews. Another issue was the fact that the original SnowPaver was not designed to have a relatively heavy power pack sitting on its frame. The weight of the power system was therefore kept to a minimum, approximately 910 kg (2000 lb), including fluids. We estimated that structural reinforcements to the SnowPaver frame would not be needed but could be added later if required.

The power-pack unit was built and mounted on a frame that was designed to sit on top of the existing framework of the paver. The power pack consisted of a 75 HP Cummins Turbo Diesel motor. Attached to this motor were two variable displacement pumps that provided the flow and pressure to operate the miller and components. The larger of the two pumps was a 100 cc piston pump that was dedicated to the miller and vibrator. The other, smaller pump was 18 cc and ran all of the other attachments. Each implement was controlled through a solenoid valve. Figure B1 is a schematic of the system.

Figure B1. System schematic.

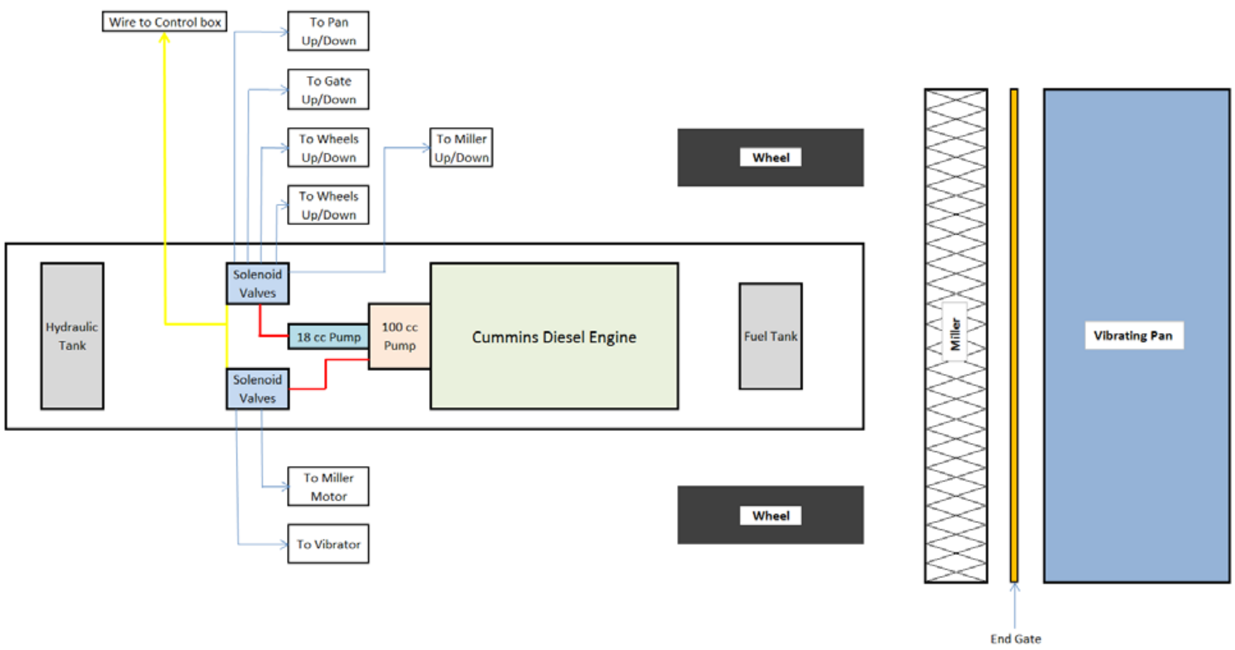
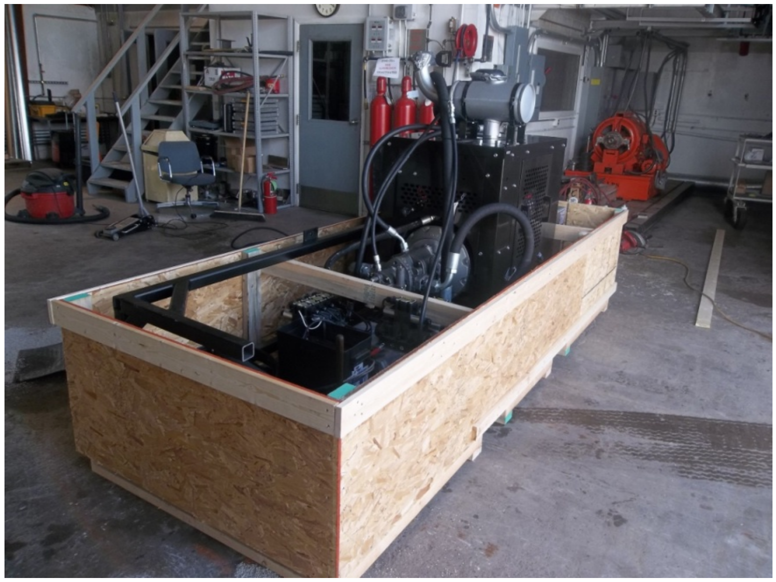


Photo B3 is the unit ready for shipment. The frame that the unit was installed on was 244 cm (96 in.) long by 69 cm (27 in.) wide. The height to the top of the engine enclosure was 102 cm (40 in.), and the maximum height to the top of the exhaust pipe was 145 cm (57 in.).

Photo B3. Power pack ready for shipment.



Power-pack installation

The power-pack unit was shipped to McMurdo in October 2012. Russ Alger and Joel Kunnari from KRC travelled to the ice on 2 November 2012 to install the unit on the SnowPaver and to test its operation by producing snow pavement test sections.

First, to install the power pack, some of the SnowPaver's existing components were removed. The old hydraulic tank and a pan that held hoses were removed (Photo B4). The unit was then lifted onto the upper framework of the paver (Photos B5 and B6). This operation was successful in the realization that the SnowPaver framework had sufficient strength to support the power pack. In fact, there was no sag in any of the frame components after installation. Additionally, testing in the field on some very rough surfaces showed no component stress.

A new hydraulic tank was also installed. It was placed on a set of legs that straddled the SnowPaver frame and was supported by the side rails of the SnowPaver. Photo B7 shows this. The frame, tank, and 40 gal. of oil weighed about 270 kg (600 lb).

Photo B4. Tank removal.

Photo B5. Unit ready to install.

Photo B6. Unit installation.

Photo B7. Hydraulic tank setup.

With these modifications, the SnowPaver has a total weight of approximately 5270 kg (11,600 lb). This consists of 4090 kg (9000 lb) for the original SnowPaver plus 910 kg (2000 lb) for the power pack and 270 kg (600 lb) for the hydraulic tank with oil. The pan is approximately 305 cm (10 ft) long by 91 cm (3 ft) wide and provides that amount of contact with the snow.

After the installation of the power pack was completed, all of the hoses were connected to the appropriate solenoid valves and the unit was filled with oil. The system was bench tested in the VMF at McMurdo to make sure that all of the systems worked properly. Photos B8 and B9 show some of the hydraulic lines on the power pack. The SnowPaver was then reconnected to the Challenger tractor tow vehicle.

Photo B8. Hydraulic hookups on the right side of the SnowPaver.

Photo B9. Hydraulic hookups on the left side of the SnowPaver.

Testing and results

The SnowPaver with the new power-pack unit was tested under several different scenarios on the ice shelf. First, it was run to be sure that all systems were operating correctly and to adjust the flows to various components. This was accomplished on the road to the LDB facility. Photo B10 is the SnowPaver at the LDB pad. Photo B11 shows the road layout on the ice shelf and the location of some of the areas tested.

Overall, the installation was a success. It was easy to operate all of the functions on the SnowPaver, and it was very efficient to operate without having to change hoses from one function to another. There was plenty of power to operate the miller, the vibrator, and other hydraulic cylinders.

Photo B10. SnowPaver.

Pegasus Road

Several times during operation of the paver, sections of the road to the LDB pad and Pegasus Road were groomed to knock down drifts and to establish a smooth compacted layer of snow on the road. These tasks showed that the SnowPaver worked well at speeds of 10 mph and more to smooth the surface and were used to train some of the McMurdo fleet staff on the operation of the unit.

Strength measurements were taken on the Pegasus Road near MP 6 on 20 November 2012. These measurements were performed as baseline strengths for the test lanes that were developed using the SnowPaver. Figure B2 is the tip dimensions for the KRC Rammsonde used for this testing. Figure B3 contains the specifications and equation used. Additional data is provided at the end of this appendix, including Rammsonde data in tabular form and Clegg strength measurement data taken at several locations during the test period. Figure B4 is a graph of Rammsonde values taken on the Pegasus Road near MP 6. The graph contains additional test data to be discussed later.

Figure B2. Rammsonde dimensions.

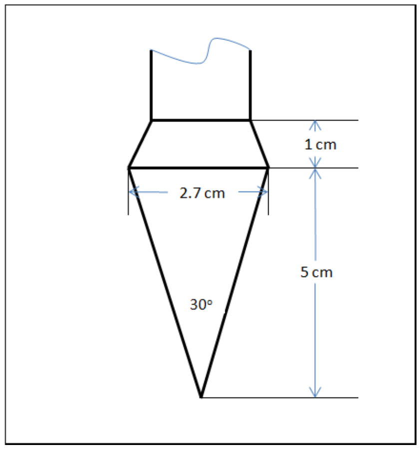


Figure B3. Rammsonde specifications and calculation.

W = wt of hammer = 1 kg

h = drop height = 30 cm

Q = penetrometer weight = 1.08 kg

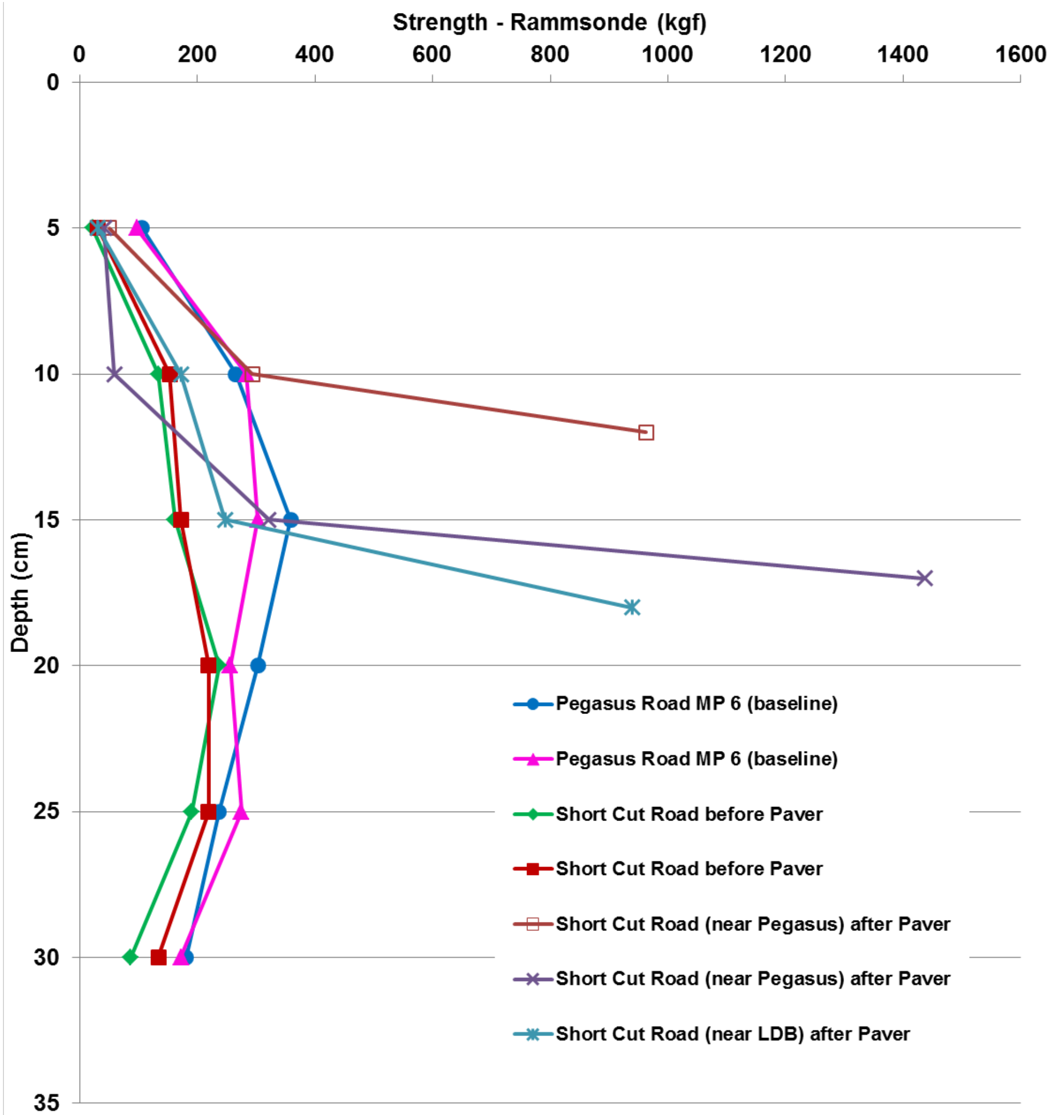
n = number of drops

x = Sinkage

R =1.56*(((W*h*n)/x) + W + Q)

$$R = 1.56 \cdot \left(\frac{W \cdot h \cdot n}{x} + W + Q \right)$$

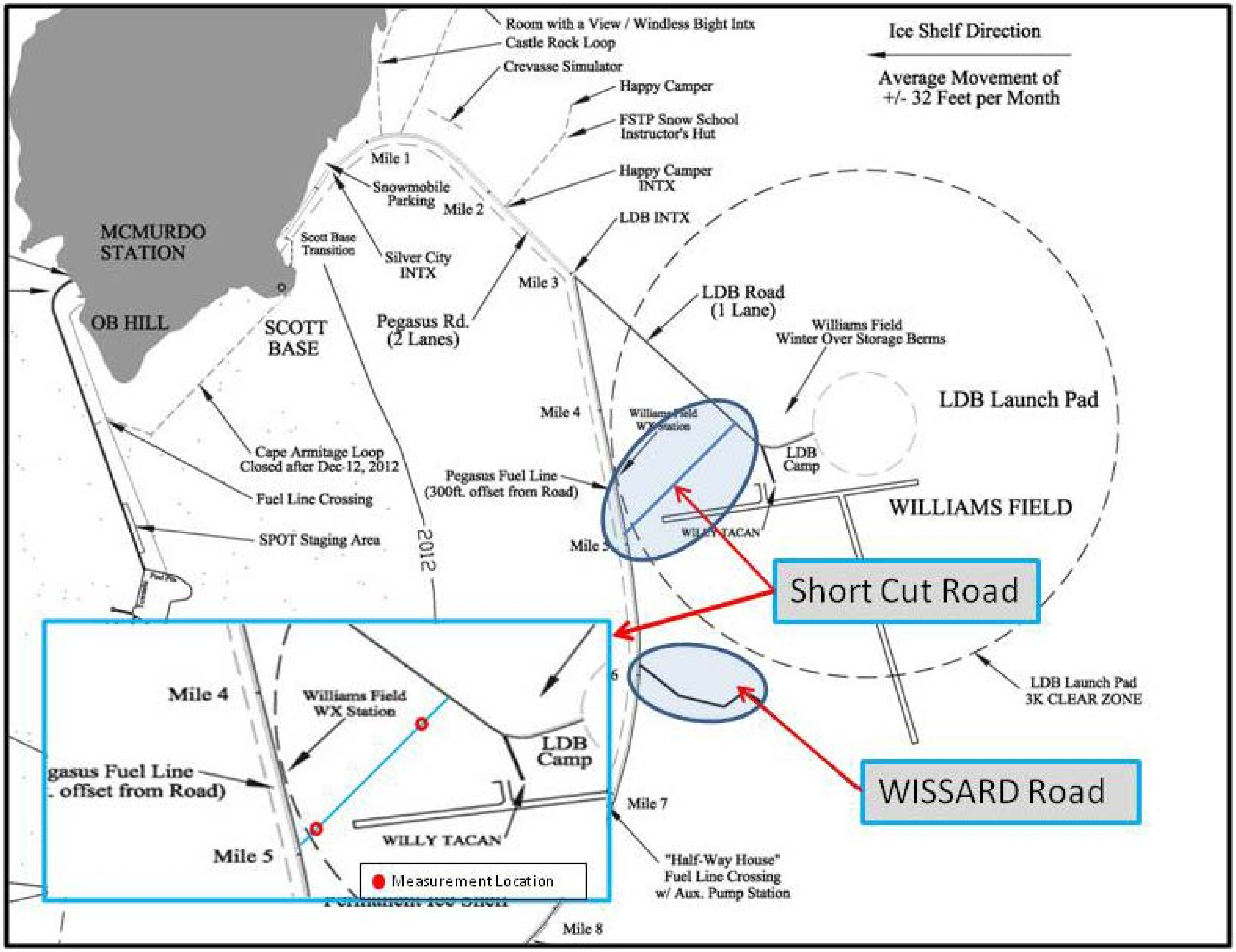
Figure B4. Rammsonde values at the Short Cut Road and MP 6 (November 2012).



Short Cut Road

A test road was developed between the LDB Road and Pegasus Road. This short road section was about one mile long and ran from the LDB Road to about MP 6 on Pegasus Road. It was designed to be a shortcut when running back and forth between the LDB pad and the Pegasus runway. For purposes of this report, this section is called the "Short Cut Road" and is shown on Figure B5.

Figure B5. Ice shelf road layout, test site and Rammsonde measurement locations.



This road section had been prepared using the sheepsfoot roller and light weight cart prior to the work with the SnowPaver. It is unknown how many passes were made, but the road was still relatively soft when the paver work was started. On 15 November, a set of Rammsonde measurements was made on the road prior to the use of the SnowPaver. Figure B4 includes these measurements. The results were slightly lower than the measurements taken at MP 6 on Pegasus Road. They showed a drop in strength at about 25 cm (10 in.) as compared to MP 6.

On 15 November, the road section was groomed with the miller and vibrator running. The operation of both of these functions was easily accomplished with the new power pack. Depth of milling was between 2 and 3 in. Full coverage of six passes over the approximately a 23.6 m (50 ft) road width was made in each direction. This full coverage of the road was accomplished twice. The road was then allowed to set up for 24 hours. On 16 November, the operation was repeated without the miller. The road had been covered with drift snow, and this snow did not appear to need milling. It was already fine grained and susceptible to bonding. The unit was run with the blades and vibrator only. This pass added to the road a new layer of approximately 2 cm (0.8 in.). On 17 November, two full coverages were again made over the road with the vibrator running, adding a layer of approximately 3 cm (1.2 in.). The Short Cut Road was not groomed with the paver after this.

After the Short Cut Road was groomed with the SnowPaver, it was trafficked by several of the snow-road maintenance vehicles, including drags, using it as a short cut to the Pegasus Road. Rammsonde measurements were made at two locations along the Short Cut Road on 20 November 2012: two measurements near the Pegasus Road and one measurement at the other end of the Short Cut Road near LDB (Figure B4). On 20 November 2012, the snow temperature at a 5 cm (2 in.) depth was −9°C (16°F). Several inches of loose and drifting snow had accumulated since the SnowPaver had processed the road three days before.

For all three Rammsonde measurements, the strength profiles show that there was a very hard layer present in the lane where the SnowPaver was used. This layer had strength of around 1000 R. The 1000 g (2.2 lb) hammer at a 30 cm (11.8 in.) drop was unable to penetrate the layer. The penetrometer just bounced with no penetration. The layer was broken through using a pointed pry bar and found to have a thickness of 3 to 4 cm (1.2 to

1.6 in.) in the areas tested. No Clegg measurements were made on 20 November due to soft snow on the surface.

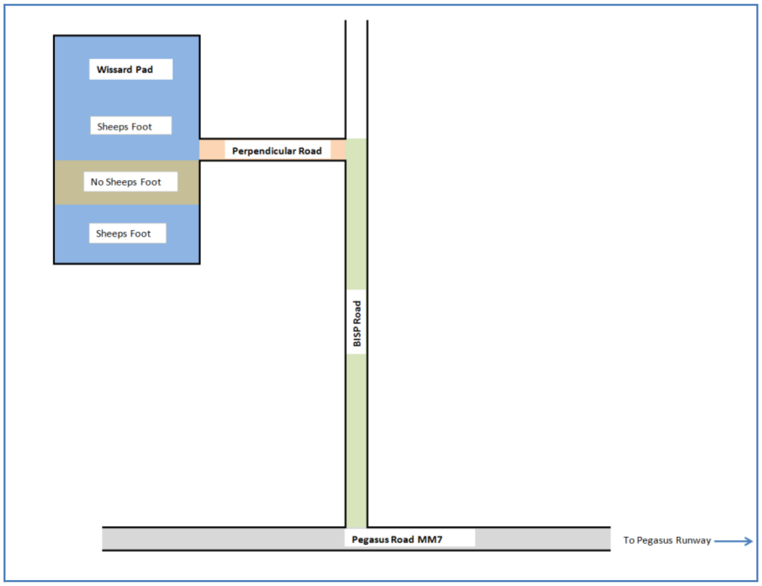
Looking back to Figure B4 and the Rammsonde data collected on the Short Cut Road, the SnowPaver's use resulted in significantly higher strength than the baseline readings taken before the SnowPaver was used. Equally interesting, the SnowPaver's use on the Short Cut Road also produced strengths much higher than occurred on a nearby location along the Pegasus Road at MP 6, which was maintained using the traditional snow-road building methods (without a SnowPaver).

WISSARD Pad

On 17 November, an area along the new Black Island/South Pole (BISP) Road and at approximately MP 7 on the Pegasus Road was set up as a shake-down drill equipment testing area for the WISSARD (Whillans Ice Stream Subglacial Access Research Drilling) project. This area was a short road section, about 2000 m (1/8 mile) long along the BISP trail, another short road perpendicular to it, and a large snow pad about 1500 m (500 ft) long by 900 m (300 ft) wide. Figure B6 shows the configuration of the roads and pad. Alger and Kunnari were asked to aid in the process of setting the area up for vehicles and equipment to be moved in. Some work was accomplished with the SnowPaver in this area, but WISSARD crews took over with their own equipment and started moving drilling equipment into the area before the roads and pads could be completed. Some results were obtained with limited time working on the area.

These areas were covered with a single pass of the sheepsfoot roller prior to work with the SnowPaver, except for one strip about 23.6 m (50 ft) wide by 900 m (300 ft) long extending across the pad. This strip was used to compare the use of the sheepsfoot to areas that were not rolled first. The roller was used on 16 November, and the sections were then allowed to set up for 24 hours. On 17 November, after operation of the paver on the Short Cut Road, the entire surface of the two road sections was covered using the SnowPaver. The pad was covered lengthwise for one full coverage and then again crosswise with the miller off. This operation was made to try to smooth the surface of the pad since it was quite rough after the coverage with the sheepsfoot roller. The area was allowed to set up for 24 hours. On 18 November, the area was again groomed in both directions with the miller. At this time, it was realized that the vibrator was not working. The diagnosis of this problem is explained in a later section. Thus, the second grooming of the area was completed without the vibrator. After the Sunday, 18 November, grooming, this area was not groomed by the SnowPaver again. The WISSARD crews started to set up and practice with their equipment at this time.

Figure B6. WISSARD pad layout

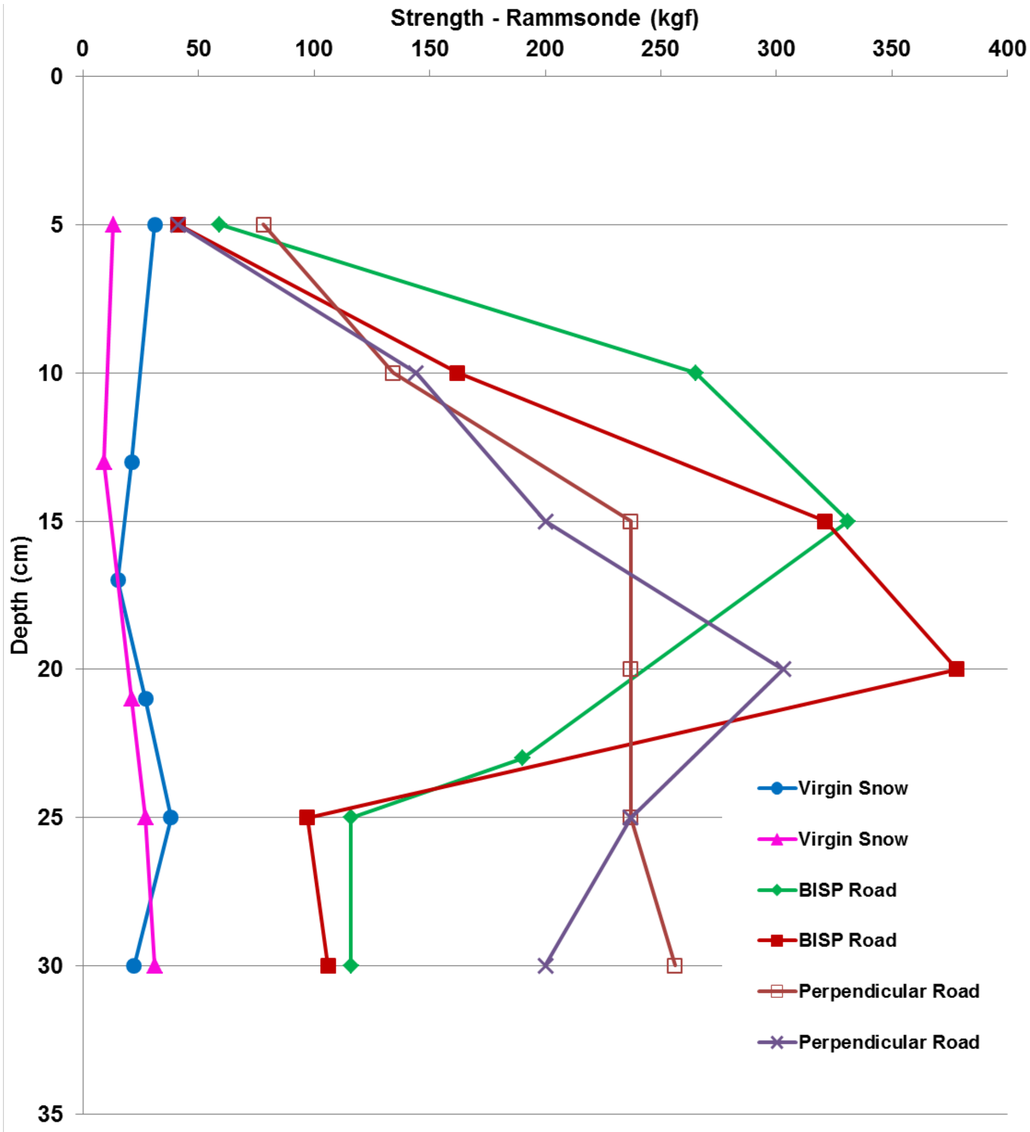


On 20 November, some strength measurements were made on the areas around the WISSARD Pad. Snow temperatures at 5 cm (2 in.) depth were between −9°C and −11°C (16°F to 12°F) at this time. Figure B7 contains Rammsonde measurements for the virgin snow in the area around the site. As expected, strengths are quite low in untrafficked and ungroomed areas.

Figure B7 also contains strength plots taken on the two road sections. Tabular data and Clegg measurements in this area are presented at the end of this appendix. This data shows some interesting trends. First, there appears to be an influence from previous tracking of the BISP road by the traverse vehicles moving across it. The strength on this section is slightly higher than it is on the perpendicular road. The thickness of the strong layer is less here, however. This is probably due because both the sheepsfoot and the vibrator could penetrate further in the virgin snow than in the area that already had some strength. Further work in this area with the paver would likely have built on the two layers as different thicknesses. In any event, strengths were starting to get to trafficable values in both of these areas. This was accomplished without the vibrator on the second coverage. Use of the vibrator and more time to work on these sections should have resulted in a road similar to the Short Cut Road.

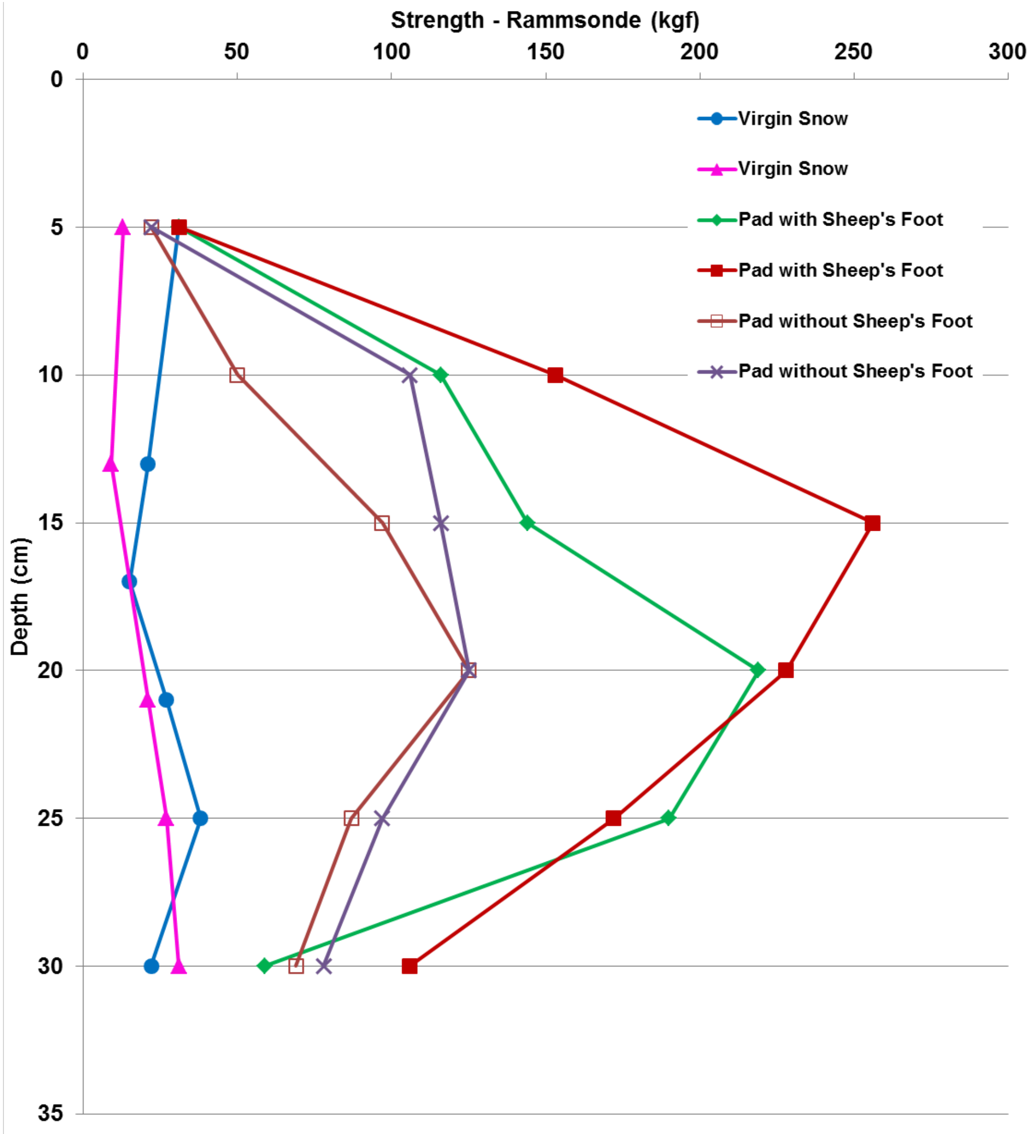
Figure B7 also shows the increase in strength over the virgin snow and a slight increase between the road section that had tractor and sled traffic prior to grooming and the perpendicular road, which had only been covered with the sheepsfoot and the SnowPaver. This strength difference is also shown by the Clegg data.

Figure B7. Rammsonde values on road sections at WISSARD (20 November 2012).



The section that was laid out for the pad was covered by the SnowPaver in both directions on two occasions. The strength values for this section are plotted in Figure B8 and also tabulated later. These strength values are in line with the measurements on the perpendicular road with one special note. It does appear that the area covered by the sheepsfoot roller prior to the use of the SnowPaver is stronger. It is likely that a single pass of the sheepsfoot roller may provide an advantage when building a new road. This strength difference is also shown by the Clegg data. This will be discussed again in the next sections.

Figure B8. Rammsonde values on the pad at WISSARD (20 November 2012).



Other observations

On 19 November, Joel Kunnari returned to Michigan. Russ Alger took the inoperable vibrator apart and found that the cover plate bolts had backed out. It appeared that the bolts had never had thread lock put on them at the factory, and there were no lock nuts on the bolts. This problem was fixed, and the vibrator was operational again. The broken vibrator is shown in Photo B11.

Photo B11. The broken vibrator.

During operation of the SnowPaver, road maintenance operators noted that there was snow escaping between the miller and the vibrating plate compactor, producing a windrow as it was deposited. To counter this, side plates were welded onto the drag to eliminate windrow formation. This operation worked well, and Photos B12 and B13 show the side panels.

Photo B12. Side panel installation.

Photo B13. A side panel.

Conclusions

Alger and Kunnari successfully completed the installation of the power-pack unit onto the SnowPaver in McMurdo during November 2012. The unit was then tested, and test sections were groomed using the equipment. This testing proved several things:

1. The power pack started and ran well at temperatures as cold as −32°C (−25°F).
2. The SnowPaver was easy to operate.
3. All SnowPaver functions could be easily controlled from within the cab of the tractor by using the control box.
4. There was plenty of power to run the miller, the vibrator, and the hydraulic cylinders.
5. The SnowPaver produced a snow pavement of considerable strength.

On the Short Cut Road, there was a significant strength increase over the section tested on the Pegasus Road. This increase in strength was accomplished in a short period of time. It is believed that the hard layer can be improved upon with time by continued grooming of fresh snow layers. It is also believed that continued grooming during warm periods could keep the road strong. The SnowPaver develops a uniform snow layer (pavement) that should help to minimize blowouts caused by weak and underdeveloped areas in the snow road.

It was shown during previous tests of the SnowPaver that vibratory compaction can produce white ice if the unit is left sitting in one place for even a short period of time. This shows that the energy input by vibration is capable of developing very high strengths even in deep snow. At slow speeds, this increase in density followed by an increase in strength can be achieved quite rapidly even at cold temperatures.

Tests on the Pegasus Road showed the SnowPaver worked well to smooth the road and to build up the thickness of the road with subsequent passes over fresh and drifted snow. The addition of side plates eliminated any windrows from forming.

Tests on the WISSARD pad showed some interesting trends although there was not enough time to work on this section to attempt to increase the strength to the values seen on the Short Cut Road. It appears that there is a benefit to the use of the sheepsfoot roller before the paver is used, but this result comes from a single test at this location. It was observed that multiple passes with the sheepsfoot roller seem to loosen the snow into a sort of snow swamp.

Additional data

Clegg measurements are reported by taking five separate measurements at locations in close proximity to each other. The value for the third drop at each location was recorded.

Table B1. Rammsonde results at MP 6, 20 November 2012.

Pegusus Road MP 6			
Drops	Depth (cm)	Sinkage (cm)	R
11	5	5	106
28	10	5	265
38	15	5	359
32	20	5	303
25	25	5	237
19	30	5	181

Pegusus Road MP 6			
Drops	Depth (cm)	Sinkage (cm)	R
10	5	5	97
30	10	5	284
32	15	5	303
27	20	5	256
29	25	5	275
18	30	5	172

Table B2. Clegg results at MP 6, 20 November 2012.

Pegasus Road MP 6	
Run #	**Clegg**
1	15
2	18.5
3	31.7
4	17
5	16.6
Average	**19.8**

Table B3. Rammsonde results at the Short Cut Road, 15 November 2012 (after sheepsfoot and light weight cart).

Short Cut Road 11/15 before Paver			
Drops	**Depth (cm)**	**Sinkage (cm)**	**R**
2	5	5	22
14	10	5	134
17	15	5	162
25	20	5	237
20	25	5	190
9	30	5	87

Short Cut Road 11/15 before Paver			
Drops	**Depth (cm)**	**Sinkage (cm)**	**R**
3	5	5	31
16	10	5	153
18	15	5	172
23	20	5	219
23	25	5	219
14	30	5	134

Table B4. Rammsonde results at the Short Cut Road, 20 November 2012, near Pegasus Road.

Short Cut Road 11/20 near Pegasus (after Paver)			
Drops	**Depth (cm)**	**Sinkage (cm)**	**R**
5	5	5	50
31	10	5	293
41	12	2	963
Penetrometer did not move for last 10 drops			

Short Cut Road 11/20 near Pegasus (after Paver)			
Drops	**Depth (cm)**	**Sinkage (cm)**	**R**
4	5	5	41
6	10	5	59
34	15	5	321
60	17	2	1407
Penetrometer did not move for last 10 drops			

Table B5. Rammsonde results at the Short Cut Road, 20 November 2012, near LDB Road.

Short Cut Road 11/20 near LDB (after Paver)			
Drops	**Depth (cm)**	**Sinkage (cm)**	**R**
3	5	5	31
18	10	5	172
26	15	5	247
60	18	3	939
Penetrometer did not move for last 10 drops			

Table B6. Rammsonde results on virgin snow, 20 November 2012, near the WISSARD Pad.

Virigin Snow near Pad			
Drops	**Depth (cm)**	**Sinkage (cm)**	**R**
3	5	5	31
3	13	8	21
1	17	4	15
2	21	4	27
3	25	4	38
2	30	5	22

Virigin Snow near Pad			
Drops	**Depth (cm)**	**Sinkage (cm)**	**R**
1	5	5	13
1	13	8	9
3	21	8	21
2	25	4	27
3	30	5	31

Table B7. Rammsonde values, 20 November 2012, on the BISP Road near the WISSARD Pad.

BISP Road to Pad			
Drops	Depth (cm)	Sinkage (cm)	R
6	5	5	59
28	10	5	265
35	15	5	331
20	20	5	190
12	25	5	116
12	30	5	116

BISP Road to Pad			
Drops	Depth (cm)	Sinkage (cm)	R
4	5	5	41
17	10	5	162
34	15	5	321
40	20	5	378
10	25	5	97
11	30	5	106

Table B8. Clegg values, 20 November 2012, on the BISP Road near the WISSARD Pad.

BISP Road to Pad	
Run #	Clegg
1	18.7
2	16.8
3	17.7
4	10.4
5	8.5
Average	**14.4**

Table B9. Rammsonde values, 20 November 2012, on the perpendicular road near the WISSARD Pad.

Perpendicular Road to Pad			
Drops	Depth (cm)	Sinkage (cm)	R
8	5	5	78
14	10	5	134
25	15	5	237
25	20	5	237
25	25	5	237
27	30	5	256

Perpendicular Road to Pad			
Drops	Depth (cm)	Sinkage (cm)	R
4	5	5	41
15	10	5	144
21	15	5	200
32	20	5	303
25	25	5	237
21	30	5	200

Table B10. Clegg values, 20 November 2012, on the perpendicular road near the WISSARD Pad.

Perpendicular Road to Pad	
Run #	Clegg
1	10.4
2	17.5
3	13.8
4	9.7
5	16.4
Average	**13.6**

Table B11. Rammsonde values, 20 November 2012, on the WISSARD Pad after the sheepsfoot.

Pad With Sheep's Foot			
Drops	Depth (cm)	Sinkage (cm)	R
3	5	5	31
12	10	5	116
15	15	5	144
23	20	5	219
20	25	5	190
6	30	5	59

Pad With Sheep's Foot			
Drops	Depth (cm)	Sinkage (cm)	R
3	5	5	31
16	10	5	153
27	15	5	256
24	20	5	228
18	25	5	172
11	30	5	106

Table B12. Clegg values, 20 November 2012, on the WISSARD Pad after the sheepsfoot.

Pad with Sheep's Foot	
Run #	Clegg
1	9
2	7.6
3	8.1
4	9.5
5	8.6
Average	**8.6**

Table B13. Rammsonde values, 20 November 2012, on the WISSARD Pad without the sheepsfoot.

Pad Without Sheep's Foot			
Drops	Depth (cm)	Sinkage (cm)	R
2	5	5	22
5	10	5	50
10	15	5	97
13	20	5	125
9	25	5	87
7	30	5	69

Pad Without Sheep's Foot			
Drops	Depth (cm)	Sinkage (cm)	R
2	5	5	22
11	10	5	106
12	15	5	116
13	20	5	125
10	25	5	97
8	30	5	78

Table B14. Clegg values, 20 November 2012, on the WISSARD Pad without the sheepsfoot.

Pad without Sheep's Foot	
Run #	Clegg
1	8.5
2	7.1
3	6
4	5
5	7.6
Average	**6.8**

Appendix C: McMurdo Personnel Comments

Ice shelf personnel SnowPaver reviews

We asked two of the McMurdo personnel to offer reviews of their experience with the SnowPaver: Kristyn Carney, ASC, and Julian Ridley, ASC. Kristy worked extensively with the SnowPaver during the 2010–2011 season. Both worked with the Snow Paver during the 2012–21013 season. Kristy has more experience than anyone in using the SnowPaver for building snow roads at McMurdo Station.

Kristyn Carney

Kristyn Carney provided the following comments on 17 January 2013:

As of right now it has 110 hours on the hour meter.

It [The SnowPaver] usually isn't my first choice when deciding what implement to use; however, today it was! It was hot and mushy snow. The snow just balls up in the drag and goose in these conditions and ends up leaving lumpy windrows. The SnowPaver is great at leveling and packing down moist snow like this. However, when it is wet like this, sometimes the snow seems to stick to the vibrator and the snow will peel up.

I'm not crazy about the custom hitch that attaches to the Challenger. It works fine; however, you cannot see the hitch, and it makes hooking up a little more challenging. I often need another person to help. Also, to get the electronic connectors up through the hole in the cab, I have to climb up the hitch on the back of the Challenger, which can be a bit precarious at times. I am also concerned about the durability of the electronic box. The small glass power light has already broken. We are looking into getting a padded box made for it to protect it when it's not in use. Once the box breaks, the SnowPaver will become inoperable. Is there anyone here that can fix that? It also needs a "safety" step mounted near the gas tank to be able to get high enough to look into the tank to see the fuel level. I have ended up stepping on some of the hoses to check the fuel level.

I used the Snow Paver at Pegasus a few weeks ago, and the day after I used it on the taxiway the Air National Guard (ANG) asked that I drag over the

SnowPaver marks because they were unhappy with the sheen that it left and worried it would become a pool of water. I also used it on the skiway, and the surface was already very uneven. The snow paver is too narrow, and I was unable to level out the surface properly; it left a stair-step surface and the ANG was unhappy about that. We ended up having to take a goose and drag and work it sideways. However, they did like how it [the SnowPaver] hardened the surface.

[The SnowPaver] works great on the roads as far as keeping a fairly level surface level and filling in ruts and packing them. It takes 4–5 passes per lane to finish; the goose and drag usually take only 2 passes, sometimes 3, to finish a lane. Therefore, [the SnowPaver] takes longer to finish the roads. I like the cutting edge and vibrator. I try to run the miller as long as it keeps turning. I would never use the SnowPaver in a camp setting like LDB town site due to the slick nature of the finished surface. I have had several near misses slipping and falling on it. It is almost like trying to walk on the HMW (high molecular weight) sheets. The SnowPaver needs something to scratch up the final surface.

I am unsure of the endurance of the compacted surface. Two years ago, we had a test lane that I think Sally Shoop and Brett Allen did testing on with a van going over and over it. The Snow Paver hardens really fast but it is unclear how well it holds up. I feel like we might need more testing like that to truly understand its value.

Julian Ridley

Mr. Ridley provided the following comments on 18 January 2013 at the request of the CRREL researchers. He reviewed the function of each component of the paver and then summarized the equipment as a whole.

Planer

The planer cuts the snow surface at a depth decided by the operator. It can also be set to not cut at all. If cutting does occur, the cut snow is then channeled to the miller or pan.

Pros:

- Cuts and channels dry snow extremely well
- Depth of cut can be very finely tuned

- Works well on roads with minor snow drift

Cons:

- The depth of the cut is greatly affected by vertical movement of the towing tractor's hitch. For example, after a good storm, a drifted road can have drift from 1 in. thick to over 2 ft. In the deeper/steeper drift, as the tractor rises to ascend the drift, the aft hitch drops/angles lower and in turn drops the planer portion lower. Conversely, when the tractor descends the drift, the hitch (and planer) rises, reducing the cut of the surface. This directly works against efficiently creating a new flat, snow surface. Additional passes are required to "weed" out the larger drift undulations.

  I feel the goose we operate does a more efficient job of drift height reduction on storm-damaged roads (i.e., fewer passes equals less operator time, less fuel, reduced equipment hours). The SnowPaver's hitch could possibly be reworked so that the hard hitch is not directly influenced by tractor movement like the goose's hitching.

- The planer cuts through a drift and leaves a "wall" on either side of the machine's width. The wall acts like an elevated windrow and is a collection point for snow drift until the wall is "feathered" out by a Goose or otherwise dealt with (i.e., track-packing along the flag line, etc.).

- Wet snow, annually seen in late November, December, and January, clogs up the planer and does not flow to the rear miller and pan areas. The cut setting can be reduced (elevated) to avoid this, but frequently at the expense of not cutting enough material to make the pass of the wet snow section worthwhile.

- In some wet snow cases, if the snow-road surface is already relatively flat, the planer can be elevated (bypassed) and just the pan can be used to compress the mushy snow surface.

- In very tall drift areas, the planer setting needs to be quite elevated so as not to cut too much snow (to avoid excessive snow build up in the cutters) and, in turn, clogging, be it wet or dry snow. However, since drifts are typically spaced apart by *x* distance, the high-cut setting is then not low enough to cut between the drifts even after the drift cut snow has been feathered out and cleared. It is not reasonable to expect micro-management of the planer to avoid this. Possibly, though, in this situation, the intention of the SnowPaver planer design is to simply cut the "highs" until the "lows" are filled in and the surface is relatively flat—at which time even planing (cutting) can resume. However, in steep drift, see hitch issue noted above.

- At speeds around 8 mph (which is common for dragging and goosing [depending on cut setting]), the snow would fly over the edge of the implement and escape before being compacted. Possibly taller side walls would avoid this and would allow for use at this speed, otherwise significantly slower seems to be best yet takes longer.

Miller/Pulverizer

Although I operated the SnowPaver in both wet and dry snow conditions, I only used the miller in wet snow. In wet snow it is quite hard to manage how much snow is fed to the miller; it frequently clogs to the point that it stops spinning. After clearing the implement of snow (highly elevating the planer) the miller eventually will spin again. It does not work too well in wet snow or at the least requires very close awareness and management.

Pan (with optional vibratory compactor)

The pan is intended to equally distribute and compact the snow it receives from either the planer or the miller. There is an optional vibratory compactor within the pan that can be activated to further compress the snow surface.

Pros:

- Dry snow feathers out fully across the pan and appears to compact nicely (with or without the compactor) for a resulting smooth, even surface

Cons:

- Snow that is more moist or wet (typical in late November, December, and January) struggles to feather out fully across the width of the pan. As a result, the pan frequently did not distribute and compact the snow the full pan width, leaving a high spot with non-smoothed edges in the middle of the Snow Paver's travelled path. I experimented a lot with this aspect and found no consistently repeatable adjustment of implement settings to remedy it. It seems the moist snow conditions dictated how well the snow was feathered out. In extremely wet snow, just the pan can be used (no planer) and the snow squishes out quite flat, though typically leaving windrows on either side of the pan.

- During pan compaction, often times the pan "pulls" the snow up behind it (friction on the pan?), resulting in pancake-like popped up areas of snow in the pan's path. These non-compacted elevated areas may create invitations for snow-road "blow outs."

- On sloped sastrugi/drift, the pan side slides sideways off the drift behind the tractor and causes the implement to cut and compact at an angle. This occurred on many relatively small slopes and of course on all greater sloped areas. As a result, the compacted results are sloped—high on one side and low on the other. As well, the side sliding created a windrow effect on the downward slope side. Additional, thought out passes could correct this . . . or it could be corrected by a drag or a goose. Side sliding of the implement is almost guaranteed on non-flat surfaces.

- I tried raising the pan to avoid the side sliding, but it had to be raised so high that no compaction was being done. Possibly low profile skags/runners could be added to the pan's underside to avoid this.

- It is already known the current, single vibratory mechanism is insufficient for the 10 ft width of this prototype. Additionally, I would say one has to travel at an extremely reduced speed (as compared to goosing or dragging) for vibration to be of worth. Possibly two vibrators per 10 feet would improve upon this.

Control Box

This item may well only be an initial design; but in its current state, it is entirely too fragile and vulnerable. Toggles and lights are exposed to easy damage. There is no secure mounting of the unit in the cab during use nor for storage during non-use.

Summary

I like the concept of the Snow Paver but am not convinced its current design is a money saver for the United States Antarctic Program (USAP).

The cost of shipping the prototype back to the contiguous U.S. may be near the cost of purchasing the existing implement itself. This may lend itself to keeping the prototype at McMurdo as it would likely be used for some time; however, my guess (with over a decade of ice experience) is it would eventually end up on a berm and the old faithful, non-mechanical implements used instead.

That said, I likely would not keep it at McMurdo unless it was modified for very focused testing. Much testing has been done with the SnowPaver; however, if I were the buyer, I would require a specific test area/proving ground dedicated to the implement for the season and see the results of that area being used as the snow roads currently are used throughout a season. Meaning, conduct testing with *only* the Snow Miller and any other implements *intended* to be used with it (once it is purchased) for snow-road preparation. As I know it, no road surface has been prepared with only the SnowPaver and its intended compliments and then tested for a significant amount time. I'm aware of and was out at LDB when snow-road testing was done (2010/2011?), but I do not feel it was to the degree that it proved the Snow Paver's effectiveness for the USAP's snow roads. This makes a buying decision a high risk when considering an order may be placed for a larger, non proto-type version with the expectation of using fewer implements for snow-road building and maintenance.

If the Snow Paver was purchased, I understand a wider unit would be ordered, offering better width coverage; however, I doubt it would successfully replace one of the three current implements used to build snow roads (i.e., goose, drag, weight cart); . . . and it is my understanding that the entire idea of the Snow Paver is just that, to reduce the cost of time, fuel, and equipment usage via making fewer lane passes with fewer implements. (One thought for fewer lane passes would be to have narrower road lanes [feasible to maintain regardless of McMurdo Ice Shelf movement]).

The implement is heavily mechanized and will require related management and repair. It would be added to the VMF Preventative Maintenance schedule. It has many hydraulics, its own large engine, a battery, vibratory compactor devices, tractor cab control box and needed cabling, requires fuel, has two large tires, etc. Compared to the current *implements* used (no engines, minimal hydraulics, no fuel), the Snow Paver will require exponentially more mechanical (VMF) attention.

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14. ABSTRACT
The snow roads at McMurdo Station are the primary transportation corridors to the surrounding airfields. However, during warm spells, deteriorating road conditions can seriously limit payloads for all types of vehicles. The Cold Regions Research and Engineering Laboratory (CRREL) has studied the construction and maintenance of the snow roads and teamed with the Keweenaw Research Center (KRC) and the National Science Foundation (NSF) to assess the feasibility of using a new SnowPaver to build snow roads in Antarctica. KRC built the SnowPaver, a single unit consisting of leveling blades, a milling unit, and a vibratory plate compactor, and shipped it to McMurdo in November 2010. In McMurdo, the SnowPaver constructed snow pavement sections that were monitored for performance based on snow-road strength and vehicle rutting. The SnowPaver was also used for reworking and compacting old and slushy snow during the height of the warm season. In November 2012, the power unit was upgraded; and snow roads built with the improved SnowPaver were 5 to 7 times stronger than the unprocessed road and 3 to 4.6 times stronger than the Pegasus Road. An economic analysis showed the SnowPaver would pay for itself in 1 to 5 years, depending on the usage.

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