Undersnow Structures:
N-34 Radar Station, Greenland
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by Malcolm Mellor

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PREFACE

This report arose from a visit by the author to observe long-term effects on a unique undersnow structure. This opportunity was utilized to analyze new and existing data to evaluate design concepts.

Mr. Mellor is a member of the Experimental Engineering Division, Mr. K.A. Linell, Chief.

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SUMMARY

Data previously obtained in a program of instrumentation and observation to appraise the performance of radar station N-34 built at an altitude of about 7000 ft in the dry-snow zone of the Greenland Ice Cap are condensed and presented. N-34 consisted of prefabricated buildings erected inside tubular corrugated-steel shells and the whole complex was interconnected with a closed network of steel tubes. The snow cover accumulation on the abandoned station, from 1957 to 1963, of more than 20 ft is still being restrained by the structural shells. Observations of long-term effects on this unique structure are utilized to analyze new and existing data in evaluating design concepts. Structural deformation, differential settlement, and heat loss are discussed, and some remarks relevant to future design are made.
UNDERSNOW STRUCTURES: N-34 RADAR STATION, GREENLAND
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Introduction

At the time of its construction in 1953, the U.S. Air Force radar station N-34 was the most sophisticated installation to be built on a polar ice cap. Little information or experience was available to guide the designers, and the structure was unique. In order to appraise its performance a program of instrumentation and observation was designed; this is described by Hansen in USA SIPRE Technical Report 23.

In the present report, some of the data obtained by Hansen and by the present author are condensed and presented. Structural deformation, differential settlement, and heat loss are discussed, and some remarks relevant to future design are made.

Construction and operation

Radar station N-34 was an AC&W (Aircraft Control and Warning) station built on the Greenland Ice Cap for the USAF by the US Army Corps of Engineers. Its location, known as Site 2, is in northwest Greenland at an altitude of about 7000 ft in the dry-snow zone of the ice cap. Site conditions, including snow properties, have been well described in SIPRE Report 20 (Bader et al., 1955) and in other SIPRE/CRREL reports.

The station consisted of prefabricated buildings erected inside tubular corrugated steel shells, and the whole complex was interconnected into a closed network of steel tubes. The station layout is shown in Figure 1: heated buildings are placed inside 18-ft diam tubes in two parallel arrays, and three corridors of 10-ft 6-in. diam (Fig. 2) run along the ends of the 18-ft diam tubes. At each end of the central corridor there is a timber chamber; one is the communications building, and the other the operations building.

The tubes were built at the surface from multi-plate culvert steel. Details of a typical 18-ft diam tube are shown in Figure 3. Although the tubes were initially set into the snow to about half-diameter depth only, wind-blown snow soon drifted over to submerge the station, leaving only the escape hatches and the radome above surface. The arrangement of a typical inner building (Clements panel building) in a tube is shown in Figure 4: the floor is carried on timber joists spanning across the tube and additionally supported by a center prop. The communications building (Fig. 5) and the operations building were constructed from heavy timbers and sheathed on the outside with plywood. Their foundations were timber rafts.

N-34 was built in the summer of 1953 and first occupied in the autumn of that year. It was continuously occupied until 1957, after which it was abandoned, having outlived its operational usefulness.

During the period of occupancy the station was buried under the snow, but load development on the tubes was reduced by heat losses melting and annealing the surrounding snow. After abandonment, snow settled firmly against the tubes and deformed them into elliptic shapes. The snow cover on the station continued to increase, and there was a slow increase of tube deformation with time. By 1962,* however, with the floor of the station almost 35 ft below surface (36.5 ft in August, 1963) and a cover of more than 20 ft on the 18-ft tubes, the shells were still successfully restraining the snow.

*Since this report was first submitted, further data have been obtained (August, 1963). These data have been added to the graphs where possible. The analysis and interpretation are unaffected.
Sewage from the mess hall and latrine was piped away on the north side of the station and finally dumped into a sink melted down into the snow almost 300 ft from the station. A leak in the sewer pipe was to cause serious differential settlement.

Deformation of the tubes

Figures 7 and 8 illustrate the deformed shapes of the tubes 7 and 9 years after construction (1960 and 1962). The loading resulted from snow cover; mean snow surface was 30 ft above floor-level datum of the station in 1960, and 34.5 ft above the same datum in 1962. Snow densities and overburden loads can be assumed to correspond with those shown in Figure 6. Figures 9 and 10 show how deformation changed with time during the life of the structures. Measurements were made as far as possible from restraining elements such as bulkheads, shafts, and connecting junctions (Fig. 1), so that deformation of the basic cylindrical structure may be assumed to conform with the outside stress field.

Figure 1. Plot plan of N-34.
During the period of occupancy, loading and load distribution were obviously affected by high temperatures in the shells. It was due to melting of snow in contact with the shells that the pressure cells described by Hansen (1955) yielded no useful data. After 1960, however, with the shells deeply buried and the thermal regime stabilized, it seems reasonable to assume that the shells are deformed elastically* in conformity with the applied loads.

With snow mechanics still in its infancy there is relatively little information which can be brought to bear on the problem of a flexible culvert buried in a densifying ice cap. We may expect, though, that the stress field surrounding a rigid or semi-rigid object buried in snow which is continuously settling under gravity will be affected both by the snow properties and the geometry and rigidity of the object.

*Maximum deflections are less than half of those given by the manufacturer as the limits for elastic deflection.
Figure 3. Typical 18-ft diam multi-plate steel shell used to shelter inner buildings at N-34.

Figure 4. Arrangement of prefabricated building in 18-ft diam steel shell.
Figure 5. Timber chamber used for main entrance and communications building.

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Figure 9. (cont'd) Changes of deformation with time, 10-ft 6-in. diam shells.
Figure 9. (cont'd) Changes of deformation with time, 10-ft 6-in. diam shells.
Figure 10. Changes of deformation with time, 18-ft diam shells.
Section R-R'

Figure 10. (cont'd) Changes of deformation with time, 18-ft diam shells.

Figure 11. Loading model for the deflection analysis.

Elastic deflection under load. For a first attempt at analysis, it is assumed that the tubes are subject to a uniformly distributed vertical pressure \( w \), and a uniformly distributed side pressure \( nw \) (Fig. 11).

A relationship between elastic deflection and loading may be obtained from strain energy considerations, using Castigliano's theorem. Since the situation is symmetrical, we consider only one quadrant, in which bending moments are developed as shown in Figure 12.
\[ dx = ds \sin \theta = R \sin \theta d\theta \]
\[ dy = ds \cos \theta = R \cos \theta d\theta \]

Figure 12. Forces and moments acting on one quadrant of a thin shell loaded in accordance with Figure 11.

We take moments about A for the equilibrium of arc AB: Moment arms for the element ds are

Horizontal: \( R(\cos \theta - \cos \phi) \)

Vertical: \( R(\sin \phi - \sin \theta) \).

The equilibrium equation is

\[ M - M_0 + wR^2 (1 - \cos \phi) = \int_0^\phi wR^2 \sin \theta (\cos \theta - \cos \phi) d\theta - \int_0^\phi n wR^2 \cos \theta (\sin \phi - \sin \theta) d\theta = 0 \]

i.e.

\[ M - M_0 + \frac{wR^2}{2} (1 - n)(1 - \cos^2 \phi) = 0. \]  \hspace{1cm} (1)

The total strain energy for the quadrant \( U \) is

\[ U = \int_0^{\pi/2} \frac{M^2}{2EI} ds = \int_0^{\pi/2} \frac{M^2 R}{2EI} \ d\phi \]  \hspace{1cm} (2)

where \( E \) is the modulus of elasticity and \( I \) is the moment of inertia of the tube section.

Substituting from eq.1 into eq.2:

\[ U = \frac{R}{2EI} \int_0^{\pi/2} \left\{ M_0 - \frac{wR^2}{2} (1 - n)(1 - \cos^2 \phi) \right\}^2 d\phi. \]

Due to symmetry there is no rotation at B as the tube deflects, so that \( \frac{\partial U}{\partial M_0} = 0 \).
Thus,
\[ 0 = \frac{a}{\rho M_0} \int_0^{\pi/2} \left( \frac{R}{2EI} \right)^2 \left\{ M_0 - \frac{\omega R^2}{2} \left( 1 - \frac{\omega R^2}{4} \right) \right\}^2 \, d\phi \]
\[ = \frac{R}{EI} \int_0^{\pi/2} \left\{ M_0 - \frac{\omega R^2}{2} \left( 1 - \frac{\omega R^2}{4} \right) \right\} d\phi \]
\[ = \frac{\pi R}{2EI} \left\{ M_0 - \frac{\omega R^2}{4} \left( 1 - \frac{\omega R^2}{4} \right) \right\}. \]

Hence,
\[ M_0 = \frac{\omega R^2}{4} \left( 1 - \frac{\omega R^2}{4} \right) \quad (3) \]

and the general moment \( M \) is, from eq 1:
\[ M = \frac{\omega R^2}{4} \left( 1 - \frac{\omega R^2}{4} \right) (2 \cos^2 \phi - 1). \quad (4) \]

The maximum bending moment therefore occurs where \( \phi = \pi/2 \), i.e., at the crown of the tube. Its magnitude is
\[ M_{\text{max}} = \frac{\omega R^2}{4} \left( 1 - \frac{\omega R^2}{4} \right). \quad (5) \]

We now proceed to find an expression for the vertical deflection in terms of the load. The vertical deflection at \( B \), \( \Delta_{VB} \), represents half of the total closure between crown and invert \( \Delta_{V} \). It is given by the partial derivative of \( U \) with respect to the vertical force at \( B \), \( wR \).

Strain energy:
\[ U = \frac{R}{2EI} \int_0^{\pi/2} M^2 \, d\phi \]

Vertical force at \( B \):
\[ W_B = wR \]

Vertical deflection at \( B \):
\[ \Delta_{VB} = \frac{\partial (2U)}{\partial W_B} \]
\[ \Delta_{VB} = \frac{\partial}{\partial W_B} \left( \frac{R}{2EI} \int_0^{\pi/2} M^2 \, d\phi \right) = \frac{R}{2EI} \int_0^{\pi/2} \frac{M^2}{2M} \, d\phi = \frac{R}{2EI} \int_0^{\pi/2} \frac{2M}{2M} \frac{\partial M}{\partial W_B} \, d\phi \]
\[ = \frac{R}{EI} \int_0^{\pi/2} \left\{ \frac{W_B R}{4} \left( 1 - \frac{\omega R^2}{4} \right) \right\} \left\{ \frac{R}{4} \left( 1 - \frac{\omega R^2}{4} \right) (2 \cos^2 \phi - 1) \right\} \, d\phi \]
\[ = \frac{W_B \pi R^3}{64EI} (1 - \frac{\omega R^2}{4})^2 = \frac{w \pi R^4}{64EI} (1 - \frac{\omega R^2}{4})^2. \quad (6) \]
Total vertical closure between crown and invert:

$$\Delta V = 2\Delta_{\text{VB}}$$

$$= \frac{w\pi R^4}{32EI} (1 - n^2)$$ (7)

Load calculations. As a first approximation the tubes are assumed to be subject to the nominal overburden pressure, i.e., they carry only the weight of the vertical snow column immediately above them. Suitable values, derived from integration of the depth-density curve for Site 2, are found from Figure 6.

Table I gives the values of $n$ computed from the observed deflections and the assumed loads. All values of $n$ are negative. We may preface comment on this result by observing that unrestrained cylindrical tunnels at shallow depth below the ice-cap surface tend to lengthen their horizontal diameters as they deform. However, in the present case we cannot accept the idea of a negative side pressure, since there is not likely to be sufficient tensile connection between the tube and the snow. It therefore seems preferable to interpret the negative $n$ values as a manifestation of vertical forces in excess of those assumed.

**Table I. Computation of $n$ in accordance with eq 7.**

<table>
<thead>
<tr>
<th>Section</th>
<th>Moment of inertia 1 (in$^4$)</th>
<th>Vertical deflection $\Delta V$ (in.)</th>
<th>Nominal radius R (in.)</th>
<th>Nominal overburden pressure $w$ (lb/in$^2$)</th>
<th>Weight of overburden column $2wR$ (lb/in. run.)</th>
<th>Ratio of horiz. to vert. load $n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-G$'$</td>
<td>0.108</td>
<td>18.0</td>
<td>108</td>
<td>4.26</td>
<td>920</td>
<td>-0.013</td>
</tr>
<tr>
<td>F-F$'$</td>
<td>0.108</td>
<td>18.0</td>
<td>108</td>
<td>4.26</td>
<td>920</td>
<td>-0.030</td>
</tr>
<tr>
<td>P-P$'$</td>
<td>0.0781</td>
<td>7.20</td>
<td>63</td>
<td>5.25</td>
<td>661</td>
<td>-0.44</td>
</tr>
<tr>
<td>A-A$'$</td>
<td>0.0781</td>
<td>6.84</td>
<td>63</td>
<td>5.25</td>
<td>661</td>
<td>-0.403</td>
</tr>
<tr>
<td>B-B$'$</td>
<td>0.0781</td>
<td>5.64</td>
<td>63</td>
<td>5.25</td>
<td>661</td>
<td>-0.275</td>
</tr>
<tr>
<td>C-C$'$</td>
<td>0.0781</td>
<td>5.76</td>
<td>63</td>
<td>5.25</td>
<td>661</td>
<td>-0.29</td>
</tr>
</tbody>
</table>

When a rigid or semi-rigid object is introduced into ice-cap snow, it obstructs the natural densification in a manner illustrated by Figure 13.
This flow obstruction creates additional shear and tensile forces in the vicinity of the structure. These may be referred to loosely as "edge effects" or "peripheral shear".

If values of $n$ can be deduced independently, the magnitude of edge effects and their relation to tube size may be estimated. Two approaches suggest themselves here:

1. Assume $n = 0$ (small open "windows" left in the sides of tubes after removal of pressure gauges showed the snow to be firmly in contact, but there was no obvious tendency for it to extrude into the tube).

2. Ignore the geometric arching effect and obtain $n$ from the viscous analogue of Poisson's ratio. Taking a mean value of Poisson's ratio for snow density of 0.5 g/cm$^3$, from compiled data we obtain $n = 0.43$.

The apparent overburden pressures corresponding to these two assumptions are given in Table II. The table also lists values for apparent edge shear when the enhanced loading is regarded as being made up of an overburden column plus edge shear forces.

The assumption of zero lateral pressure $(n=0)$ leads to a wide discrepancy between the edge shears for large and small tubes. The assumption of positive lateral pressure $(n=0.43)$ leads to edge shears which are more nearly the same for small and large tubes. By analogy with the Kerr theory for strip foundations in snow (Kerr, 1962) it seems reasonable to expect that edge shear should be a fairly constant increment for a given snow type, and by this token the second assumption, $n = 0.43$, is perhaps preferable.

**Table II. Computation of loadings for assumed values $n=0$ and $n=0.43$.**

<table>
<thead>
<tr>
<th>Section</th>
<th>Nominal overburden pressure $w$ (lb/in$^2$)</th>
<th>Equivalent overburden pressure $(n=0)$ $w_1$ (lb/in$^2$)</th>
<th>Equivalent overburden pressure $(n=0.43)$ $w_2$ (lb/in$^2$)</th>
<th>Apparent edge shear $(n=0)$ $S_1$ (lb/in. run.)</th>
<th>Apparent edge shear $(n=0.43)$ $S_2$ (lb/in. run.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-G'</td>
<td>4.26</td>
<td>4.36</td>
<td>13.4</td>
<td>21</td>
<td>1,970</td>
</tr>
<tr>
<td>F-F'</td>
<td>4.26</td>
<td>4.51</td>
<td>13.9</td>
<td>43</td>
<td>2,080</td>
</tr>
<tr>
<td>P-P'</td>
<td>5.25</td>
<td>10.9</td>
<td>33.6</td>
<td>712</td>
<td>3,569</td>
</tr>
<tr>
<td>A-A'</td>
<td>5.25</td>
<td>8.54</td>
<td>26.3</td>
<td>414</td>
<td>2,654</td>
</tr>
<tr>
<td>B-B'</td>
<td>5.25</td>
<td>10.35</td>
<td>31.8</td>
<td>643</td>
<td>3,349</td>
</tr>
<tr>
<td>C-C'</td>
<td>5.25</td>
<td>8.71</td>
<td>26.8</td>
<td>439</td>
<td>2,714</td>
</tr>
</tbody>
</table>

**Differential settlement**

Levels taken at the edges of the floor plates in various years are shown in Figure 14; an arbitrary datum is taken in the same position each year (lower right in the figures). The points are insufficient to justify contouring. In Figure 15 differential settlements and section rotations can be seen more graphically, although the space relationship between sections is not apparent.
Figure 14. Relative elevation of floor plates for the years 1954-1962.
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In 1954, soon after completion of construction, the complex was reasonably level with one corner (lower left in Fig. 1) slightly low. By 1955 there was a marked drop in the center of the left fuel-storage corridor (center left in Fig. 1), with only minor change elsewhere. In 1956 the entire fuel corridor was decidedly low, the deepest point still being in the center. The central corridor had also dropped significantly with respect to the datum. In 1957 the features were similar to those of 1956, but more strongly marked. It might be noted that the center of the right fuel corridor was lower than its ends in 1956 and 1957. In 1960 some of the old level stations were inaccessible, but enough points were leveled to show the situation; the left fuel trench was 4 ft below datum in some spots and severe rotation had occurred. An odd feature of the 1960 situation was the level of the central corridor, which showed less relative settlement than in 1957. In 1962 settlement and rotation had put one survey point 5 ft below datum, and other sections were more than 4 ft low. The central corridor was relatively lower than in 1960, but not as low as in 1957.

There can be little doubt that differential settlements of the magnitude observed were caused by temperature differences in the snow. Pressures beneath the tube inverters were probably quite uniform, since enhanced external vertical loads on the smaller tubes would be offset to some extent by the weight of buildings and equipment in the big tubes. Snow density beneath the tubes should also have been uniform in any given horizontal layer before differential settlement began.

If temperature disturbance had been due solely to heat loss from the complex of tubes, the station would probably have settled in a bowl-shaped pattern, since heat loss would be more intense at the center of the complex. Direct heat loss from the station, however, was apparently of minor importance compared with the melting and localized thermal disturbance caused by a leak in the sewage outfall pipe close to the left fuel corridor.

The leak went undetected for a long period, so that there was a large transfer of sensible and latent heat to the snow immediately adjacent to the left fuel corridor. The leaking liquids may also have melted out a cavity, which later subsided. This accident points up the need for precautions against pipe rupture and leakage in future designs.

Settlement relative to a deep bench mark

Beneath the main corridor a steel tape was run vertically from an anchor set deep in the snow to a water level recorder installed in the corridor (Fig. 16). The distance from the anchor to the recorder was initially about 25 ft.

Figure 17 shows the settlement of the corridor relative to the deep bench mark. Continuous readings terminated in 1956, and the recorder was eventually removed. However, a reading on the tape was made in 1963.

The rate of settlement declined over the years, showing that the densification of snow under the tube increased its deformation resistance more rapidly than the increasing overburden raised the bearing pressure. "Strain hardening" of this kind should tend to limit differential settlement.

Station deformation in the horizontal plane

At the time N-34 was built, it was suspected that horizontal strains in the ice cap might affect the station, and horizontal angles were turned from time to time to check for overall deformation in the horizontal plane. The theodolite was set up at points 4, 5, and 9 in Figure 1, and various angles were turned by sighting on plumb lines suspended at 1, 4, 5, 8, 9, and 12. An abstract of the data is given in Table III.
Figure 15. Differential settlement and tube rotation during the period 1954-1962.
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Figure 15. (cont'd) Differential settlement and tube rotation during the period 1954-1962.
Table III. Angular changes in the horizontal plane.

<table>
<thead>
<tr>
<th>Date of observation</th>
<th>8-5-4</th>
<th>8-5-9</th>
<th>1-4-5</th>
<th>1-4-9</th>
<th>12-9-5</th>
<th>12-9-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>July and Sept 1954</td>
<td>89°58'</td>
<td>89°57'</td>
<td>90°03'</td>
<td>89°53'</td>
<td>89°56'30''</td>
<td></td>
</tr>
<tr>
<td>July 1955</td>
<td>89°45'10''</td>
<td>90°08'40''</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>July 1956</td>
<td>90°20'35''</td>
<td>90°17'46''</td>
<td>89°40'22''</td>
<td>90°13'47''</td>
<td>89°47'59''</td>
<td>89°51'05''</td>
</tr>
<tr>
<td>July 1957</td>
<td>90°24'11''</td>
<td>90°18'45''</td>
<td>89°28'46''</td>
<td>90°21'35''</td>
<td>89°38'16''</td>
<td>89°43'58''</td>
</tr>
<tr>
<td>Aug 1963</td>
<td>91°02'07''</td>
<td>91°50'29''</td>
<td>88°49'20''</td>
<td>90°46'34''</td>
<td>89°01'54''</td>
<td>89°13'58''</td>
</tr>
</tbody>
</table>

All the readings show systematic increase or decrease of the angle measured, and can therefore be accepted as indicating real movements. Angles 8-5-4 and 8-5-9 increased, angles 12-9-4 and 12-9-5 decreased, angle 1-4-5 decreased, and angle 1-4-9 increased. The magnitude of the change in each case is roughly 1°, which represents a linear movement of almost 3 ft at the sighting distance of approximately 165 ft.

The data are consistent with a racking of the tube network in the horizontal plane, assuming that the network remained truly horizontal and the tubes did not rotate. Actually the left fuel corridor has rotated and differential settlement has taken place, but these displacements cannot fully explain the systematic change of horizontal angles in terms of secondary strain.

Heat loss

Since the sewer leak which caused the serious differential settlements was on the opposite side of the station from the thermohm strings, more than 120 ft from the nearest string (Hole A, Fig. 16), these installations may indicate the temperature disturbance which would have resulted if no accidents had occurred. We can check whether the sewer leak influenced Hole A by examining the temperature rise in that string.

If a longitudinal section is taken through the snow beneath the central corridor, it can be regarded as a semi-infinite mass subject to one-dimensional heat conduction, governed by the equation

$$\frac{\partial^2 \theta}{\partial z^2} - \frac{1}{\alpha} \frac{\partial \theta}{\partial t} = 0$$

(8)

where $\theta$ is snow temperature at depth $z$ and time $t$; $z$ is depth below the tube invert, and $t$ is time taken from the date when the tube began to disturb the natural temperature regime. $\alpha$ is the mean thermal diffusivity of the snow beneath the tube, given by

$$\alpha = \frac{k}{\gamma c}$$

(9)

where $k$ is the thermal conductivity, $\gamma$ the density, and $c$ the specific heat (per unit mass) of the snow. Taking $\gamma = 0.51$ g/cm³ from Figure 6, $c = 0.49$ cal. g⁻¹ C⁻¹.
and estimating \( k \) from the Kondrat'eva equation

\[
k = 0.0085 \gamma^2 \text{ cal cm}^{-1} \text{ sec}^{-1} ^\circ \text{C}^{-1}
\]

we obtain a value for \( \alpha \) of

\[
\alpha = 8.84 \times 10^{-3} \text{ cm}^2 \text{ sec}^{-1}.
\]

A solution of eq 8 is required for the condition where the medium is initially at zero temperature* and the surface is raised to constant temperature \( V \) at time \( t = 0 \). This is a standard solution available from Carslaw and Jaeger (1959):

\[
\theta(z, t) = V \text{erfc} \left( \frac{z}{2 \sqrt{\alpha t}} \right)
\]

After construction of the station it appears from the record of thermohm 4 on string A (Fig. 18) that temperature fluctuated about a mean of approximately \(-10^\circ\text{C}\), with a major period of roughly 1 year. At a depth of 25 ft or more we can neglect the harmonic variations of temperature, since the amplitude of the wave has been severely attenuated by that depth. Hence we assume the surface temperature \( V \) constant at \(-10^\circ\text{C}\), i.e., 13.5 degrees higher than the original uniform temperature of the medium (the "zero" of our model).

A temperature rise at thermohm 9 of string A can be calculated for the period 1954–1957, assuming that the temperature of that thermohm is disturbed only by conduction of heat from the tube above:

\[
z = 24.6 \text{ ft} = 7.5 \times 10^2 \text{ cm}
\]

\[
t = 3 \text{ yrs} = 9.46 \times 10^4 \text{ sec}
\]

\[
\alpha = 8.84 \times 10^{-3} \text{ cm}^2 \text{ sec}^{-1}
\]

\[
V = 13.5 \text{ C}
\]

\[
\theta = 13.5 \text{erfc} \left( \frac{7.5 \times 10^2}{2 (8.84 \times 9.46 \times 10^4)^{\frac{1}{2}}} \right) = 13.5 \text{erfc} 0.410
\]

\[
= 13.5 \times (1 - \text{erf} 0.410) = 7.6^\circ\text{C}
\]

The calculated temperature rise at thermohm 9 is thus 7.6°C from 1954 to 1957. The observed temperature rise was 7.9°C. Similar calculations for thermohms 8, 10, and 11 are compared in Table IV.

<table>
<thead>
<tr>
<th>Thermohm</th>
<th>Depth below tube (ft)</th>
<th>Calculated temperature rise (°C)</th>
<th>Observed temperature rise (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>19.6</td>
<td>8.7</td>
<td>8.8</td>
</tr>
<tr>
<td>9</td>
<td>24.6</td>
<td>7.6</td>
<td>7.9</td>
</tr>
<tr>
<td>10</td>
<td>29.6</td>
<td>6.6</td>
<td>5.9</td>
</tr>
<tr>
<td>11</td>
<td>34.6</td>
<td>5.6</td>
<td>4.5</td>
</tr>
</tbody>
</table>

*In stipulating "zero" temperature we merely take the original uniform temperature as datum for disturbances.
Figure 16. Locations of thermohms. Hole "B" is situated midway between two 18-ft diam shells.

Figure 17. Settlement of the central corridor at point T relative to a deep bench mark.
Figure 18. Thermohm records, Hole "A".
Table IV indicates that heat loss at the sewage leak had only localized effects during the period the station was occupied. Temperature changes recorded by the thermohms represent the effects of normal heat loss from the station.

The data from string B (Fig. 19) show that snow between the 18-ft diam tubes was warmed roughly 15°C above the undisturbed ambient temperature for the site. In the snow layers beneath the station, temperatures in string B are similar to those for corresponding depths in string A. String C (Fig. 20) indicates that, for practical purposes, temperature disturbance at this distance was negligible during the period of occupancy.

Remarks concerning the performance of N-34

Tube deformation. The analysis of tube deflection shows that deformations are more severe than might be expected by designing in accordance with soils practice. For example, an assumption of vertical load equal to 54% of the overburden column, in accordance with the findings of the American Railway Engineering Association (Spindler, 1955), together with a positive value for the ratio of horizontal to vertical stress, would lead to a dangerous underestimate of required strength for the structure. The analysis given above may provide a basis for rational design; it is suggested that N-34 should be kept under observation as the overburden increases, so that further data may be obtained.

Overall, the performance of the tubular structures is encouraging. If they should be used again, it would probably be worthwhile to assemble them in trenches almost as deep as the full diameter of the largest tubes, bedding them firmly into a layer of milled snow (Peter snow). The tubes should perhaps be prestressed by jacking or cable-stressing during backfilling by milled snow; the props or cables would be released after the milled snow had age-hardened for several days.

The propped beam used to support inner buildings (Fig. 3) was an unfortunate choice. As the tube deformed into an elliptic shape the prop was forced up against the beam, causing it to hog severely and thus crack the building longitudinally. Transverse cracking of the inner building was caused by tube deformation being more severe in the center than at the ends, which were restrained by bulkheads.

Deformation in the horizontal plane. From the horizontal angle data the writer tentatively concludes that the network of tubes has been distorted in the horizontal plane since, on the face of it, horizontal components of displacements caused by tube rotation and differential settlement at the observation points seem insufficient to produce the changes actually observed.

The idea that the horizontal racking is caused by strains in the ice cap itself cannot be dismissed. While appreciable shearing corresponding to horizontal gradients of velocity seems rather unlikely over such a small area (200 ft square) on the inland ice, the displacement might well be explained by longitudinal strain in a direction coinciding with a diagonal of the station.

Heat control. In undersnow cavities which are unrestrained or partially restrained, heat loss is usually intolerable, since deformation of the snow is accelerated by rising temperatures. In a fully restrained structure such as N-34, some temperature rise may actually be advantageous, as it tends to relieve stress concentrations in the adjacent snow. However, indiscriminate heat loss will usually warm the surrounding snow non-uniformly and bring about differential settlement. This can be particularly serious if temperatures rise locally to near the melting point. It is probably wise, then, to contain high temperatures within the heated buildings, exhausting these buildings directly to the surface so that shell temperatures remain low.

The leak in the N-34 sewer outfall pipe had serious consequences; in all future designs some thought should be given to providing a flexible outer seal at bends, pipe joints, and other places susceptible to rupture. This consideration also applies
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Figure 19. Thermohm records, Hole "B".
Figure 20. Thermohm records, Hole "C".
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to other pipes which carry liquids; diesel fuel, glycol, or other liquids may adversely affect load-bearing snow.

Vertical shafts. Steel risers set on top of tubes may pick up vertical shear forces from the adjacent densifying snow and transfer additional load to the tube beneath. At N-34 there do not appear to be any serious consequences from this effect, but the risers at N-34 do not extend very high (they are now deeply buried). Fixed ladders from the floor plates of the station into the risers have buckled due to the elliptic deformation of the tubes. Slide joints would eliminate this problem.

Wooden structures. The two timber chambers at N-34 showed no signs of failure in 1962, a remarkable performance for ice cap structures. These chambers were of heavy construction, but their long life fully justifies the expense of materials. It might be pointed out here that failure of a basic structure at an ice cap station involves abandonment of much heavy and expensive plant and equipment, so that conservative design of the main structure is fully justified.

REFERENCES


