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Research Report 189
TEMPERATURE DEPENDENCE
AND MECHANISM OF SINTERING

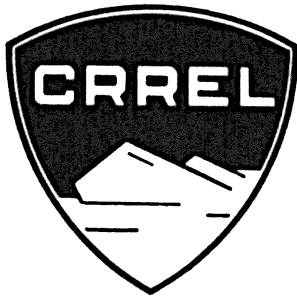
by

René O. Ramseier
and
Gary W. Sander

JULY 1966

U.S. ARMY MATERIEL COMMAND
COLD REGIONS RESEARCH & ENGINEERING LABORATORY
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PREFACE

This report was prepared by René O. Ramseier, Research Mechanical Engineer and SP5 Gary W. Sander, Research Division, James A. Bender, Chief.

The authors would like to thank Drs. J. Bailey, P. Hobbs, K. Itagaki and R. Wolfson for their helpful discussions during the preparation and revision of this paper.

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SUMMARY

Both the degree of sintering of snow and the rate constant as a function of temperature can be represented satisfactorily by an exponential equation. The results strongly suggest that the sintering process is one of evaporation, diffusion through the ambient temperature, and condensation.

TEMPERATURE DEPENDENCE AND MECHANISM OF SINTERING

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INTRODUCTION

Jellinek (1957) found that the process of sintering* could be represented by an exponential equation of the form

$$\left(\frac{\sigma_f - \sigma_t}{\sigma_f - \sigma_0} \right) = \exp(-kt) \quad (1)$$

where σ_f is the final strength of snow after sintering for a long period, σ_t is the strength of snow at a given time t , σ_0 is the initial strength at $t = 0$ and k is a rate constant with the dimension of t^{-1} . Since then Butkovich (1962) and Gow and Ramseier (1963) have studied certain types of sintering but did not investigate k as a function of temperature (k may vary with size distribution, shape, density, etc.). A subsequent attempt to do so using the data of Wuori (1963) in addition to that cited above was not successful, probably because there was too little control over variables other than temperature. All the data mentioned above can be fitted satisfactorily by eq 1. This encouraged us to make another attempt to study the sintering process as a function of temperature, keeping size distribution, shape, and density nearly constant.

Jellinek suggests that the rate constant k for sintering may follow an exponential expression of the form

$$k = A \exp(-E/RT) \quad (2)$$

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

EXPERIMENTAL METHODS

The convenient and widely used unconfined compression test method was used. Snow was harvested during the winter of 1963/64 in Hanover, New Hampshire, and stored at -20°C . At the start of the test equal amounts of this snow were placed in coldrooms at five different temperatures (Table I). After the snow had reached equilibrium with room temperature, it was disaggregated on a sieve of 0.707-mm mesh. The disaggregated snow was compacted to a density of $0.538 \pm 0.012 \text{ g cm}^{-3}$ in a mold consisting of two half cylinders coated with Teflon (polytetrafluorethylene) on the inside for easy removal of the compacted snow cylinder, following the method of Gow and Ramseier (1963).

After the snow cylinders had been sintered at the different temperatures, ranging from -3°C to -38°C , for a given time† (Table I) they were moved to a

*Sintering, often termed age hardening, here is restricted to the process of adhesion or welding (bond growth between touching grains) of surfaces in contact. The effects of sintering on densification as a function of temperature are not considered.

†It was assumed that during the sintering process the density would stay nearly constant. Gow and Ramseier (1963) found no significant changes during a long sintering process at -49°C and a density of $\sim 0.550 \text{ g cm}^{-3}$. This is shown to be in agreement with the mechanism of sintering (see discussion).

coldroom at -38C and allowed to reach thermal equilibrium. The snow cylinders were then crushed with a motorized Soiltest press at a rate of 20 cm min^{-1} and the strength was calculated from the proving ring dial gauge indication.

RESULTS

Results are given in Table I. Data for South Pole snow (SP), from Gow and Ramseier (1963), are included. When the density difference among replicas was great enough to require a correction, the unconfined compression data were plotted against the sample density on log-log scale and the unconfined compressive strength for a density of 0.538 g cm^{-3} was chosen.

Figures 1 and 2 show the unconfined compressive strength as a function of time for the various groups aged at different temperatures and crushed at a lower common temperature. Figures 1 and 2 were obtained by first plotting σ_t versus t and σ_f * was determined approximately by inspection (Fig. 2). Then $(\sigma_f - \sigma_t)$ was plotted on a semi-log scale versus t to determine the values of σ_0 (Fig. 1). This provided all the information required to calculate k from eq 1. Equation 1 was then extrapolated to $\sigma_t = 0$ as shown in Figure 2. The data for the South Pole are given for comparison.

It may be of significance that the extrapolated curves converge at a point between -6 and -7 days at σ_f . The meaning of the convergence, if indeed it has a physical meaning, is not clear at present.

As can be seen from Figure 1 the strength σ_0 at time $t = 0$ is rather sharply temperature dependent. The reason for this is imperfectly understood. However, it seems probable that the initial strength σ_0 at $t = 0$ was acquired due to compaction. A number of grains have been welded together, producing the same general effect as sintering. This effect is of great interest but is not within the scope of this paper and will be treated in more detail elsewhere.

In Figure 2, σ_f is taken as the final or ultimate compressive strength of snow (crushed at a common temperature (-38C), but sintered at different temperatures) for the density with which we are working. The curve for group A (-3C) becomes asymptotic to σ_f rapidly, reaching 95% of its ultimate strength at 18 days whereas group E (-38C) would take 310 days to reach this strength (Table I). Group D includes only one value as the other samples were accidentally lost through warm-up of a coldroom. The temperature for the SP group (which was tested as well as sintered at -49C) was corrected from -49C to -38C using the temperature correction which is implicit in the relationship developed by Ballard and McGaw (1965).

$$\sigma_f = \sigma_i \left(1 - \frac{n}{n_l}\right) \quad (3)$$

Here σ_f is the failure strength of snow, σ_i is the strength of clear lake ice parallel to the long crystal axis (Butkovich, 1954), n is the porosity, and n_l is a limiting porosity which varies with different types of snow. All temperature effects are included in σ_i .

There is good agreement with the present data, and we can also check the value of n_l for both conditions. For the SP group $n_l = 0.540$ and for the snow used

*It was taken as $\sim 16.0\text{ kg cm}^{-2}$. Later it was calculated according to eq 3 to be 15.8 kg cm^{-2} which is in good agreement with the experimental value.

Table I. Experimental results.

| Group | Age (days) | Temp (C) | Number samples tested | Avg ρ (g cm^{-3}) | Avg σ_t ($\text{g cm}^{-2} \times 10^3$) | σ_0 ($\text{g cm}^{-2} \times 10^3$) | Rate constant k (day^{-1}) | t ($0.95\sigma_t$) (days) |
|-------|------------|----------|-----------------------|-----------------------------------|---|---|---------------------------------------|-----------------------------|
| A | 2 | -3 | 5 | 0.550 | 13.0 \pm 1.4 | 11.55 | 0.206 | 18 |
| | 4 | | 4 | 0.545 | 14.1 \pm 0.9 | | | |
| | 9 | | 5 | 0.541 | 15.3 \pm 1.5 | | | |
| | 16 | | 4 | 0.545 | 15.8 \pm 0.7 | | | |
| B | 2 | -10 | 3 | 0.538 | 9.5 \pm 0.4 | 8.1 | 0.113 | 30 |
| | 4 | | 3 | 0.538 | 10.9 \pm 0.1 | | | |
| | 16 | | 8 | 0.538 | 14.7 \pm 1.4 | | | |
| D | 2 | -14 | 3 | 0.544 | 7.7 \pm 1.2 | 6.3 | 0.0768 | 40 |
| C | 2 | -19 | 8 | 0.538 | 5.9 \pm 0.6 | 4.75 | 0.0511 | 60 |
| | 4 | | 4 | 0.534 | 6.8 \pm 0.6 | | | |
| | 9 | | 4 | 0.536 | 8.9 \pm 0.7 | | | |
| E | 2 | -38 | 4 | 0.535 | 1.95 \pm 0.1 | 1.7 | 0.0127 | 310 |
| | 4 | | 4 | 0.531 | 2.3 \pm 0.5 | | | |
| | 10 | | 1 | 0.533 | 3.2 | | | |
| SP | 2 | -49 | 10 | 0.550 | 0.2 \pm 0.1 | 0.4 | 0.0033 | 880 |
| | 4 | | 10 | 0.550 | 0.5 \pm 0.1 | | | |
| | 9 | | 10 | 0.550 | 0.75 \pm 0.3 | | | |
| | 16 | | 10 | 0.550 | 0.9 \pm 0.1 | | | |

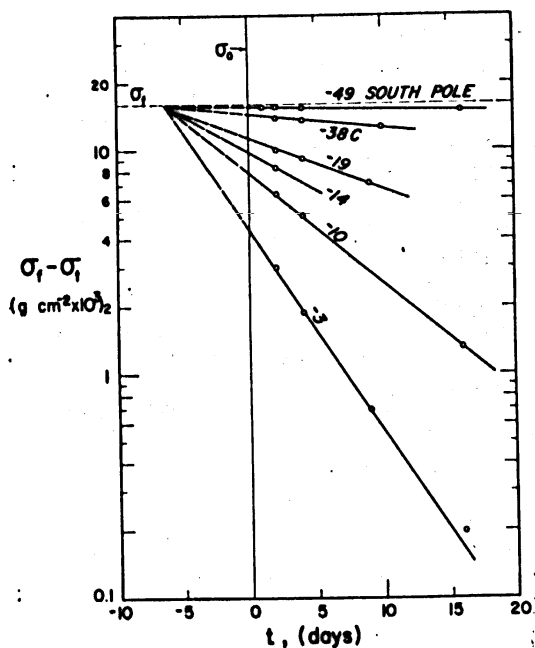


Figure 1. Experimental data plotted as the difference between the final strength of snow and the strength at time t versus time.

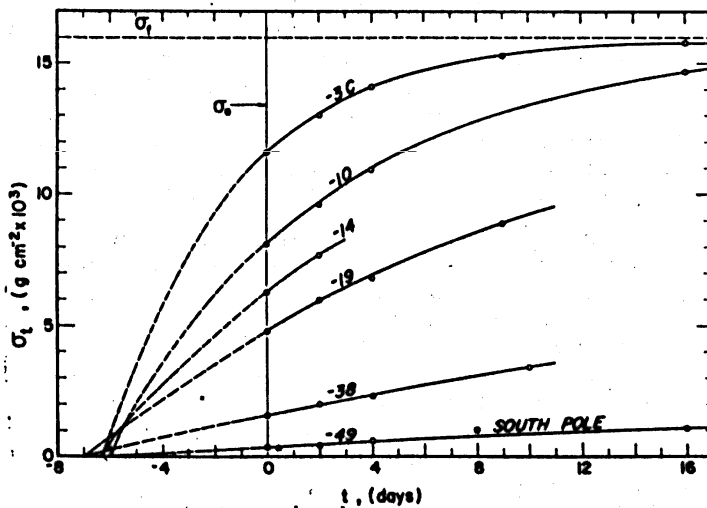


Figure 2. The unconfined compressive strength of snow as a function of time.

in this experiment $n_f = 0.532$. From this we see that the particular snow we used is similar to the snow at the Amundsen-Scott South Pole Station.

In Figure 3 we have plotted the rate constant k against temperature. Equation 2 fits the data well.

DISCUSSION

For snows of a given density, in Figure 4 we see that all curves will eventually reach the same final strength σ_f . Snow at a temperature near zero (-3C) will sinter faster than snow at a lower temperature (-38C) and will reach its ultimate strength in a relatively short time. This permits us to make a good estimate of σ_f , which we need to be able to calculate the rate constant k from eq 1. If the strength of snow is tested at a temperature different from the sintering temperature, the only increase or decrease in strength is due to the temperature effect given by eq 3.

There are three possible mechanisms for the sintering of snow: bulk transport, surface transport, and vapor-phase transport. Because of the low volume self diffusion coefficient of ice, it seems very unlikely that bulk transport could be the dominant mechanism. This coefficient has been measured by Dengel and Riehl (1963) using tritium as a tracer. Its value is of the order of $2.9 \times 10^{-11} \text{ cm}^2 \text{ sec}^{-1}$ at -3.0C, decreasing to $14 \times 10^{-12} \text{ cm}^2 \text{ sec}^{-1}$ at -33.3C (Fig. 5). The corresponding activation energy is $13.5 \text{ kcal mole}^{-1}$ (Dengel and Riehl, \perp to c-axis). Although Kuroiwa (1961) concluded that volume diffusion is responsible for sintering, at least above -15C the more recent determination of the volume diffusion constant does not support this position.

In the absence of any quantitative theoretical or experimental treatment of surface diffusion, we cannot draw any definite conclusions about surface transport. Hobbs and Mason (1964), from theoretical calculation, found that the surface mass transport coefficient should be similar in magnitude to the volume diffusion coefficient. Kingery (1960a) on the other hand claims that surface transport is the dominant mechanism in sintering. However, his experimental activation energy of $27.5 \text{ kcal mole}^{-1}$ is too high, as Hobbs and Mason point out, "being more than twice the latent heat of sublimation!" The issue is further obscured by the current disagreement as to the nature of the surface. It has been found that impurities on the surface can cause the presence of a thin layer of liquid below freezing (deQuervain, 1945; Nakaya and Matsumoto, 1954; Hobbs and Mason, 1964). This could account for the rapid growth of the neck, at least in the case of impure ice. Arguments by Jellinek (1961) and Fletcher (1962) support the idea that the "liquid-like" layer is responsible for the transport mechanism.

Vapor phase transport, if circumstances permit, is known to be rapid enough to explain sintering. deQuervain (1963) developed a specific model which is based on the presence of a vapor (temperature) gradient. Hobbs and Mason in their experiments derive a vapor mass transport coefficient for evaporation and condensation of the order of $10^{-7} \text{ cm}^2 \text{ sec}^{-1}$ at -5C (Fig. 5). The growth of bonds in air at atmospheric pressure can thus take place by the evaporation of material from the surface of the spheres (or grains), diffusion through the air, and condensation in the concave regions of the aggregate. In other words, the material is preferentially redeposited where the spheres or grains are in contact. In this process, the distance between the centers of the snow particles remains constant so that no shrinkage of the aggregate occurs; only the configuration of the pores changes. Hence, the snow density remains unchanged (Kingery, 1960b).

The apparent activation energy for the sintering process (k vs $1/T$) was found to be $10.2 \text{ kcal mole}^{-1}$. In order to compare the present results with the one obtained by Hobbs and Mason (1964) the apparent activation energy for the increase in strength (i. e. increase in bond area) had to be determined. A value of $6.8 \text{ kcal mole}^{-1}$ was obtained. From Hobbs and Mason's data and equations a value of $5.0 \text{ kcal mole}^{-1}$ was determined. The difference is due to several factors. In snow the increase in strength is not only

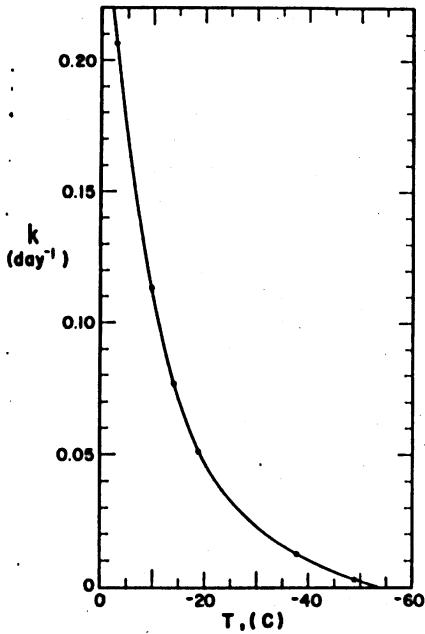


Figure 3. Temperature dependence of the rate constant k .

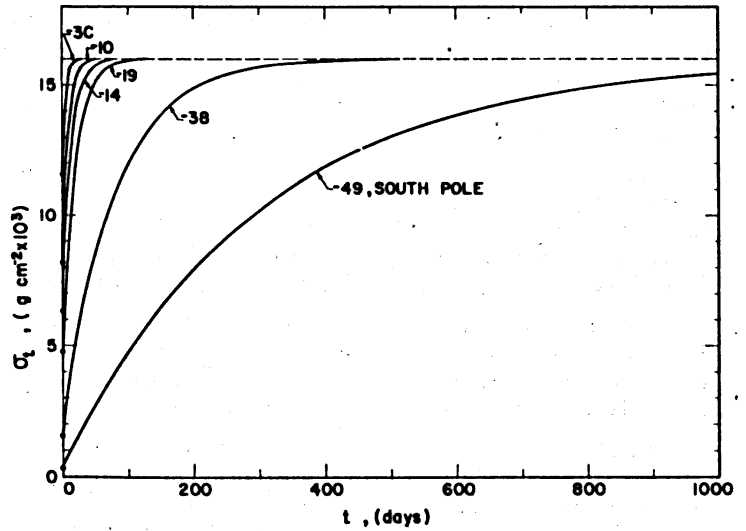


Figure 4. Sintering curves of different temperatures tested at a common temperature (-38C) extrapolated using eq 1.

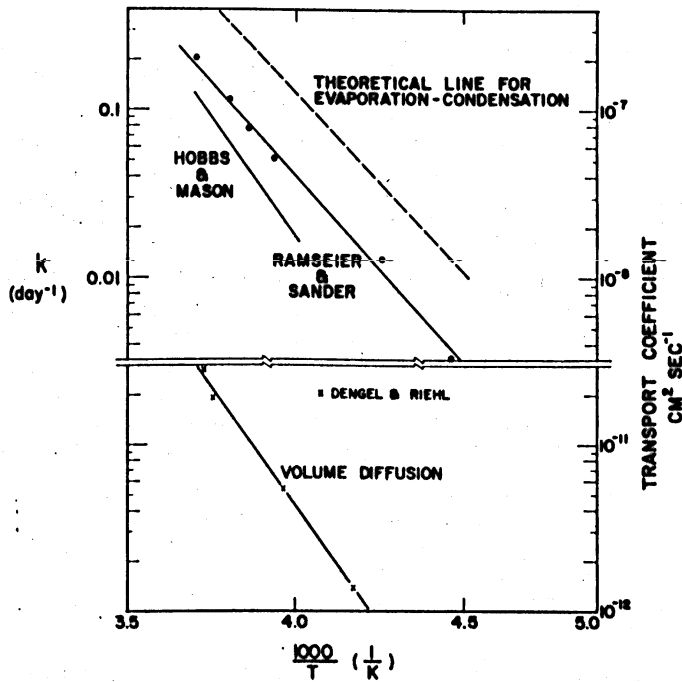


Figure 5. Comparison between different transport coefficients.

due to the increase in bond size but also to the creation of new bonds during the sintering process. This complicates the analysis considerably; Hobbs and Mason's experiment studied the growth of single necks. A further discrepancy comes in the form of the mathematical analysis since Hobbs and Mason use a power relationship and the present authors an exponential one.

Considering the above limitations, the agreement between Hobbs and Mason and the present study is good. The results suggest that the sintering process proceeds via the transport of material through the vapor phase. Additional experiments conducted by Ramseier and Keeler (1966) on the sintering of snow in silicon oil definitely support the above conclusions.

The present studies were conducted at one average density (Table I). For practical purposes, it is essential that the findings apply as well to other densities, ranging from newly fallen snow to $\sim 0.55 \text{ g cm}^{-3}$. The highest average density achieved experimentally for snow grains of uniform size is about 0.55 g cm^{-3} ; therefore, this can be used as the upper limit (Ramseier, 1963).

Thus, with the information available here (eq 1, 2, 3), we can calculate the unconfined compressive strength of snow at any age and temperature. The only assumption necessary is that the mechanism of sintering which has been shown above is the same for different densities.

In Figures 6 and 7 theoretical values for σ_t have been plotted for various temperatures. Here again we observe that for a snow near the melting point we have a rapid increase in strength to its final value σ_f . For a low temperature snow, the sintering process takes a long time but will eventually reach a higher final strength. The higher σ_f is due to temperature dependence. It is clearly seen then that the sintering process and the temperature dependence are working against each other at one stage. In other words high strength within a short time is best obtained by sintering the snow at a higher temperature and then cooling it to a working temperature. In Appendix A, Table AII the calculated σ_t and $\sigma_f - \sigma_t$ values have been given as a function of temperature including those at which testing was conducted. These curves are the result of strength determination tests conducted at the same temperature as the sintering process.

These findings can be applied to the seasonal snow cover or part of the snow cover where there is no appreciable temperature gradient to cause constructive metamorphism. deQuervain (1963) describes destructive metamorphism as resulting in "fine-grained snow that can be compacted by external forces to a high density and strength." Destructive metamorphism starts with disintegration of the snowflakes, small particles being taken up by larger ones. Finally an aggregate of irregular, rounded grains, usually of uniform size, is formed. At some point during this process sintering starts, i. e., touching grains are joined by necks which increase in size with an accompanying size decrease of the original grains. During this process the density remains constant. Here we can apply the findings of sintering as a function of temperature. If the snow is fully sintered, we can use the formulation of the final strength of snow (eq 3) as a function of temperature to find its respective strength.

There has been an increase in avalanche catastrophes in this country in recent years due to the opening of new ski areas and highways in remote regions. An understanding of the sintering process and temperature dependence together with correct application to the prevailing snow conditions (density, temperature), would give the avalanche forecaster a better way of analyzing the situation, and minimize avalanche accidents.

Another important application is in the construction field in places such as Greenland and Antarctica where snow as a material is abundant and can be used for constructing camps and snow runways for wheeled aircraft. In the latter case, processed snow is being used which obeys the rules described in this paper.

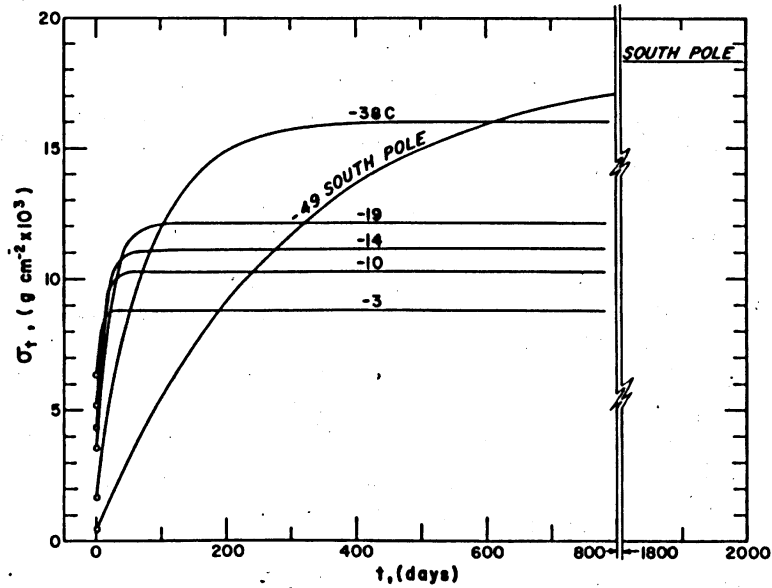


Figure 6. Sintering curves evaluated at different temperatures.

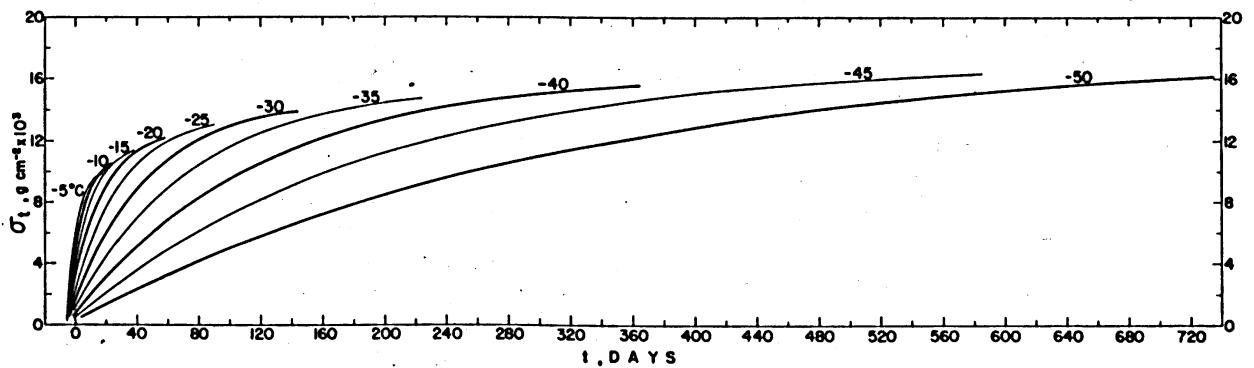


Figure 7. Sintering curves (calculated) at different temperatures.

CONCLUSIONS

It has been shown that the sintering of snow can be represented satisfactorily by eq 1. It is reasonable to assume that the findings will apply over the entire density range from freshly fallen snow to about 0.55 g cm^{-3} . One must be aware, however, that, especially in the case of freshly fallen snow, the sintering process will also be affected strongly by densification.

The sintering of snow as a function of temperature can be represented by an Arrhenius equation (eq 2). From the apparent activation energy obtained, one can say that the most probable mechanism of sintering of snow is one of evaporation, diffusion through the ambient atmosphere, and condensation.

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APPENDIX A

In Figure A1 (Jellinek, 1961) sintering curves have been combined and fitted to a theoretical curve. As can be seen from Figure A1 the sintering starts at $\tau = 0$. If the samples have been compacted to some extent, even by sample weight, the sintering process starts with a finite value. This causes the snow to have an initial strength equivalent to 6 days of sintering and this value is defined as σ_0^* .

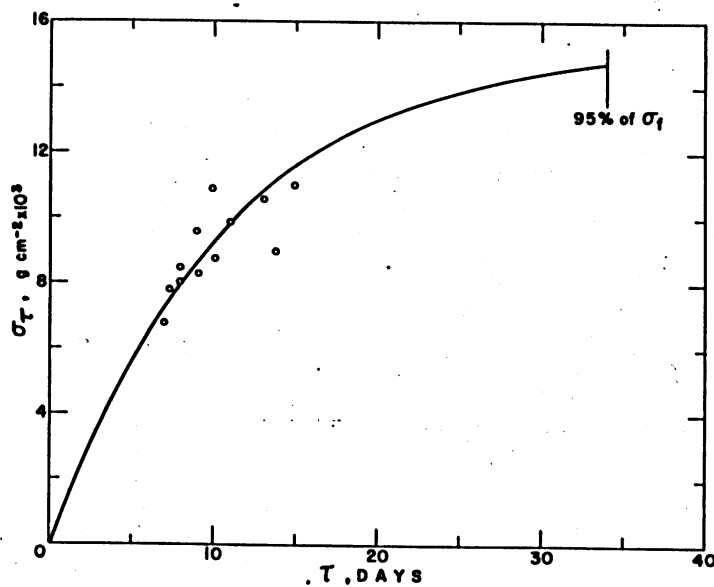


Figure A1. Sintering curve at -10°C evaluated from Jellinek data (1961).

*The implication mentioned has been investigated and the results will be published in the near future ("Role of sintering in snow runway construction" by R. O. Ramseier and "Theory of compaction" by J. Bailey and R. O. Ramseier).

Table AI. Jellinek's constants used for calculating the theoretical curves.

| | |
|-----------------------------|--|
| Density | $\rho = 0.555$ |
| Porosity | $n = 0.4$ |
| Limiting porosity | $n_l = 0.58$ |
| Preexponential factor | $A = 2.8 \times 10^7 \text{ day}^{-1}$ |
| Final strength of snow | $\sigma_f = 15.4 \text{ kg cm}^{-2}$ |
| Strength of ice | $\sigma_i = 49.6 \text{ kg cm}^{-2}$ |
| Temperature | $T = -10\text{C}$ |
| Strength at 0.95 σ_i | $= 49.6 \text{ kg cm}^{-2}$ |

Table AII. Theoretical values for various temperatures.

Here again the sintering starts at $\tau=0$. Comparison with Figures 6 and 7 ($\tau=t-6$) will give the appropriate answer for σ_t . Example: How old is snow with a strength $\sigma_\tau = 11.0 \text{ kg cm}^{-2}$ at -15C ? Looking at Table AII we obtain a value for $\tau=36$ days. The age is then $\tau -6=30$ days.

| T(C) | -3.0 | | -5.0 | | -10.0 | |
|------------------|--|---|--|---|--|---|
| τ (days) | σ_τ (kg cm^{-2}) | $\sigma_f - \sigma_\tau$ (kg cm^{-2}) | σ_τ (kg cm^{-2}) | $\sigma_f - \sigma_\tau$ (kg cm^{-2}) | σ_τ (kg cm^{-2}) | $\sigma_f - \sigma_\tau$ (kg cm^{-2}) |
| 0 | 0 | 9.9 | 0 | 10.2 | 0 | 11.1 |
| 2 | 2.8 | 7.1 | 2.6 | 7.6 | 2.0 | 9.1 |
| 4 | 4.8 | 5.1 | 4.5 | 5.7 | 3.7 | 7.4 |
| 6 | 6.3 | 3.6 | 6.0 | 4.2 | 5.1 | 6.0 |
| 8 | 7.3 | 2.6 | 7.0 | 3.2 | 6.2 | 4.9 |
| 10 | 8.1 | 1.8 | 7.9 | 2.3 | 7.1 | 4.0 |
| 12 | 8.6 | 1.3 | 8.5 | 1.7 | 7.8 | 3.3 |
| 14 | 8.9 | 1.0 | 8.9 | 1.3 | 8.4 | 2.7 |
| 16 | 9.2 | 0.7 | 9.2 | 1.0 | 8.9 | 2.2 |
| 18 | 9.4 | 0.5 | 9.5 | 0.7 | 9.3 | 1.8 |
| 20 | | | 9.7 | 0.5 | 9.6 | 1.5 |
| 22 | | | 9.8 | 0.4 | 9.9 | 1.2 |
| 24 | | | | | 10.1 | 1.0 |
| 26 | | | | | 10.3 | 0.8 |
| 28 | | | | | 10.4 | 0.7 |
| 30 | | | | | 10.6 | 0.5 |

Table AII (cont.) Theoretical values for various temperatures.

| T(C) τ (days) | -14.0 | | -15.0 | | -19.0 | |
|--------------------------|---|---|---|---|---|---|
| | σ_{τ} (kg cm ⁻²) | $\sigma_{\tau} - \sigma_{\tau}$ (kg cm ⁻²) | σ_{τ} (kg cm ⁻²) | $\sigma_{\tau} - \sigma_{\tau}$ (kg cm ⁻²) | σ_{τ} (kg cm ⁻²) | $\sigma_{\tau} - \sigma_{\tau}$ (kg cm ⁻²) |
| 0 | 0 | 11.8 | 0 | 12.0 | 0 | 12.7 |
| 2 | 1.6 | 10.2 | 1.6 | 10.4 | 1.2 | 11.5 |
| 4 | 3.1 | 8.7 | 3.0 | 9.0 | 2.3 | 10.4 |
| 6 | 4.3 | 7.5 | 4.1 | 7.9 | 3.3 | 9.4 |
| 8 | 5.3 | 6.5 | 5.1 | 6.9 | 4.2 | 8.5 |
| 10 | 6.2 | 5.6 | 6.0 | 6.0 | 5.1 | 7.6 |
| 12 | 7.0 | 4.8 | 6.8 | 5.2 | 5.8 | 6.9 |
| 14 | 7.7 | 4.1 | 7.4 | 4.6 | 6.5 | 6.2 |
| 16 | 8.2 | 3.6 | 8.1 | 3.9 | 7.1 | 5.6 |
| 18 | 8.7 | 3.1 | 8.5 | 3.5 | 7.6 | 5.1 |
| 20 | 9.2 | 2.6 | 9.0 | 3.0 | 8.1 | 4.6 |
| 22 | 9.5 | 2.3 | 9.4 | 2.6 | 8.5 | 4.2 |
| 24 | 9.8 | 2.0 | 9.7 | 2.3 | 8.9 | 3.8 |
| 26 | 10.1 | 1.7 | 10.0 | 2.0 | 9.3 | 3.4 |
| 28 | 10.4 | 1.4 | 10.3 | 1.7 | 9.6 | 3.1 |
| 30 | 10.6 | 1.2 | 10.5 | 1.5 | 9.9 | 2.8 |
| 32 | 10.7 | 1.1 | 10.7 | 1.3 | 10.2 | 2.5 |
| 34 | 10.9 | 0.9 | 10.9 | 1.1 | 10.4 | 2.3 |
| 36 | 11.0 | 0.8 | 11.0 | 1.0 | 10.6 | 2.1 |
| 38 | 11.1 | 0.7 | 11.1 | 0.9 | 10.8 | 1.9 |
| 40 | 11.2 | 0.6 | 11.2 | 0.8 | 11.0 | 1.7 |
| 42 | | | 11.3 | 0.7 | 11.2 | 1.5 |
| 44 | | | 11.4 | 0.6 | 11.3 | 1.4 |
| 46 | | | | | 11.5 | 1.2 |
| 48 | | | | | 11.6 | 1.1 |
| 50 | | | | | 11.7 | 1.0 |
| 52 | | | | | 11.8 | 0.9 |
| 54 | | | | | 11.9 | 0.8 |
| 56 | | | | | 11.9 | 0.8 |
| 58 | | | | | 12.0 | 0.7 |
| 60 | | | | | 12.1 | 0.6 |

Table AII. (cont.) Theoretical values for various temperatures.

| T(C) τ (days) | -20.0 | | -25.0 | |
|--------------------------|--|---|--|---|
| | $\sigma\tau$ (kg cm ⁻²) | $\sigma_f - \sigma\tau$ (kg cm ⁻²) | $\sigma\tau$ (kg cm ⁻²) | $\sigma_f - \sigma\tau$ (kg cm ⁻²) |
| 0 | 0 | 12.8 | 0 | 13.7 |
| 2 | 1.2 | 11.6 | .8 | 12.9 |
| 4 | 2.2 | 10.6 | 1.6 | 12.1 |
| 6 | 3.2 | 9.6 | 2.3 | 11.4 |
| 8 | 4.0 | 8.8 | 3.0 | 10.7 |
| 10 | 4.8 | 8.0 | 3.7 | 10.0 |
| 12 | 5.5 | 7.3 | 4.3 | 9.4 |
| 14 | 6.2 | 6.6 | 4.9 | 8.8 |
| 16 | 6.8 | 6.0 | 5.4 | 8.3 |
| 18 | 7.3 | 5.5 | 6.0 | 7.7 |
| 20 | 7.8 | 5.0 | 6.4 | 7.3 |
| 22 | 8.3 | 4.5 | 6.8 | 6.9 |
| 24 | 8.7 | 4.1 | 7.2 | 6.5 |
| 26 | 9.1 | 3.7 | 7.6 | 6.1 |
| 28 | 9.4 | 3.4 | 8.0 | 5.7 |
| 30 | 9.7 | 3.1 | 8.3 | 5.4 |
| 32 | 10.0 | 2.8 | 8.7 | 5.0 |
| 34 | 10.2 | 2.6 | 9.0 | 4.7 |
| 36 | 10.5 | 2.3 | 9.3 | 4.4 |
| 38 | 10.7 | 2.1 | 9.5 | 4.2 |
| 40 | 10.8 | 2.0 | 9.8 | 3.9 |
| 42 | 11.1 | 1.7 | 10.0 | 3.7 |
| 44 | 11.2 | 1.6 | 10.2 | 3.5 |
| 46 | 11.4 | 1.4 | 10.4 | 3.3 |
| 48 | 11.5 | 1.3 | 10.6 | 3.1 |
| 50 | 11.6 | 1.2 | 10.8 | 2.9 |
| 52 | 11.7 | 1.1 | 11.0 | 2.7 |
| 54 | 11.8 | 1.0 | 11.2 | 2.5 |
| 56 | 11.9 | 0.9 | 11.3 | 2.4 |
| 58 | 12.0 | 0.8 | 11.5 | 2.2 |
| 60 | 12.1 | 0.7 | 11.6 | 2.1 |
| 62 | 12.1 | 0.7 | 11.7 | 2.0 |
| 64 | 12.2 | 0.6 | 11.8 | 1.9 |
| 66 | | | 12.0 | 1.7 |
| 68 | | | 12.1 | 1.6 |
| 70 | | | 12.2 | 1.5 |
| 72 | | | 12.3 | 1.4 |
| 74 | | | 12.3 | 1.4 |
| 76 | | | 12.4 | 1.3 |
| 78 | | | 12.5 | 1.2 |
| 80 | | | 12.6 | 1.1 |
| 82 | | | 12.6 | 1.1 |
| 84 | | | 12.7 | 1.0 |
| 86 | | | 12.8 | 0.9 |
| 88 | | | 12.8 | 0.9 |
| 90 | | | 12.9 | 0.8 |
| 92 | | | 12.9 | 0.8 |
| 94 | | | 13.0 | 0.7 |
| 96 | | | 13.0 | 0.7 |

Table AII. (cont.) Theoretical values for various temperatures

| T(C) τ (days) | -30.0 | | -35.0 | |
|--------------------------|--------------------------------------|---|--------------------------------------|---|
| | σ_T (kg cm ⁻²) | $\sigma_f - \sigma_T$ (kg cm ⁻²) | σ_T (kg cm ⁻²) | $\sigma_f - \sigma_T$ (kg cm ⁻²) |
| 0 | 0 | 14.6 | 0 | 15.5 |
| 5 | 1.4 | 13.2 | 1.0 | 14.5 |
| 10 | 2.7 | 11.9 | 1.9 | 13.6 |
| 15 | 3.8 | 10.8 | 2.8 | 12.7 |
| 20 | 4.9 | 9.7 | 3.6 | 11.9 |
| 25 | 5.8 | 8.8 | 4.3 | 11.2 |
| 30 | 6.7 | 7.9 | 5.0 | 10.5 |
| 35 | 7.4 | 7.2 | 5.7 | 9.8 |
| 40 | 8.1 | 6.5 | 6.3 | 9.2 |
| 45 | 8.8 | 5.8 | 6.9 | 8.6 |
| 50 | 9.3 | 5.3 | 7.4 | 8.1 |
| 55 | 9.8 | 4.8 | 8.0 | 7.5 |
| 60 | 10.3 | 4.3 | 8.4 | 7.1 |
| 65 | 10.7 | 3.9 | 8.9 | 6.6 |
| 70 | 11.1 | 3.5 | 9.3 | 6.2 |
| 75 | 11.4 | 3.2 | 9.7 | 5.8 |
| 80 | 11.7 | 2.9 | 10.0 | 5.5 |
| 85 | 12.0 | 2.6 | 10.4 | 5.1 |
| 90 | 12.3 | 2.3 | 10.7 | 4.8 |
| 95 | 12.5 | 2.1 | 11.0 | 4.5 |
| 100 | 12.7 | 1.9 | 11.3 | 4.2 |
| 105 | 12.9 | 1.7 | 11.5 | 4.0 |
| 110 | 13.0 | 1.6 | 11.8 | 3.7 |
| 115 | 13.2 | 1.4 | 12.0 | 3.5 |
| 120 | 13.3 | 1.3 | 12.2 | 3.3 |
| 125 | 13.4 | 1.2 | 12.4 | 3.1 |
| 130 | 13.5 | 1.1 | 12.6 | 2.9 |
| 135 | 13.6 | 1.0 | 12.8 | 2.7 |
| 140 | 13.7 | 0.9 | 13.0 | 2.5 |
| 145 | 13.8 | 0.8 | 13.1 | 2.4 |
| 150 | 13.9 | 0.7 | 13.3 | 2.2 |
| 155 | | | 13.4 | 2.1 |
| 160 | | | 13.5 | 2.0 |
| 165 | | | 13.7 | 1.8 |
| 170 | | | 13.8 | 1.7 |
| 175 | | | 13.9 | 1.6 |
| 180 | | | 14.0 | 1.5 |
| 185 | | | 14.1 | 1.4 |
| 190 | | | 14.2 | 1.3 |
| 195 | | | 14.2 | 1.3 |
| 200 | | | 14.3 | 1.2 |
| 205 | | | 14.4 | 1.1 |
| 210 | | | 14.5 | 1.0 |
| 215 | | | 14.5 | 1.0 |
| 220 | | | 14.6 | 0.9 |
| 225 | | | 14.6 | 0.9 |
| 230 | | | 14.7 | 0.8 |

Table AII. (cont.) Theoretical values for various temperatures

| T(C) τ (days) | -38.0 | | -40.0 | | -45.0 | |
|--------------------------|--------------------------------------|---|--------------------------------------|---|--------------------------------------|---|
| | σ_T (kg cm ⁻²) | $\sigma_f - \sigma_T$ (kg cm ⁻²) | σ_T (kg cm ⁻²) | $\sigma_f - \sigma_T$ (kg cm ⁻²) | σ_T (kg cm ⁻²) | $\sigma_f - \sigma_T$ (kg cm ⁻²) |
| 0 | 0 | 16.0 | 0 | 16.3 | 0 | 17.2 |
| 10 | 1.5 | 14.5 | 1.3 | 15.0 | 0.9 | 16.3 |
| 20 | 2.9 | 13.1 | 2.5 | 13.8 | 1.7 | 15.5 |
| 30 | 4.1 | 11.9 | 3.6 | 12.7 | 2.4 | 14.8 |
| 40 | 5.2 | 10.8 | 4.6 | 11.7 | 3.2 | 14.0 |
| 50 | 6.3 | 9.7 | 5.5 | 10.8 | 3.9 | 13.3 |
| 60 | 7.2 | 8.8 | 6.4 | 9.9 | 4.5 | 12.7 |
| 70 | 8.0 | 8.0 | 7.2 | 9.1 | 5.2 | 12.0 |
| 80 | 8.8 | 7.2 | 7.9 | 8.4 | 5.7 | 11.5 |
| 90 | 9.5 | 6.5 | 8.5 | 7.8 | 6.3 | 10.9 |
| 100 | 10.1 | 5.9 | 9.2 | 7.1 | 6.9 | 10.3 |
| 110 | 10.6 | 5.4 | 9.7 | 6.6 | 7.4 | 9.8 |
| 120 | 11.1 | 4.9 | 10.3 | 6.0 | 7.9 | 9.3 |
| 130 | 11.6 | 4.4 | 10.7 | 5.6 | 8.3 | 8.9 |
| 140 | 12.0 | 4.0 | 11.2 | 5.1 | 8.8 | 8.4 |
| 150 | 12.4 | 3.6 | 11.6 | 4.7 | 9.2 | 8.0 |
| 160 | 12.7 | 3.3 | 12.0 | 4.3 | 9.6 | 7.6 |
| 170 | 13.0 | 2.9 | 12.3 | 4.0 | 10.0 | 7.2 |
| 180 | 13.3 | 2.7 | 12.6 | 3.7 | 10.3 | 6.9 |
| 190 | 13.6 | 2.4 | 12.9 | 3.4 | 10.7 | 6.5 |
| 200 | 13.8 | 2.2 | 13.2 | 3.1 | 11.0 | 6.2 |
| 210 | 14.0 | 2.0 | 13.4 | 2.9 | 11.3 | 5.9 |
| 220 | 14.2 | 1.8 | 13.7 | 2.6 | 11.6 | 5.6 |
| 230 | 14.4 | 1.6 | 13.9 | 2.4 | 11.9 | 5.3 |
| 240 | 14.5 | 1.5 | 14.1 | 2.2 | 12.1 | 5.1 |
| 250 | 14.6 | 1.4 | 14.2 | 2.1 | 12.4 | 4.8 |
| 260 | 14.8 | 1.2 | 14.4 | 1.9 | 12.6 | 4.6 |
| 270 | 14.9 | 1.1 | 14.6 | 1.7 | 12.8 | 4.4 |
| 280 | 15.0 | 1.0 | 14.7 | 1.6 | 13.1 | 4.1 |
| 290 | 15.1 | 0.9 | 14.8 | 1.5 | 13.3 | 3.9 |
| 300 | 15.2 | 0.8 | 14.9 | 1.4 | 13.5 | 3.7 |
| 310 | 15.3 | 0.7 | 15.1 | 1.2 | 13.6 | 3.6 |
| 320 | | | 15.2 | 1.1 | 13.8 | 3.4 |
| 330 | | | 15.2 | 1.1 | 13.9 | 3.3 |
| 340 | | | 15.3 | 1.0 | 14.1 | 3.1 |
| 350 | | | 15.4 | 0.9 | 14.3 | 2.9 |
| 360 | | | 15.5 | 0.8 | 14.4 | 2.8 |
| 370 | | | 15.5 | 0.8 | 14.6 | 2.6 |
| 380 | | | | | 14.7 | 2.5 |
| 390 | | | | | 14.8 | 2.4 |
| 400 | | | | | 14.9 | 2.3 |
| 410 | | | | | 15.1 | 2.1 |
| 420 | | | | | 15.2 | 2.0 |
| 430 | | | | | 15.3 | 1.9 |
| 440 | | | | | 15.4 | 1.8 |
| 450 | | | | | 15.4 | 1.8 |
| 460 | | | | | 15.5 | 1.7 |
| 470 | | | | | 15.6 | 1.6 |
| 480 | | | | | 15.7 | 1.5 |
| 490 | | | | | 15.8 | 1.4 |
| 500 | | | | | 15.8 | 1.3 |

Table AII. (cont.) Theoretical values for various temperatures

| T(C) τ (days) | -49.0 | | -50.0 | |
|--------------------------|---|--|---|--|
| | σ_{τ} (kg cm ⁻²) | $\sigma_f - \sigma_{\tau}$ (kg cm ⁻²) | σ_{τ} (kg cm ⁻²) | $\sigma_f - \sigma_{\tau}$ (kg cm ⁻²) |
| 0 | 0 | 17.9 | 0 | 18.1 |
| 10 | 0.6 | 17.3 | 0.5 | 17.6 |
| 20 | 1.2 | 16.7 | 1.1 | 17.0 |
| 30 | 1.7 | 16.2 | 1.6 | 16.5 |
| 40 | 2.3 | 15.6 | 2.1 | 16.0 |
| 50 | 2.8 | 15.1 | 2.6 | 15.5 |
| 60 | 3.3 | 14.6 | 3.0 | 15.1 |
| 70 | 3.8 | 14.1 | 3.5 | 14.6 |
| 80 | 4.3 | 13.6 | 3.9 | 14.2 |
| 90 | 4.7 | 13.2 | 4.4 | 13.7 |
| 100 | 5.2 | 12.7 | 4.8 | 13.3 |
| 110 | 5.6 | 12.3 | 5.2 | 12.9 |
| 120 | 6.0 | 11.9 | 5.6 | 12.5 |
| 130 | 6.4 | 11.5 | 5.9 | 12.2 |
| 140 | 6.8 | 11.1 | 6.3 | 11.8 |
| 150 | 7.2 | 10.7 | 6.7 | 11.4 |
| 160 | 7.5 | 10.4 | 7.0 | 11.1 |
| 170 | 7.9 | 10.0 | 7.4 | 10.7 |
| 180 | 8.2 | 9.7 | 7.7 | 10.4 |
| 190 | 8.5 | 9.4 | 8.0 | 10.1 |
| 200 | 8.8 | 9.1 | 8.3 | 9.8 |
| 210 | 9.1 | 8.8 | 8.6 | 9.5 |
| 220 | 9.4 | 8.5 | 8.9 | 9.2 |
| 230 | 9.7 | 8.2 | 9.2 | 8.9 |
| 240 | 10.0 | 7.9 | 9.4 | 8.7 |
| 250 | 10.3 | 7.6 | 9.7 | 8.4 |
| 260 | 10.5 | 7.4 | 10.0 | 8.1 |
| 270 | 10.8 | 7.1 | 10.2 | 7.9 |
| 280 | 11.0 | 6.9 | 10.4 | 7.7 |
| 290 | 11.2 | 6.7 | 10.7 | 7.4 |
| 300 | 11.5 | 6.4 | 10.9 | 7.2 |
| 310 | 11.7 | 6.2 | 11.1 | 7.0 |
| 320 | 11.9 | 6.0 | 11.3 | 6.8 |
| 330 | 12.1 | 5.8 | 11.5 | 6.6 |
| 340 | 12.3 | 5.6 | 11.7 | 6.4 |
| 350 | 12.5 | 5.4 | 11.9 | 6.2 |
| 360 | 12.6 | 5.3 | 12.1 | 6.0 |
| 370 | 12.8 | 5.1 | 12.3 | 5.8 |
| 380 | 13.0 | 4.9 | 12.4 | 5.7 |
| 390 | 13.2 | 4.7 | 12.6 | 5.5 |
| 400 | 13.3 | 4.6 | 12.8 | 5.3 |
| 410 | 13.5 | 4.4 | 12.9 | 5.2 |
| 420 | 13.6 | 4.3 | 13.1 | 5.0 |
| 430 | 13.8 | 4.1 | 13.2 | 4.9 |
| 440 | 13.9 | 4.0 | 13.4 | 4.7 |
| 450 | 14.0 | 3.9 | 13.5 | 4.6 |
| 460 | 14.2 | 3.7 | 13.7 | 4.4 |
| 470 | 14.3 | 3.6 | 13.8 | 4.3 |
| 480 | 14.4 | 3.5 | 14.0 | 4.1 |
| 490 | 14.5 | 3.4 | 14.1 | 4.0 |
| 500 | 14.6 | 3.3 | 14.2 | 3.9 |

Table AII. (cont.) Theoretical values for various temperatures.

| T(C) τ (days) | -45.0 | | -49.0 | | -50.0 | |
|--------------------------|--|---|--|---|--|---|
| | $\sigma\tau$ (kg cm ⁻²) | $\sigma_f - \sigma\tau$ (kg cm ⁻²) | $\sigma\tau$ (kg cm ⁻²) | $\sigma_f - \sigma\tau$ (kg cm ⁻²) | $\sigma\tau$ (kg cm ⁻²) | $\sigma_f - \sigma\tau$ (kg cm ⁻²) |
| 510 | 15.9 | 1.3 | 14.7 | 3.2 | 14.3 | 3.8 |
| 520 | 16.0 | 1.2 | 14.8 | 3.1 | 14.4 | 3.7 |
| 530 | 16.0 | 1.2 | 14.9 | 3.0 | 14.5 | 3.6 |
| 540 | 16.1 | 1.1 | 15.0 | 2.9 | 14.6 | 3.5 |
| 550 | 16.1 | 1.1 | 15.1 | 2.8 | 14.7 | 3.4 |
| 560 | 16.2 | 1.0 | 15.2 | 2.7 | 14.8 | 3.3 |
| 570 | 16.2 | 1.0 | 15.3 | 2.6 | 14.9 | 3.2 |
| 580 | 16.3 | 0.9 | 15.4 | 2.5 | 15.0 | 3.1 |
| 590 | 16.3 | 0.9 | 15.5 | 2.4 | 15.1 | 3.0 |
| 600 | | | 15.6 | 2.3 | 15.2 | 2.9 |
| 610 | | | 15.7 | 2.2 | 15.3 | 2.8 |
| 620 | | | 15.7 | 2.2 | 15.4 | 2.7 |
| 630 | | | 15.8 | 2.1 | 15.5 | 2.6 |
| 640 | | | 15.9 | 2.0 | 15.5 | 2.6 |
| 650 | | | 15.9 | 2.0 | 15.6 | 2.5 |
| 660 | | | 16.0 | 1.9 | 15.7 | 2.4 |
| 670 | | | 16.1 | 1.8 | 15.8 | 2.3 |
| 680 | | | 16.1 | 1.8 | 15.8 | 2.3 |
| 690 | | | 16.2 | 1.7 | 15.9 | 2.2 |
| 700 | | | 16.2 | 1.7 | 16.0 | 2.1 |
| 710 | | | 16.3 | 1.6 | 16.0 | 2.1 |
| 720 | | | 16.4 | 1.5 | 16.1 | 2.0 |
| 730 | | | 16.4 | 1.5 | 16.1 | 2.0 |
| 740 | | | 16.5 | 1.4 | 16.2 | 1.9 |
| 750 | | | 16.5 | 1.4 | 16.3 | 1.8 |
| 760 | | | 16.5 | 1.4 | 16.3 | 1.8 |
| 770 | | | 16.6 | 1.3 | 16.4 | 1.7 |
| 780 | | | 16.6 | 1.3 | 16.4 | 1.7 |
| 790 | | | 16.7 | 1.2 | 16.5 | 1.6 |
| 800 | | | 16.7 | 1.2 | 16.5 | 1.6 |
| 810 | | | 16.8 | 1.1 | 16.6 | 1.5 |
| 820 | | | 16.8 | 1.1 | 16.6 | 1.5 |
| 830 | | | 16.8 | 1.1 | 16.7 | 1.4 |
| 840 | | | 16.9 | 1.0 | 16.7 | 1.4 |
| 850 | | | 16.9 | 1.0 | 16.7 | 1.4 |
| 860 | | | 16.9 | 1.0 | 16.8 | 1.3 |
| 870 | | | 17.0 | 0.9 | 16.8 | 1.3 |
| 880 | | | 17.0 | 0.9 | 16.9 | 1.2 |
| 890 | | | | | 16.9 | 1.2 |
| 900 | | | | | 16.9 | 1.2 |
| 910 | | | | | 17.0 | 1.1 |
| 920 | | | | | 17.0 | 1.1 |
| 930 | | | | | 17.0 | 1.1 |
| 940 | | | | | 17.1 | 1.0 |
| 950 | | | | | 17.1 | 1.0 |
| 960 | | | | | 17.1 | 1.0 |
| 970 | | | | | 17.2 | 0.9 |
| 980 | | | | | 17.2 | 0.9 |

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13. ABSTRACT

The results are presented of a study of the sintering process as a function of temperature, keeping size distribution, shape, and density nearly constant. The confined compression test method was used. It is shown that the degree of sintering of snow and the rate constant as a function of temperature can be represented satisfactorily by an exponential equation. The results indicate that the sintering process is one of evaporation, diffusion through the ambient temperature, and condensation.

| 14. KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|--------|----|--------|----|--------|----|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Snow--Sintering Ice--Sintering Snow--Metamorphism | | | | | | |

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