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SNOW-ROAD CONSTRUCTION – A SUMMARY OF TECHNOLOGY FROM PAST TO PRESENT

by J. L. Barthelemy

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During 1947, Naval Construction Forces built a compacted-snow airstrip on the Ross Ice Shelf in Antarctica. Research methods since then have improved the use of snow as a construction material. Snow-compaction techniques and equipment initially developed by the Civil Engineering Laboratory (CEL) for runway construction have been used to build durable, high-strength roads. At the present time, properly constructed and routinely

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INTRODUCTION

Most areas of the Arctic and Antarctic are covered by light to moderate amounts of snow during the fall, winter, and spring; the polar ice caps, in fact, are perennial snow fields. Historically, the conventional means of transportation in those regions has been by tracked vehicle and sled train. It has long been recognized that dependable wheeled-transportation systems reduce travel time and personnel and maintenance requirements. However, in areas of perennial snow, roads must be provided. In particular, heavy-haul, wheeled-transportation equipment require high-strength snow roads while operating on deep snow fields. The Civil Engineering Laboratory (CEL) has developed snow-compaction techniques and equipment which utilize specially processed snow as a building material for durable, high-quality roads.

The Navy first researched snow compaction during Operation Highjump in 1947 [1]. In that year, Naval Construction Forces built a compacted-snow airstrip on the Ross Island Ice Shelf, Antarctica, near Little America IV. The pavement proved satisfactory for repeated operations of R4D aircraft on skis; however, it provided only occasional support during wheeled taxi tests. In spite of the many surface failures (attributed to nonuniform strength and inadequate depth of compaction), the taxi tests encouraged further research to develop methods for using snow as a construction material. As a result, the state-of-the-art technology of present-day polar operations includes well-defined procedures and recommendations for constructing and maintaining year-around snow roads. Properly constructed and preserved roads are able to support gross combinations of vehicle weights up to 75,000 pounds for vehicles equipped with flotation tires.

This final report documents and summarizes the evolution of road systems on snow. It is not written esoterically, but rather as a synoptic overview, and reviews all aspects of snow-road technology, from basic theoretical considerations to historical progress and recommended construction procedures. No extensive data or detailed test results are presented. Instead, detailed Reference and Bibliography sections present a comprehensive listing of supplemental reports dealing with snow-compaction technology. In this respect, this report is especially useful to those readers not already familiar with the principles of snow-road construction.

The basic time-dependent mechanical properties of snow, and how they may be altered to accentuate bearing strength and surface hardness, are introduced first. Methods for measuring these strength properties are also described. Next, terminology used to describe specific steps of cold-processing compaction is defined in terms of procedure and desired effect. Background material highlights the special types of equipment developed to accomplish each of these steps. Finally, a brief history summarizes CEL's role in Antarctic snow-road construction since the first road was built.

The Reference and Bibliography sections of this report provide a historical perspective of CEL's research and development effort in snow-compaction technology.

MECHANISMS OF SNOW PROPERTIES

The two mechanical properties of snow most important in snow-road construction are density and hardness. Density is dependent upon the packing efficiency of snow crystals – that is, the degree to which a unit volume of snow is free of void space. Hardness is dependent upon the tendency of neighboring crystals to bond to each other by ice bridges. Both density and hardness are metamorphic processes – that is, they change with the passage of time and state of external environment. Methods used in snow-road construction alter the state of natural metamorphism so that the rate at which density and hardness increase is accelerated.

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Densification

Freshly fallen snow is deposited upon the earth in the form of flaky crystals, or grains. It usually accumulates on the ground at a density between 0.01 and 0.2 gm/cc, the variation of which is a function of temperature and wind velocity during the deposit period [2]. Not all crystals are the same size. As a result, a state of thermodynamic disequilibrium exists within the snow cover: "The vapor pressure over small crystals is high and over large crystals it is low, hence there is a continuous movement of vapor from a small crystal to a large one. Since the crystal must be in equilibrium with its vapor, excess vapor which accumulates about the larger crystal is deposited on and incorporated in that crystal. The deficiency of vapor over the small crystal is made up by loss from the solid mass of that crystal. In this way the large crystal gains mass and the small one loses it." [3] The natural metamorphic process by which some grains grow at the expense of others is called densification. This process continues until much of the original flake snow changes to granular particles. As metamorphism continues, the snow cover settles; the void space diminishes, and the volume of snow mass decreases. In other words density increases. In the absence of significant bonding between grains, resistance to compression is due largely to interference between contiguous grains and is, therefore, density dependent.

Density's most important effect on the strength of processed snow occurs only during the period between processing and the early stages of bond growth. The highest possible density is achieved by compacting the snow as soon as possible after processing. Densities between 0.60 and 0.65 gm/cc are possible and result in very strong snow. However, densities between 0.5 and 0.6 gm/cc are more common in processed-snow roads.

Hardening

Hardening, also a metamorphic process, causes marked changes in the mechanical properties of snow, independent of those produced by a change in density alone. Even in newly fallen snow, the points of contact between crystals may be rapidly fused by ice bonds. In dense, pulverulent snow both the total contact area between grains and the number of contacting grains is maximized. A high degree of bonding is achieved, providing thermodynamic conditions are conducive to that type of metamorphism. Like densification, hardening requires a state of physical disequilibrium. There must be, at least temporarily, an excess of either the liquid or vapor phase beyond that supportable by the heat content of the snow mass.

The process of hardening over a period of time is called age-hardening. The age-hardening of snow begins almost immediately after processing during snow-road construction. It progresses rapidly for the first few days and then slows down with time. The importance of the age-hardening process in developing a trafficable surface and increasing the load-bearing capacity of a compacted snow mass cannot be overemphasized.

Alteration by Processing and Compaction

The specialized techniques developed for snow-road construction effectively accelerate natural metamorphism. In processing the particles of snow are broken up into fine, disaggregated crystals. Compaction immediately follows processing, thereby pressing the small grains into a dense mat before intercrystalline bonding begins. In this manner, when bonding does start, each grain is guaranteed a maximum number of crystal contacts and a minimum exposure to void air space.

Processing serves another important function. Hardening was defined as the tendency for neighboring crystals to bond together. Certain snow crystals will not automatically unite with each other simply because of proximity; thermodynamic instability is required. Processing creates a state of physical disequilibrium that increases the probability of bonding between contact surfaces and, therefore, increases the development of a greater degree of hardness throughout the mass.

Temperature Dependency

The most important environmental factor influencing the quality and survival of a snow road is temperature. During construction, the presence of cold temperatures within the snow mass has a marked influence on the mechanical properties. More particularly, steep temperature gradients between the air and snow surface, as well as within the snow itself, are conducive to rapid age-hardening. Also, in general, low air temperatures are most conducive to rapid age-hardening; however, there are practical limits. Studies conducted at the South Pole have shown that the rate of age-hardening is slow in the temperature range -20° to -40°F and extremely slow below -40°F [4]. At the opposite extreme, temperatures above 25°F severely retard age-hardening and promote sublimation. Figure 1 shows a typical hardness-growth sequence in a single layer of double depth-processed snow, and the delay in hardness growth resulting from temporary temperature conditions above 25°F.

The strength of a completed, processed-snow road changes as temperatures fluctuate throughout the year. The upper layers are especially sensitive to air temperature and solar radiation. During the summer months, sustained air temperatures near the melting point may soften the pavement surface to such an extent that the road becomes unsuitable for vehicle traffic. Also, the absorption of solar radiation decreases parabolically with depth so that the upper layers are additionally heated by the sun's rays [5].

Measurement

Successful snow roads necessitate a hard, compacted snow mat of uniform bearing capacity. Field instruments are used to accurately monitor time-dependent strength characteristics of the consolidated construction material. Prior to 1963, the most common test device for determining hardness, or strength, was the CRREL* Rammsonde cone penetrometer, which gave a relative in-place snow-hardness index. However, the device had limited application, especially in hard, compacted snow. Early observations of compacted snow pavements showed that a punching failure, or wheel break-through, directly under the wheel was actually the principal type of failure [6]. It was also observed that only the snow directly under the wheel was displaced in the failure area. Because the typical mode of failure appeared to be vertical shearing of the compacted mat, a more suitable device was developed to establish failure criteria and predict load-bearing potential. The confined shear apparatus, designed by CEL, was used to relate the total shear strength of a compacted snow pavement to maximum allowable surface-bearing loads for wheeled vehicles and aircraft.

Hardness Index. The hardness index as described in this report is the average resistance to penetration of a snow mass as measured by a Rammsonde cone penetrometer. The test device consists of a cone-tipped rod that is manually driven into the snow with a drop hammer. The basic unit uses a 1-meter-long rod fitted with a 1-1/2-inch-diameter cone tip and a 70-cm-long hammer guide. Two hammers are provided for driving the rod into the snow, one weighing 1 kg and one weighing 3 kg. Rod extensions one meter long are also provided for deep-snow tests [7].

Hardness measurements taken by CEL crews along single-processed, compacted-snow roads were usually obtained using the 1 kg hammer. Double-processed roads required the heavier hammer for penetration. Additionally, to speed up sampling along heavily compacted roads, NCEL developed a special 1-inch-diameter tip for the Rammsonde rod. Numerous tests using the two sizes of hammer with the 1-1/2-inch cone have shown that no linear correspondence exists between results. The same is true of the two different tip sizes. CEL developed curves to correlate the data of all Ramm tests (regardless of tip size or hammer weight) in terms of an equivalent hardness index using the 1-1/2-inch-diameter tip and 1-kg hammer. These standardized hardness numbers are identified by the suffix "R." Standardized hardness values (using the basic 1-1/2-inch-diameter cone tip and 1-kg hammer) are obtained from the following relationship [7]:

$$\text{Hardness R} = \frac{WH}{S} + W + Q$$

where W = weight of hammer

H = height of fall

S = penetration from one hammer blow

Q = weight of penetrometer

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* U. S. Army Cold Regions Research and Engineering Laboratory.

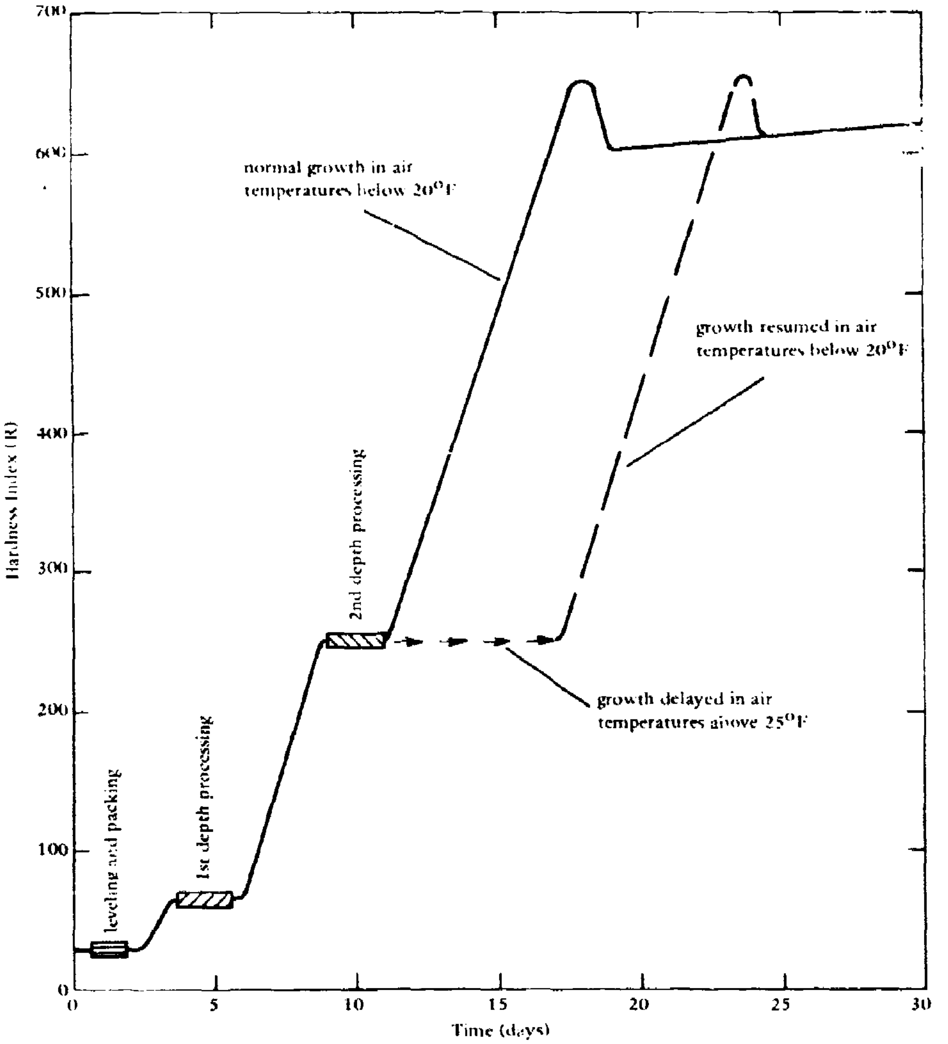

Figure 1. Typical hardness growth in a single layer of double depth-processed snow.

Hardness numbers in CEL publications are unitless since CEL has preferred to use Ramm values strictly as relative indices of hardness.

Figure 2 is an example of a hardness correlation curve. It converts data for the 1-inch-diameter cone and 1-kg hammer combination into equivalent R-values for the standard 1-1/2-inch cone with 1-kg weight setup [2]. It should be stressed, however, that the Rammsonde rod penetrometer is suitable primarily for loosely consolidated or virgin snow. The reliability of data gathered on heavily compacted snow is questionable. Hardness measurements involve the repeated impact displacement of the penetrometer by blows from a heavy hammer. The resistance of dense, hard snow is often such that a portion of impact energy is lost to rebound and lateral shaking of the rod, or buckling of the jointed connections. Lost energy results in erroneous results.

Confined Shear Strength. Since 1963, CEL has used vertical shear strength as the major failure criteria [8]. The confined shear strength apparatus developed by CEL measures short-term primary shear on confined specimens of compacted snow. The device is designed to receive 3-inch-long cores obtained with a 3-inch-diameter SIPRE coring auger. The specimen is placed in a confining cylinder, and a shearing force is applied through heads which are positioned so as to align the shearing edges of the device. The core fits snugly without binding; the heads fit loosely, but do not allow the specimen to deflect other than in the direction of applied force. A positive displacement hydraulic plunger mounted on a soil-type compression tester frame applies the load to the top shear head. The bottom head rests on a load cell attached to the lower plate of the tester frame. As the load is applied, the force with time is inscribed on a penchart recorder.

Figure 3 presents the experimentally determined relationship between Ramm hardness and confined shear strength. It should be noted that hardness values are not reliable above 800R with the 1-1/2-inch-diameter tip or above 3,600R with the 1-inch-diameter tip due to excessive rebound and clatter.

CEL field studies uncovered a useful empirical relationship between shear strength measurements within the thickness of a compacted-snow mat and expected bearing potential. In early confined shear tests a full-depth core was extracted from the processed, compacted snow pavement. The core was cut up into individual increments which were each tested for shear strength. It was noted that the total resistance to shear, obtained by summing the individual shear strengths, was approximately four times the ground pressure that could be supported at the surface [6]. In other words, the load-carrying capacity (measured in psi) of a compacted snow pavement is approximately 25% of the total resistance to shear (measured in pounds) offered by the compacted pavement.

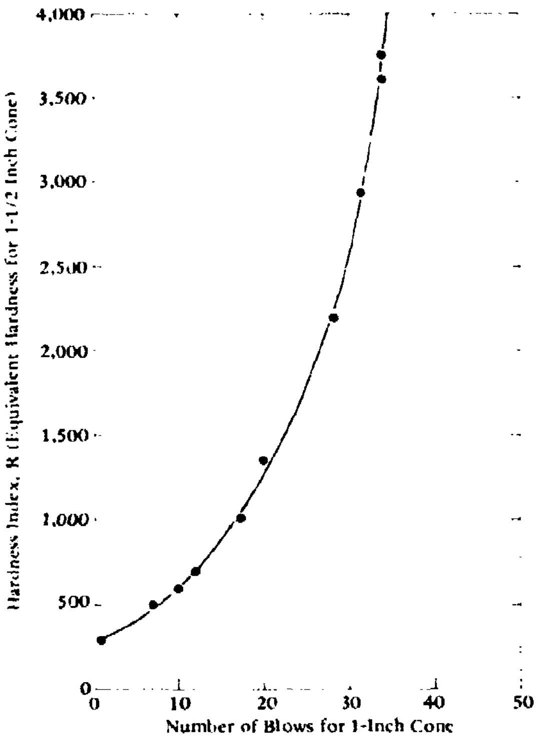

Figure 2. Curve for converting penetration resistance of 1-inch cone Rammsonde to equivalent hardness for 1-1/2-inch cone. Both cones are used with a 1-kilogram hammer.

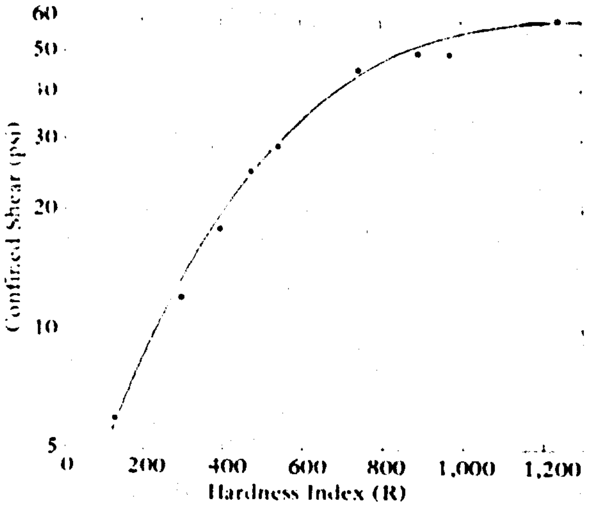

Figure 3. Confined shear strength compared with Rammsonde hardness index.

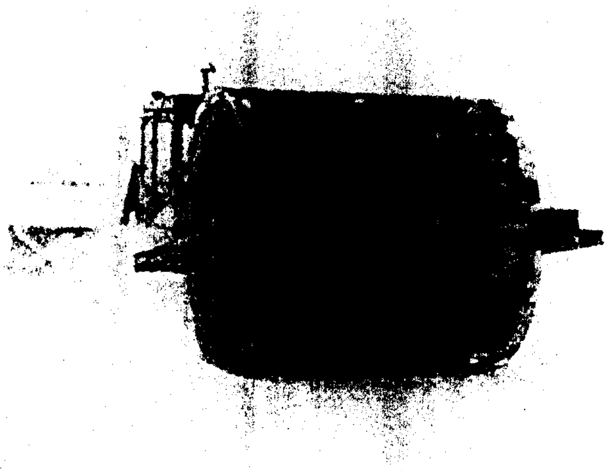

Figure 4. LGP D4 tractor pulling the CEL 8-foot-diameter snow-compacting roller.

REVIEW OF CONSTRUCTION TECHNOLOGY AND EQUIPMENT

Present-day snow-road technology is a natural outgrowth of procedures initially developed for the construction of compacted-snow runways in polar regions. This section introduces basic snow-compaction terminology. The various steps of cold-processing compaction are briefly defined in terms of procedure and effect. Also, historical material highlights the special types of equipment developed for each stage of construction (also see the Appendix). A brief discussion of recommended present-day procedures and equipment, and how they are integrated into a well-coordinated work effort, is presented in the Summary section of this report.

Compaction

Walking on snow is a primitive form of compressive compaction. Historically, a variety of sizes and shapes of drags, rollers, and other devices has been used to pack snow. However, these devices are only effective on shallow snow because, regardless of the weight of the equipment, there is a limit to the degree of density and hardness that can be achieved by compressive compaction alone. The enhancement of mechanical properties of snow is restricted to a limited depth below the surface. For instance, a relatively lightweight, large-diameter roller developed by the Navy for high-speed compaction of large snow areas can effectively compact natural, undisturbed snow to a depth of 10 inches. This snow-compacting roller, which measures 8 feet in diameter and 8 feet in length and weighs 10,240 pounds, is usually pulled by a low ground pressure (LGP) tractor [9]. The tandem combination compacts and smooths the snow after it is depth-processed. Figure 4 shows the snow-compacting roller being pulled by an LGP D4 tractor.

Compressive compaction techniques are also employed to initially compact the natural snow surface along a selected road course. This precompaction procedure produces a dense and smooth roadbed of uniform strength. Precompaction is especially necessary in Sastrugi where snow-road construction accentuates the natural undulations of a surface and produces a finished mat whose surface has the appearance of a miniature roller coaster [2]. When this occurs the surface must be leveled.

Depth-Processing

In the procedure of depth-processing a depth of natural snow is mechanically disturbed and then mixed. Processing damages the crystalline structural forms of snow particles, breaking them into small grains or crystals, and thereby exposing the freshly broken surfaces to unstable thermodynamic conditions. Subsequent compressive compaction improves the material strength: density increases due to increased packing efficiency; hardness increases due to thermodynamic disequilibrium and maximized crystal contact.

Single depth-processing involves initially processing and then, if necessary, reprocessing a previously undisturbed area of snow. The successive passes are done quickly (less than 1 hour between each pass) before the snow has time to begin hardening.

During the early years of snow-road construction when equipment was less refined, double depth-processing of natural snow was common. This technique resulted from observations made in Greenland [10]. It was noted that single depth-processing pulverized only a limited number of particles, regardless of the number of mixer passes. Incomplete pulverization limited the number of particle contacts after processing. It was reasoned that reprocessing well-bonded, once-processed snow should result in more thorough pulverization and smaller particle size. This rationale was substantiated by subsequent tests. Processing equipment, however, has been improved over the years, and the more sophisticated equipment of present-day operations usually makes double depth-processing unnecessary. The improvement of mechanical properties realized by the added procedure and delay is marginal.

The earliest depth-processing equipment were commercially available, towed, construction mixers mounted on skis. In time, standard engine-driven earth pulverizers were modified as two sizes of Navy snow mixer [11]. One, a model 24 snow mixer, had a 24-inch-diameter rotor with a maximum rotor speed of 790 rpm and maximum peripheral speed of 4,960 ft/min. The other, a model 42 snow mixer, had a 42-inch-diameter rotor with maximum rotor speed of 515 rpm and maximum peripheral speed of 5,660 ft/min. Both models had a two-ski support system with drawbar steering and were towed by LGP snow tractors. Each weighed nearly 15,000 pounds. These snow mixers were effective in depth-processing to produce high-strength snow; however, continued use indicated that certain modifications might result in higher quality snow with fewer mixer passes.

The model 36/42 snow mixer is an improved version of the commercial in situ mixer [12]. This modified unit uses an interchangeable cutter system of 36-inch-diameter and 42-inch-diameter rotors that increase the maximum peripheral speed to 7,560 ft/min at a rotor speed of 687 rpm. The front skis of the LGP tractor-towed unit are pinned through yokes to permit steering and allow the skis to conform to the snow surface. The wide rear ski helps level and compact the pulverized material during depth-processing. Also, the total 20,000-pound weight of this snow mixer allows transport by C-130 aircraft.

This modified configuration proved to be effective during field trials in the Antarctic (DF-66*). A two-pass tailgate processing technique, developed by closely spacing two model 36/42 snow mixers (one directly behind the other), produced snow pavements with strengths tantamount to those obtained by double depth-processing and six mixer passes with the model 24 and 42 snow mixers [12]. However, it was sometimes difficult to maintain the second mixer on a common course – that is, directly in the tracks of the lead mixer. Figure 5 shows two LGP D4 tractor-towed model 36/42 snow mixers pulverizing snow using the two-pass tailgate processing technique.

A piece of equipment called the Dual Drum Snowpaver was conceived as a means of removing the problem of common tracking and, at the same time, reducing both the manpower and equipment required during processing. Conceptually, it was viewed as a single-pass snow mixer housing two rotors within a common frame. This arrangement was expected to automatically confine the real rotor to the same material as that freshly processed by the lead rotor. Such a snowpaver was fabricated according to CEL specifications and delivered to the Antarctic in February 1971. However, it never attained operational status. First, the test and evaluation program was delayed when the unit was damaged while being transported locally. After the damaged components were repaired and the mixer started, pervasive contamination of the hydraulic pumping system for the rear rotor was discovered. A technical representative from the manufacturing company was sent to the Antarctic test location in DF-72; however, a reasonable engineering and economic solution was never realized.

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* DF is an abbreviation for Deep Freeze and covers the same span of time as the fiscal year.

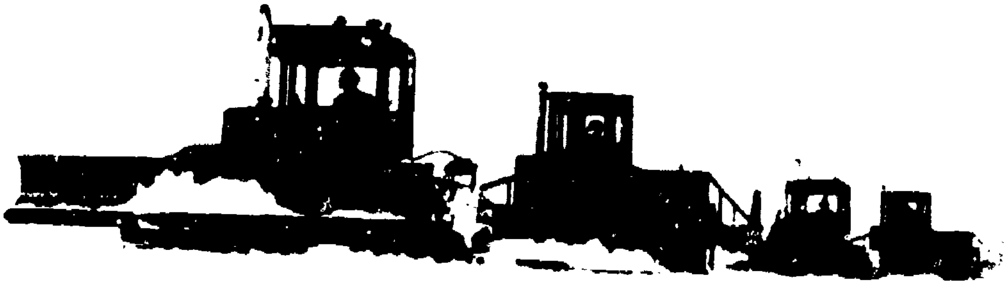

Figure 5. Two tractor-towed model 36/42 snow mixers operating in the two-pass tailgate configuration.

Layered-Compaction

Snow-road construction using depth-processing and compaction procedures alone produces a finished pavement that is necessarily depressed below the surface of the surrounding natural snow. A depressed road acts effectively as a snow trap, becoming heavily covered with drift during storm winds. The technique of layered compaction counters this problem. The roadbed is built up to a desired elevation by the successive compaction of differential layers of snow; the required borrow material is removed from surrounding natural snow areas. Drifting on the elevated surface is postponed until the bordering natural snow attains a height tantamount to that of the elevated pavement (a process which ordinarily takes several years).

In addition to the advantage of minimized drifting, the layered-compaction technique provides two quality-control benefits [1]. The first benefit concerns hardness. As previously stated, compressive compaction produces the greatest hardness increase in the upper depths of snow near the surface. By depositing and packing snow in successive layers, the net results can be an overall greater thickness and a more evenly distributed hardness than obtained by compressive compaction alone. These two effects increase the load-bearing potential of a pavement.

The second benefit is realized by the distribution of low-strength areas, or holidays as they are sometimes called. Holidays are actually areas of pulverized snow that are missed or inadequately processed. In unelevated roads, though holidays usually occur sporadically, any single flaw may extend through the entire thickness of the pavement. In layered roads, the probability of such flaws coinciding is small in two layers of compacted snow and remote in three or more layers.

In the primitive days of snow-road construction, the major objection to the layered-compaction technique was that it required the removal and transportation of vast amounts of borrow material from neighboring snowfields. No suitable equipment was available for that task. The earliest elevated snow roads were actually a result of natural interference when depressed snow roads were covered by wind-blown drift snow. Drift was not removed; but rather, the snow cover was depth-processed and compacted, often elevating the road above the surrounding terrain [13]. However, deliberate drift control was not a practical way of obtaining construction material since it depended upon the capriciousness of nature. At the same time, bulldozers and sleds were rejected as being too slow for moving snow on a large scale. Conventional scrapers were also rejected because of the extensive modifications necessary to operate them on snow. Two snowplanes were used as graders during DF-62 to elevate a 4,000-foot-long by 24-inch-high compacted-snow runway. However, those units also spread snow at a relatively slow rate.

The snowplow was eventually selected as the most suitable piece of equipment to move and accurately place large quantities of snow. This piece of equipment employs a cutting head assembly which pulverizes the natural snow cover alongside a snow-road site. The pulverized snow is mechanically forced into an impeller where it is directionally cast onto the roadbed. An initial feasibility trial was conducted during DF-62 using a small, self-propelled, track-mounted model. This small unit was efficient only for close-in work involving limited amounts of snow; however, it was successful in stimulating an impetus for further development [13].

During the summer months of DF-63, a larger truck-type model rotary snowplow was mounted on a standard D8 Caterpillar tractor. This combination was used to elevate a 170-foot-wide by 2,000-foot-long section for a compacted-snow runway. Eighty-foot-wide areas along each side of the test section were used as borrow pits for fill snow. The rate of snow deposit was six times faster than that of the snow planes, even though the snowplow was casting at only 21% of rated capacity. Snow-intake efficiency was limited by the pitch and roll of the tractor and also by the inefficient feed of snow material into the cutter assembly. As a result of these problems, the model 40 snowplow carrier was developed. The carrier, a 40-foot-long, ski-mounted frame designed to be tractor-towed, featured a set of angle blades mounted ahead of the plow to funnel the pickup snow directly into the impeller. The four-point ski-suspension system and steerable rear skis minimized pitching and rolling of the snowplow on deep snow and permitted a more uniform removal of snow from borrow pits [13].

The prototype model 40 snowplow carrier was designed to carry a Sicard Model BK snowplow. The combination was used to elevate a 3-mile-long road near McMurdo Station during DF-64 and DF-65. After that date, a larger snowplow and carrier assembly was developed to handle even greater quantities of snow more efficiently. The model 1000 snowplow carrier was built to remove structural weaknesses encountered in the model 40 unit and provide greater snow transport capacity. It was first assembled and tested on-site near McMurdo Station during DF-68. It is still used for present-day snow-road construction in conjunction with a modified Snowblast model R-1000L rotary loader attachment. Figure 6 presents the model 1000 snowplow carrier and loader attachment during snow-road construction.

The towed model 1000 snowplow carrier with an overall length of 56 feet 9 inches consists of a main frame in which the rotary head and engine are mounted. Two snow-gathering blades at the front of the frame funnel snow into the modified cutter assembly.

The model 1000 snowplow carrier accommodates a model R-1000L loader attachment which is rated at 1,000 tons of snow per hour. The original loader attachment employed a rotary cutting head equipped with four helical cutting blades; the modified assembly carries a specially constructed cutting head with eight helical blades. The modification further simplifies snow-road construction. During DF-73, a section of road was built near McMurdo Station using the technique of layered-compaction. No snow mixers were used; the modified cutting heads produced a pulverulence of sufficient uniformity and fineness so that separate depth-processing was not necessary [14].

Surface-Hardening

Early tests indicated that the hardness distribution throughout the thickness of a depth-processed and compacted snow pavement was not uniform. As previously stated, repeated compaction was effective only within a limited depth below the surface. The actual vertical hardness distribution was found to be parabolic, with the bulk of hardness in the middle two-thirds of the mat. This phenomenon is depicted in Figure 7 [2]. Of course, the parabolic distribution was removed when layered-compaction methods were used since that technique required depositing and compacting many individual layers. However, even for layered roads, the surface layer of compacted snow is relatively soft and easily damaged.

Surface-hardening involves a special rolling technique. A standard 13-ton, pneumatic-tired, wobbly wheeled roller is pulled over the roadbed several times. This surface-hardening roller hardens the top 1 inches of the mat so that the surface can effectively resist damage from wheeled vehicular traffic [9]. Figure 8 shows the surface-hardening

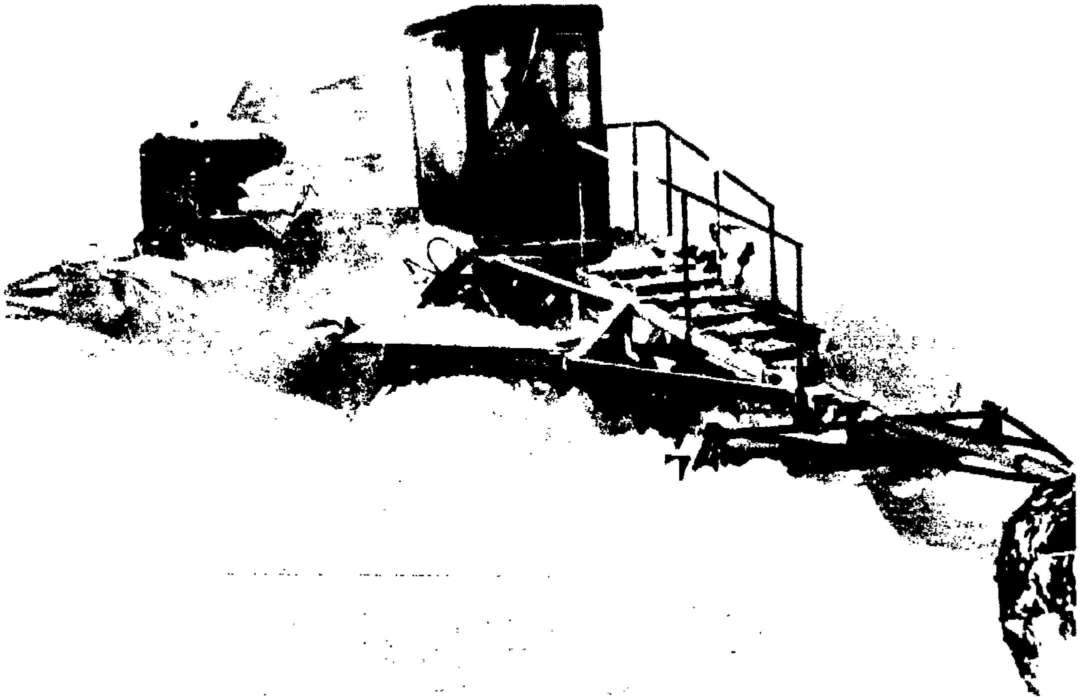

Figure 6. Model 1000 snowplow carrier with loader attachment during snow-road construction.

roller being towed by an LGP D4 tractor. In present-day operations a rubber-tired tow vehicle is required. Usually a 3-day delay is required between the completion of compaction and the initiation of surface hardening procedures. This delay lets the roadbed harden sufficiently so that the tires of the wobbly wheeled roller do not cut furrows into the compacted material.

Leveling

During early snow compaction field trials, test lanes were satisfactorily leveled and planed with various types of drags. Success was attributed to the relatively flat snowfields selected for the trials and the small plots constructed for tests. However, in the construction of compacted snow runways on the Greenland Ice Cap, considerable grading was necessary to produce a level surface. Experimentation with a towed, hand-operated grader and a ski-mounted, hand-operated land plane for leveling and grading sastrugi resulted in the modification of two sizes of commercially available towed land planes for use on polar snow. One size, the model 40 snow plane, has a 40-foot span; the model 80 snow plane has an 80-foot span and is pictured in Figure 9 [15].

The snow plane is suitable for both grading and planing operations. Both models are tractor-towed and utilize a four-point ski-suspension system for over-snow operations. The rear skis are hydraulically steered by the operator, and the front skis are steered by the towing vehicle through a drawbar arrangement. The planing element, located equidistant between front and rear skis, is 12 feet wide and hydraulically actuated for vertical movement. The planing bowl can be quickly converted to a grading

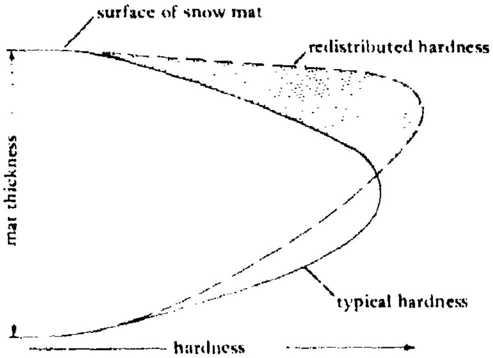

Figure 7. Typical vertical hardness in compacted snow compared with its redistribution after surface-hardening.

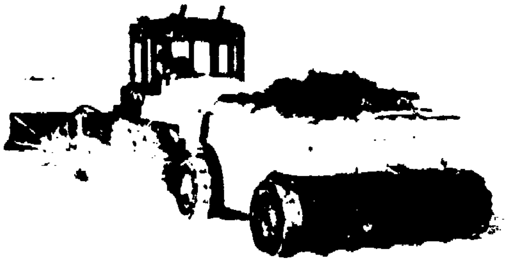

Figure 8. LGP D4 tractor-towed, surface-hardening roller during DF-67.

blade by raising or lowering the bowl and rotating it on a supporting turntable into position. In the grading configuration detachable wings used for leveling are removed from the blades.

The snow plane is a satisfactory piece of equipment for planing natural and compacted snow, grading drift snow, and laterally moving snow to build up or level a snowfield. Snow planes serve to smooth and level roadbed sites prior to compaction, although it is sometimes necessary to first prepack and rough-level with a bulldozer. When used in conjunction with snowmixers, snow planes are especially critical; the roadbed must be smooth and level because snowmixers do not level out contours or uneven surfaces but tend to amplify them. In the layered-compaction technique, it is necessary to smooth and level the surface of the road each time new snow is added.

HISTORY

Early Compacted-Snow Runways

The history of snow-road construction is one of continual testing and development. Present-day techniques are an outgrowth of research initially conducted during the development of compacted-snow runways. Naval involvement began during Operation Highjump in 1947 when a compacted-snow skiway was built on the Ross Island Ice Shelf in Antarctica. Then, during Hard Top I in 1953, a 150-foot by 5,000-foot experimental runway 16 inches thick was built on the Greenland Ice Cap [10]. The entire airstrip was single-depth-processed at an average density of 0.46 gm/cc. A double-depth-processed extension of 3,000 feet at an average density of 0.51 gm/cc was added. The single-processed snow failed under the main wheels (60 psi) of a C-47 aircraft, but the double-processed snow supported the C-47, except for occasional soft spots traced to processing holidays.

During Hard Top II in 1954, a three-layer, 33-inch-thick, snow-compacted runway was constructed at the site of the 1953 runway [16]. It was built up from natural drift. Precompaction preparations and double depth-processing were practiced during the placement of each layer. The runway was used successfully for tests of landing, taxiing, parking, takeoff, and hard-impact landing of a C-47 on wheels. Following the C-47 tests, the runway was tested with a P2V aircraft on wheels. It supported the P2V on a serpentine taxi test except for one 300-foot section where several failures occurred under the main wheels. Those failures were traced to localized holidays in the processed snow. It was noted that

Figure 9. Tractor-towed, 80-foot snow plane leveling previously deposited snow.

during taxi tests the free-castering nose wheel (100 psi) dug in the snow and plowed a 3- to 5-inch furrow in the surface. At that time the special rolling technique described under Surface-Hardening was applied to the runway surface. Thus, surface hardness was increased, and the free-castering nose was adequately supported.

Squaw Valley

In 1960, a 50-man team of Seabees under direction of CEL constructed and maintained a compacted-snow road 1 mile long and 100 feet wide at Squaw Valley, California, for the VII Olympic Winter Games. This effort followed several years of Laboratory investigation as to the feasibility of compacted snow for roads on annual and perennial snowfields. The road connected the main entrance road into the Valley with a 125-acre compacted-snow parking lot also built by the Naval support force. The underlying snow cover was 5 feet deep along most of the right-of-way. Snow planes, occasionally assisted by bulldozers, were used to complete the excessive grading and leveling required prior to the start of construction. Once the roadway was level, it was compressively compacted, depth-processed, surface-hardened, and covered with a 1/4-inch layer of sawdust [17].

The road was trafficked over 20,000 times the first day of use. In all, after 8 days, it was trafficked over 100,000 times by all types of vehicles up to 30-ton trucks. The surface of the road remained smooth and level, permitting traffic speeds up to 60 mph.

Antarctica

Snow-Road Technology. The bulk of Naval snow-compaction experience was derived from research conducted in the Antarctic. In the spring of 1960, the staff construction officer at McMurdo Station requested CEL to investigate the practicability of building roads on snow-covered sea ice to improve transportation between McMurdo Station and the air-support facilities. The initial product was a snow road 25 feet wide and 4 miles long, completed on the ice between McMurdo Station and the sea-ice runways at Williams Field in the fall of 1960. (At that time Williams Field was located about 3 miles out on McMurdo Sound.) The first offshore mile was located on bare ice, and the next 3 miles were located on a 4-foot snow pack. Construction procedures included precompaction, double depth-processing, compaction and surface-hardening [18].

Depression of the completed roadbed about 10 inches below the natural terrain accelerated the accumulation of drift, which was windrowed to the edges of the road following each storm. Eventually, berms 2 feet high were produced along each side of the road. The roadway was abandoned in mid December after a 3-day blizzard filled it with snow.

A 10-man team of Seabees constructed the roadway using two snow tractors, two model 24 snow mixers, two snow-compacting rollers, one model 80 snow plane, one finishing drag, and one surface-hardening roller. The road was used continuously for a 10-day period in November by all types of wheeled vehicles, including 30-ton tractor-trailer rigs. The project demonstrated the feasibility of vehicle roads on snow in Antarctica. However, it also demonstrated rather dramatically the need to elevate such roads above the surrounding terrain [18].

After 1960, many miles of snow roads were constructed around McMurdo Station, connecting it to outlying activities such as the sea-ice runway, the glacier-ice runway at Outer Williams Field, and the skiways at Williams Field. Figure 10 shows a typical road network. Road systems changed often as a result of failure and relocation of old roads and construction of new roads. CEL field teams made almost yearly trips to the Antarctic to further develop snow-road technology. Of course, not all road construction was performed by CEL. CEL roads were primarily research-oriented, although they were also designed and strategically placed to simultaneously satisfy transportation requirements. The Public Works Department at McMurdo Station was responsible for building the required network of service roads. However, for the most part, they used equipment and procedures developed or recommended by CEL personnel.

Overview. A brief year-by-year review of progress in Antarctic snow-road technology is next presented to give the reader a historical overview of development.

As previously stated, the initial Antarctic snow road was built in the austral summer of DF-61. In DF-62, the small, self-powered, track-mounted Peter Junior Snow Miller was used to cast snow for a 200-foot-wide by 300-foot-long test pad. The following year the larger Sicard model BK Snowmaster, a truck-type rotary snowplow, was tested by building a 170-foot-wide by 2,000-foot-long section of compacted-snow runway. Snow-intake efficiency was limited by pitch and roll of the mounted tractor. As a result, a special model 40 snowplow carrier was fabricated to carry the model BK snowplow. It was tested successfully near McMurdo Station during DF-64 and DF-65 [13].

The model 36/42 snow mixer was also introduced to the Antarctic during DF-64; extensive tests were conducted in DF-65 [12]. In that year, two experimental snow-road sections were constructed by CEL to better establish minimum strength requirements on deep snow for vehicle-weight and tire-pressure combinations up to 70,000 pounds and 30 psi, respectively. One road section, paved with snowplow-blown snow, was elevated 2 feet above the undisturbed-snow surface. The other section was paved by depth-processing the natural snow to a depth of 16 inches using the model 36/42 snow mixer followed by compaction rolling. The test section was depressed about 8 inches below the surrounding terrain. The density of the virgin snow at the site of the two test sections was 0.36 gm/cc. The density in the completed blown-snow pavement was 0.51 gm/cc; in the mixer-snow pavement, 0.57 gm/cc.

During DF-66, the two-pass tailgate method -- that is, the method whereby one model 36/42 snow mixer follows directly behind a lead mixer -- was perfected. That technique reduced the total number of passes required during mixing and, as a result, greatly decreased processing time. Another improvement was the introduction of the model 1000 snowplow carrier in DF-68. That unit had a greater snow transport capacity than its predecessor, the model 40 snowplow carrier. The model 1000 carrier assumed a fully operational status at the end of successful field trials during DF-69.

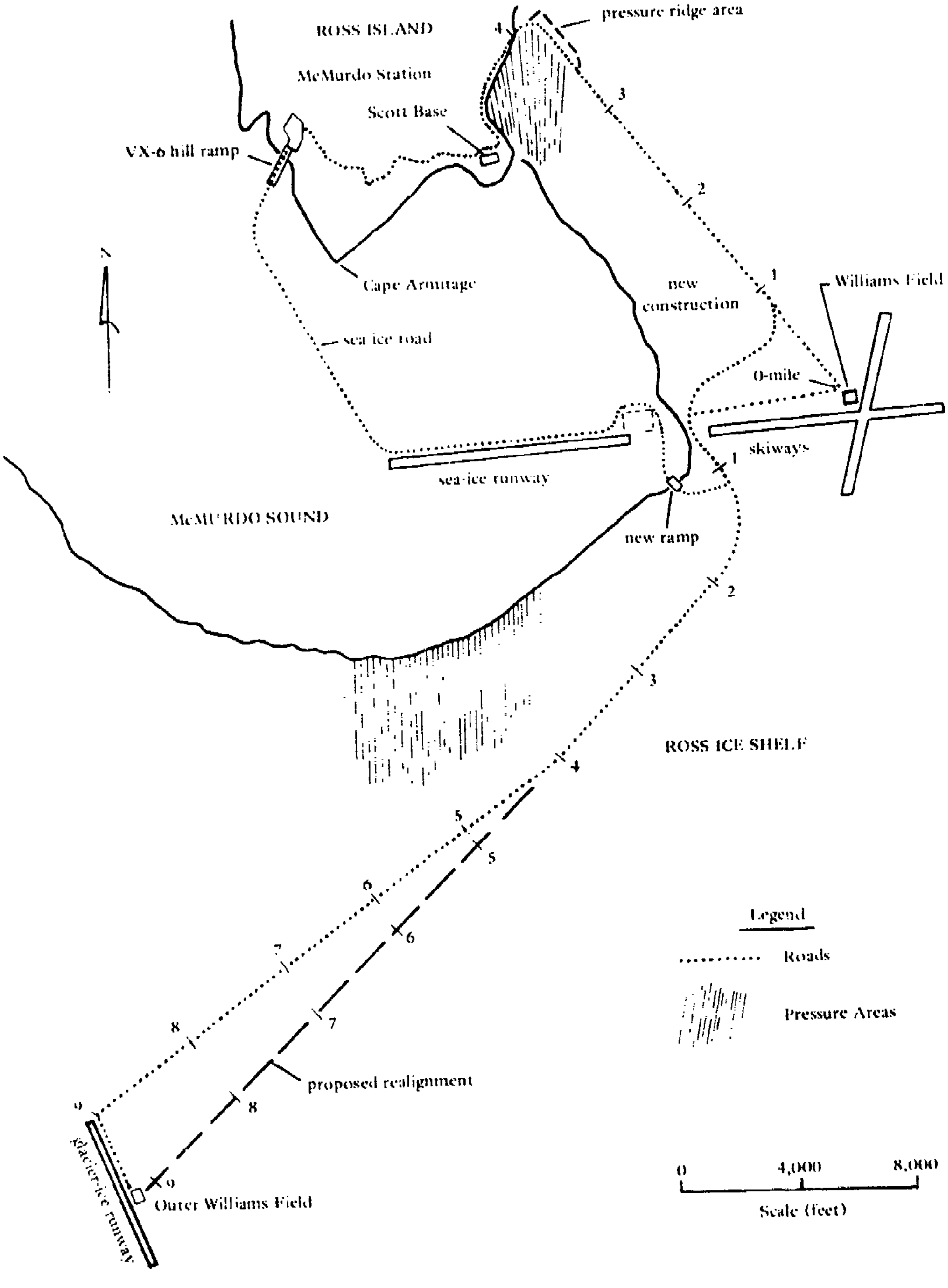

Figure 10. Snow-road network surrounding McMurdo Station on 9 November 1968

The Dual Drum Snowpaver was sent to the Antarctic in DF-71. However, because of damage sustained during transport and contamination within the rear-rotor hydraulic system, only limited tests were conducted. A technical representative from the manufacturing company was sent to the field site during DF-72 but was unable to adequately solve the contamination problems.

During DF-73, a 1-mile experimental road section was constructed using the process of layered compaction. No snow mixers were employed. Instead, the model 1000 snow transporter, carrying a modified cutting-head assembly with eight helical blades, was used to gather, pulverize, and deposit the snow material. The deposited snow was spread as individual 4-inch layers and compacted to an elevation of 24 to 30 inches. Test results showed that snow density and shear strength compared favorably with those associated with roads built by pulvimixing [14].

CEL CONTRIBUTION

Snow-compaction studies were begun initially in order to develop methods for building high-strength runways for wheeled aircraft. However, tested compaction techniques were not amenable to the sensitivity and nonuniformity of snow properties. As a result, it was not possible to construct totally reliable runways due to inconsistent material strength and surface hardness. On the other hand, snow-compaction research did result in the evolution of snow-road technology. At the present time, snow roads that are properly constructed and routinely maintained can support passenger vehicles, pickups, vans, trucks, and truck/tractor-trailer combinations fitted with flotation tires at gross weights up to 75,000 pounds.

Technique of Layered-Compaction

Two methods for constructing elevated snow roads have been developed by CEL. The most recent technique, that of layered-compaction, minimizes the number of operators and equipment required since snowmixers are not used. It involves elevating the pavement to a desired height by compacting successive 4-inch layers of snow. A rotary snowplow is used to gather, process, and deposit the snow material. The procedures are outlined in detail in Reference 19. The basic equipment and construction procedures recommended in that publication are summarized below.

Equipment:

- Tracked personnel and cargo carrier
- LGP D8 tractor (four required for optimum construction)
- LGP D4 tractor with angle blade
- Ski-mounted snow plow
- Snow plane 40- or 80-foot model
- Pneumatic-tired, wobbly wheeled roller
- Eight-foot-diameter steel roller
- Timber drag
- Large rubber-tired tow vehicle

Procedures:

1. Select and stake roadbed site
2. Compact and level the roadbed
3. Deposit and shape snow along sides of road for containment berms
4. Elevate to grade by compacting successive 4-inch layers of snow blown onto roadbed
5. Level, finish, and age-harden

The finished pavement is at least 30 feet wide and elevated 24 to 30 inches above the surrounding terrain.

Technique of Depth-Processing

The alternative method of snow-road construction involves depth-processing. The same basic construction equipment is required as previously described, plus the addition of two snow mixers (one mixer can be used, but this is less desirable). Unlike the layered-compaction technique, the snowplow is not an essential item of operation when depth-processing is used; snow may be pushed onto the roadbed using bulldozers. Therefore, in situations where a snowplow is not available, the alternative scheme is preferred.

Snow-road construction using the process of depth-processing is outlined in detail in Reference 20. The procedures are summarized briefly below.

Procedures

1. Select and stake roadbed site
2. Deposit snow on roadbed using rotary snowplow or bulldozers
3. Level with 40- or 80-foot snow plane
4. Depth-process using snow mixers
5. Relevel, finish, roll, and age-harden

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Appendix

TECHDATA SHEETS

The Techdata Sheets which compose this Appendix summarize the design and performance characteristics of the various types of equipment used to construct elevated snow roads.

December 1972 72-6

Naval Civil Engineering Laboratory

Port Hueneme, California 93043

NCEL
Techdata Sheet

SNOW COMPACTION EQUIPMENT—SNOW ROLLERS

Figure 1. Snow-compacting roller.

Figure 2. Snow-hardening roller.

PROBLEM

In polar regions, the most accessible building material for roads and runways is snow. The Navy therefore, has investigated the feasibility of producing static and dynamic load-bearing snow. The Naval Civil Engineering Laboratory has been instrumental in developing cold-processing techniques that produce high-strength snow capable of supporting vehicles and aircraft on both annual and perennial snow fields.

SNOW ROLLERS

The Laboratory has developed two rollers that are used together in a series of passes to process snow:

- Snow-Compacting Roller—A 10,240-pound, 8-foot-diameter roller that initially compacts the snow (compressively) and also compacts new snow on previously compacted areas (Figure 1).

April 1973 73-14

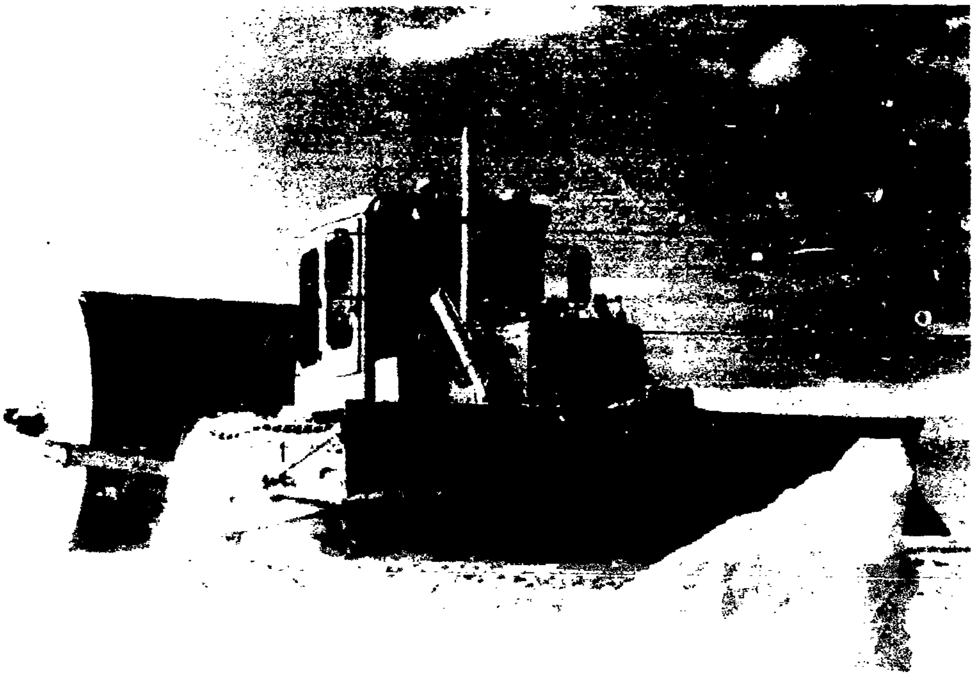
Naval Civil Engineering Laboratory

Port Hueneme, California 93043

NCEL

Techdata Sheet

D4 LOW GROUND PRESSURE SNOW TRACTOR



The LGP snow tractor is a basic D4 tractor, modified to achieve required ground pressure (4 psi), minimum shipping weight, and lower gear ratio. Other features are:

- Dual-rail track system with 36-inch aluminum tracks
- Standard and underspeed transmissions
- Angle bulldozer
- Winterized steel cab

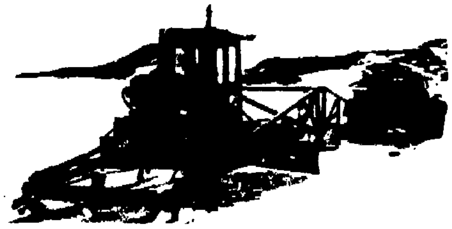
October 1974 74-05

Civil Engineering Laboratory

Naval Construction Battalion Center
Port Hueneme, California 93043

CEL
Techdata Sheet

SNOW-LEVELING AND GRADING EQUIPMENT
40- AND 80-FOOT SNOW PLANES



40-Foot Snow Plane

80-Foot Snow Plane

Most annual and perennial snow fields in polar regions must be graded and leveled to achieve the uniform compaction required to produce high-strength, load-bearing snow. CEL has developed two snow planes which effectively accomplish this job: (1) the 40-foot snow plane, which adequately levels and grades both natural and compacted snow and (2) the 80-foot snow plane, which was developed specifically to level snow fields that have long-wave sastrugi. The latter plane is very similar to the Model 40 except for its larger size. The snow plane is an important piece of equipment in the layered compaction method of snow-road construction; it is used to distribute the snow over the road surface after the snow is deposited by a snowblower.

FEATURES OF THE SNOW PLANE

The Model 40 and 80 snow planes are modified versions of commercially available agricultural land planes with the following features:

- Tractor-drawn unit with eight basic components: frame, skis, tongue, turntable, bowl/blade, hydraulic system, operator cab and load platform.

- Portable hydraulic power-pack unit, mounted on the frame.

	40-Foot Plane	80-Foot Plane
• Weight, pounds	6,120	12,350
• Length with tongue, feet	57	96
• Width-frame (outside skis), feet	8.5	11
• Blade width, feet	12	15
• Height, with cab, feet	9	10

ADVANTAGES OF THE SNOW PLANE

- Levels up to 3-1/4 acres of snow per hour; grades up to 3 acres per hour.
- Hydraulically powered by either hydraulic power-pack mounted on snow plane or tow tractor.
- Easily operated by trained personnel.
- Requires only routine maintenance.
- Converts simply from planer to grader and back under field conditions.
- Can be constructed in small shops.
- Is relatively easy to disassemble for shipment on all types of carriers.

REFERENCES

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October 1974 74-06

Civil Engineering Laboratory

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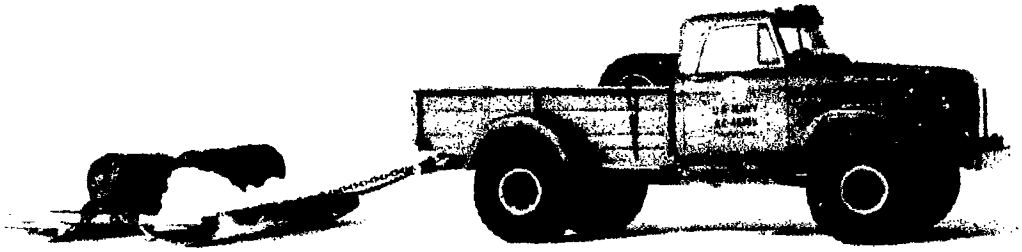
CEL
Techdata Sheet

SNOW-COMPACTION EQUIPMENT–SNOW DRAGS

Snow Leveling Drag



Snow Finishing Drag

High-strength compacted snow is vital for construction of roads, runways, and skiways, a fundamental need in year-round polar operations. For use in constructing and maintaining compacted snow, two CEL snow drags have been developed: one for leveling and one for finishing. The leveling and finishing drags are described in detail in Y&D Drawings 813537 and 813538 (1 September 1959), respectively.

FEATURES OF THE SNOW DRAGS

Snow-Leveling Drag — Used to finish and maintain surface of completed snow road, spread windrows left by other equipment, spread and level shallow drift and light snowfall and remove slight surface irregularities.

- Weight – 925 pounds; made of Douglas fir
- 12 feet wide, 8 feet long
- Tow speed (general operation) 350 feet per minute (about 4 mph)

Snow-Finishing Drag — Used in final construction when required to obtain a hard, smooth finish on compacted snow. This drag is used primarily for maintenance of snow runways.

- Weight – 2,830 pounds; made of steel
- 12 feet wide, 7 feet 6 inches long
- Tow speed in general operation – 350 feet per minute (about 4 mph)

ADVANTAGES OF THE SNOW DRAGS

- Are highly maneuverable on all types of snow
- Function effectively in temperatures down to -50°F
- Can be used singly or in multiple tow
- Can be constructed in small fabricating shops
- Are easily disassembled and packaged for shipment by any type of carrier.
- Can be assembled under adverse field conditions without difficulty.

REFERENCE

Based on NCEL Technical Report R-109: Snow-Compaction Equipment—Snow Drag, by J. B. Camm, October 1960.

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Civil Engineering Laboratory

Naval Construction Battalion Center

Port Hueneme, California 93043

CEL

Techdata Sheet

SNOW TRANSPORT EQUIPMENT
MODEL 1000 TOWED SNOWPLOW CARRIER

The CEL Model 1000 Towed Snowplow Carrier is an important piece of equipment in the layered compaction method of elevated snow-road construction. The snowplow is used to deposit blower-processed snow from borrow pits onto the road surface to create each new 4-inch layer to be compacted. These elevated roads are comparatively immune to severe drifting. In addition, the snowplow is effective in clearing drift snow from previously compacted snow and ice roads. Specification details for the snowplow are given in NCEL Drawings 67-38-1F through 17F

FEATURES OF THE TOWED SNOWPLOW

- 56 feet 9 inches long
- Ski mounted
- Two hydraulically controlled grader blades which windrow snow into the cutter blades and impeller
- Liquid-cooled, 6-cylinder diesel engine
- 175 horsepower at 2,800 rpm
- Shipping weight: 34,000 pounds
- Shipping cube: 2,700 cubic feet

ADVANTAGES OF THE TOWED SNOWPLOW

- Long frame permits uniform removal of snow from borrow pits in construction of snow roads and other snow removal operations.
- Ski-mount eliminates pitching and rolling on deep snow.
- Casting chute allows controlled placement of snow, depositing it as far as 100 feet, at rates up to 1,700 cubic yards per hour.
- Snowplow is easily assembled in approximately 108 man- hours in the field, using standard weight-handling equipment.

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