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Undersnow Structures Byrd Station, Antarctica

by

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PREFACE

This report describes engineering studies made at Byrd Station by U. S. Army Cold Regions Research and Engineering Laboratory (USA CRREL). The project was supported in part by the National Science Foundation under grants NSF (G-17894) and (GA-2). The work was under the direction of Mr. Malcolm Mellor, civil engineer, Experimental Engineering Division, (Mr. K. A. Linell, Chief). Project personnel for the 1961-62 field season were Spc P. Morelli and Spc V. Aleksandravicius, and for the 1962-63 field season Spc G. Hendrickson, Spc R. Rowland, and Spc T. Pavlak. Logistic support was provided by the U. S. Navy.

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SUMMARY

Bvrd Station consists of a network of shallow tunnels containing light, T-5-type, prefabricated buildings and other items of equipment. Some small buildings (e.g., aurora tower, balloon pavilion, rawin dome) are elevated above the snow surface on extensible columns. The tunnels were constructed by the "cut-and-cover" method. Data are given concerning tunnel deformation, floor levels and foundation settlement, temperature measurements, ventilation, and other tests. Deformation data are analysed to provide design information for future construction, and it is shown that heat loss from buildings increases the rate of tunnel deformation substantially. The appendixes discuss snow reinforcement tests, air permeability of snow and the ventilation of under-snow camps, and the thermal effects of water wells and sewage sinks.

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UNDERSNOW STRUCTURES: BYRD STATION, ANTARCTICA

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INTRODUCTION

The present Byrd Station is an undersnow complex built to replace the earlier IGY station of the same name. It was constructed during the Antarctic summers of 1960-61 and 1961-62 by U. S. Navy Seabees to a design by the U. S. Navy Bureau of Yards and Docks. It is primarily a research station for scientific studies sponsored by the National Science Foundation.

The design is broadly similar to that of Camp Century, Greenland, which has received intensive study by U. S. Army Cold Regions Research and Engineering Laboratory (USA CRREL). It was decided that engineering studies should be made at Byrd also to provide data needed for efficient operation of the base, improvement of future designs, and comparison of the Greenland and Antarctic environments. A CRREL team therefore undertook a study during the 1961-62 and 1962-63 Antarctic summers, supported in part by a grant from the National Science Foundation and aided by logistic support from the U. S. Navy. Instruments installed by CRREL were read during the winters of 1962 and 1963 by civilian scientists wintering at the station, and data were transmitted to CRREL by radio.

The project afforded opportunities to make additional studies, outside the scope of the original plan, at Byrd Station, at the South Pole, and at McMurdo Sound. These studies are reported separately. Details of the first season's activities have been reported by Mellor and Morelli (1962).

CONSTRUCTION AND OPERATION

Byrd Station consists of a network of shallow tunnels containing light, prefabricated buildings and other items of equipment. While most facilities (e.g. quarters, mess, galley, workshops, offices, power plant, storage rooms) are housed inside the tunnels, some small buildings (e.g. aurora tower, balloon pavilion, rawin dome) are elevated above the ever-rising snow surface on extensible columns. Access to the tunnels is provided by steel-lined vertical shafts. A few facilities (radio noise, VLF, and ionosphere laboratories), which require freedom from electromagnetic disturbance, are located at some distance from the station, without subsurface communication. The general layout of the tunnel complex can be seen in Figure 1.

The tunnels were constructed by the "cut-and-cover" method (Fig. 2). Trenches were rapidly and precisely excavated by a Swiss Peter rotary snow plow. There were two principal types of trench cross-section: the wide, vertical wall type for roofing by 30 or 40 ft diam Wonder Arch, and the narrower, undercut type for roofing by 14-ft span corrugated arch. Details and dimensions can be obtained from the figures showing tunnel deformation. Timber sills were laid on the abutments as foundations for the steel roofing arches. For the more important arches, abutment pads of Peter snow were cast before the timber sills were laid. Snow from the excavations was placed as backfill around the arches by the Peter plow. Figure 3 shows the interior of a 30 ft wide Wonder Arch tunnel before the inner buildings were erected.

Inner buildings are prefabricated structures of the T-5 type. Foundations consist of two longitudinal timber sills spanned by open-web pressed steel joists.

Electric power is generated by a diesel plant and distributed through overhead wires. Water produced from a snow melter which utilizes waste heat from the generators is distributed by a pipe to quarters and galley. Sewage is discharged by pipe to a sink melted down into the snow. Buildings are heated mainly by individual oil-fired hot air systems. Furnace exhaust is carried directly to the surface, but waste heat from most buildings escapes to the tunnels; an exception is the power plant, which exhausts waste heat directly to the surface. Tunnel ventilation was originally a horizontal circulation intended to discharge to M-1, the central corridor, but this system was later changed to permit withdrawal of air at the arch crowns in all heated areas.

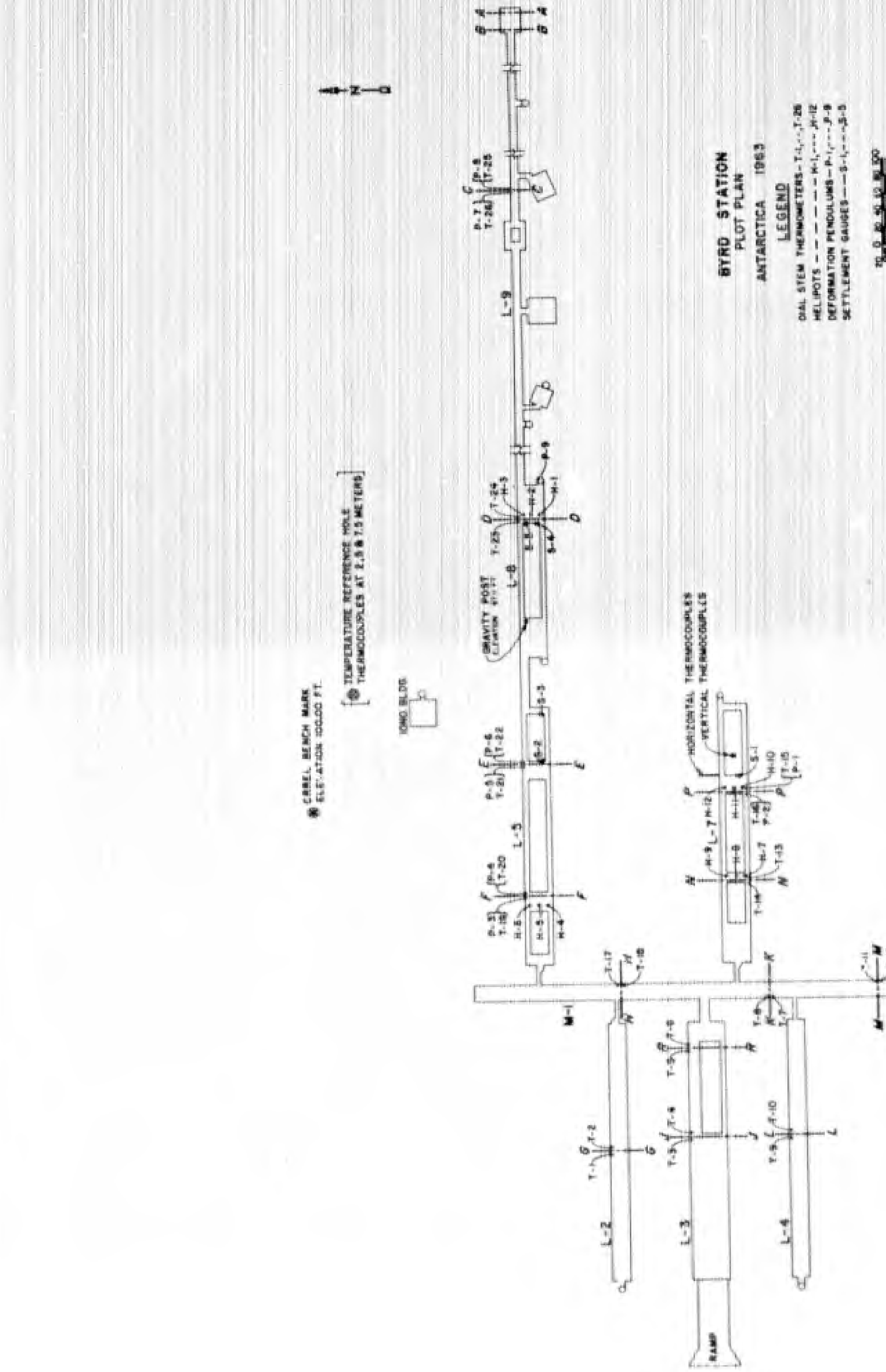


Figure 1. Plot plan of Byrd Station showing locations where measurements were made.

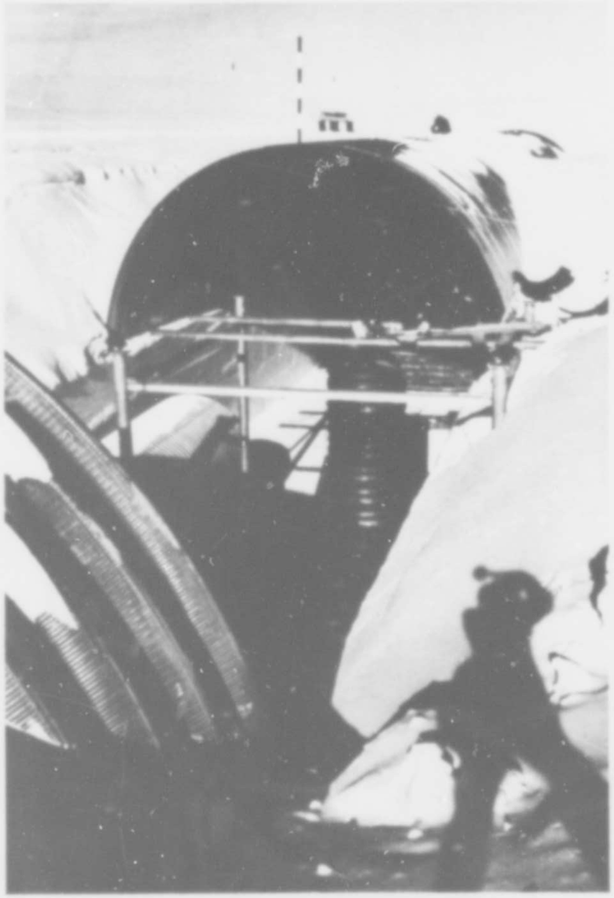


Figure 2. Typical trench roofing using 30-ft Wonder Arch. (Official U. S. Navy photograph).

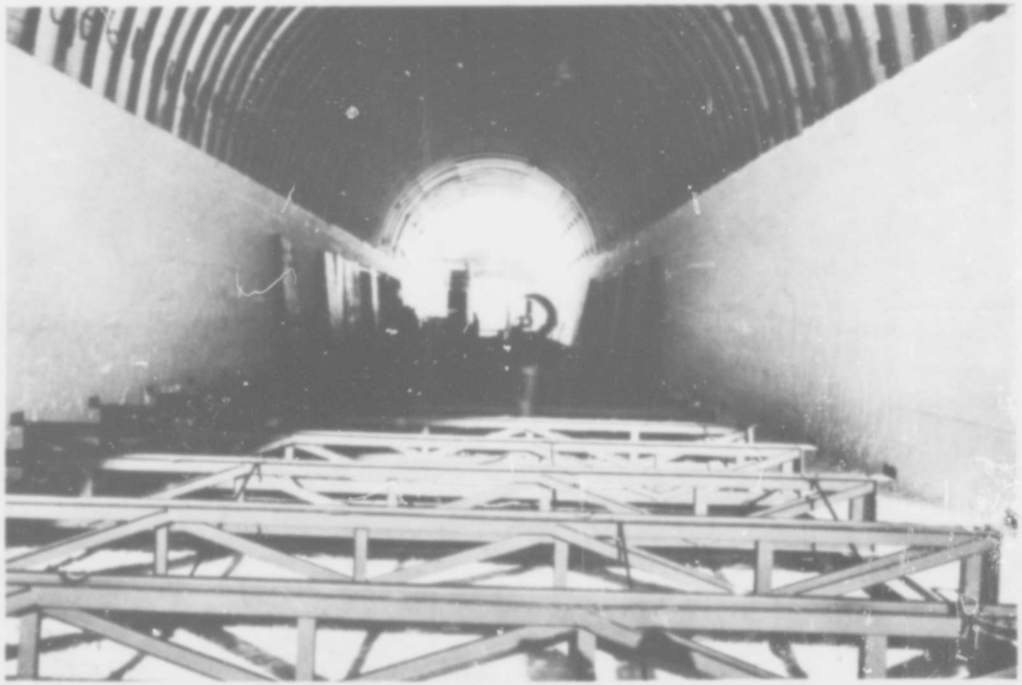
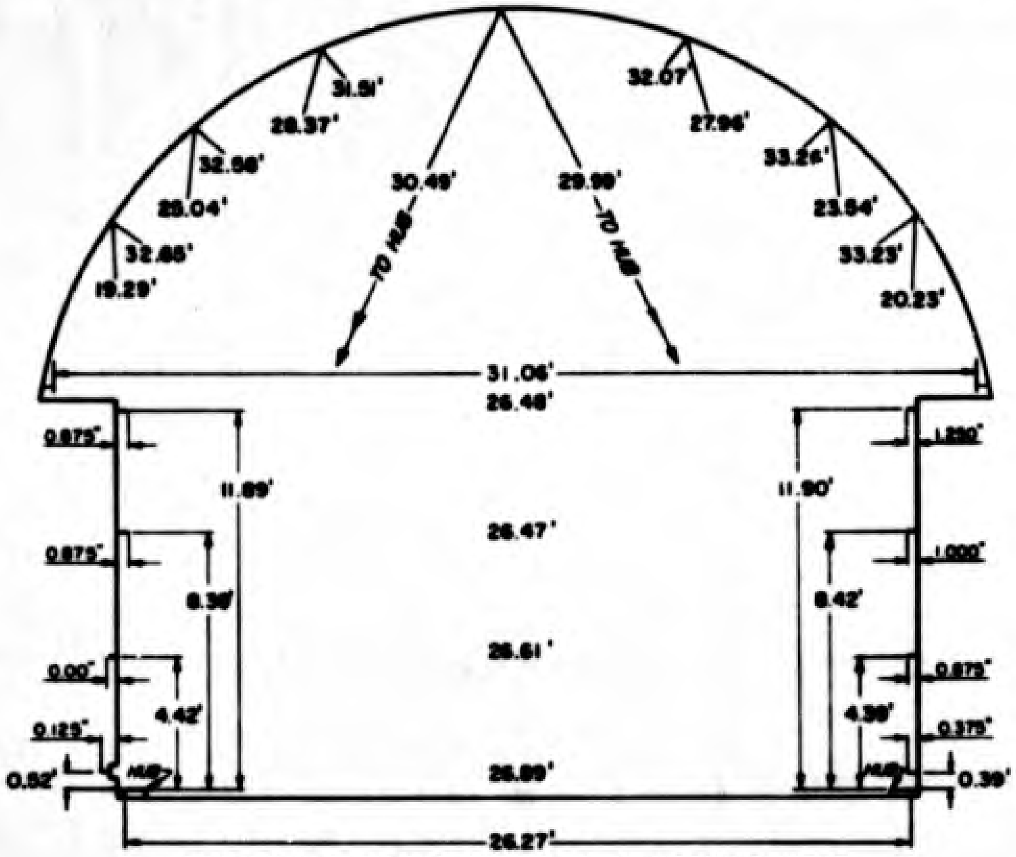


Figure 3. Foundations for the meteorology building in trench L-8. The open-web joists span between timber sills. (Official U. S. Navy photograph)



TRENCH L-7, CROSS-SECTION N-N, LOOKING WEST

Figure 4. Typical data sheet for cross-section measurements in a Wonder Arch tunnel.

Original plans called for the installation of a nuclear reactor, which could carry the full heat, light and power load, but this installation has been deferred.

During winter the station is occupied by about 25 civilian scientists and Navy support personnel. Only one vehicle access opening is maintained, and most hatches to the surface are closed. Conditions then are favorable for maintenance of the strict temperature control necessary in a "deformable" undersnow facility, particularly as very cold surface air is available for cooling problem areas. In summer, though, there is a heavy influx of transient personnel and more openings to the surface are used. This creates problems of heat control.

So far there has been considerable surface activity at Byrd during the summer seasons. Temporary buildings, supplies stored on the surface, and parked vehicles have all produced large deposits of drift snow. This has been aggravated by mounds of spoil left by bulldozers after "digging-out". The effect has been to increase the snow accumulation locally and irregularly, with consequent effects on the overburden pressure for subsurface structures.

MEASUREMENTS

Tunnel deformation

Main interest centers on deformation of the tunnels and the resulting losses of headroom and clearance. Changes of size and shape in the tunnels have been followed by measuring and plotting cross-sections at a number of locations (see Fig. 1). Locations were chosen to include all typical cross sections employed in the design, and were such that effects of marked temperature variation or structural anomaly would be reflected in the results. Measurements were made in Nov 1961, Feb 1962, Nov 1962 and Feb 1963.* The cross sections were measured by using steel tapes to take dimensions from two fixed hubs whose relative positions were checked by taping and leveling (Fig. 4).

*Since this report was first submitted, further data have been obtained (Dec 1963). These data have been added to the graphs where possible. The analysis and interpretation are unaffected.

The reference hubs were 2 x 2-in. timbers driven firmly into the snow floor at the base of the trench wall on each side of the tunnel. All such hubs were included in level surveys made throughout the station, using a special bench mark as reference. This bench mark was established outside the station, in the undisturbed "science quadrant", by augering a vertical hole to a depth corresponding to the general level of tunnel floors, and placing a rigid column set on a timber foot inside the hole. The column was made from sectional aluminum scaffolding pole, and the hole was sufficiently large to leave an annular space around the column, thus eliminating disturbance by settlement of the adjacent snow.

To provide data on tunnel deformation at more frequent intervals, particularly during the winter when CRREL men were not on site, remote-indicating deformation gages were installed. The first type, the helipot, consisted of a helical potentiometer sealed inside an aluminum case, with an external pulley wheel to drive the potentiometer wiper (Waterhouse, 1961). Helipots were attached to fixed supports, and inextensible cords, tensioned by counterweights at their free ends, were run from the pulleys to the deforming points. Helipot locations are given in Figure 1 and their arrangements are shown diagrammatically in Figure 25. As tunnel closure occurred, the cords rotated the potentiometers. Readings were made by connecting a portable Wheatstone bridge to each helipot lead in turn; resistance changes were converted to linear distances with the aid of a prepared calibration sheet.

Since displacements were quite large, additional gages were added to the system in the second season. These, termed "pendulum gages", were simply phosphor-bronze cords spanning the dimensions to be monitored, and arranged so that a length of steel measuring tape at one end ran past a fixed reference mark.

Where man-tunnels penetrated the walls of the central trench (M-1) to give access to side trenches, deformation grids were sprayed onto the snow early in 1962. String-line frames were held on the snow and the string-lines marked by spraying paint from an aerosol can, so that a visible grid was left on removal of the frames. All the grids were photographed. Node points of the grid were marked with nails as insurance against evaporation of the snow (Fig. 5). These grids were almost obscured by smoke-blackening during a fire; some were also mutilated by equipment scraping by and others were made inaccessible by temporary piles of stores. It was not feasible to secure a photographic record of the grids in the 1962-63 season, but they can be restored at some future date by running cords between the fixed nails.

Floor levels and foundation settlement

Elevations of trench floors and building foundations relative to the bench mark were checked from time to time, using ordinary leveling methods. For closer observation of foundation settlement rates, dial micrometers were attached to some buildings. Reference blocks were frozen into snow adjacent to the foundations, at a minimum distance equivalent to three times the footing width.

Temperature measurements

Bimetallic dial thermometers were inserted into the snow walls at most of the cross-sections monitored for deformation. These thermometers were usually in pairs, one with an 8-in. stem and the other with an 18-in. stem. This arrangement gave a rough indication of the magnitude and direction of the temperature gradient in a direction perpendicular to the wall surface.

Strings of thermocouples were placed in the snow near the diesel generator building, one string running vertically down beneath the tunnel floor and the other running horizontally into the wall. String dimensions and spacings of junctions are shown in Figure 6. One thermocouple was placed underneath the foundation pad of the diesel generators, and another was placed in an air well nearby. The first winter's thermocouple readings are suspect; air sucked from the snow because of a ventilation complication aspirated the thermocouples.

As temperature reference, a vertical thermocouple string was placed in the snow of the undisturbed quadrant outside the station.

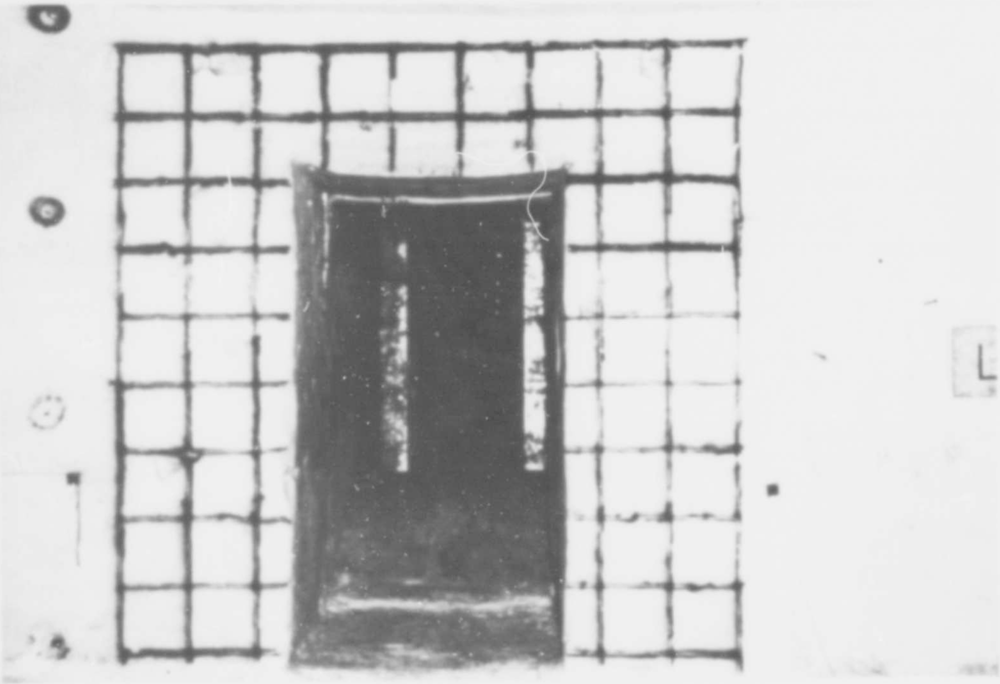


Figure 5. Deformation grid marked on the snow wall at the entrance of the passageway from M-1 into L-2. The sagging roof of the passage, and the faintly visible natural strata, show that some deformation occurred before the grid was marked. (Official U. S. Navy photograph)

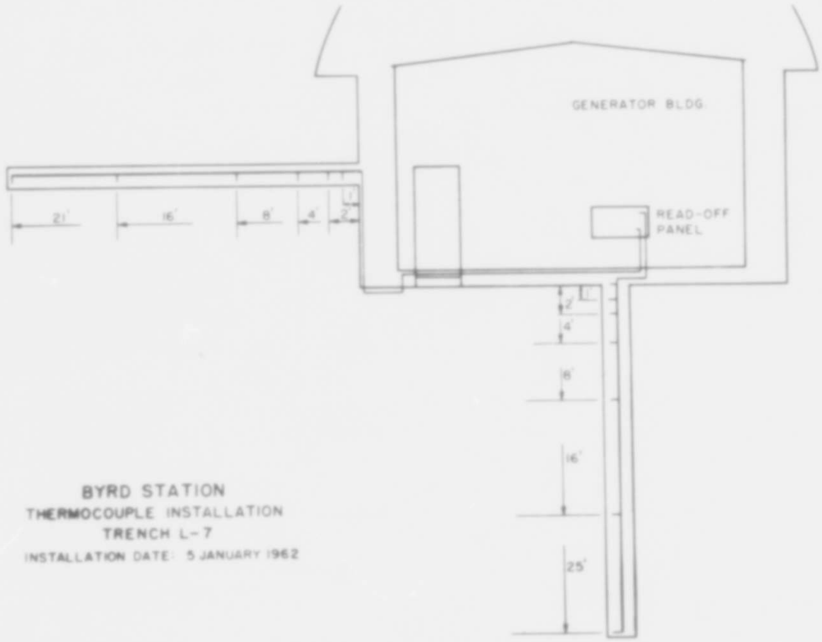


Figure 6. Arrangement of thermocouples in trench L-7.

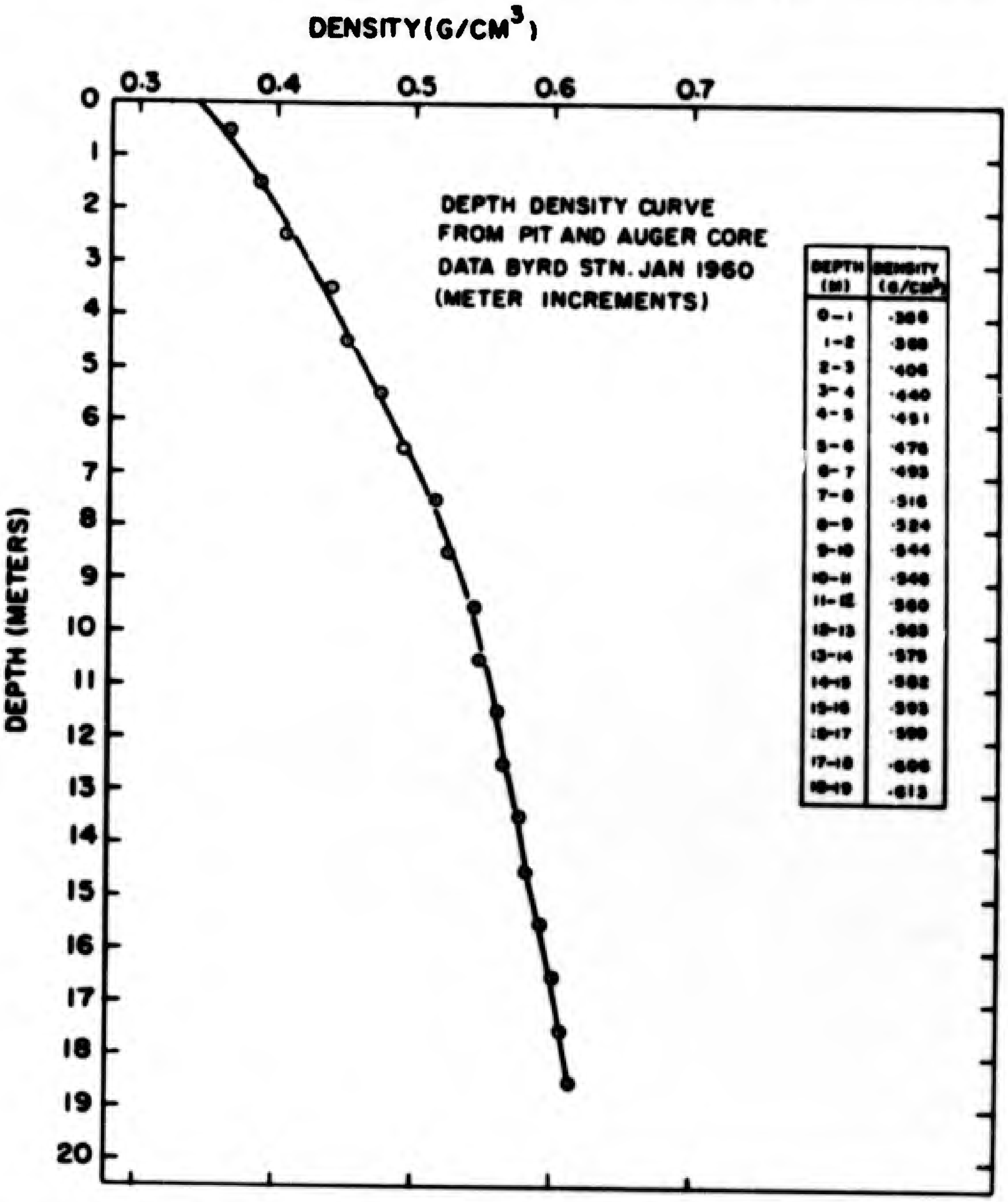


Figure 7. Depth-density profile measured in undisturbed snow at the Old Byrd Station. (After Gow, 1961)

Ventilation survey

A ventilation survey was made in November 1962 while the station ventilation was operating as designed. A second detailed survey was made in January 1963 after modification of the ventilation system. Although air flow meters, anemometers, and thermometers were available for the survey, little quantitative information was collected, since the shortcomings of the system were so gross that first interest lay in correcting directions of flow.

Additional tests

Foundation tests were made in a special trench some distance from the main station. Test procedures have been described, and preliminary data presented. A detailed analysis of the tests will be reported separately. Results of confined compressive creep tests are reported in USA CRREL Research Report 138 (Mellor and Hendrickson, in press). Some experiments on artificial reinforcement of snow were made. These are described in Appendix A.

DATA

Site Data

Byrd Station is located at approximately 80° S latitude, 120° W longitude, some 6 miles from the old IGY station. Its altitude is about 5000 ft above sea level. There is an average net accumulation of snow equivalent to 15 - 18 cm of water per year. The density of the surface snow layer is about 0.38 g/cm³, which means that the annual accumulation is 14 - 17 in. of snow. The density of lying snow increases with depth below the surface as shown in Figure 7.

The mean annual surface temperature at Byrd is -19F. The highest temperature recorded in the 5-yr period from 1957-1961 was 30F, and the lowest -82F. Mean monthly wind speeds range from about 13 to 23 mph through the year, and the highest 1-minute gust recorded between 1957 and 1961 was 78 mph. Temperature and wind data are summarized in Figures 8 and 9.

Tunnel deformation

In Figures 10-14 data are given for five cross sections in tunnels roofed by 30-ft span Wonder Arches. Successive profiles at each cross section show the changes which occurred.

Figures 15 and 16 give corresponding data for trench L-3, which is roofed by a 40-ft span Wonder Arch. One cross section was inaccessible in 1962-63, so that data are given only for November 1961 and February 1962.

Figures 17-21 show measured profiles for the undercut trenches M-1, L-2, and L-4.

Figures 22 and 23 show changes in the profile of the seismometer vault from February 1962 to December 1963 at two cross sections. In this vault, Wonder Arch extends to the floor, so that only the floor itself is unrestrained.

Figure 24 shows the deformation which occurred in a section of trench L-9 roofed by unrestrained Peter snow.

Figure 25 gives the records of vertical and horizontal deformation from helipot readings. The vertical measurements indicate the rate at which headroom is being lost, i.e. they show the deformation of the snow walls, deformation of the steel arch, and hogging of the snow floor. The horizontal measurements are not very reliable, since the installation was such that the arch seats from which measurements were made moved in an arc relative to the helipots. If necessary, a correction can be applied by referring to the vertical measurements.

Figure 26 shows the readings obtained from the pendulum-type deformation gages. The vertical readings from the pendulums may be expected to be somewhat smaller than those from the helipots, since they register changes in height of the snow wall only; hogging of the snow floor and deformation of the arch steel do not affect these readings. Horizontal deformation records from the pendulums are believed to be more accurate than those from the helipots.

Floor levels and foundation settlement

The changes in relative elevation of the pegs at control cross sections are shown in Figure 27. First readings were made in November 1961, towards the end of the construction period, and the final readings given here were made in December 1963. Readings on foundations do not represent true settlement, since the snow floors are hogging, and settlement gages were installed in November 1962 to provide more detailed information on the settlement of building foundations relative to the adjacent snow. Data are given in Figure 28.

Temperatures

Records from the dial thermometers are given in Figure 29. Figures 30 and 31 show the measurements made by the thermocouple strings. Certain readings for February and March 1962 may be incorrect, perhaps as a result of errors in reading occasioned by a changeover of personnel.

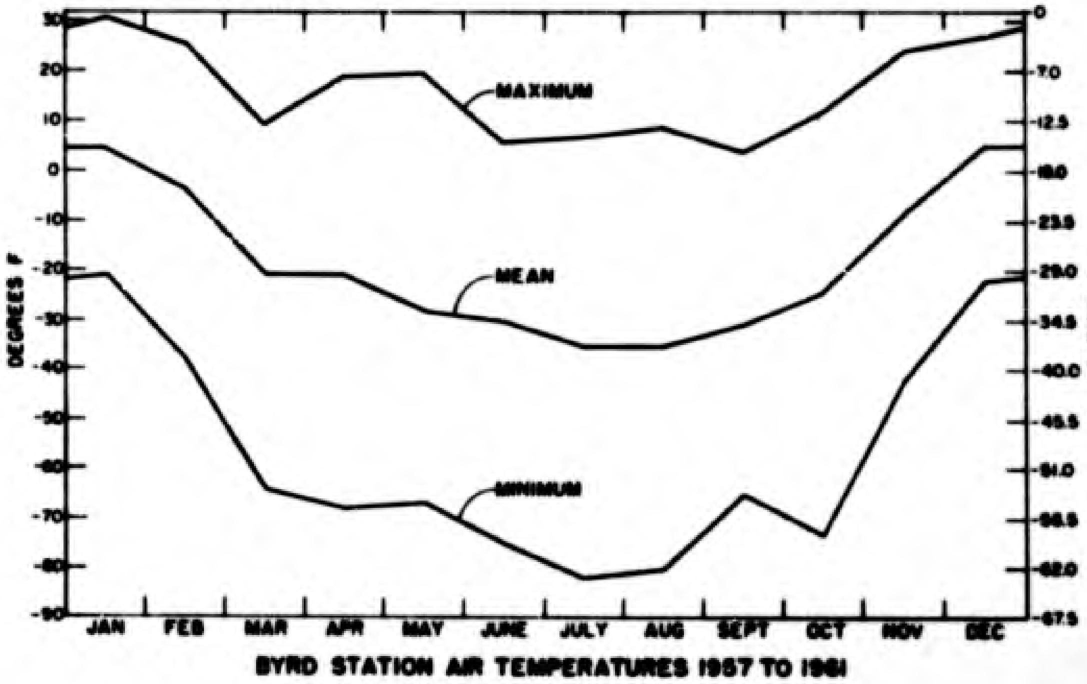


Figure 8. Surface air-temperature records for the period 1957-1961. The curves show monthly mean temperatures for the 5-yr period and absolute maximum and minimum temperatures recorded in each month over a 5-yr period. (From U. S. Weather Bureau records for the old Byrd Station)

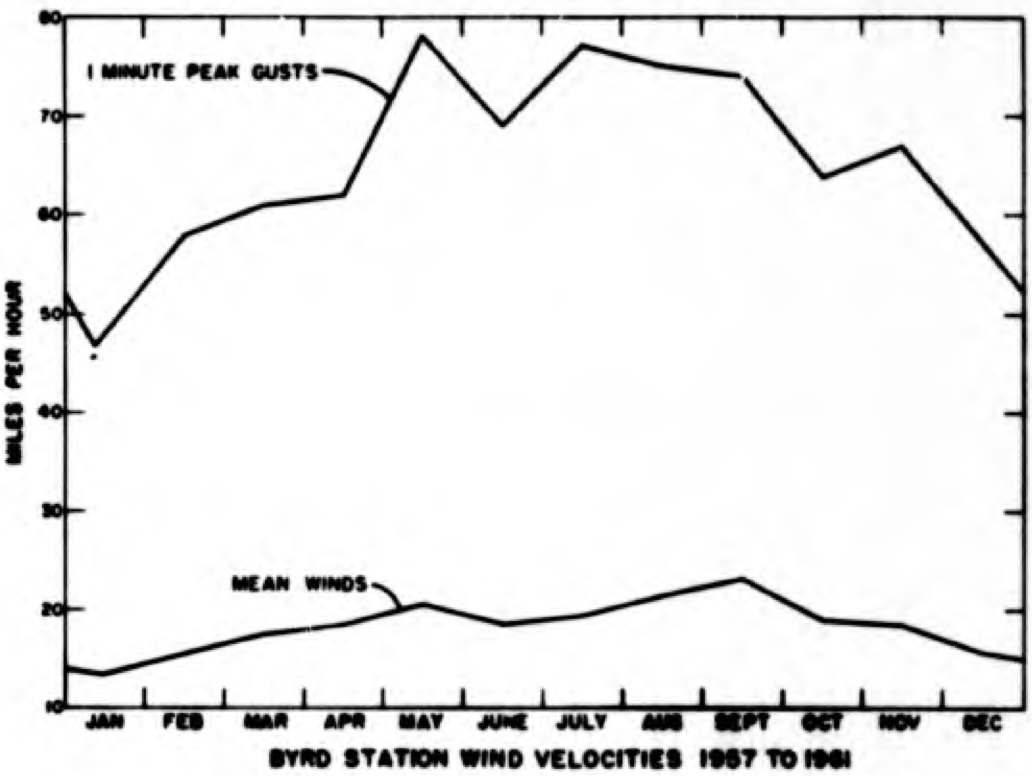


Figure 9. Surface wind data for the period 1957-1961. The monthly mean wind speed for 5 yr of record is given, together with the maximum 1-min gust recorded in each month during the 5-yr period. (From U. S. Weather Bureau for the old Byrd Station)

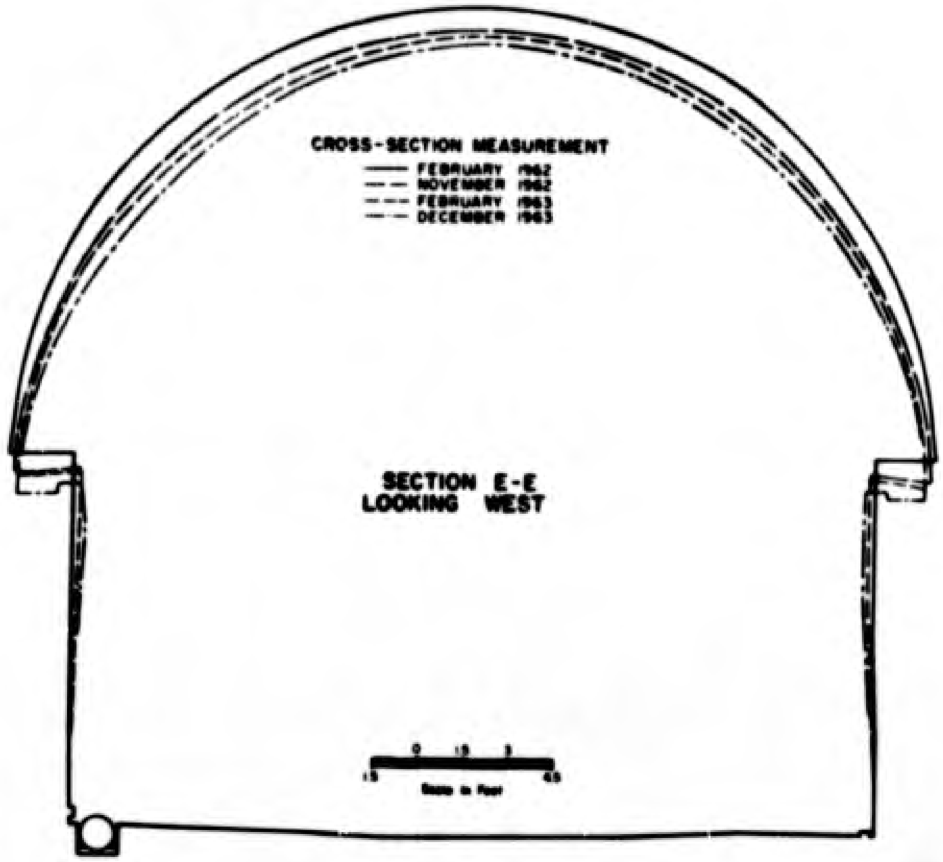


Figure 10. Cross-section profiles at section E - E in trench L - 5.

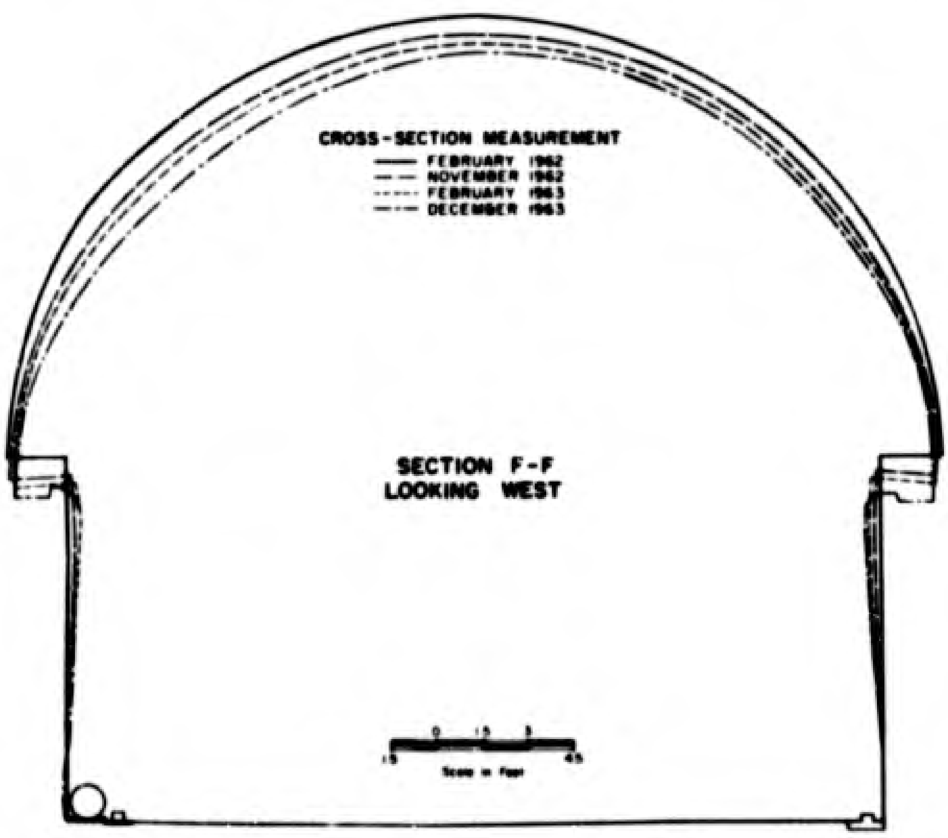


Figure 11. Cross-section profiles at section F - F in trench L - 5.

Figure 12. Cross-section profiles at section P - P in trench L - 7.

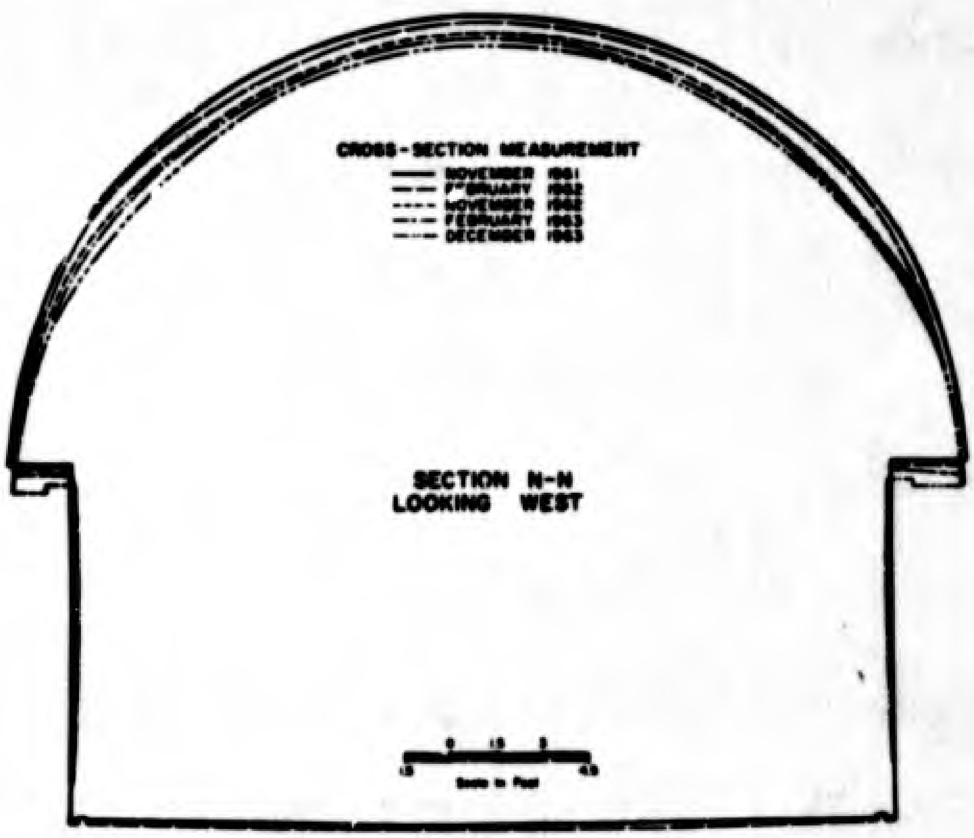


Figure 13. Cross-section profiles at section N - N in trench L - 7.

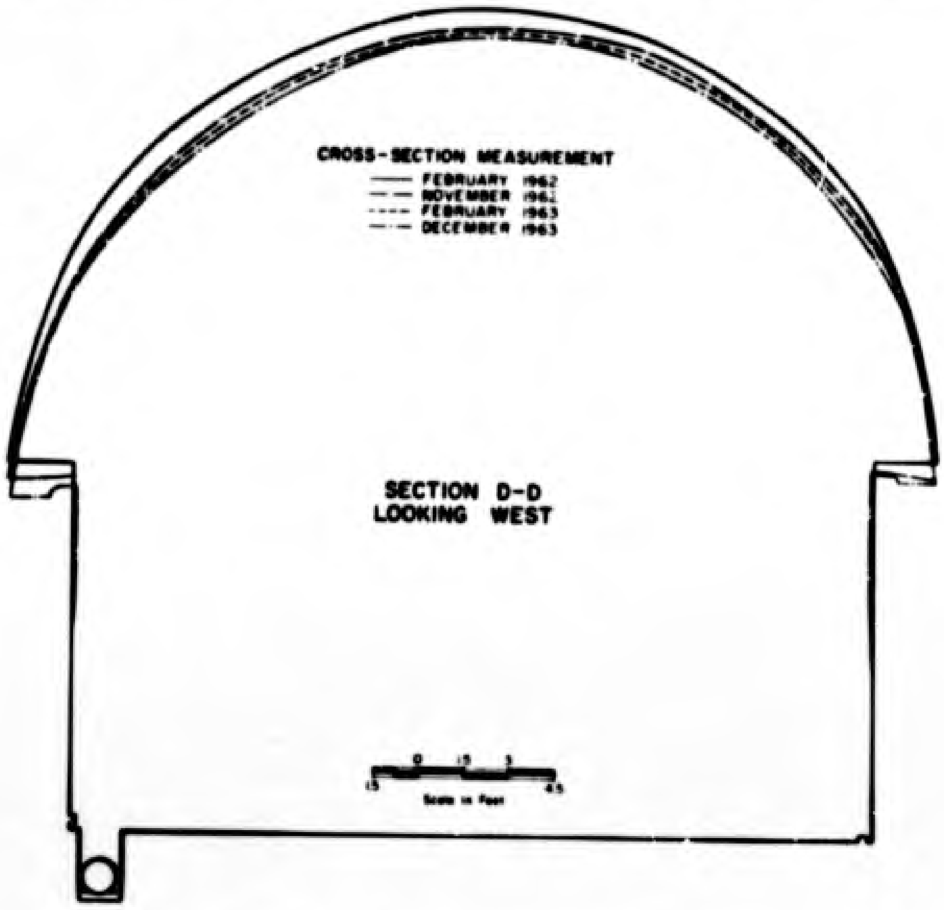


Figure 14. Cross-section profiles at section D - D in trench L - 8.

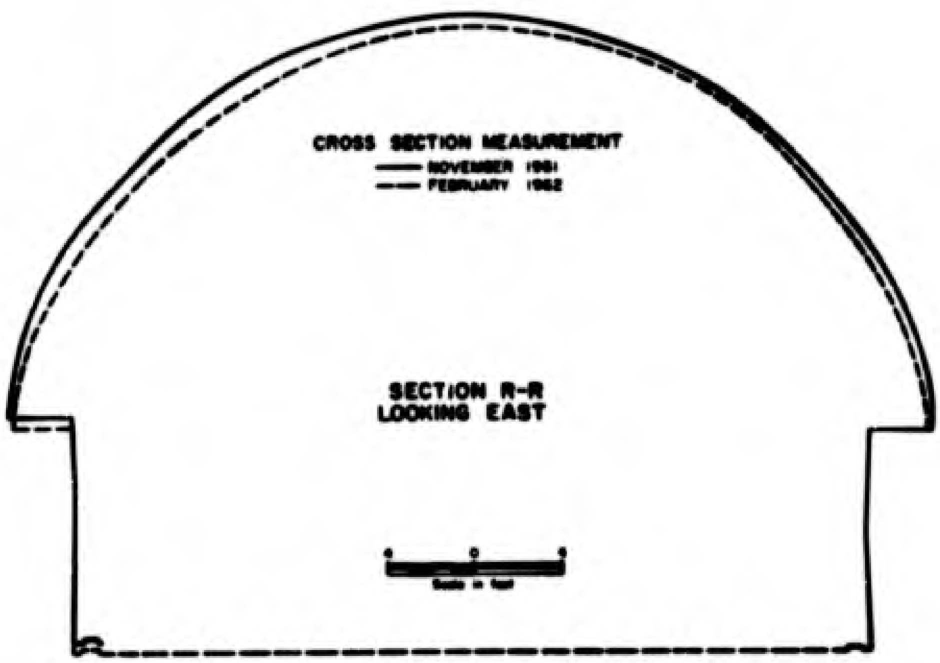


Figure 15. Cross-section profiles at section R - R in trench L - 3.

Figure 16. Cross-section profiles at section J - J in trench L - 3.

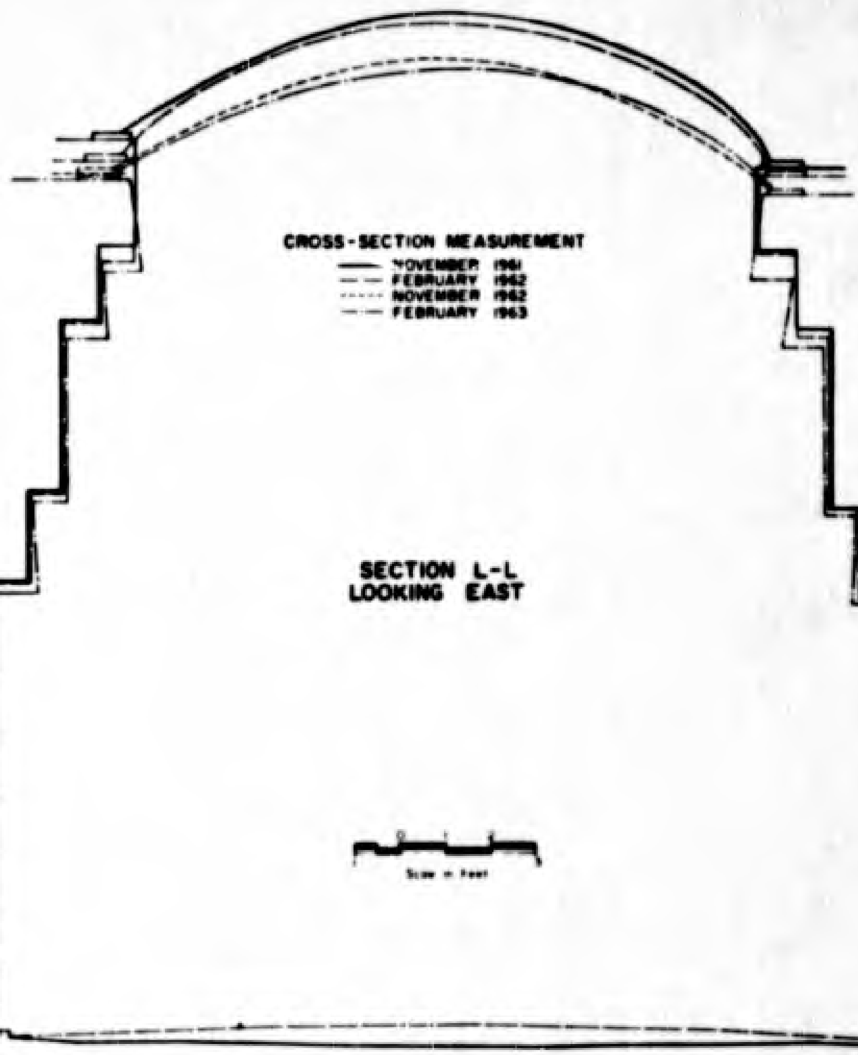


Figure 17. Cross-section profiles at section L - L in trench L - 4.

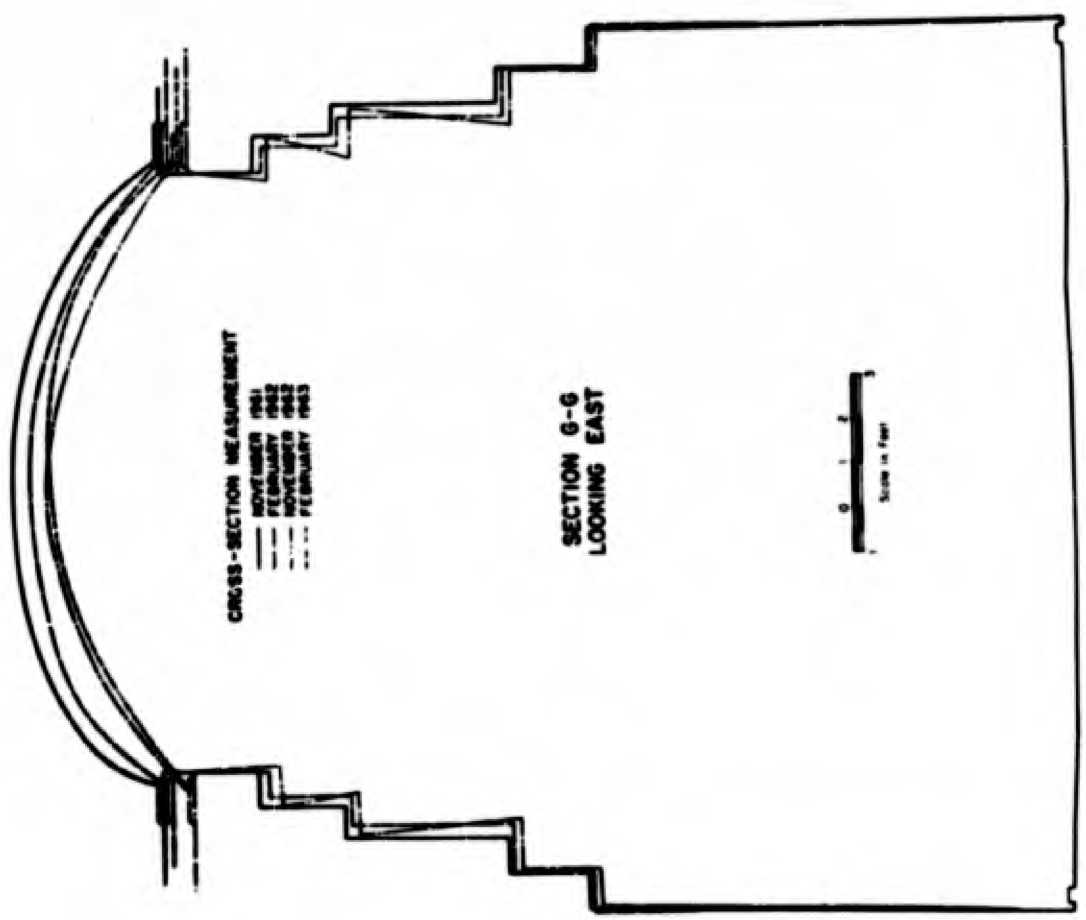


Figure 18. Cross-section profiles at section G - G in trench L - 2.

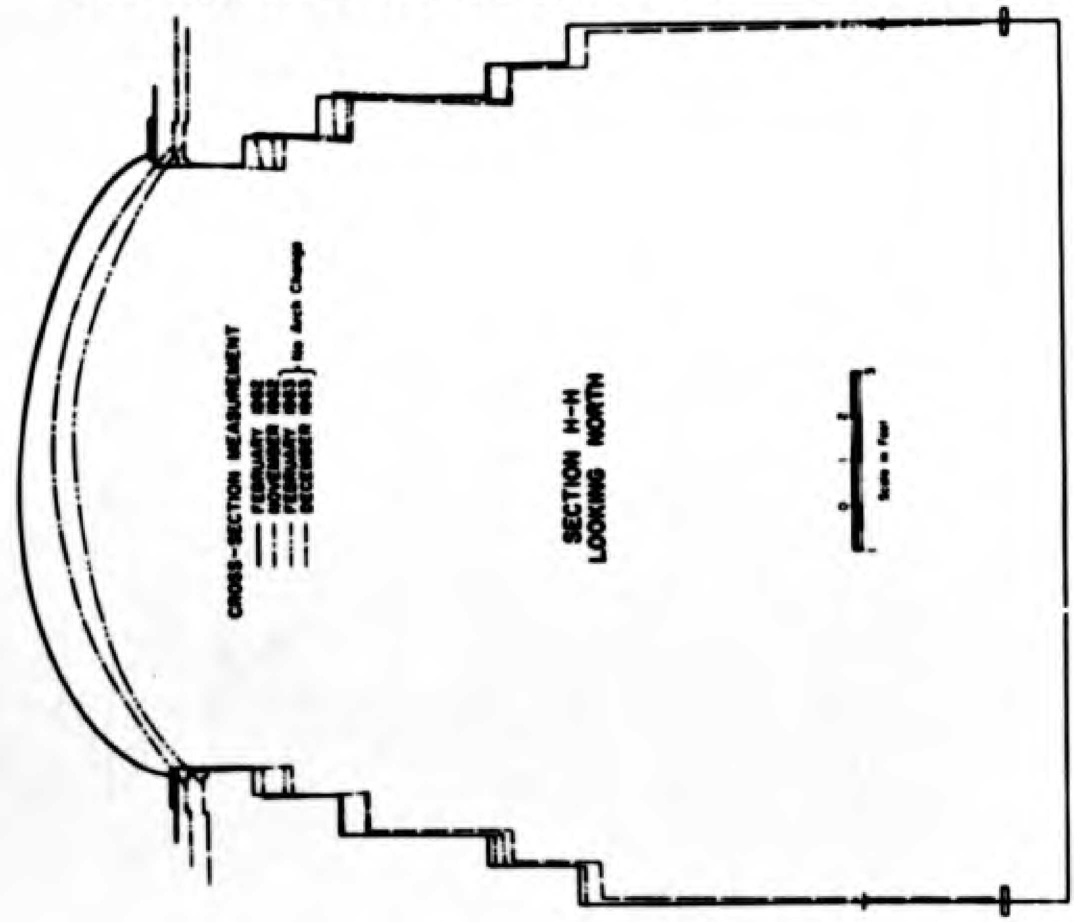


Figure 19. Cross-section profiles at section H - H in trench M - 1.

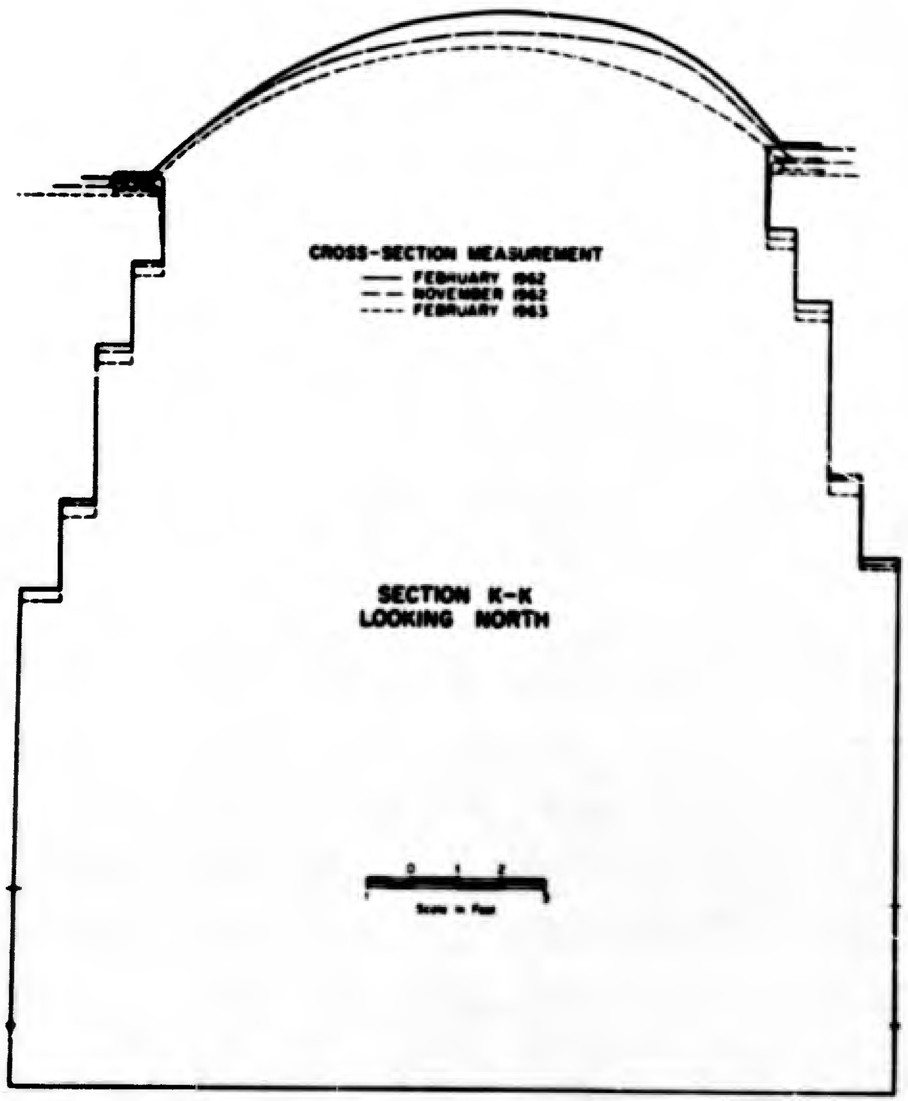


Figure 20. Cross-section profiles at section K - K in trench M - 1.

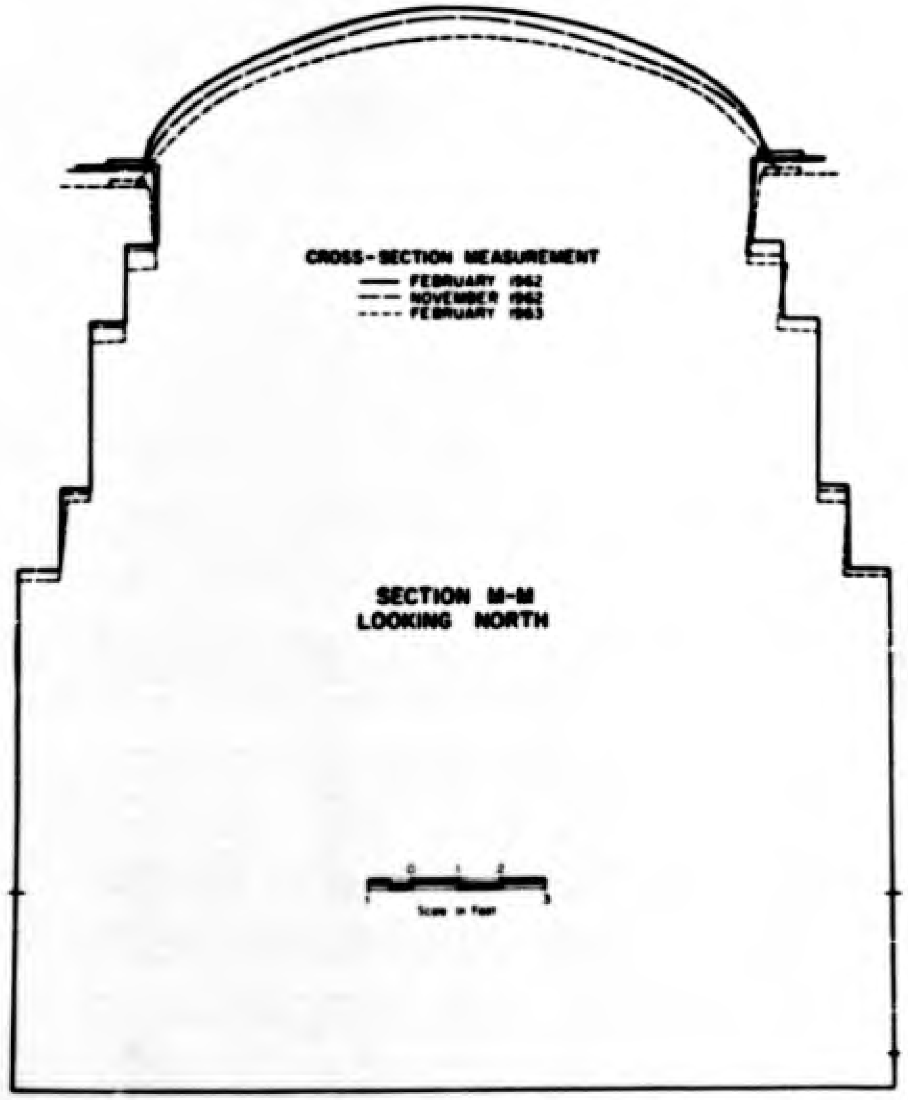


Figure 21. Cross-section profiles at section M - M in trench M - 1.

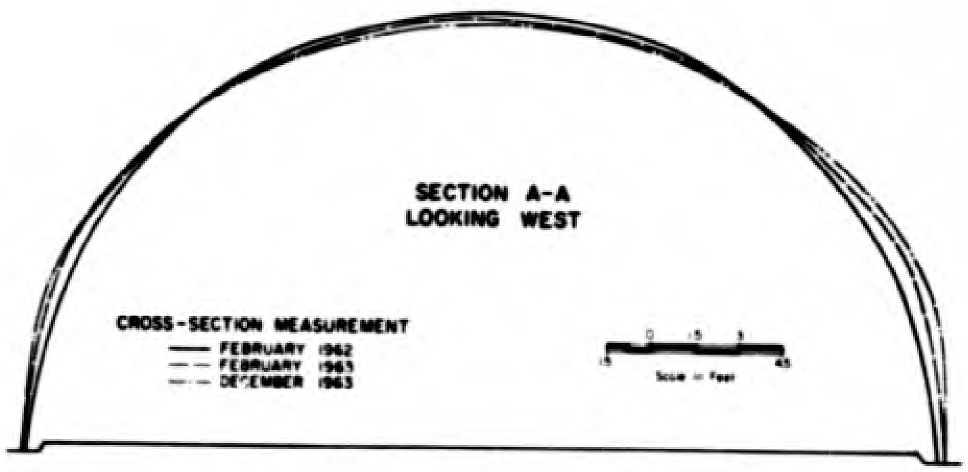


Figure 22. Cross-section profiles at section A - A in seismometer vault.

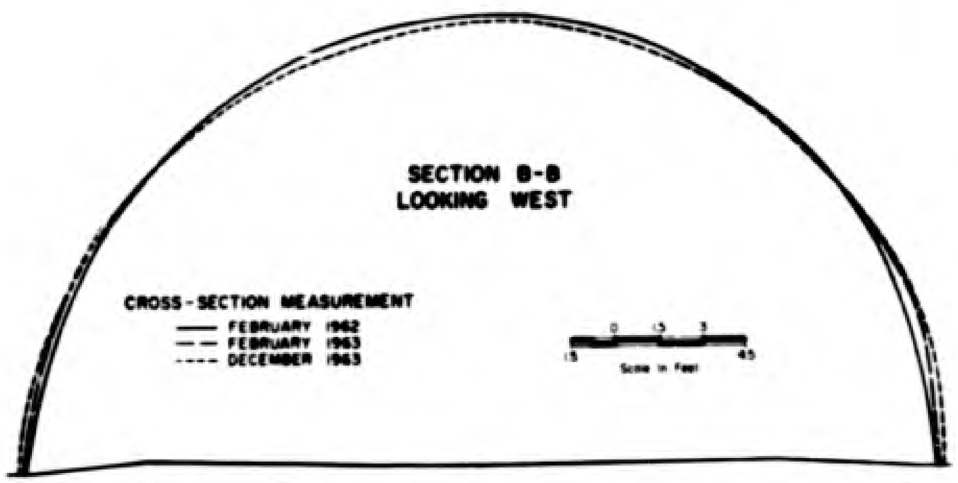


Figure 23. Cross-section profiles at section B - B in seismometer vault.

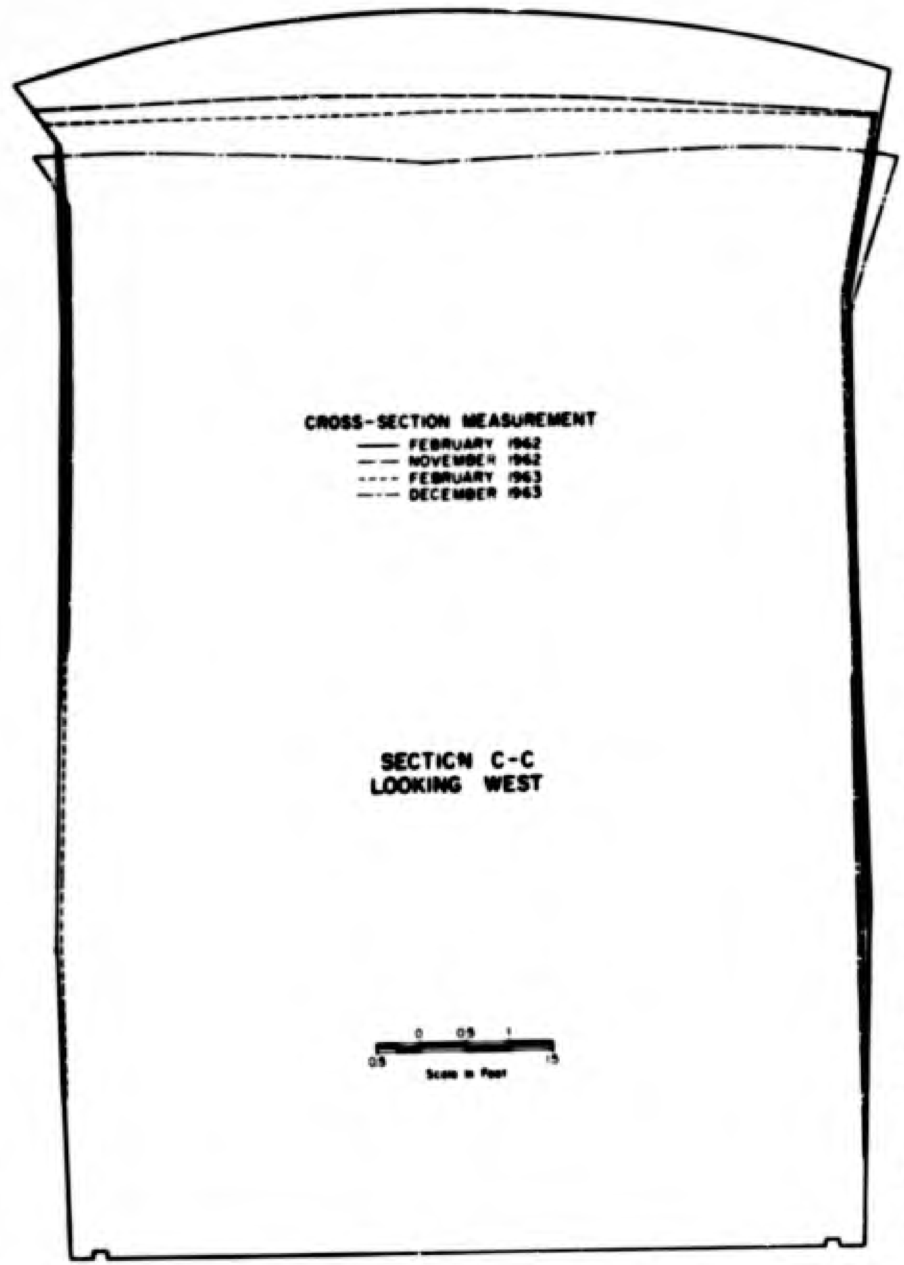


Figure 24. Cross-section profiles at section C - C in trench L-9.

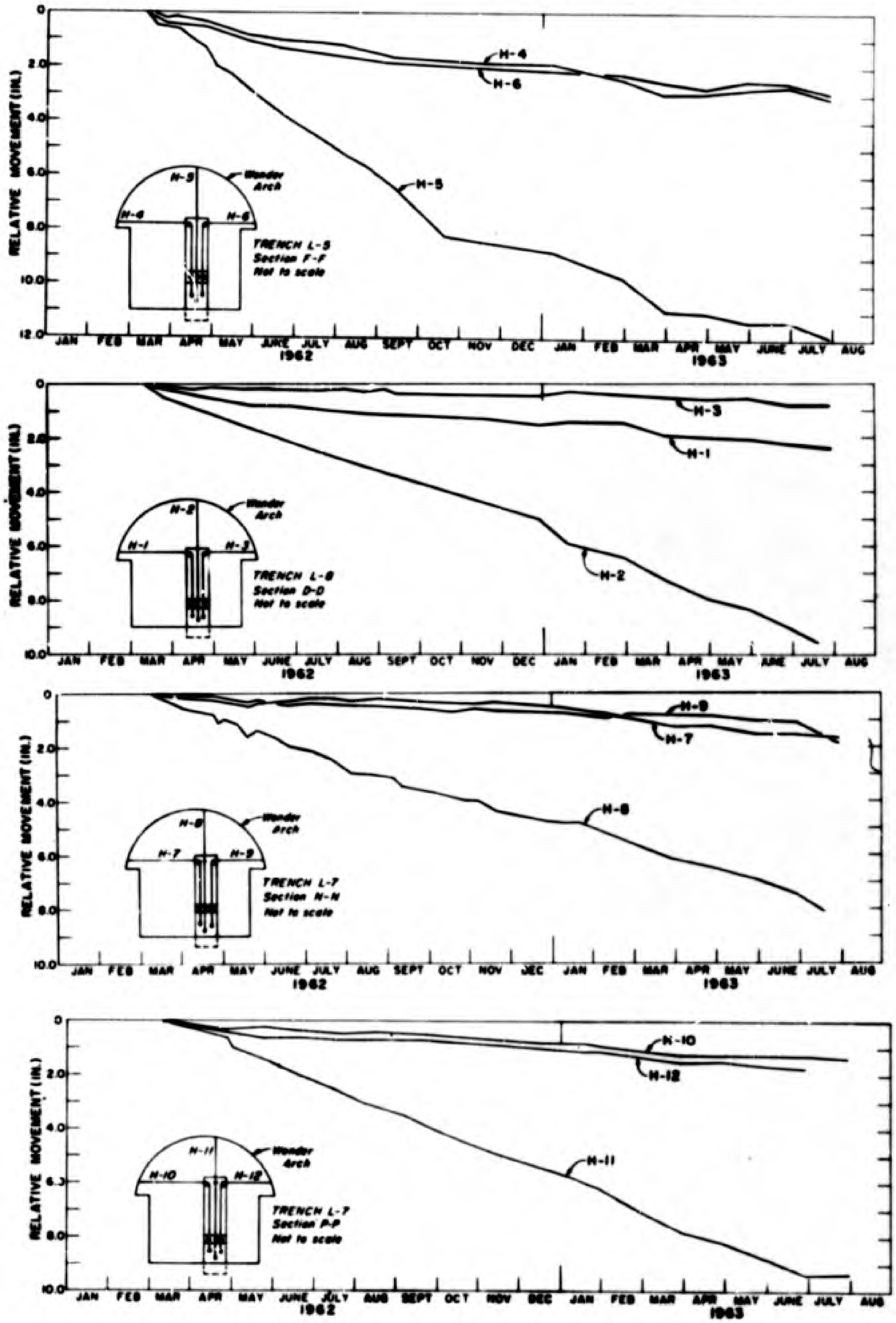


Figure 25. Helipot records.

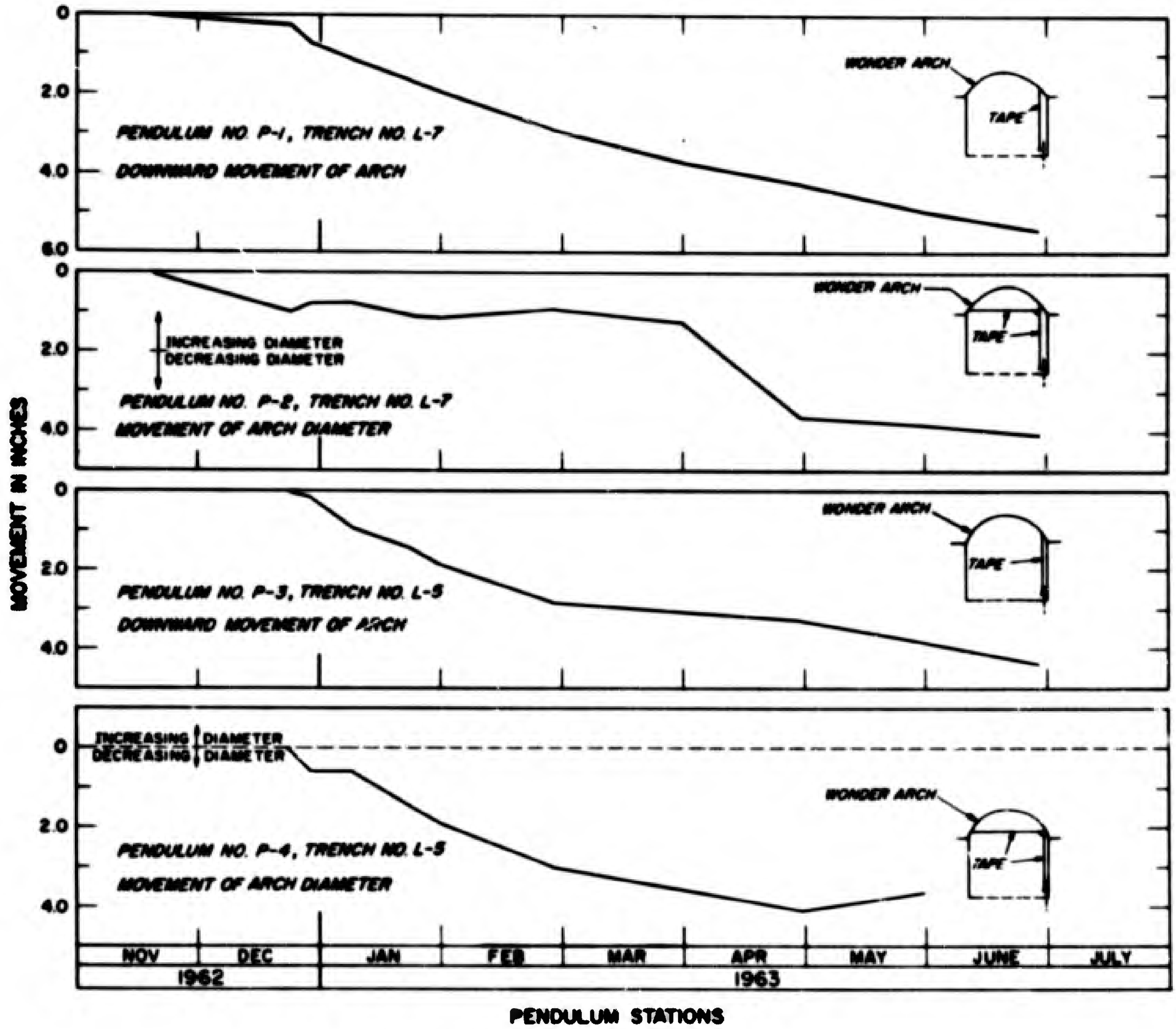


Figure 26. Records for pendulum gages.

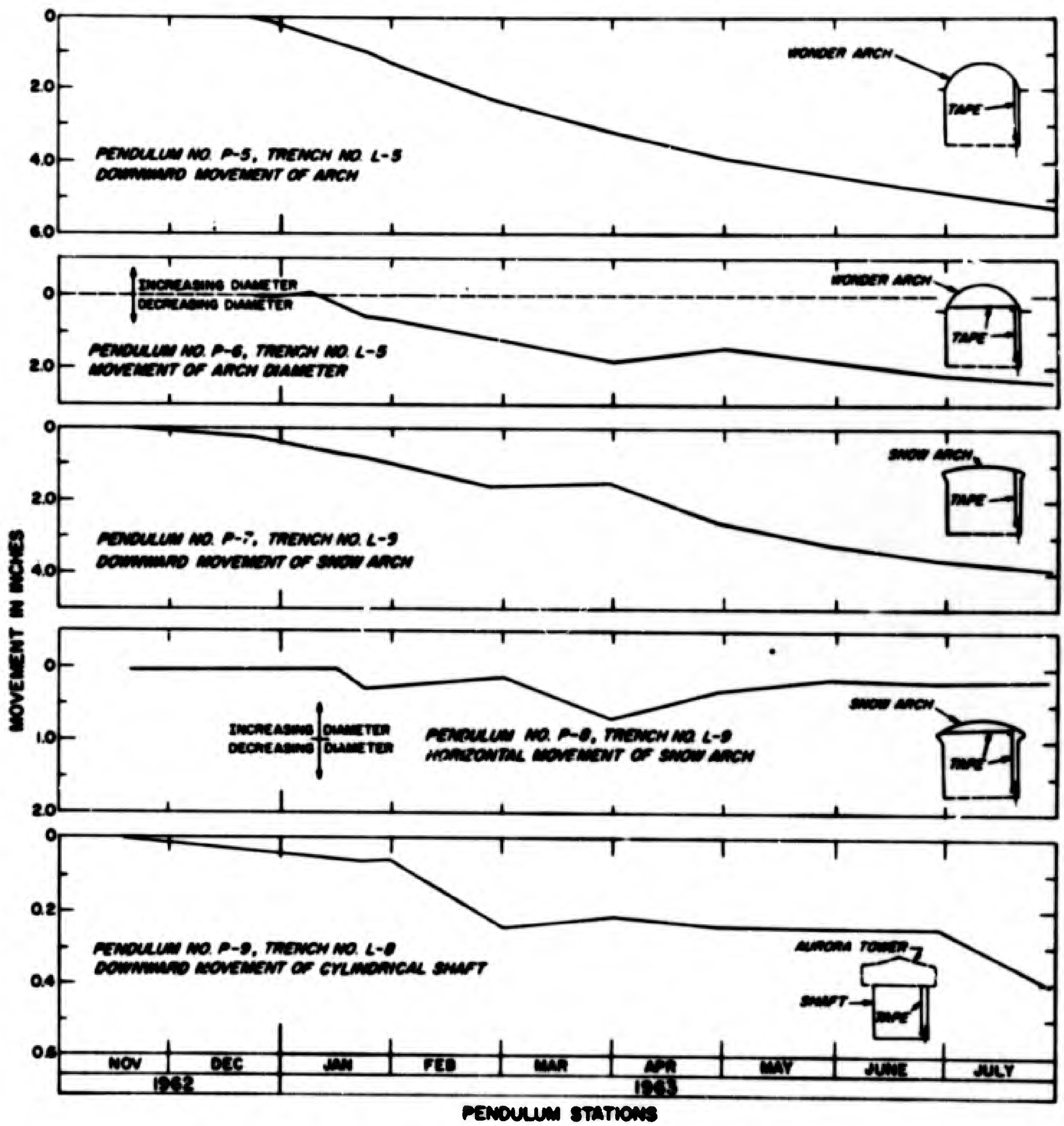


Figure 26 (Cont'd). Records for pendulum gages.

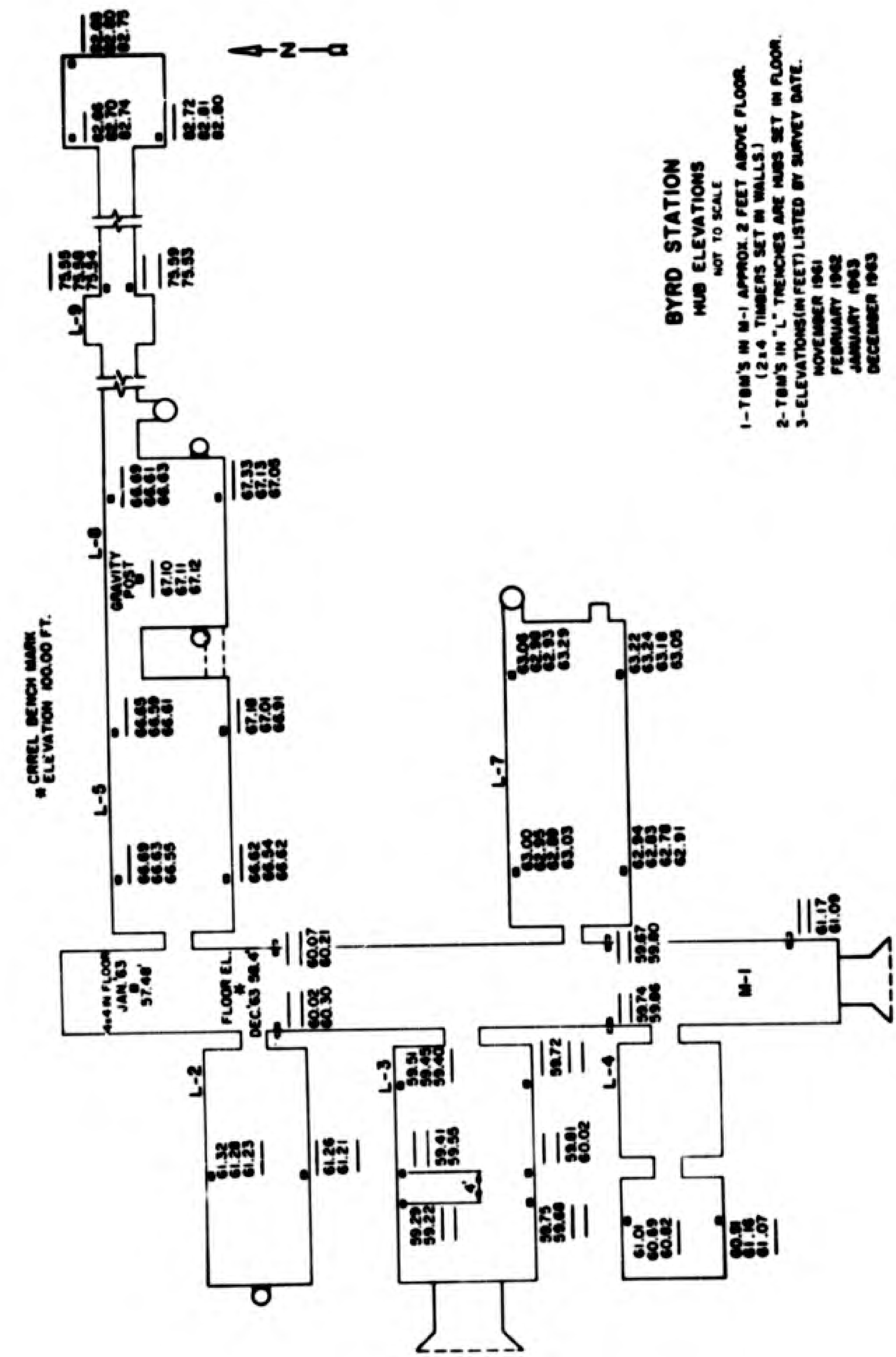


Figure 27. Changes of trench floor elevation from November 1961 to December 1963.

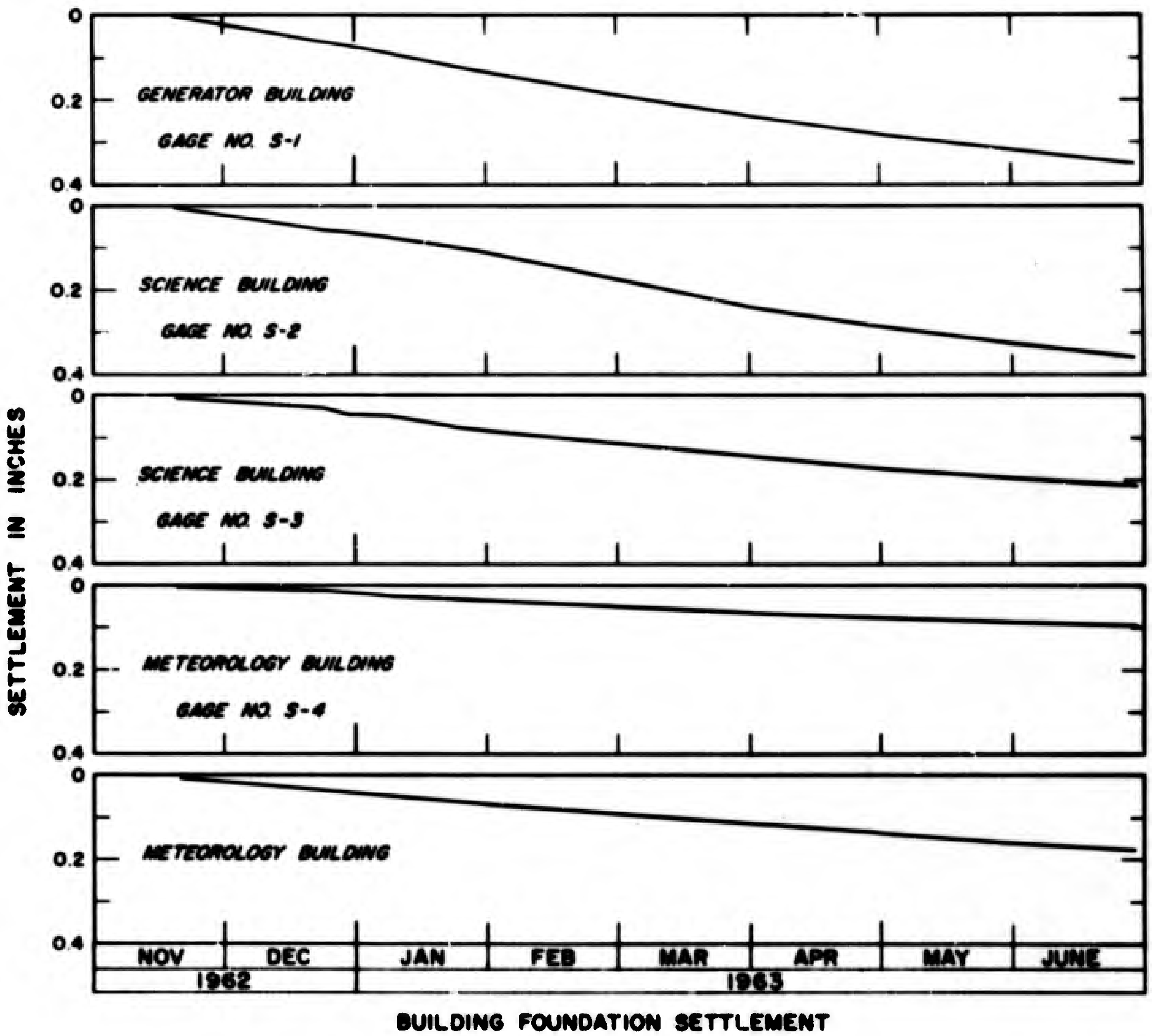


Figure 28. Records for foundation settlement gages.

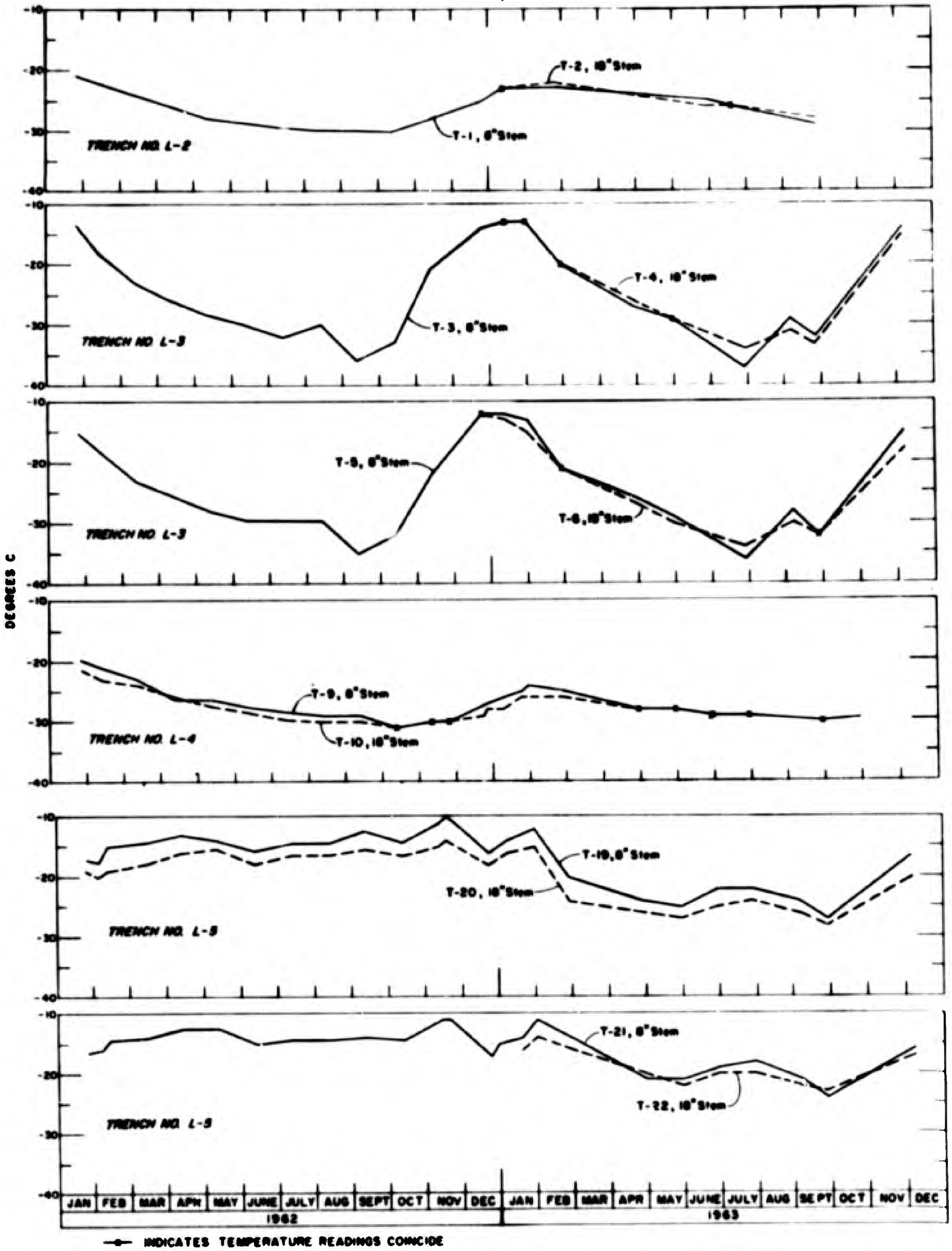


Figure 29. Records from dial thermometers in trench walls.

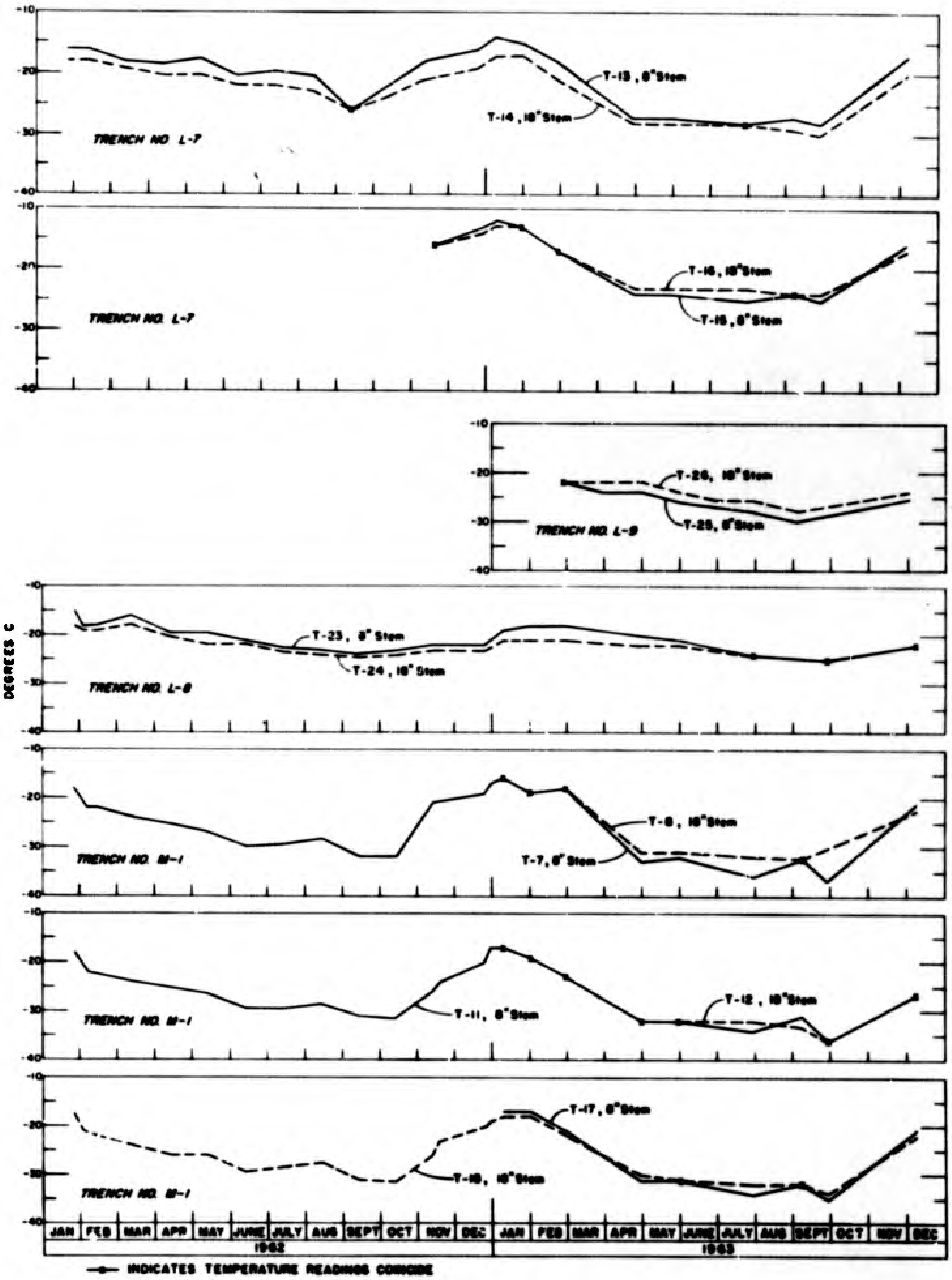


Figure 29 (Cont'd). Records from dial thermometers in trench walls.

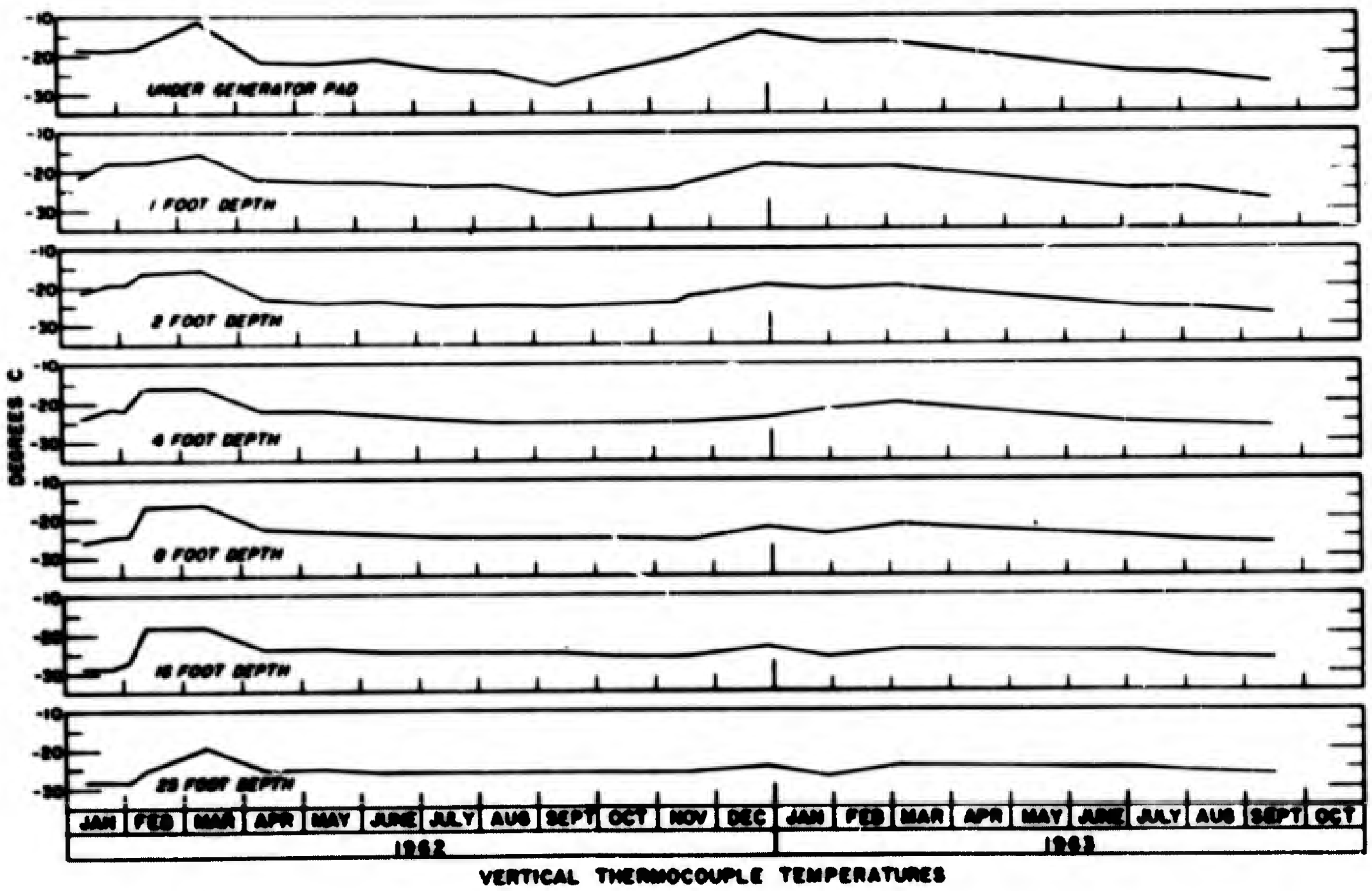


Figure 30. Records from the vertical thermocouple string in trench L - 7.

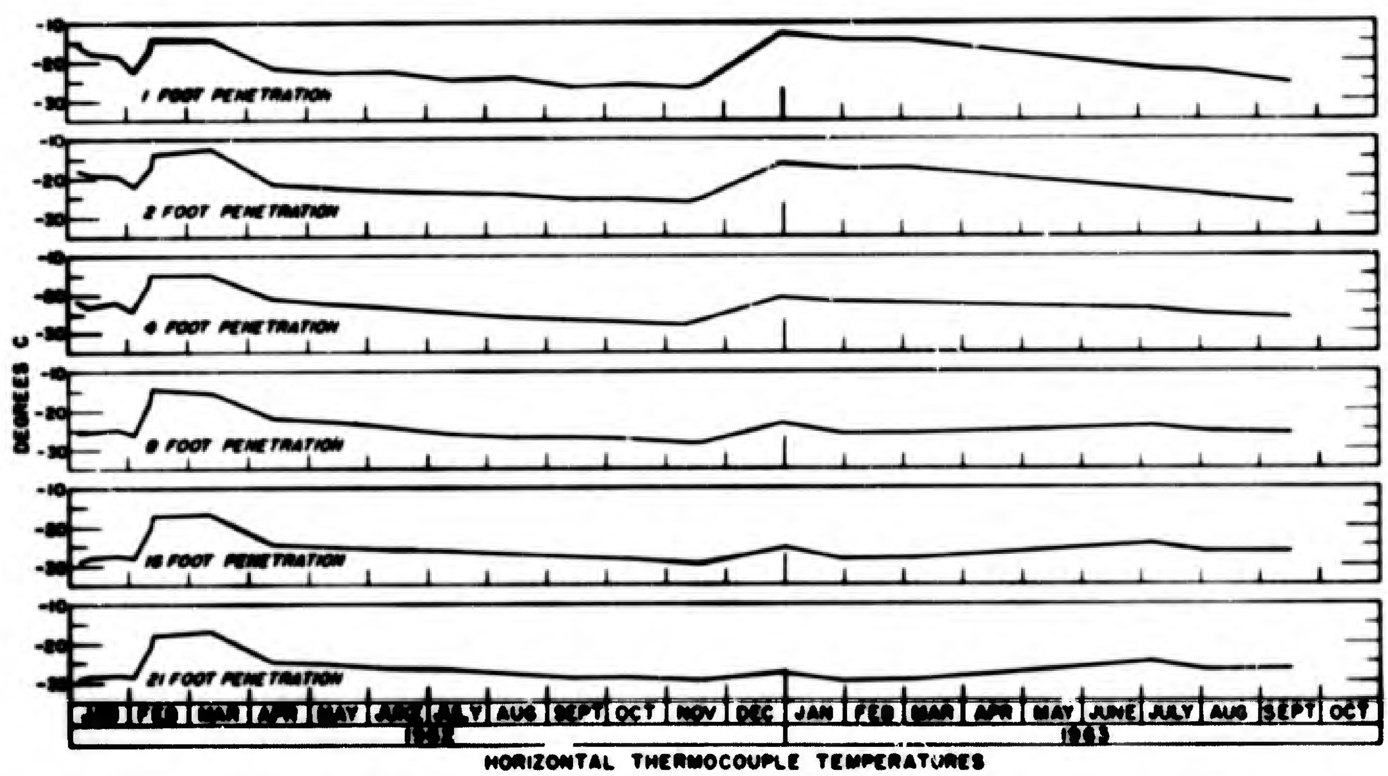


Figure 31. Records from the horizontal thermocouple string in trench L - 7.

Ventilation survey

Results of the first ventilation survey are outlined in the notes below, which are taken from a field report by one of the authors. Results of the second survey are given in Figures 32 and 33: one set of airflow and temperature measurements was made with all operable fans running, and another set of measurements was made the following day (when, unfortunately, outside wind conditions had changed) with all fans of the side tunnels shut down.

Ventilation situation in October-November, 1962. On the author's arrival at Byrd Station on 31 October, no air wells were operating but roof and bulkhead fans were running. The L-3 ramp was open and hatches on the vertical shafts of L-2, L-4 and L-7 were open. The doors separating L-5 and L-7 from M-1 would not close because of frame distortion.

Before 1 November 1962. The principal inflow of outside air came down the L-3 ramp and into M-1 through the communicating passage (the amount of loose snow on the floor of L-3 indicated that this had been the usual situation in winter). Air left M-1 through two roof fans, and also flowed from M-1 into L-5 and L-7 through the open bulkhead doors. The bulkhead fans of L-5 and L-7 pushed uselessly against the natural convective flow; air came through the fans, turned around, and immediately re-entered the trenches through the open doors. The door of L-2 was quite snug, and the bulkhead fan drew air from the trench and passed it into M-1. The air entering L-5 from M-1 passed along the trench and flowed out to L-8 via the 9-ft multi-plate culvert. Air warmed by the galley, together with direct exhaust from the galley, rose and formed a condensate of frost crystals on the Wonder Arch and the upper part of the snow walls. There was slight evaporation from the lower parts of the snow walls. The air entering L-8 from L-5 escaped through the roof fan and through undetected exits in the L-9 area (strong drafts blew up the shafts giving access to the towers when hatches were opened). The air entering L-7 from M-1 left mainly through the annular openings surrounding the generator exhaust stacks. Circulation in L-4 was very slight; air was drawn out of the antechamber by the roof fan, and replenished by seepage from the snow walls and by leakage through the M-1 and fuel chamber bulkheads.

Smoke-blackening caused by the winter fire in L-3 gave an indication of air circulation at that mid-winter period, and eye-witness reports added detail. It seems that winter circulation was essentially the same as that described above for late October. Smoke passed from L-3 to M-1, completely filling that trench and thoroughly blackening the walls. There was apparently no serious infiltration of smoke into L-2 and L-4. L-5 and L-7 were kept quite free of smoke by the closed doors and the bulkhead fans, but it was necessary to block smoke seepage by plugging gaps under doors and around bulkheads, and the cavity at the water pipe penetration.

November 1962. In early November, the bulkheads of L-5 and L-7 were repaired and the doors were kept closed. This modified the circulation in L-5, L-7, L-8 and L-9. Instead of air flowing from M-1 into L-5 and L-7 under the natural pressure gradient, a small net transfer into M-1 was achieved. At this time the station ventilation system was operating more or less as originally planned by the designers (except that air wells were inoperative); the results are described below, and comments, made at the time of the survey, are given.

L-2

Inflow: From cargo shaft and seepage through snow walls.
Outflow: To M-1 via bulkhead fan.
Comments: Should probably be isolated during summer, i.e. cargo hatch closed and fan shut off. Under present arrangement it is pulling surface air, which is warmer than the trench walls. During winter, fan should run with cargo hatch closed. This would pull cold surface air through the pores of the snow walls.

L-3

Inflow: From open ramp.
Outflow: To surface via one roof fan; to M-1 via passageway.
Comments: Ventilation completely unsatisfactory. Roof fan should be supplemented

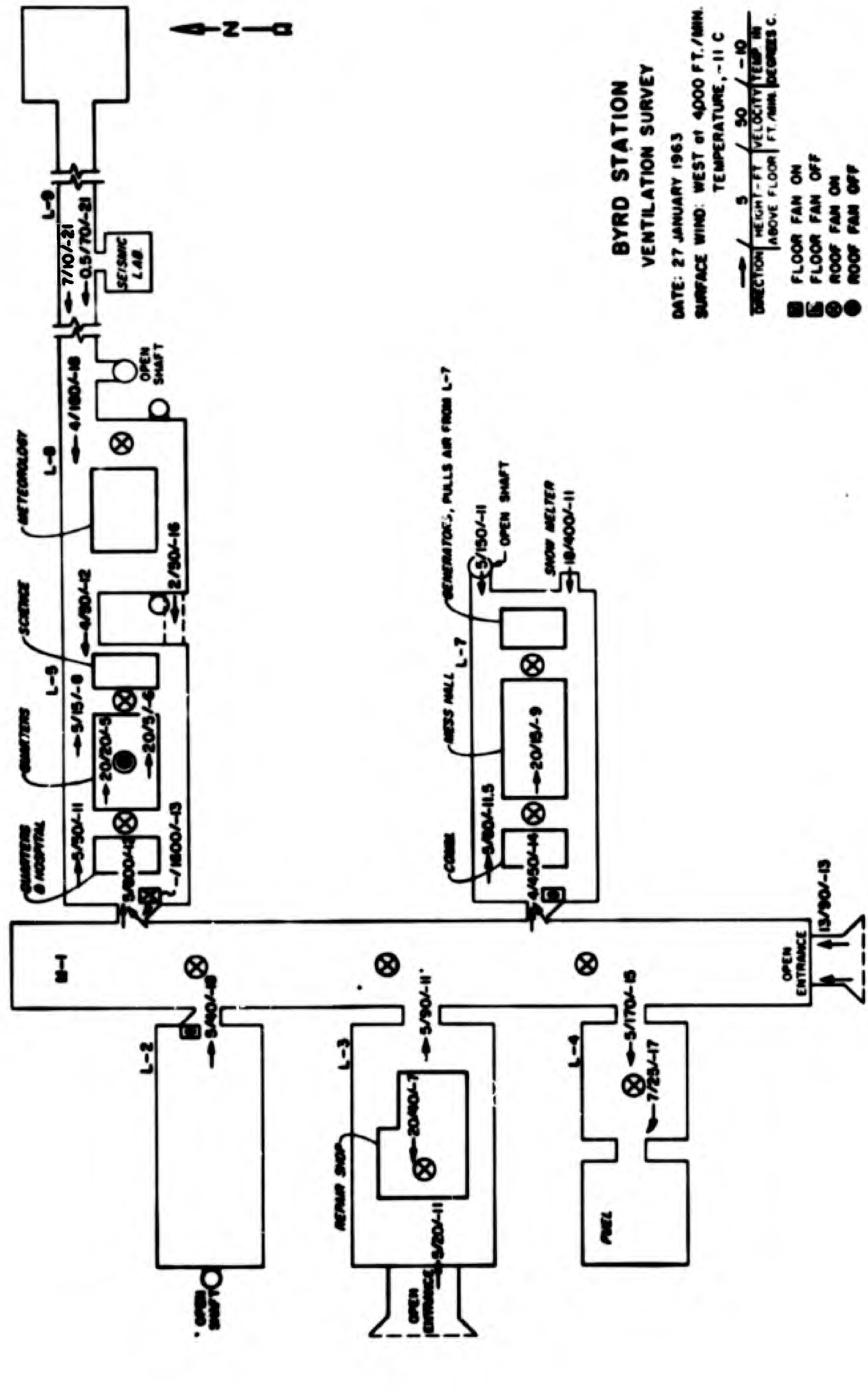


Figure 32. Air temperatures and air current velocities with hatches and doorways open and roof fans running.

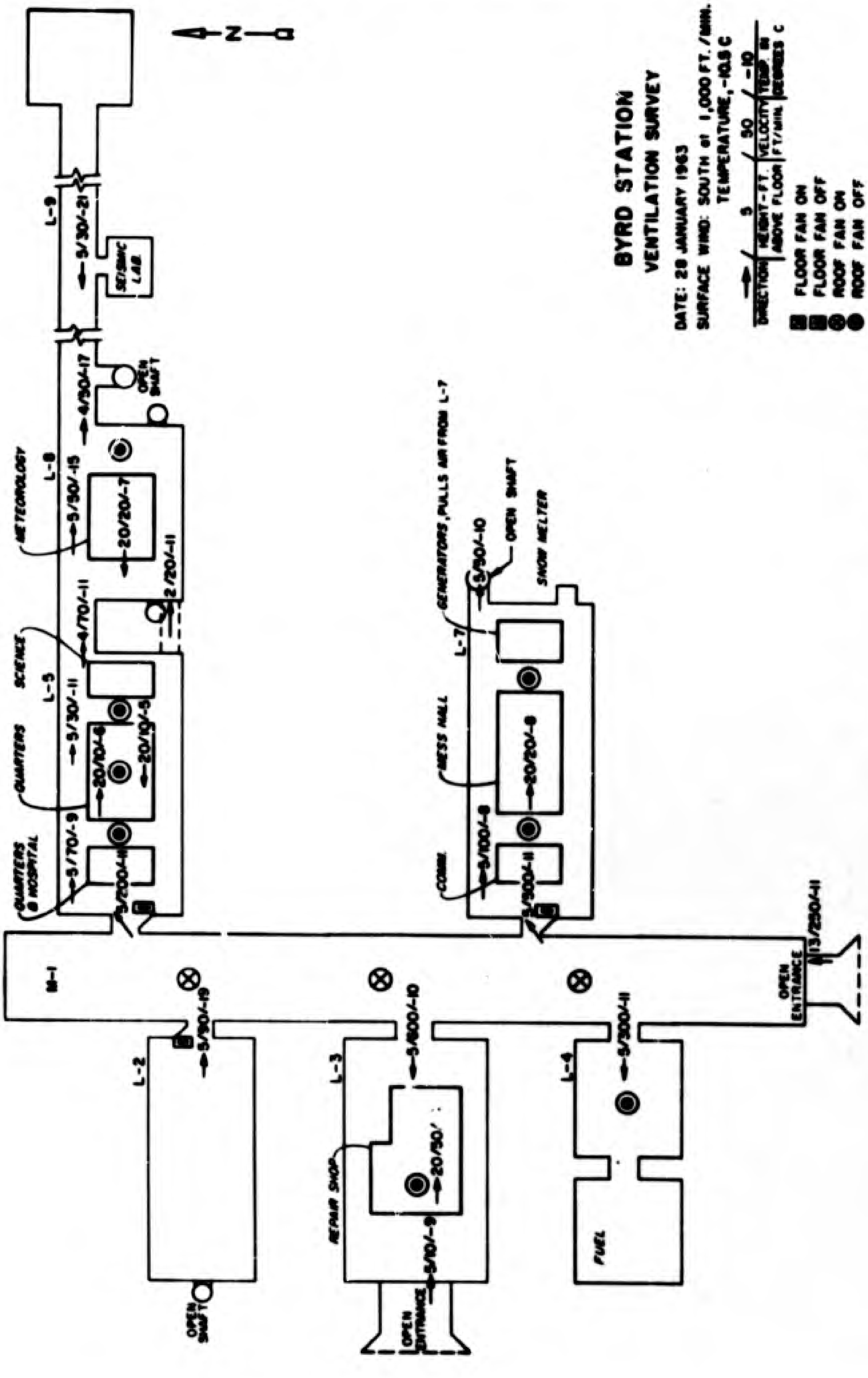


Figure 33. Air temperatures and air current velocities with roof fans closed down as far as possible.

by three vent shafts (which need not have fans) rising from the arch crown to about 10 ft above current snow surface. Bulkhead should be fitted across the passageway to M-1 to prevent transfer of exhaust fumes.

L-4

(a) Antechamber

Inflow: From M-1 via leaky bulkhead; from main fuel chamber via slight bulkhead leaks; from snow walls.

Outflow: To surface via roof fan.

Comments: Roof fan unnecessary under present circumstances.

(b) Main fuel chamber

Inflow: From access shaft and from snow walls.

Outflow: To antechamber via bulkhead leaks.

Comments: Circulation very sluggish and temperature satisfactorily low. Under present circumstances shaft could be closed. Occasional "flushing" of the air might be desirable to remove any fuel fumes.

L-5

Inflow: From L-8 via culvert passage.

Outflow: To M-1 via bulkhead fan.

Comments: A sluggish circulation, which is inadequate for temperature control, is being maintained by a fan that works against a natural pressure gradient. Air leaks back at the M-1 bulkhead through gaps under and around the doorway, through "Swiss cheese holes", and through the water pipe penetration. Exhausting through a floor level fan is inefficient. Two roof fans with high exhaust stacks should be provided. The fan could be removed from the M-1 bulkhead. The bulkhead should be sealed and the door provided with a strong closer. The L-9 area would serve as a cold plenum for inflow.

L-7

Inflow: From vertical access shaft; from snow walls.

Outflow: To surface via annular spaces surrounding generator exhausts; to M-1 via bulkhead fan.

Comments: Temperature control in this tunnel quite good so far, mainly due to independent air intake for generators and adeouate roof venting. Fan in M-1 bulkhead inefficient, since it pushes against a natural pressure gradient. Comments given for corresponding situation in L-5 apply here also. Bulkhead fan could be removed and placed in new vent stack above communications building. Snow coming down access shaft is a nuisance.

L-8

Inflow: From L-9.

Outflow: To surface via one roof fan; to L-5 via culvert passage.

Comments: Adequate under existing circumstances.

L-9

Inflow: Probably by seepage through snow walls and by hatch leakage.

Outflow: To L-8, and to surface via high shafts when hatches are opened.

Comments: Circulation adequate under present circumstances.

M-1

Inflow: From L-3 via passageway; from L-5 and L-7 via bulkhead fans; from L-2 via bulkhead fan.

Outflow: To surface via two roof fans; to L-4 via bulkhead leaks.

Comments: Exhaust stacks would need raising if M-1 were to remain a central exhaust trench, but no changes are required if above recommendations for other trenches are adopted.

Table I. Tunnel settlement.

Section	Trench number and type	Elapsed time months	Vertical settlement feet	Horizontal displacement feet	Average temperature -°C
D-D	L-8 30' wonder arch	12	0.75	0.36	21
E-E	L-5 30' wonder arch	12	1.00	0.54	23
F-F	L-5 30' wonder arch	12	1.02	0.81	15
P-P	L-7 30' wonder arch	15	0.75	0.24	21
N-N	L-7 30' wonder arch	15	0.72	0.21	20
R-R	L-3 40' wonder arch	3	0.60	-	15
J-J	L-3 40' wonder arch	15	1.12	-	24
H-H	M-1 undercut trench	12	0.70	0	25
K-K	M-1 undercut trench	12	0.50	0	25
M-M	M-1 undercut trench	12	0.50	0	24
L-L	L-4 undercut trench	15	0.85	0.35	26
G-G	L-2 undercut trench	15	0.65	0.50	26

DISCUSSION

Tunnel deformation

Inspection of the data reveals that the undercut trenches, M-1, L-2, and L-4 settled vertically at average rates ranging from 0.5 in./month to 0.7 in./month during the first year of occupancy. This represents settlement rates ranging from 2.7% to 3.8% per year. In trenches L-2 and L-4 there was some horizontal closure, the average rates being 0.4 in./month and 0.3 in./month respectively, at the level of maximum deformation (about two-thirds the height of the snow wall). These rates represent closure of 2.5% and 1.8% per year at that level. The horizontal deformation at floor level and at the arch springings was zero for practical purposes. In M-1 there was no measurable horizontal closure over the first year of occupancy.

Table I summarizes data taken from the cross-sections. Temperatures in the three undercut trenches were similar, being 2 - 4C above the undisturbed mean temperature for the site. There was no correlation between settlement rate and temperature; differences in settlement rate were more likely to be caused by irregularities in the overburden due to snow drifting.

Vertical settlement rate for undisturbed snow in the layer occupied by the trenches can be calculated using an expression developed by Waterhouse and Steeves (1960) from the densification theory of Bader. This gives the rate at which the layer would have shrunk vertically if there had been no tunnel there.

$$V + A\left(\frac{1}{\gamma_1} - \frac{1}{\gamma_2}\right) \tag{1}$$

where V = vertical settlement rate (cm/yr)
A = snow accumulation rate (g/cm^2-yr)
γ_1 = snow density at the level of the arch springings (g/cm^3)
γ_2 = snow density at floor level (g/cm^3)

Substituting $A = 16$ g/cm^2-yr, $\gamma_1 = 0.39$ g/cm^3, $\gamma_2 = 0.52$ g/cm^3, it is found that the undisturbed vertical settlement rate for the layer occupied by undercut trenches is 10.2 cm/yr, i.e. 0.33 in./month or 1.7% per year for the undisturbed site temperature of -28C.

Thus the undercut trenches settled 1.6 to 2.2 times as fast as undisturbed snow. Part of this may be attributable to the somewhat higher temperature in the snow walls of the trenches; if the undisturbed snow were at -25C instead of -28C it would settle 1.4 times as fast, assuming the activation energy of the snow to be 14,000 cal/mole.

It appears that the undercut trenches are settling vertically at a rate little higher than that for undisturbed snow under the same temperature conditions.

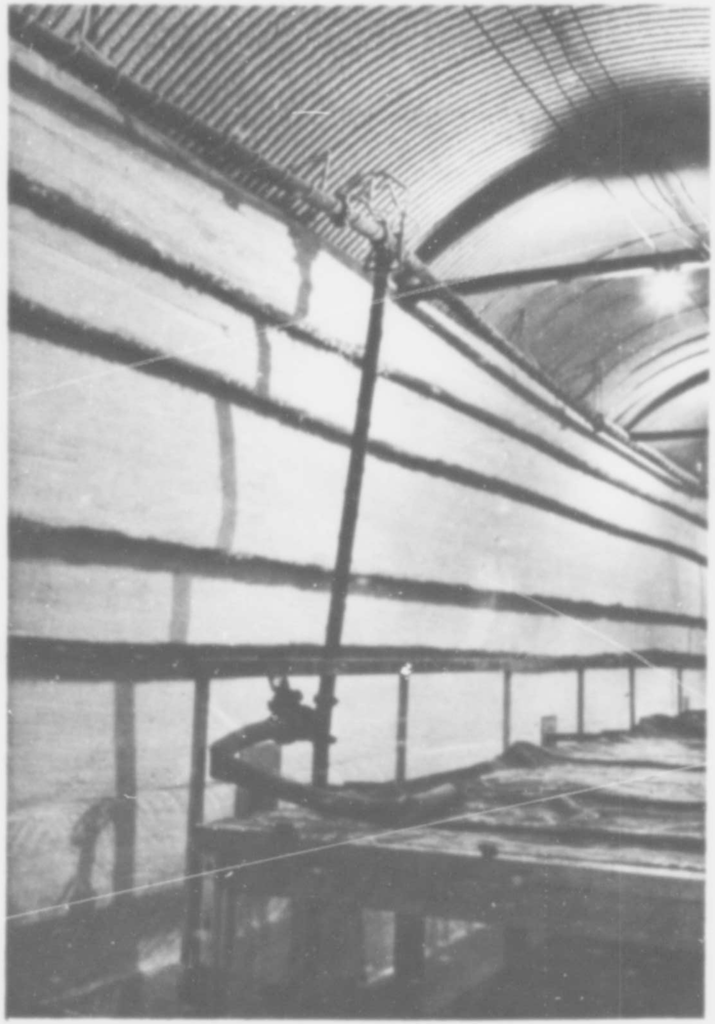


Figure 34. Typical result of placing a rigid member between the trench floor and the roof. As the wall deforms, the vertical pipe distorts the horizontal pipe to which it is connected, and itself begins to buckle. (Official U. S. Navy photograph)

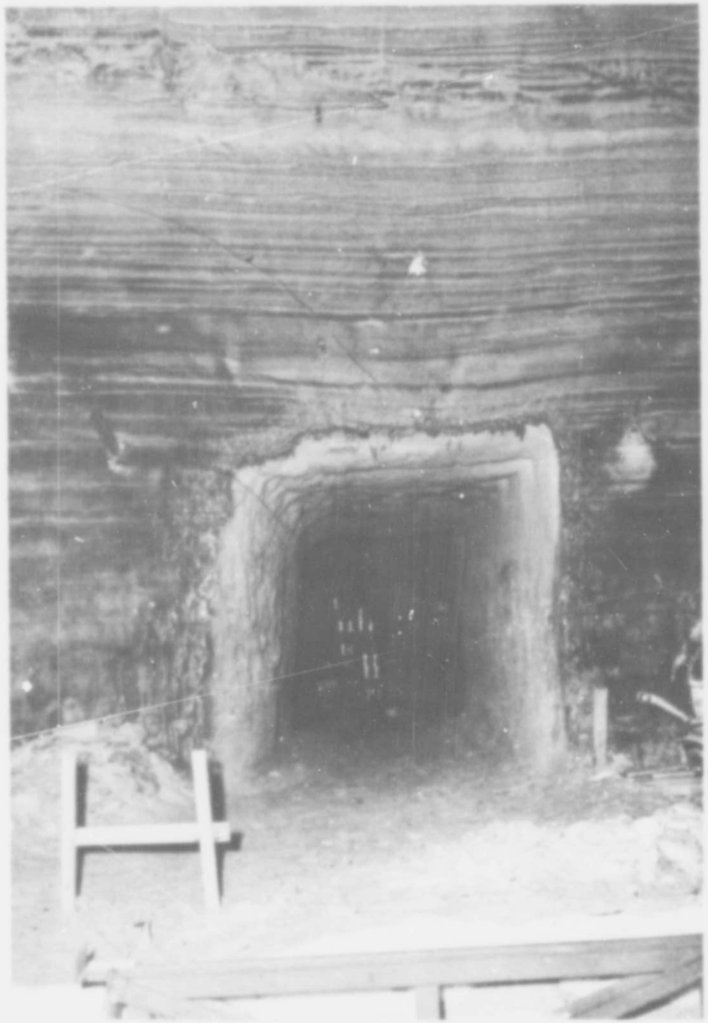


Figure 35. The deformation pattern of snow strata above a small tunnel. The details of the natural snow stratigraphy have been brought out by etching and smoke blackening during a fire which burned down a workshop. (Official U. S. Navy photograph)

In the Wonder Arch tunnels, there is little deformation of the metal arches themselves so far, and most of the change results from vertical settlement at the arch seats. There is a slight indication of side-sway in the Wonder Arch at some cross-sections. Some horizontal closure of the snow walls has taken place, maximum movement being at a level slightly below the arch seats.

In tunnels with 30-ft arches and 12-ft snow walls (L-5, L-7, L-8) vertical settlement rates ranged from 0.58 in./month to 1.02 in./month. Horizontal closure rates were in the range 0.17 in./month to 0.81 in./month (0.62% to 3.0% per year). Although mean temperatures for the period varied from place to place in the range -15 to -23C, there was no correlation between average settlement rate and snow wall temperature.

In the tunnel roofed by 40-ft Wonder Arch (L-3), measurements at section J-J indicate a vertical settlement rate of 0.9 in./month. Measurements at section R-R are not very reliable, since obstructions prevented remeasurement in 1963. No reliable data on horizontal closure are available for this trench, since the walls were melted back when a temporary workshop burned down in the winter of 1962.

Wonder Arches were used to permit construction of wide-span tunnels but it is of interest to consider their effectiveness in providing vertical restraint. This may be examined by calculating the vertical settlement rate for undisturbed snow in the layer corresponding to the tunnel height (the layer between arch crown depth and trench floor depth). Substituting appropriate values for accumulation (16 g/cm³) and density (from Fig. 7) into eq 1, the settlement rate for undisturbed snow in the tunnel layer turns out to be 0.43 in./month, or 1.7% per year. Thus, actual vertical closure between arch crown and trench floor was 1.4 to 2.4 times as fast as vertical settlement for undisturbed snow. Most tunnel wall temperatures were about 6C warmer than undisturbed snow remote from tunnels; if the undisturbed snow were at -22C instead of -28C it might be expected to settle twice as fast, assuming the activation energy of the snow to be 14,000 cal/mole. Thus the loss of headroom in the tunnels takes place at a rate about equal to the settlement rate of undisturbed snow at the same temperature.

Since virtually all the settlement results from compression of the snow walls, vertical closure can be regarded as a problem of foundation settlement at the arch seats, which are essentially strip footings.

Settlement of the arch seats relative to the snow adjacent to them can be found by subtracting "natural" densification of the snow wall (calculated from eq 1 and corrected for temperature) from the total settlement of the arch relative to the fixed hubs at floor level. Taking density values for arch seat level and floor level from Figure 7, eq 1 gives a "natural" settlement rate of 0.13 in./month for the snow walls of the 30-ft Wonder Arch tunnels. Adjusting this value to -20C instead of -28C, the settlement rate is 0.33 in./month. The average settlement rate (total) for the 30-ft tunnels was 0.79 in./month, so that settlement of the arch seats relative to the adjacent snow proceeded at an average rate of about 0.46 in./month.

In order to consider the significance of the above settlement rate we require an estimate of the nominal bearing pressure of the arch seats. This can be done by computing the dead load vertical reactions of the Wonder Arch in accordance with information given in engineering design handbooks. The vertical reactions for zero snow cover at the arch crown are (Armco Handbook, 1958)

$$V_{D0} = \left(\frac{0.50 \times 62.4}{100}\right) \times 4800 \text{ lb/lineal ft} \tag{2}$$

The rise/span ratio of the Wonder Arch is 0.5; the term in brackets in eq 2 is a correction for Peter snow density, since the handbook graph is for fill material weighing 100 lb/ft³. Assuming 3 ft of snow cover at the crown, the additional increment of dead load reaction is

$$V_{D3} = \left(\frac{0.50 \times 62.4}{100}\right) \times 1500 \times 3 \text{ lb/lineal ft.} \tag{3}$$

The total vertical reaction due to dead load is thus

$$V_D = V_{D0} + V_{D3} = 1500 + 1400 = 2900 \text{ lb/lineal ft.}$$

The arch seats consist of a 2-in. x 12-in. timber sill, so that the nominal bearing pressure is 2900 lb/ft².

Foundation tests were made at Byrd Station; an expected settlement rate for the arch seats can be calculated from the results of these tests. The test foundations were 3- x 3-ft footings, whereas the arch seats are continuous sills 1 ft wide; some difference in settlement rate will result from size and geometry differences alone, but these effects are probably small enough to be ignored for practical purposes. The tests were made with a nominal bearing pressure of 1000 lb/ft²; results have to be adjusted to give rates for a pressure of 2900 lb/ft². The tests were made on snows of 0.44 g/cm³ and 0.50 g/cm³ density; the data for the 0.50 g/cm³ test can probably be accepted without density correction, since the natural snow on the arch abutments was replaced by a layer of Peter snow. The tests were at undisturbed site temperature, averaging about -28C; results have to be adjusted to the -20C average for the arch seats.

Calculation of the factor for settlement rate under higher loadings can be based on a hyperbolic sine relationship between strain rate and stress:

$$\dot{\epsilon} = \frac{\sigma_0}{\eta_c} \sinh\left(\frac{\sigma}{\sigma_0}\right) \tag{4}$$

where $\dot{\epsilon}$ = strain rate of settlement
σ = stress
η_c = "compactive viscosity"
σ_0 = a site constant, found by Bader to be 765 g/cm² (1570 lb/ft²) for Byrd.

The foundation test data are converted by applying eq 4 in the form

$$\frac{\dot{\epsilon}_{2900}}{\dot{\epsilon}_{1000}} = \frac{\sinh(2900/1570)}{\sinh(1000/1570)} = 4.55$$

The factor accounting for temperature difference is calculated from an exponential relationship between strain rate and absolute temperature:

$$\dot{\epsilon} = A e^{-\frac{Q}{rt}} \tag{5}$$

where $\dot{\epsilon}$ = strain rate
A = a constant for given stress and snow type
Q = activation energy, assumed to be 14,000 cal/mole
R = the gas constant = 1.987 cal/mole-deg
T = absolute temperature, deg K.

The factor is given by:

$$\frac{\dot{\epsilon}_{-20}}{\dot{\epsilon}_{-28}} = e^{7040(1/245 - 1/253)} = 2.50.$$

The foundation test on snow of 0.50 g/cm³ density showed a settlement rate of 0.023 in./month for 1000 lb/ft² loading at -28C. Using the factors calculated above:

Settlement rate for 2900 lb/ft² and -20C = 0.023 x 4.55 x 2.50 = 0.26 in./month.

Thus the arch-seat settlement rate deduced from observation is about 1.8 times as high as the rate calculated from the foundation test data. It is to be expected that actual deformation will exceed calculated, since there is an absence of lateral restraint on one side of the snow beneath the arch seats. If the overall vertical deformation of the tunnel is calculated, on the basis of densification theory and foundation settlement, the agreement with observation is rather good:

Calculated deformation = calculated "natural" wall settlement + calculated arch seat settlement

= 0.33 + 0.26 = 0.59 in./month

Observed deformation (average) = 0.79 in./month

$$\frac{\text{Observed}}{\text{Calculated}} = \frac{0.79}{0.59} = 1.34.$$

This is within the range of variations from tunnel to tunnel.

In the seismometer vault (sections A-A and B-B) the arch seats are sinking, but no attempt will be made to analyze this settlement, since there is no reliable level datum. The snow floor is hogging, and it appears that the reference hubs are being displaced by snow movement near the arch seats. The Wonder Arch at sections A-A and B-B is apparently being deflected into a semi-elliptical shape.

Section C-C (Fig. 24) illustrates the deformation of a small trench roofed by an arch of unsupported Peter snow. The arch has deformed badly, which is hardly surprising in view of the small initial rise to span ratio. The snow arch has exerted a horizontal thrust outward in deforming, thus forcing the walls apart near the arch springings. Lower down, the snow walls bulge inward in the usual way.

Floor levels and foundation settlement

The levels show that no significant differential floor settlement has occurred over the station area during the period of observation. There is, however, a sinking of all the reference hubs relative to the foot of the bench mark. This foot is set on undisturbed snow at approximately the same level as the floor of L-5/L-8, so that densification of snow between hub level and bench mark level is negligible. It also seems rather unlikely that the entire station area is settling uniformly at a more rapid rate than the corresponding horizons in the surrounding undisturbed snow. We therefore conclude that the snow at the base of the tunnel walls is moving downward relative to its original snow horizon. It is usually said that the floor of a snow tunnel bulges upward after deformation has proceeded for some time; it may be more correct to regard the edges of the floor as being pushed down by concentration of vertical load at the snow wall, while the center of the floor heaves following stress relief.

The foundation gages show building settlement (relative to the snow floors) of 0.16 to 0.58 in./yr. The generator house is settling at 0.57 in./yr according to the single gage fitted to it. It is not a heavy building, as the generators are carried on an independent foundation, but it is continuously vibrating. The "left front" of the science building (building aspects here are always described for an observer facing toward M-1) is settling at 0.58 in./yr, while the right rear of the same building is settling at only 0.35 in./yr. There are insufficient gages to define the axis of tilt, but the front of the building seems to have heavier floor loads than the rear, and has a frequently-used heavy door which vibrates the building on closing. The strip footing on the left side is adjacent to the sewer trench, which carries a heated pipe. The meteorology building, which is similar in size and weight to the science building, is settling at a lower rate. The right rear is settling at 0.30 in./yr and the left rear at 0.16 in./yr. The tunnel it occupies (L-8) is cooler than that occupied by the science building (L-5). The direction of tilt is unexpected, since there is a deep sewer trench cut alongside the left footing (Fig. 36). However, the sewer pipe has been removed from this trench, leaving it unheated.

Snow temperatures

In undisturbed snow at Byrd Station temperatures in the uppermost 50 ft or so are controlled by the surface temperature. Over the year, surface temperature can be assumed to vary sinusoidally, peaking in December-January, and reaching a minimum in July-August. At any given depth below the surface, temperature also varies sinusoidally through the year, but the amplitude of the subsurface wave is smaller than that of the surface wave, and it lags behind the surface wave, so that maximum and minimum temperatures occur at later dates than they do on the surface. This behavior has been studied, and can be analyzed by application of standard conduction theory.

Figure 36. Sewer trench cut alongside the foundation of the meteorology building in trench L-8. Excavating so close to a foundation is bad practice. (Official Navy photograph)

Few readings from the CRREL temperature reference hole have been received, but the broad features of natural temperature regime in the snow at Byrd can be deduced using data reported from the old Byrd Station by Pirritt and Doumani (1961), together with station meteorological records.

Analysis of the damping of the annual temperature wave with depth yields the average diffusivity, and hence thermal conductivity, of the snow mass. Making the simplifying assumption of a pure sinusoidal temperature variation with time, wave attenuation is given by

$$A_z = A_0 \, e^{-z\sqrt{\frac{\pi n}{\alpha}}} \tag{6}$$

where A_z = wave amplitude at depth $\underline{z}$

A_0 = surface amplitude

n = wave frequency (1 cycle per year)

α = thermal diffusivity = $\left(\frac{\text{thermal conductivity}}{\text{density x specific heat}}\right)$

Thus, when $\ln\left(\frac{A_z}{A_0}\right)$ is plotted against depth $\underline{z}$, the slope of the line is $-\sqrt{\frac{\pi n}{\alpha}}$, permitting diffusivity α to be evaluated.

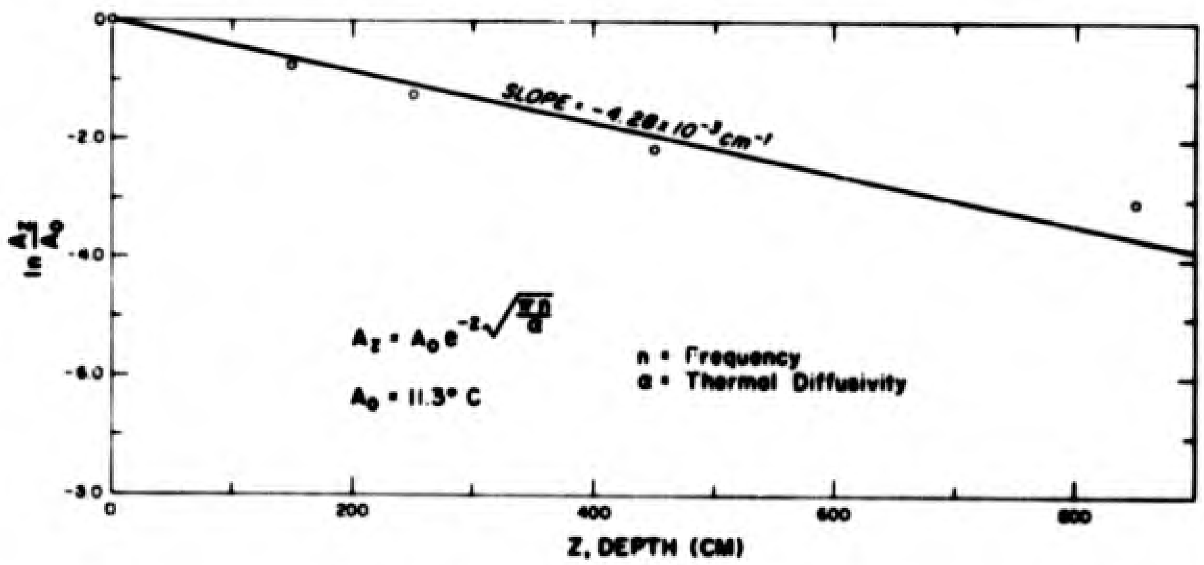


Figure 37. Plot of $\ln\left(\frac{A_z}{A_0}\right)\left(= \ln \frac{\text{amplitude at depth } z}{\text{surface amplitude}}\right)$ against depth $\underline{z}$.

The data of Pirritt and Doumani for nominal depths 1, 2, 4, and 8 m were used, together with the mean surface air temperature curve from meteorological records. The temperatures given for air, snow surface, and $\frac{1}{2}$-m depth were discarded in view of certain dubious features. Likewise the data for 16-m depth were not used, since the indications were that true temperature fluctuations at that depth were less than the sensitivity and stability of the measuring instrument. In Figure 37 $\ln \frac{A_z}{A_0}$ is plotted against $\underline{z}$, and diffusivity is given by the slope $\underline{m}$:

$$a = \frac{\pi n}{m^2} = \frac{\pi}{1.83 \times 10^{-5} \times 3.16 \times 10^{7}} = 5.43 \times 10^{-3} \text{ cm}^2/\text{sec.}$$

The average thermal conductivity $\underline{k}$ for snow in the uppermost 8 m (26 ft) is given by

$$k = a\gamma c = 5.43 \times 10^{-3} \times 0.45 \times 0.46 = 1.12 \times 10^{-3} \text{ cal/cm-sec-°C}$$

(taking average density as 0.45 g/cm³ and specific heat $\underline{c}$ at an average temperature of -28C as 0.46 cal/g-°C).

The value for the thermal conductivity turns out to be almost identical to the values predicted by the empirical equations of Proskuriakov and Jansson. It is lower than the value 1.72×10^{-3} cal/cm-sec-°C predicted by the more commonly used equation of Kondrat'eva, $k = 0.0085\ \gamma^2$.

The time of occurrence of the maximum temperature at each depth gives the penetration velocity of the temperature wave. The data are somewhat inadequate, but from a plot of time for maximum temperature against depth it appears that the temperature wave penetrates the snow at about 4 cm/day. This can be checked from the amplitude measurements, since theory gives the temperature penetration velocity as

$$V = 2\sqrt{\pi n a} \tag{7}$$

$$= 2\sqrt{\frac{\pi \times 5.43 \times 10^{-3}}{3.16 \times 10^{7}}} = 4.64 \times 10^{-5} \text{ cm/sec} = 4.01 \text{ cm/day.}$$

We can therefore accept 4 cm/day as the rate of temperature penetration by conduction through the natural snow.

With this information on the temperature regime in undisturbed snow we can consider temperatures in the snow surrounding tunnels.

It is seen from Figure 29 that temperatures in the snow walls of all tunnels undergo cyclic variation through the year, but these changes do not simply reflect the sinusoidal temperature variation of the general snow mass. The dial thermometers were set at depths of 25 - 30 ft below the surface, where there is a temperature lag of about 7 months behind the surface changes when conduction alone operates. The tunnel wall temperatures actually show that their maxima lag the surface temperature maximum by no more than 1 month, while their minima do not lag by more than about 2 months. Further, the wave amplitudes are much greater than amplitudes for corresponding depths in the undisturbed snow. Since it is obvious that the annual temperature cycles in the tunnels are not in direct response to heat losses from interior installations (several of the tunnels contain no heated buildings), it seems that convection from the surface is the prime cause of tunnel temperature changes. This seems to be confirmed by the small temperature amplitude in tunnels largely blocked off from air flow (L-2, L-4, L-8), and the big amplitude in tunnels with open ramps (M-1 and L-3). Further evidence is the rapid temperature rise after opening of the tunnels in October.

A rather curious feature of the records of snow wall temperature is that the dial thermometers with 18-in. stems almost always show lower readings than those with 8-in. stems, indicating that temperature decreases with penetration into the wall at all times of year. This implies heat flow into the snow from the tunnels, even during periods when snow temperature is decreasing with time. Cooling of the snow by air flowing through the intergranular pores and into the tunnels is a possible explanation. This kind of air seepage was certainly occurring in October 1962 (see ventilation notes). Temperatures in the wall of the corridor tunnel, L-9, are an exception to this pattern; for the three autumn months of record the face of the wall has been colder than the snow behind the face. This is hardly surprising, as cold surface air is probably flowing along L-9.

The records show clearly that heat losses from interior buildings have affected mean temperatures in the tunnels. In L-2 and L-4, which contain no heated structures, mean annual temperatures are not much higher than the mean annual temperature for undisturbed snow, even though some circulation of surface air occurs in summer (this is probably offset to some degree by the sinking of cold air - the tunnels would actually become colder than undisturbed snow if left alone). Even in M-1 and L-3, which are fully opened to summer air and are occupied by vehicles with engines running, the mean annual temperature is still lower than -20C, although summer temperatures do get high. In L-5 , L-7 and L-8, however, mean annual temperatures for 1962 were unfavorably high as a result of heat loss from buildings. Mean temperatures for L-7 and L-8 were close to -20C, while L-5 had a mean temperature of about -15C.

When the thermocouple strings were inserted into the snow alongside and below the power plant it was believed that temperature changes in the snow would be governed by conduction; this assumption proved false, and convection along the conduits containing the wires greatly reduced the value of the data (data are <u>not</u> representative of the temperature field of the aspirated snow remote from the conduits). Nevertheless, some conclusions can be drawn from the thermocouple records. Data for the horizontal string (disregarding erroneous readings for February and March 1962) show that temperature decreases with penetration at all times, which is in general agreement with data from the dial thermometers. The suggestion made above that this is consistent with air seepage through the snow into the tunnels appears to be supported by the complete lack of phase lag along the horizontal thermocouple string; maximum temperatures and minimum temperatures occur synchronously at all penetrations. The thermocouple string descending vertically into the snow beneath the tunnel floor seems less affected by convection, as might be expected in the deeper and less permeable snow; there is some wave attenuation and phase lag. Temperatures at 1-ft depths under the snow floor, and under the foundation pad of the generators, are quite similar to tunnel wall temperatures alongside the power plant, averaging about -20C over the year. In midsummer the temperature of the generator foundation seems to rise unfavorably high (maximum of -14C). Mean annual snow temperature decreases with depth below the tunnel, but at 25 ft the mean is still some 3C higher than the undisturbed annual mean for the site.

Ventilation

The original ventilation system of Byrd Station was unsatisfactory; it failed to provide an adequate supply of clean air for breathing and also failed to remove waste heat from the tunnels. The trouble stemmed mainly from the inability of fans to compete with natural convection produced by temperature differences, by differences of elevation at the various openings to the surface, and by surface winds.

The air wells never made any useful contribution to the station ventilation, and it seems unlikely that they will prove to have general value in their present form. A criticism of air wells is given in Appendix B, and an alternative scheme for drawing air from the snow mass is outlined.

Good ventilation in an undersnow station is essential for the health and safety of the occupants; it is also the most effective means of prolonging the life of the station since it keeps snow temperatures to a minimum. An efficient system will utilize natural convection by taking in surface air at low-elevation portals and exhausting it at high-elevation openings or stacks. Air flow can be controlled to some extent by bulkheads, but a bulkhead fitted against snow is incapable of maintaining a strong pressure difference over an extended period (see App. B). Fans can stimulate flow in local areas, but they are ineffective in attempting to reverse the natural air flow.

The general impression gained from ventilation and temperature measurements at Byrd Station is that good air supply and effective cooling of the deformable snow can be achieved by attention to the following points:

1. Direct transfer to the surface (in closed pipes) of engine exhaust, stove and furnace exhaust, and foul air from buildings and work areas.

2. Air outlets, with fans if necessary, at the highest points of all tunnels containing buildings or heat sources.

3. Intensive cooling of deformable snow during the winter period, using circulated surface air.

4. Limitation of surface air circulation during the warmest summer periods, and utilization of cold air from the snow mass.

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APPENDIX A: SNOW REINFORCEMENT TESTS

The usefulness of snow as a structural material is limited by its poor creep resistance and its very low tensile strength. The only currently practical field method for improving the strength of snow consists of disaggregation by a rotary snow plow followed by aging of the resulting high-density, well-graded deposit, but the tensile strength of milled snow is still of no structural value.

In November 1961 some simple field experiments were initiated to check the effects of fibrous additives and reinforcing materials in Peter snow. Using scrap materials available on site, beams of Peter snow were cast in wooden forms and reinforced with wood fiber (excelsior), expanded metal mesh, and with pre-tensioned fibrous cord*. After the forms were stripped, the beams were simply supported on roller bearings and allowed to deform under their own weight. Deformation was measured periodically for 10 months.

At the first try, six beams 1 x 1 x 8 ft were cast in two beds of three forms each (Fig. A1). Two beams were of unreinforced Peter snow, two had shredded excelsior added progressively as the forms were filled, one had eight fibrous cords (four in the top third and four in the bottom third) pre-tensioned into the form, and one had expanded metal mesh laid in the upper and lower thirds. Surface snow from the ice cap at Byrd was milled by a Peter Junior plow and blown directly into the forms (Fig. A2). The snow was then screeded, parachute cloth covers were stapled over the forms, and the beams were left to age-harden for 4 weeks before the forms were stripped.

When the forms were stripped the beams were carefully handled, but in spite of all care the unreinforced beams and the beam containing cord broke. A second set of unreinforced beams was cast, but again these broke on stripping the forms. The reinforced beams containing excelsior and mesh were sufficiently robust to withstand handling by a forklift tractor.

A set of smaller, unreinforced beams was finally cast and mounted. Two beams measured 6 in. x 6 in. x 4 ft, and one measured 8 in. x 8 in. x 4 ft.

Beam deflections were measured vertically from a wooden reference block set in the center of the upper surface to a horizontal piano wire under constant tension. The data yielded the creep curves of Figures A3 and A4. For the first 5 weeks the reinforced beams deflected at relatively rapid, but decelerating, rates, afterwards settling to a linear deformation rate. The beam reinforced with expanded metal showed good deformation resistance, with a total deflection of 1.3 in. after 10 months, and a secondary deformation rate of 0.51 in./yr. The beam containing a liberal addition of excelsior deflected 6.5 in. after 10 months, and had a secondary creep rate of 2.9 in./yr. The beam containing a smaller concentration of excelsior deflected 13.3 in. in 10 months, and had a secondary creep rate of 5.6 in./yr.

The beams reinforced with excelsior did not break under the severe deflections, even though they initially had transverse grooves across the lower face as a result of evaporation through cracks in the formwork during the age-hardening. When the beams were cut up at the completion of testing, the excelsior appeared to be well bonded with snow; the sinuous and tangled character of the strands seemed more important than surface bonding on individual fibers.

The unsuccessful beam containing fibrous cord apparently failed because no bond with the cord was developed. The cord could be pulled out with ease.

The beam reinforced with expanded metal could not be tested to destruction, as no loading facilities were available. It successfully resisted attempts to break it by two men jumping up and down on it. The expanded metal appeared to be well bonded to the snow, with a dense icy layer surrounding the metal strands. Since the beam never reached temperatures anywhere near the melting point, it seems that the ice crust against the metal must have been formed by preferred deposition during vapor diffusion in the snow pores.

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*Thin jute rope with a rough, "hairy" surface.

The deformation of the small unreinforced beams cannot be compared quantitatively with the deformation of the large beams, since standard elastic beam theory is not applicable. There can be no doubt, however, that an unreinforced beam would deflect much faster than one reinforced with expanded metal or excelsior.

The main indications of the tests are:

1. Fibrous additives and coarse metal mesh greatly improve the resistance of snow to abrupt loading. The tensile strength under short-duration loading is increased.

2. Fibrous additives and coarse metal mesh improve the deformation resistance of snow elements subject to tensile strains. The compressive deformation resistance may also be improved.

It is suggested that possibilities for application be considered. Reinforcement might be feasible where snow is used structurally and where tensile strains are anticipated. It is also conceivable that snow runway surfaces could be made to bear wheeled aircraft by incorporation of fibrous material or cheap metallic mesh.

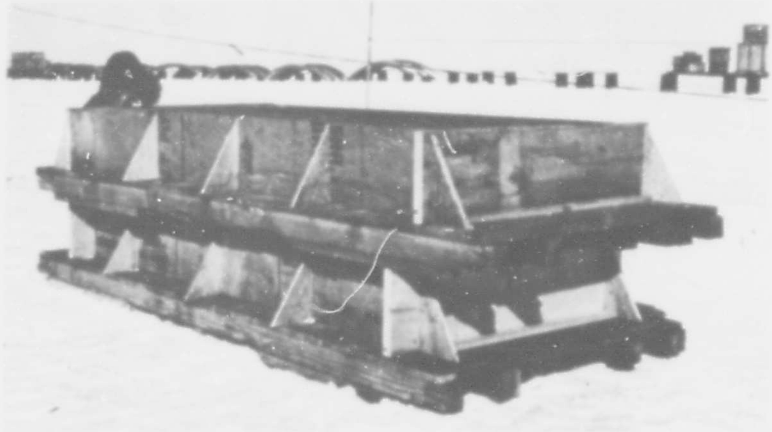

Figure A1. Casting beds for processed snow beams.

Figure A2. Peter Junior rotary plow casting milled snow into beam forms.

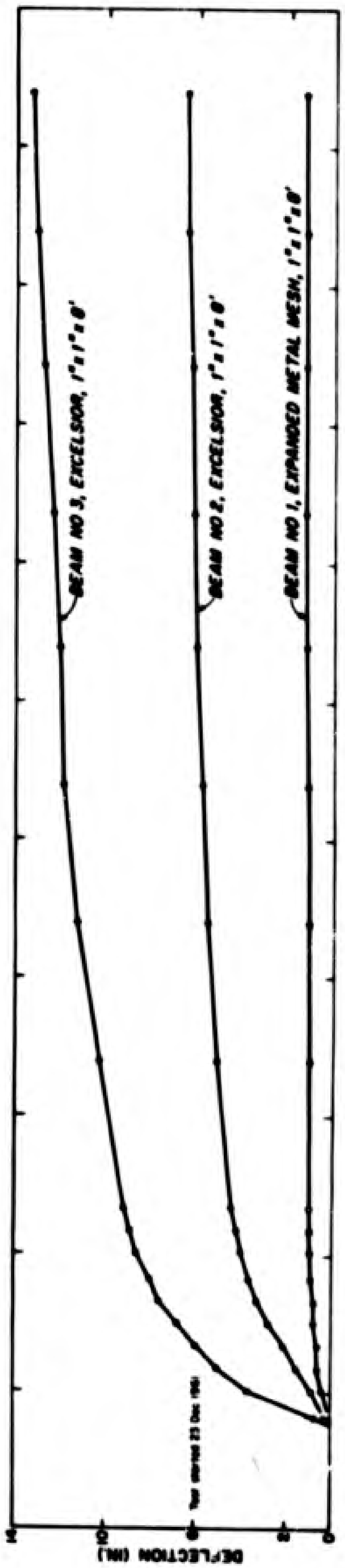

Figure A3. Deformation as a function of time for reinforced snow beams 1 ft x 1 ft x 8 ft long.

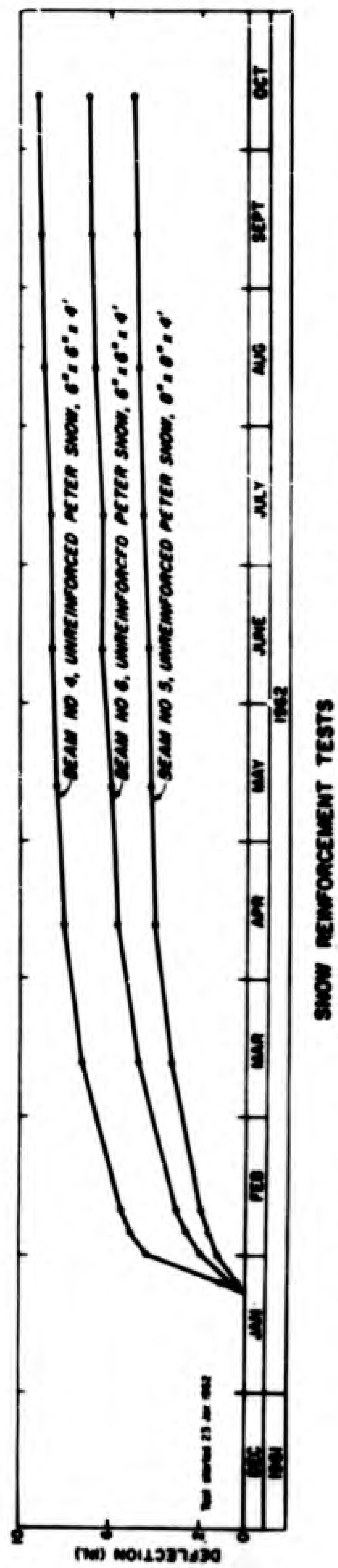

Figure A4. Deformation as a function of time for small unreinforced beams of Peter snow.

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APPENDIX B: AIR PERMEABILITY OF SNOW AND THE VENTILATION OF UNDERSNOW CAMPS

(Abstracted from an unpublished report, Mellor, 1962b)

Air permeability of dry snow

The surface snow of polar ice caps and ice shelves is usually a dry aggregation of fine snow grains cemented into a coherent porous mass by intergranular bonds formed as a result of sublimation and surface diffusion. The density of the surface snow is generally in the range 0.3 - 0.4 g/cm³ (porosity 67% - 56%); and in this condition it is quite permeable. Snow beneath the surface progressively increases in density with depth, and air permeability decreases as the density increases. When the density reaches about 0.8 g/cm³, the snow becomes impermeable. In many regions thin icy crusts occur in the snow mass, and these effectively reduce the permeability for air flow in a vertical direction.

Air permeability is dependent on porosity; it increases as porosity increases. The size and shape of the snow grains also influence permeability. For a given porosity (or density), permeability is highest for large grain sizes, and for snow in which grains have become rounded by metamorphism, leaving smooth pores between them.

Temperatures in dry polar snow

Snow temperature at the surface of an ice cap corresponds closely to the prevailing air temperature, so that there is cyclic seasonal variation. Below the surface the snow also follows seasonal temperature cycles, but the amplitude of the surface temperature wave decreases with depth below the surface, and there is a progressive time lag with depth.

Air wells

In undersnow camps where snow is used as a structural material, temperatures must be kept as low as possible to minimize deformation. During winter it is possible to combat heat loss from inner buildings by ventilating with cold air from the surface, but in summertime surface air is too warm to be useful. Since snow is permeable and the temperature below a depth of 25 ft stays constant throughout the year, an alternative summer cooling system was devised whereby cold air was sucked from the pores of the snow beneath the tunnels of a camp.

Holes of 12 to 14 in. diam were bored to a depth of about 40 ft in tunnel floors and steel casing was sunk to a depth of 16 ft or so. Air was pulled from the lower, uncased portion of the hole by a fan set in the casing.

In practice it was found that air wells drew warm air from the tunnel through the floor and snow surrounding the well casing, and into the lower section of the well. This air then passed back into the tunnel via the well casing and the fan. This re-cycling of air through a localized snow mass resulted in appreciable and detrimental warming of that snow mass. A further effect was that the volumetric output of a well for a given fan power decreased with time, probably because of glazing of the tunnel floor by use and condensation from warm air entering the snow pores.

Induced air seepage - other examples

Seepage of air through permeable snow is known to occur where a pressure gradient exists. For example, when barometric pressure changes at the surface, the snow beneath "breathes." In a system of undersnow tunnels, pressure changes can be induced by natural convective air currents (the stack effect of low intakes and high outlets, or the ram and extraction effects of surface winds), and by blowing air into or out of tunnels with fans. Such artificial pressure gradients stimulate the seepage of air through the surrounding snow.

At Camp Century, Greenland, the pressure in certain tunnels is reduced below prevailing free atmosphere pressure by fans drawing air from the tunnel. The effect is strongly marked in the air blast cooler tunnel of the nuclear reactor section. Here powerful fans suck air into the cooling coils, and replenishment air flows from the snow walls beneath the Wonder Arch vaulting. Air flow out of the wall is sufficiently vigorous for evaporation to occur at the free surface, leaving the walls pocked with thousands of holes much larger than the natural pores. Figure B1 shows "Swiss cheese holes" in the wall of the Camp Century ABC tunnel. They represent preferred seepage routes, and arrange themselves in horizontal lines along bands of relatively coarse-grained snow (which is, of course, more permeable than adjacent fine-grained snow). At the wall surface the holes are from $\frac{1}{8}$ to 2 in. diam, and the diameter tapers down with increasing distance into the wall. In section, the holes are readily identifiable to a distance of 9 in. from the wall surface, and the maximum detectable distance measured was 17 in.

At Byrd Station, relative elevations of access openings were such that they stimulated air flow in a direction contrary to the planned ventilation directions. Where the natural flow was impeded by doors and bulkheads in the corridors, air circumvented the obstructions by seeping through the snow, evaporating cavities around bulkheads and pipe penetrations in the process.

During the winter of 1962 the snow mine at the South Pole received an inflow of air much colder than the snow in which the mine is excavated. Since the mine entrance was in a relatively warm corridor of the station, it seems likely that the cold air sank in through the highly permeable snow above the upper chambers of the mine.

An alternative scheme for summer ventilation

Present air well systems have very limited applications. They have the undesirable side effect of heating the surrounding snow, and their output falls with time. They are also inefficient in their power utilization; they go unnecessarily deep into low permeability snow, and their small radius of action necessitates high seepage velocities, leading to high friction losses.

In tunnels with Wonder Arch vaults, the free snow walls are 20 to 30 ft below surface, at a level where temperature stays constant in undisturbed snow. They thus provide a suitable and extensive intake surface for air.

Exhaust stacks are necessary at the crown of all Wonder Arch vaults so that warmed air can escape. If these stacks are fitted with fans, they can reduce the pressure in a closed tunnel, so that air flows out of the snow walls (and floor). With seepage across such an extensive area, large volumes of air can flow while seepage velocities in the snow pores are still low (Fig. B2). Since the walls and floor are essentially equipotential planes, seepage velocities for a given fan power depend only on the permeability of the snow. In general, the highest seepage velocities will occur near the top of the walls; this is satisfactory, since the arch seats are critical deformation zones.

In addition to tunnel ventilation by the above method, direct exhausts from all heated interior structures are mandatory. Waste heat and foul air from buildings must be carried direct to the surface. No exhaust of warm air to the tunnels can be permitted.

Figure B1. Holes in the surface of a snow wall, produced by evaporation as air flows out into the tunnel from the pores of the snow mass.

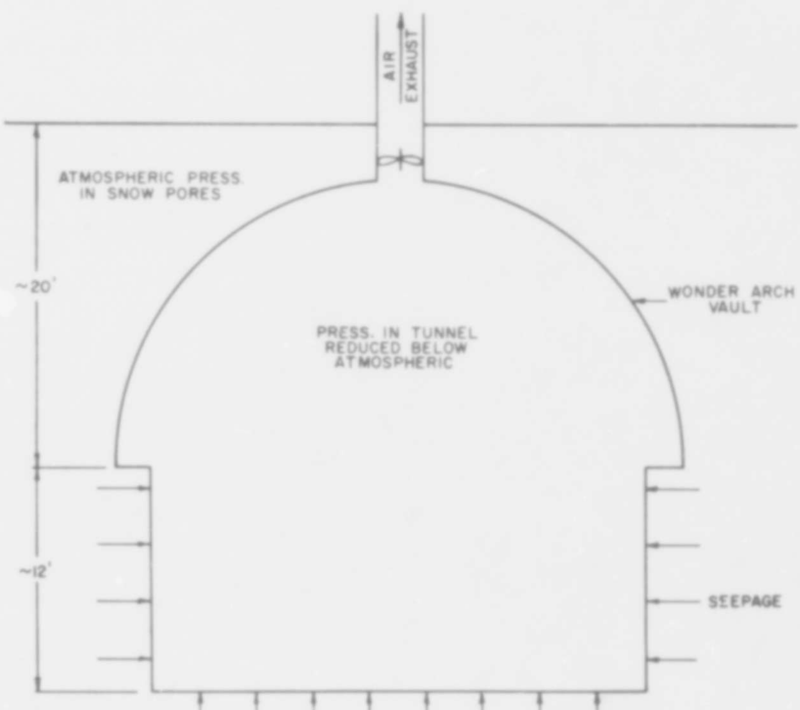

Figure B2. Proposed method for drawing cold air into a closed tunnel from the permeable snow mass.

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APPENDIX C: THERMAL EFFECTS OF WATER WELLS AND SEWAGE SINKS

Water wells and sewage sinks in the ice cap represent heat sources, and must not be located near snow foundations and other structural snow masses. It appears that in the past, the positions were determined largely by guesswork, horizontal separations between well and nearest critical snow mass being stipulated in the range 100 - 1000 ft. For safe and economical design a better approach is required.

There are two main considerations in siting a water well or sewage sink (assuming conditions for adequate hygiene are met):

1. The closest foundation or structural snow mass must be safely outside the radius of the englacial water pond or sewage lens, since there is a possibility of cavity subsidence, and the boundary temperature of the pond or lens will be close to the melting point, giving accelerated snow settlement.

2. The nearest foundation or structural snow mass must be sufficiently remote that temperature rise by heat conduction will be slight, even after a long period (say 10 years).

Observational data from Greenland bases may be used to determine safe limits according to criterion no. 1. Water wells usually begin producing at depths exceeding 120 ft and they have been allowed to penetrate to almost 400 ft; their pond diameters may remain less than 50 ft but expansion to 100 ft has been reported. Sewage sinks should be driven to depths of 100 ft or more before heavy discharge commences; the maximum diameter of a sewage lens observed by drilling in Greenland is 180 ft, although greater spread is possible.

The temperature rise due to heat conduction, as a function of time and distance, can be calculated with sufficient accuracy by regarding the well or sink as a heated spherical zone in an infinite snow mass with uniform thermal properties. We assume that the snow mass is initially at zero temperature throughout; this is an arbitrary zero, which is usually the natural temperature of undisturbed snow (mean annual temperature of the site). The radius of the spherical zone representing the well pond or sewage lens is $\underline{a}$, and its surface temperature is $\underline{V}$; since the pond or lens interface is at the melting point, $\underline{V}$ is numerically equal to the undisturbed site temperature in degrees Centigrade, but of positive sign. The radial distance from the center of the heated sphere to the foundation, or other point of interest, is $\underline{r}$. The thermal diffusivity of the snow, assumed constant, is α. A solution of the conduction equation for this model is given by Carslaw and Jaeger (1959):

$$\theta_{r,t} = \frac{a}{r} \; V \operatorname{erfc}\left(\frac{r-a}{2\sqrt{\alpha t}}\right) \qquad \text{(C1)}$$

where $\theta_{r,t}$ is snow temperature at radius $\underline{r}$ and time $\underline{t}$, relative to the arbitrary zero (i.e. it is the temperature rise due to conduction from the well or sink).

We may check the magnitude of the conduction effect for Byrd Station conditions, taking $\underline{a}$ = 60 ft for a large sewage lens, and assuming that the density of the snow in the conduction field is 0.7 g/cm³.

a = 60 ft = 1830 cm
V = 28°
$\alpha \sim 0.01$ cm²/sec.

From condition no. 1, no important structure would be placed closer than 200 ft. We therefore check for $\underline{r}$ = 200 ft after 1, 5, and 10 yr.

From eq C1,

$$\theta = 8.4 \operatorname{erfc}\left(\frac{2135}{\sqrt{\alpha t}}\right)$$

After 1 yr, the temperature rise at $r = 200$ ft is completely negligible, since erfc 3.81 is very small ($\sim 10^{-7}$).

After 5 yr, the temperature rise at $r = 200$ ft is 0.14C.

After 10 yr, the temperature rise is 0.75C.

As time tends to infinity, the temperature rise is 8.4C, since erfc $0 = 1$.

The analysis thus shows that heat conduction from a water well or sewage sink can be neglected at installations designed for a working life of 10 - 20 yr. In siting these shafts, with respect to critical snow masses, the only requirement is that they be at a distance of more than 100 ft in excess of the maximum expected radius of spread.

Assur (1961) suggests that the maximum radius of spread of a sewage lens can be calculated by assuming that it has a paraboloidal cross-section, and a constant rate of vertical growth at the base of the shaft. The maximum radius $\underline{r}$ is then given by

$$r = \sqrt{\frac{2}{n\pi} \cdot \frac{dV}{dh}}$$

where $\underline{n}$ is porosity of the snow at ponding depth and $\frac{dV}{dh}$ is rate of change of lens volume with center height $= \frac{\text{sewage discharge rate}}{\text{vertical build-up rate}}$.

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