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ROLE OF SINTERING IN SNOW CONSTRUCTION

by

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PREFACE

This paper was prepared by René O. Ramseier, Research Physicist, of the Research Division (James A. Bender, Chief), U. S. Army Cold Regions Research and Engineering Laboratory.

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CONTENTS

	Page
Preface	ii
Summary	iv
Introduction	1
Theoretical considerations	1
Practical considerations	3
Construction of snow runways	5
Site II Greenland	5
McMurdo Sound, Antarctica	6
Amundsen-Scott South Pole Station	7
Conclusion	9
Literature cited	9

ILLUSTRATIONS

Figure		
1.	Sintering curve for Site II, Greenland	4
2.	Required minimum strength of snow pavement for various aircraft as a function of depth	5
3.	Sintering curves as a function of porosity at -20C, Site II, Greenland	7
4.	Sintering curve for McMurdo Sound, Antarctica	7
5.	Sintering curves for Amundsen-Scott South Pole Station	8
6.	Temperature profiles at Amundsen-Scott South Pole Station	8

TABLES

Table		
I.	Limiting porosity n_ℓ	4
II.	Parameters for calculating sintering curves for various stations	4
III.	Strength of snow tested at various temperatures and porosities after sintering for 30 days at -20C	6

SUMMARY

The mechanism of sintering and the effect of compaction on snow is discussed. Examples of possible snow runway construction using processed snow for Site II, Greenland, and McMurdo Sound and Amundsen-Scott South Pole Station, Antarctica, are given. From theory and the examples discussed, it is concluded that snow runways capable of handling large aircraft can be constructed in any polar or temperate region with enough snow and temperatures below the melting point for a sustained period.

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INTRODUCTION

Because of the almost complete lack of roads in the polar regions, the ability to land aircraft on snow has always been of great importance in polar operations. In Greenland the first operation that utilized aircraft landings on snow was that of Ellsworth and Amundsen with Riiser-Larsen and Dietrichson as pilots in 1925. The following year Byrd flew his ski-equipped Fokker trimotor to the North Pole with Floyd Bennett as pilot. In 1928-29 the skiplane was introduced to the Antarctic by Byrd (Mellor, 1963). Since then landing on skis in Greenland and the Antarctic has gradually become a routine matter. Since World War II, prepared runways where large aircraft without skis can operate have predominated. The demand for prepared runways increased with the construction of the early warning sites in Greenland and the Antarctic phase of IGY in 1956. Presently, the large aircraft being used in polar operations are the C-124 (Globemaster) and the C-130 (Hercules), both with wheeled landing gear. The latter is also equipped with a ski-wheel type modification for Greenland and Antarctic use; however, this reduces the load-carrying capacity.

Since not all aircraft are equipped with skis the capability of landing wheeled aircraft on snow runways has become of considerable interest. In addition wheels are much lighter than skis, cause less drag on take off, and have no air drag. For ski-equipped aircraft longer runways are needed to lift the same amount of weight and air speed is lowered appreciably by air drag. A snow runway was constructed at Site II, Greenland, in 1955 and was successfully used for landing wheeled aircraft with cargo (C-124, C-47) and personnel (C-54) (Bender, 1957). Similar attempts have been made in the Antarctic, but without success.

It is the purpose of this paper to theoretically and experimentally analyze the problem of snow runways and establish criteria permitting adequate site evaluation and effective construction of landing strips. The results are applicable not only to polar regions but also to temperate areas with a heavy annual snow accumulation.

THEORETICAL CONSIDERATIONS

It is important to consider the two distinct temperature-dependent processes affecting the physical properties of snow: the process of sintering and the process of strength increase and decrease with decreasing and increasing temperature.

Under suitable circumstances snow particles adhere to each other and as the time or temperature increases the extent of the bonding increases so that what was originally a loose layer of snow becomes a porous solid having a certain physical strength. In low density snow it has also been observed that the density of the snow layer increases during the sintering process. This, however, has not been observed at densities of $0.5\,g\,cm^{-3}$ and above. Sintering then may be considered to consist of two stages: the welding of snow particles in contact and the elimination of porosity. These phenomena are observed regardless of whether the snow is initially compacted or not.

In earlier publications on snow, the word age-hardening has been used to refer to the sintering process. Because age-hardening has a different meaning in the material sciences, the term sintering is used in this paper.

Ramseier and Sander (1965) have studied sintering of one type of snow as a function of temperature. They confirmed the equation proposed by Jellinek (1957) and also showed that the mechanism responsible for sintering of snow is very likely one of evaporation from the grain surface, diffusion through the ambient atmosphere, and condensation at places where grains are in contact.

The sintering equation is:

$$\frac{\sigma_f - \sigma_t}{\sigma_f - \sigma_0} = \exp - (kt) \tag{1}$$

where σ_f is the final unconfined compressive strength of snow after it is fully sintered, σ_t is the unconfined compressive strength of snow at a given time t, σ_0 is the initial strength due to compaction at $t = 0$, and k is a rate constant defined as

$$k = A \exp - \left(\frac{E}{RT}\right). \tag{2}$$

Here A and E are constants, E being the activation energy of the sintering process,* R the gas constant, and T the absolute temperature.

Combining eq 1 and 2 the following is obtained:

$$\frac{\sigma_f - \sigma_t}{\sigma_f - \sigma_0} = \exp - \left[A\,t \exp - \left(\frac{E}{RT}\right)\right]. \tag{3}$$

When $\sigma_0 = 0$, $t + t_0 = 0 = \tau$. The t_0 is the time it would take the uncompacted snow to sinter to the strength σ_0 as a result of mechanical compacting. Substituting this into eq 3 a solution can be found for

$$\sigma_\tau = \sigma_f \left\{1 - \exp - \left[A\,\tau \exp - \left(\frac{E}{RT}\right)\right]\right\}. \tag{4}$$

The appropriate limits are:

at $\tau = 0$, $\sigma_t = 0$ and at $\tau \to \infty$, $\sigma_t \to \sigma_f$.

This is exactly what is observed in nature. (Densification effects are not included in this equation.)

The only unknowns in this equation are A and σ_f. σ_f can be determined very easily as will be shown in the discussion on hardening effects produced by temperature. A on the other hand is more difficult to obtain. Because it is a function of both density and snow structure, it must for both cases be found experimentally. The strength of fully sintered snow can be represented satisfactorily by (Ballard and McGaw, 1965):

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* $E = 10.18$ kcal · mole^{-1}

$$\sigma_f = \sigma_i\left(1 - \frac{n}{n_\ell}\right) \tag{5}$$

where σ_i is the unconfined compressive strength of fine-grained, randomly oriented, bubble-free ice, n is the porosity, and n_ℓ is the limiting porosity which is assumed to be an indicator of snow structure or snow type. It has been experimentally verified (Table I) that n_ℓ does not vary greatly. The n_ℓ value given by Ballard and Feldt (1966) represents the upper limit. They have also expressed σ_f for the entire snow density range. Their expression is complicated and has little bearing on the present problem since low-density snow is unsuitable for runways.

The n_ℓ can be obtained experimentally by performing a series of unconfined compression tests on fully sintered snow as a function of porosity (density) at a given temperature. σ_i is defined as follows (Butkovich, 1954):

$$\sigma_i = 41.83 - 0.778\,\theta \tag{6}$$

where θ is the temperature in °C. This equation seems to hold up to -3C (Bender, 1957).

Strength increase of snow with decreasing temperature can easily be obtained by eq 5. For a snow with constant n and n_ℓ but different σ_i a new σ_f can be calculated to be

$$\sigma_f' = \sigma_f\left(\frac{\sigma_i'}{\sigma_i}\right). \tag{7}$$

PRACTICAL CONSIDERATIONS

Sintering at a temperature near the melting point will give a rapid increase in the strength properties of the snow and 95% of the final strength of the snow will be reached in a relatively short time. With a decrease in temperature the process of sintering is slowed down considerably. The most efficient way to obtain good strength properties would, therefore, be to allow the snow to sinter after processing near the melting point until the bonds between the grains are fully developed, and then have a drop in the snow temperature which will significantly increase the strength of snow.

The curve shown in Figure 1 has been calculated for snow having no bonds initially* at time $\tau = 0$. The strength gained from compaction, however, seems to be equal to that resulting from sintering for 6 days. Ramseier and Keeler (1966) have shown that the initial rapid increase after compaction is due to the creation of new bonds. It is, of course, obvious that the strength acquired depends on the density obtained before sintering which depends in turn on the temperature at which the snow was compacted. It would, therefore, be advantageous to compact the processed snow at the highest temperature possible to obtain the highest possible density.

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* All sintering curves have been calculated up to $0.95\ \sigma_f$.

Table I. Limiting porosity n_ℓ (various investigators).

	n_ℓ
Ballard and Feldt (1966)	0.6
Butkovich (1956)	0.557
Ramseier (1963)	0.540
Ramseier and Sander (1965)	0.532

Table II. Parameters for calculating sintering curves for various stations.

	Site 2							McMurdo		South Pole			
T(C)	-20							-3	-10	-30	-40	-50	-60
n	0.457	0.455	0.433	0.411	0.389	0.367	0.346	0.324		0.400			
n_ℓ	0.57							0.540		0.540			
A(day^{-1})	4.6×10^7							2.8×10^7		3.05×10^7			
0.95 σ_f	10.9	11.1	13.2	15.3	17.5	19.6	21.6	16.9	19.0	16.1	18.0	19.9	21.8
τ (day)	45							20	34	150	370	380	2300
σ_f	11.4	11.6	13.8	16.0	18.2	20.4	22.5	17.7	19.8	16.9	18.9	20.9	22.9

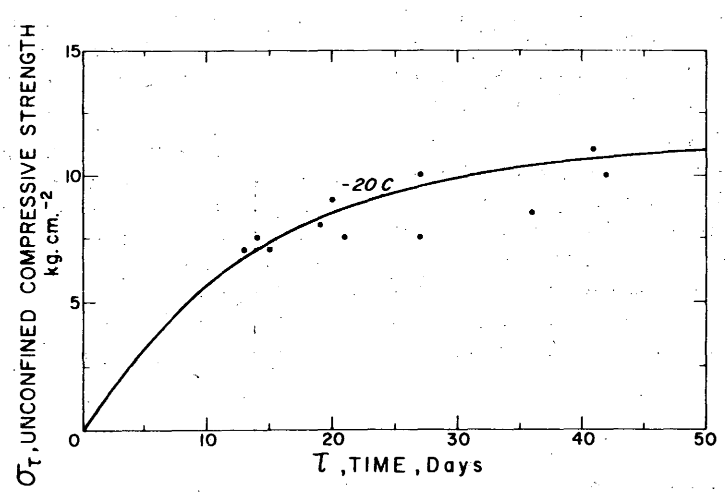

Figure 1. Sintering curve for Site II, Greenland (data from Butkovich, 1962).

CONSTRUCTION OF SNOW RUNWAYS

With these points in mind, it is now possible to present a cookbook version of how to construct a runway with processed snow. Factors essential to construction of a snow runway include good weather forecasting, records of the past years' daily mean temperature, and an understanding of the mechanics of sintering and compaction. Three examples of construction will be given – one for dry snow conditions in Greenland (Site II), the second for conditions at McMurdo Sound where the snow temperature reaches the melting point occasionally, and the third for areas of low mean annual temperatures such as the South Pole. Table II contains various parameters used to calculate the sintering curves.

SITE II GREENLAND

Site II is located at 76°59'29" North and 56°05'42" West on the Greenland Ice Cap. The mean annual temperature is -24.3 ± 0.2C. Butkovich (1962) found that uncompacted processed snow deposited by a Peter snow miller at Site II had a reasonably uniform density profile with a representative average density of 0.498 g cm^{-3}. The temperature was approximately constant at -20C. The increase of strength with time (Butkovich, 1962) is shown in Figure 1. A curve was fitted to the data according to eq 4. The critical porosity n_ℓ was assumed to be 0.570 and the preexponential factor $A = 4.6 \times 10^7$ day^{-1}. Ninety-five percent of the final unconfined compressive strength was reached after 44 days of sintering, corresponding to 10.9 kg cm^{-2}. The final strength was 11.4 kg cm^{-2}. It should be noted here that the actual sintering time was (τ - 6) days because of the initial compaction due to the weight of the snow itself. This gives a sintering time of 38 days. For the remainder of this paper sintering times will be understood to be equal to τ - 6.

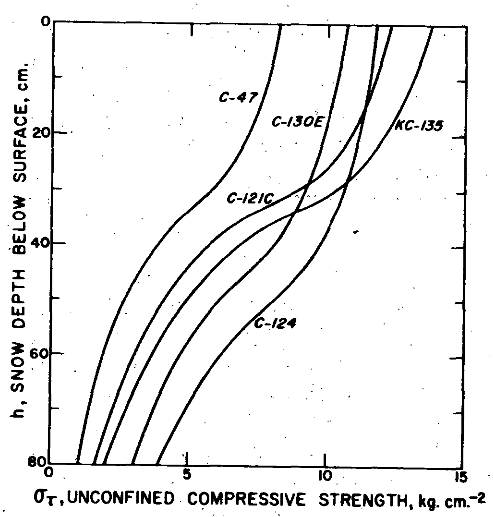

Figure 2. Required minimum strength of snow pavement for various aircraft as a function of depth (Abele and Frankenstein, 1967).

Figure 2 gives the required strength of a snow pavement for various aircraft (Abele and Frankenstein, 1967). In the case of the Navy version of the C-130E (Hercules) the minimum strength requirement at the surface is 10.7 kg cm^{-2}. This value corresponds to a sintering time of 34 days (Fig. 1), i.e., a C-130E could land after the snow had sintered for at least 34 days. On the other hand, this snow will never gain sufficient strength to permit landing a KC-135, which requires a minimum strength of 13.7 kg cm^{-2} (Fig. 2), regardless of the sintering time (see Fig. 1). A different runway preparation method is required. Temperature can not be decreased, but the density can be increased. Wuori (1963) obtained densities of ~0.6 g cm^{-3} for Peter processed snow after running a D-8 LGP tractor over the snow approximately 8 times. In Figure 3 sintering curves have been plotted for various porosities at -20C. Table III gives the strength of snow after it sinters for 30 days at -20C for various temperatures and porosities.

Table III. Strength of snow tested at various temperatures and porosities after sintering for 30 days at -20C.

T	n	0.346	0.367	0.389	0.411	0.433	0.455
- 5		18.0	16.4	14.5	12.7	11.0	9.3
-10		19.4	17.8	15.8	13.7	12.0	10.0
-15	σ_τ	21.1	19.3	17.0	15.0	12.9	10.9
-20		22.5	20.4	18.2	16.0	13.8	11.6
-30		25.7	23.4	20.8	18.3	15.8	13.3

In 1955 a runway was built at Site II using a heat process technique. Landings were made by C-47, C-54 and C-124 aircraft (Bender, 1957). This runway was used at a time in late summer when the airstrip was already getting cold, i.e., 1) warm summer temperatures and heat processing speeded up sintering and, 2) cold early fall weather gave it additional strength (Bender, personal communication). Since this construction the techniques of building a runway have been much improved and simplified (Abele and Frankenstein, 1967; Abele, Ramseier and Wuori, 1966).

McMURDO SOUND, ANTARCTICA

The mean annual air temperature at Williams Field on McMurdo Sound is ~-17C (Péwé, 1960). Between late November and early February the temperature may rise a few degrees above 0C causing the snow to melt and form ice lenses. During these occasional periods of high temperature the sea ice runway becomes unusable. Because of this and the possibility of the breakup of the sea ice, an emergency landing facility was needed. One possible answer was to build a snow runway for wheeled aircraft. The data available for a study of possible snow runway conditions at McMurdo Sound are very scanty. The only reliable temperature and strength data on the snow were collected by Abele and Frankenstein (1967). Using these data it was, however, possible to obtain the sintering curve shown in Figure 4.

The strength necessary to support a C-130E is reached after 4 days at -10C. At -3C it is only necessary to compact the snow to obtain the minimum strength of 10.7 kg cm^{-2} at a density of 0.62 g cm^{-3}. When temperatures are above 0C landing is inadvisable because of weakened surface layers. Unfortunately, the strength behavior near the melting point is not satisfactorily understood. Butkovich (1954) gives 20.2 kg cm^{-2} as an average for the strength of ice near 0C. This is just half the extrapolated value for the temperature dependence of ice near 0C. If an estimate for a fully sintered snow is made it would correspond to a strength of ~8 kg cm^{-2}. This is in good agreeement with the point at τ = 21 days in Figure 4. At the time this point was measured the air temperature was near 0C and previously had been above 0C. It is very likely that the snow was near 0C and was wet* which would cause even lower strength properties because the water

* Snow grains are covered with a liquid layer of water.

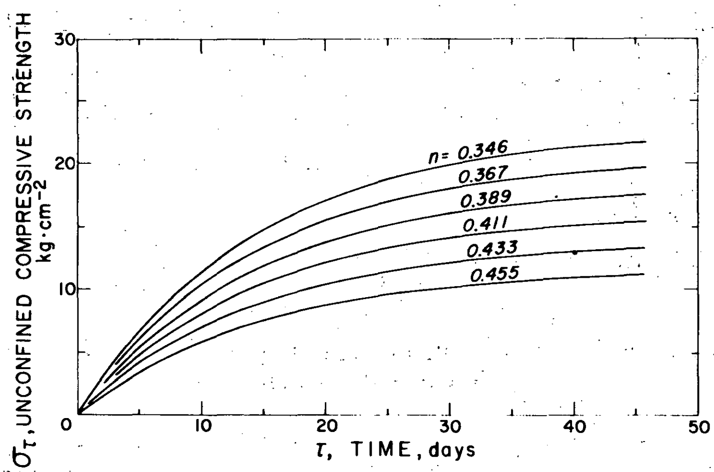

Figure 3. Sintering curves as a function of porosity at -20C, Site II, Greenland.

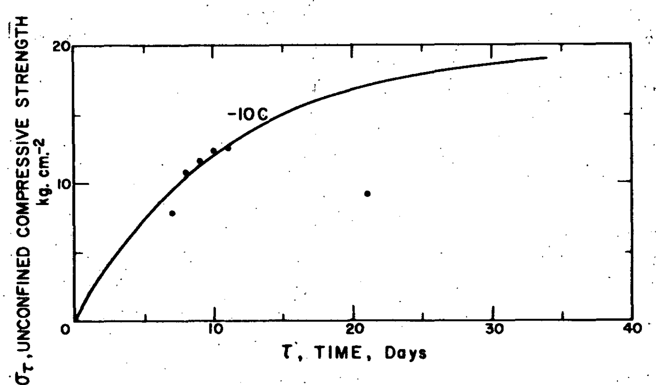

Figure 4. Sintering curve for McMurdo Sound, Antarctica (data from Abele and Frankenstein, 1967.

would act as a lubricant. Thus, it would appear possible to land aircraft in the McMurdo area except when the snow is at 0C or slightly below freezing with a liquid layer of water surrounding the snow grains.

AMUNDSEN-SCOTT SOUTH POLE STATION

This station has a mean annual snow temperature of -51C. The maximum density which can be obtained is ~0.55 g cm^{-3} (Gow and Ramseier, 1963). $\underline{A}$ and n_ℓ were found to be 3.05 x 10^7 day^{-1} and 0.54 respectively. In Figure 5 several sintering curves are shown at different temperatures. At -50C it takes about 240 days to reach the minimum strength required to support a C-130E. Figure 6 shows some temperature profiles (Giovinetto, 1960) at this location. It is possible to have snow temperatures as high as -25C for short periods of time near the surface. The temperature at a depth of 50 cm can be as high as -30C. The average monthly mean air temperature for January over a period of 5 years is ~-28C (Ramseier, 1962).

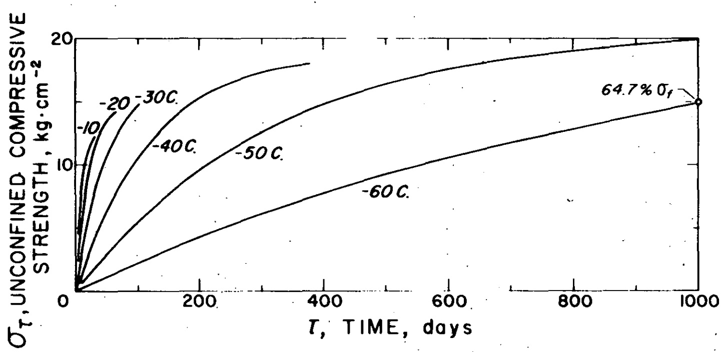

Figure 5. Sintering curves for Amundsen-Scott South Pole Station.

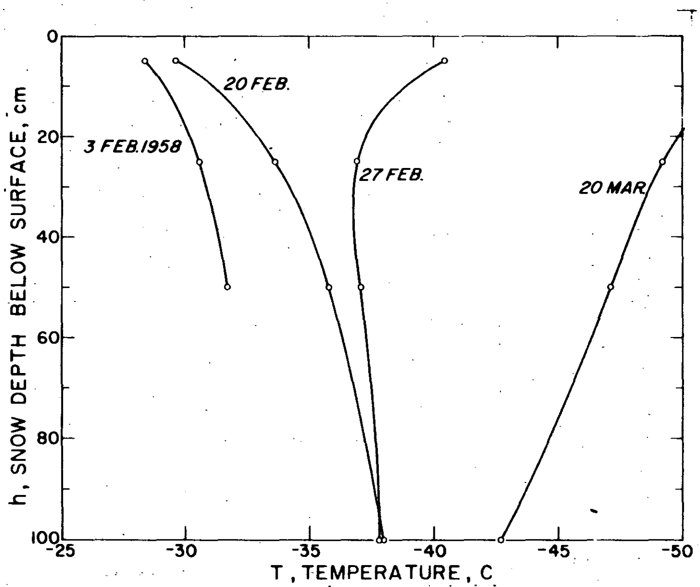

Figure 6. Temperature profiles at Amundsen-Scott South Pole Station (data from Giovinetto, 1960).

One can then assume that for a period of 30 days the upper layers of snow may be at -30C. The strength after 30 days is 7.7 kg cm^{-2}. In February the snow temperature will drop to a mean of -40C. This will cause an increase in strength to 8.6 kg cm^{-2} due to the temperature dependency. Sintering increases the strength to σ = 10.7 kg cm^{-2}. In all it would take about 60 days to reach the minimum strength required to support a C-130E. There is an additional increase in strength due to solar radiation (Gow and Ramseier, 1963). How much it will affect the snow in situ is not known.

Under the circumstances mentioned above it is possible to build a processed compacted snow runway even at the South Pole. Because of the short summer season it is suggested that the strip be used the season following its construction. Since there is a snow accumulation of only 7 g cm^{-2} yr^{-1} water equivalent or 19-20 cm a year (Gow, 1965) the snow can be removed very easily with a bulldozer before the opening of the new season.

Another possibility is to preheat the snow in the chute of the Peter snow miller. This would increase the initial rate of sintering for a short time, probably resulting in a substantial increase in strength. It is, however, not highly recommended because of equipment problems at low temperatures.

Construction of snow runways by compaction is possible anywhere in the high plateau region in the Antarctic even where the mean annual snow temperature drops to -61.7C (Kartashov, 1962) (near the Pole of Inaccessibility).

CONCLUSION

According to the theory of sintering and compaction it is possible to build compacted snow runways in almost any polar area. There are some restrictions where the snow temperature reaches 0C during which periods no landing should be made. At the other extreme, low temperatures cause a long delay before the snow runway can be used. The time can be shortened if the snow is heated during processing and before it is redeposited.

It is very necessary to obtain good temperature records and strength determinations during construction and maintenance of the snow runway. The effect of grain size and distribution on the sintering rate is currently being studied.

The use of processed snow as a construction material is of course not limited only to snow runway construction. As early as 1913 Koch and Wegener (1930) used this concept on a Greenland expedition. They mixed ice chips with snow to build bridges across crevasses which could be crossed by horses and sledges the following day. A more recent application has been the use of processed snow to cover metal arches over a trench in Greenland. After a few days the metal arches were removed, leaving a self supporting snow arch. The same technique would not have been possible using naturally deposited snow. In the Antarctic at Byrd Station processed snow was used as foundations for the snow arches spanning a 13 m wide trench.

At McMurdo Sound, Antarctica, the Navy has successfully built and operated a processed snow road for wheeled vehicles to transport material between the sea ice landing field and McMurdo Station. As can be seen, there are numerous applications where processed snow can be used successfully as a construction material, but snow runway construction is the most difficult and, therefore, the most challenging.

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13. ABSTRACT

The mechanism of sintering and the effect of compaction on snow is discussed. Examples of possible snow runway construction using processed snow for Site II, Greenland, and McMurdo Sound and Amundsen-Scott South Pole Station, Antarctica, are given. From theory and the examples discussed, it is concluded that snow runways capable of handling large aircraft can be constructed in any polar or temperate region with enough snow and temperatures below the melting point for a sustained period.

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Snow--Sintering						
Snow compaction--Airfields						
Snow (Construction material)--Test results						
Snow (Processed)--Metamorphism						