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Cooling of an Undersnow Camp

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PREFACE

This report was prepared by Dr. Yen, Chemical Engineer, Materials Research Branch, and Mr. Bender, chief, Research Division. The work was done under SIPRE* Project 5010.01136.

The concept of cooling warm air from an undersnow installation by circulating it through the cold reservoir in the snow pack was conceived by Mr. Bender, who undertook the preliminary investigation in 1959. The 1960 investigations were made by Dr. Yen.

This report has been reviewed and approved for publication by the Office of the Chief of Engineers, United States Army.



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SUMMARY

An investigation was conducted at Camp Century, Greenland, to study the feasibility of using air wells to cool undersnow structures in the arctic during the summer months. From results obtained during the summers of 1959 and 1960 and late November, 1960, it was found that the air well is a practical and effective means of providing a -20°C air supply at volumetric flow rates of 1200 to 1700 ft^3/min . The extent and rate of warming of the snow beneath the trench floor by heat exchange between the air and the snow foundation was found to depend upon trench air temperature, fan capacity, fan arrangement, and casing length. For example, in a well cased to a depth of 17.5 ft and equipped with a 5 hp fan drawing in air at a rate of 1700 ft^3/min , the maximum warming was found to be 12.5°C during a 42-day period. Snow temperature differences of about 7°C were found between similar trenches with and without a fan installation. The minimum permissible distance between two adjacent fans to eliminate overlap in warming up the snow foundation is approximately 80 ft.

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by

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The installation of Camp Century and its nuclear power plant in the Greenland Ice Cap, approximately 120 miles east of Thule Air Base, presented serious problems in regard to heat dissipation and its effect on stability of the snow structures. The camp was constructed in snow trenches cut by Peter snow millers* and roofed with compacted snow placed over thin arched steel forms. The portable nuclear reactor installed by the U. S. Army Polar Research and Development Center has a thermal capacity of 10 megawatts providing 2000 kw of electric power, plus steam for heating the camp rated at close to 1,000,000 Btu per hour. Gamma radiation from the reactor, heat losses from equipment (such as heat exchanger, condenser, air blast cooler, steam turbine, and transmission lines) for converting steam into electricity, and losses from heated buildings installed in the snow trenches all tend to warm the surrounding snow walls and roofs of the trenches. Since the structural properties of snow are highly temperature dependent, it was necessary to devise a simple, economical, and practical means of lowering the temperature of the air in the trenches and thus of the snow walls to prevent excessive deformation.

Numerous field workers have observed that the natural snow temperature decreases rapidly with depth (and varies with the ambient air temperature) until it reaches a constant value equal to the mean annual air temperature. At Camp Century, where the mean annual air temperature is close to -24C, this constant is reached in the snow pack at a depth of about 20 ft (Fig. 1). A means of utilizing this reservoir of cold to cool the trenches was desired and the air well was decided upon as being the most promising. In 1959 and 1960 the authors tested the practical application of this concept in the new camp to determine its effectiveness in maintaining stable temperatures in the walls and floors of an undersnow camp.

Theoretical background

The extent of the heat exchange between air and snow, under the conditions and using the methods given above, depends on the following factors:

1. Delivery pressure of the fan or the driving force created by the fan.
2. Air permeability of the snow.
3. Temperature of the air coming from the trench surface.

Mathematical equations representing the heat exchange process between air and snow can be summarized as follows:

The heat balance of the fluid phase is

$$n \frac{\partial t_a}{\partial \theta} = -ha(t_a - t_s) - \frac{\partial}{\partial z} (v_z t_a) - \left[\frac{\partial}{\partial r} (v_r t_a) + \frac{t_a v_r}{r} \right] + \frac{nk_a}{\rho_a c_a} \left[\frac{\partial^2 t_a}{\partial z^2} + \frac{1}{r} \frac{\partial t_a}{\partial r} + \frac{\partial^2 t_a}{\partial r^2} \right]. \quad (1)$$

Similarly, for the snow phase, the following equation can be formulated

$$\frac{\partial t_s}{\partial \theta} = \frac{ha(t_a - t_s)}{\rho_s c_s (1-n)} + \frac{1}{\rho_s c_s} \left[\frac{\partial}{\partial z} \left(k_s \frac{\partial t_s}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r k_s \frac{\partial t_s}{\partial r} \right) \right] \quad (2)$$

where n = porosity of snow

ha = heat transfer coefficient based on unit volume of snow

t_a, t_s = temperature of air and snow respectively

v_r, v_z = velocity of air in cylindrical coordinates

* A rotary snow plow of Swiss manufacture.

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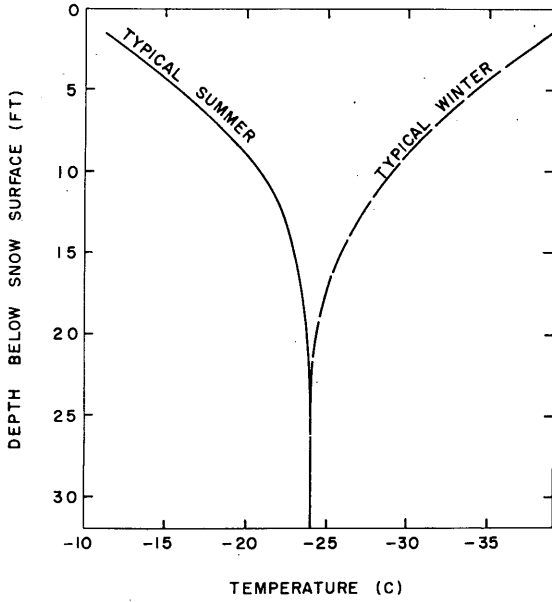


Figure 1. Snow temperature vs depth below snow surface, Camp Century, Greenland.

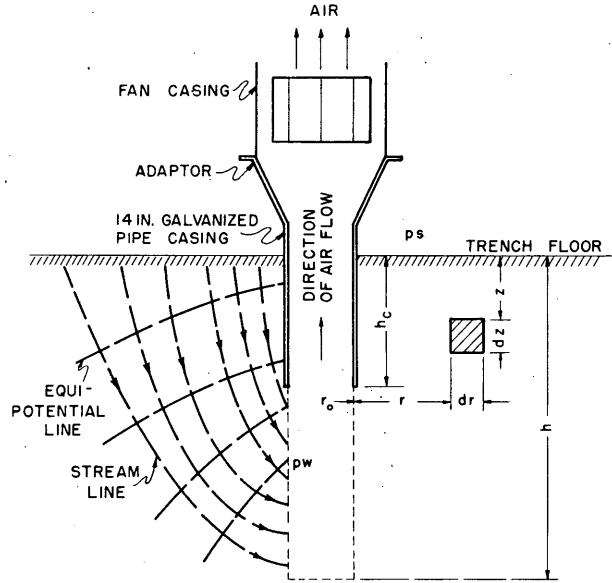


Figure 2. Schematic view of an air well.

k_a, k_s = thermal conductivity of air and snow respectively

ρ_a, ρ_s = density of air and snow respectively

c_a, c_s = specific heat of air and snow respectively

r, z = cylindrical coordinates

θ = time.

The solution of the above unsteady-state simultaneous partial differential eq 1 and 2 depends on the values of $\frac{v_z}{z}$ and $\frac{v_r}{r}$ which are obtained by solving the following equation of continuity (see Fig. 2):

$$\nabla \left(\rho_a \frac{K}{\mu} \text{grad } p \right) = n \frac{\partial \rho_a}{\partial \theta} \quad (3)$$

for $r > r_0, z > 0$

$r > 0, z \geq h$

with $p = p_s$, for $z = 0, r > r_0$

$p = p_w$, for $h \geq z \geq h_c, r = r_0$

and $\frac{\partial p}{\partial r} \Big|_{r=r_0} = 0$ for $0 \leq z \leq h_c$

where h = depth of air well

h_c = depth of cased portion of well

r_0 = radius of well

K = air permeability of snow

μ = viscosity of air

p_s = pressure in trench floor

p_w = pressure in air well.

Since air permeability of snow is a function of density, eq 3 cannot be solved analytically with the mixed boundary conditions shown above.

For the special case: $h_a = \infty$, i. e., putting $t_a = t_s$ and $k_a = k_s = 0$, eq 1 and 2 reduce to:

$$n \frac{\partial t_a}{\partial \theta} = - \frac{\partial}{\partial z} (v_z t_a) - \left[\frac{\partial}{\partial r} (v_r t_a) + \frac{t_a v_r}{r} \right]; \quad (4)$$

$$\rho_s c_s \frac{\partial t_s}{\partial \theta} = 0. \quad (5)$$

on the other hand, if $h_a \neq \infty$, and $k_a = k_s = 0$, eq 1 and 2 assume the following form:

$$n \frac{\partial t_a}{\partial \theta} = -h_a (t_a - t_s) - \frac{\partial}{\partial z} (v_z t_a) - \left[\frac{\partial}{\partial r} (v_r t_a) + \frac{t_a v_r}{r} \right] \quad (6)$$

$$\rho_s c_s \frac{\partial t_s}{\partial \theta} = h_a \frac{(t_a - t_s)}{(1 - n)}. \quad (7)$$

Without exception, values of \underline{v}_r , \underline{v}_z , and \underline{h}_a must be determined before any numerical solution of these equations is attempted. The authors are presently working on the numerical solution of eq 3 by the relaxation method and will publish the results in a separate report.

Test method and equipment

The air well consists of a straight pipe, a fan, and the necessary auxiliaries to connect the fan and the pipe (Fig. 2). Holes of 14 in. diam* and 40 ft deep were drilled into the trench foundation and 14 in. diam galvanized iron pipes were lowered part way into them. The pipe serves essentially two purposes:

1. To carry out cold air after it has passed through the snow.
2. To increase contact time between the warm air and the snow foundation; i. e., to prevent the air from being returned to the trench by the fan immediately after its entry into the foundation before the desired heat transfer has been effected.

The air well draws warm air from the trench through the trench walls and floor and through cold snow to the walls of the air well below the casing, from which point the cooled air is drawn back into the trenches.

Test operations

At the time of the pilot study in 1959, construction of Camp Century had just begun and it was therefore impossible to conduct the investigation under the same conditions as would exist when the camp was completed. However, two experiments were completed, one on the surface of the ice cap and the other in the water supply trench which was cut to serve the construction camp.

Figure 3 shows the arrangements of the fan and thermistors used. In the surface installation, a $1\frac{1}{2}$ hp, 220 v, single-phase fan was placed at the mouth of a $4\frac{1}{2}$ in. air well. The well was 40 ft deep and was cased down 16 ft. With this arrangement the fan delivered about 425 ft³/min. The fan outlet air temperature varied from day to day and showed no obvious dependence on the fluctuations of the ambient air temperature (Fig. 5). The temperature changes in the snow (Fig. 4) cannot be related to distance from the fan and depth from the snow surface as expected. This may be the result of imperfect contact of the thermistors with the snow, or the holes may not have been completely refilled after placing of the thermistors, permitting air flow in the drill holes. The fluctuations in temperature readings for thermistor no. 4, which was located 3 ft from the fan, might be due to variations of the atmospheric air temperatures.

* There was no theoretical background for choosing a 14 in. diam pipe; it happened to be the largest available.

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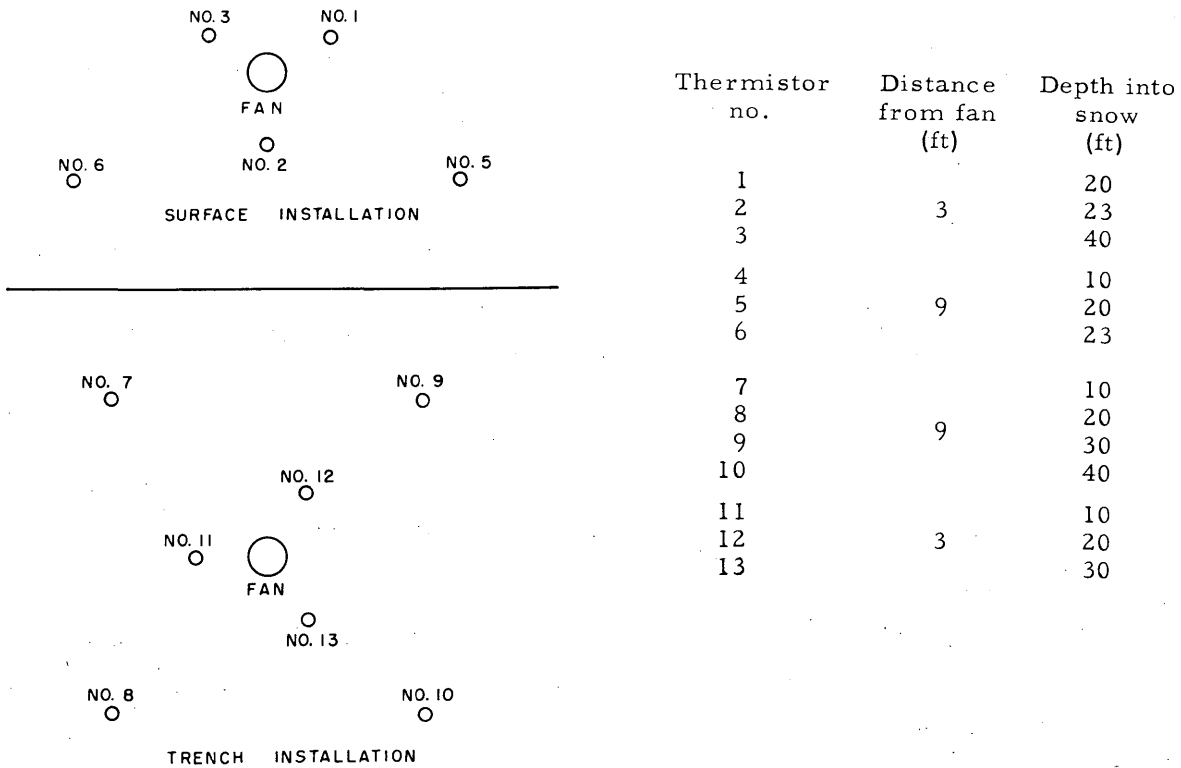


Figure 3. Plan view of the relative locations of fans and thermistors.

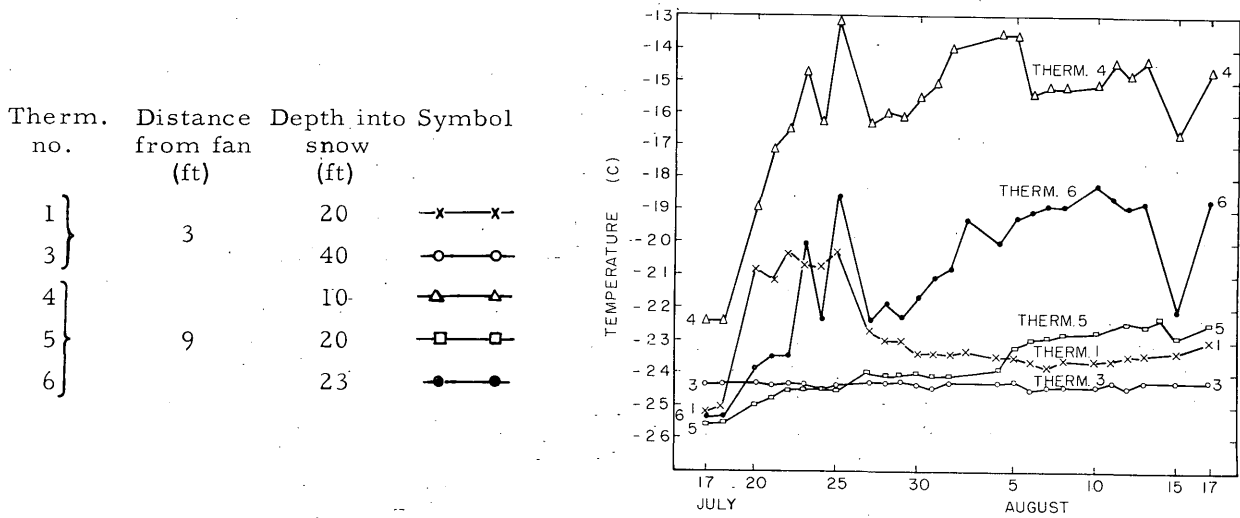


Figure 4. Snow temperature fluctuation due to operation of 1 1/2 hp fan, surface installation, summer 1959.

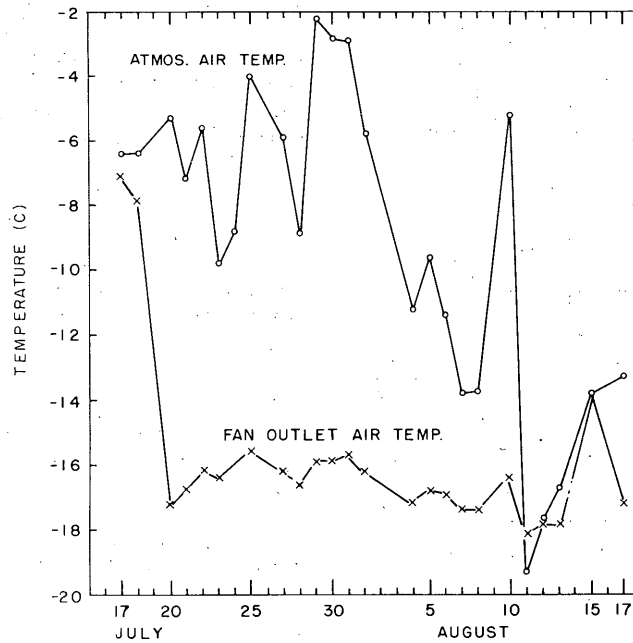


Figure 5. Fan-outlet air temperature and atmospheric air temperature vs time, surface installation, summer 1959.

Therm. no.	Distance from fan (ft)	Depth into snow (ft)	Symbol
7	9	10	—x—
8	9	20	—o—
11	3	10	—△—
12	3	20	—□—

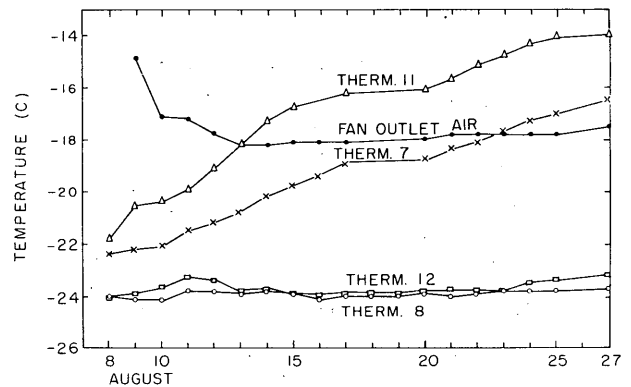


Figure 6. Fan-outlet air temperature and snow temperature vs time, trench installation, summer 1959.

In the water supply trench, a 5-hp fan was installed in a well 1 ft in diam and 28 ft deep. A 10-in. ID casing was installed to a 16 ft depth. Figure 6 shows some of the temperature readings taken from this study. In contrast to the data from the surface installation, there is a systematic temperature change as function of distance from fan. Temperature readings for thermistors no. 9, 10, and 13 are not shown on the figure as these thermistors gave more or less the same reading during the whole experimental period. The fan outlet temperature was quite constant in this case because the surface water supply trench was closed at one end and only partially open at the other. It is interesting to note, however, that no indication of warming of the snow is shown by thermistors no. 8 and 12 located 20 ft deep and 9 and 3 ft from the fan respectively.

The data taken from these two experiments were not conclusive but did show that the use of air wells in snow is practicable and indicated the need for continuing the investigation.

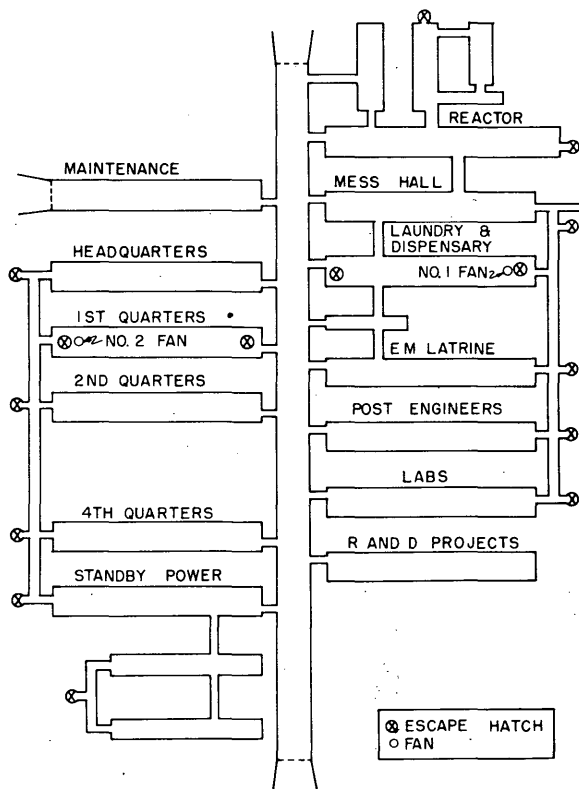


Figure 7. Plan view of Camp Century showing location of fans.

Furthermore, as the air permeability of snow is a function of its density, the quantity of air which can be drawn by a fan is affected by the depth below the snow surface. Therefore, the data obtained from this surface installation would not necessarily hold true for an undersnow camp.

The investigation was therefore moved into the trenches of the new undersnow Camp Century in summer 1960. Figure 7 shows the general layout of the camp and the location of the fans. Experimental work was limited to only two fans (one in the 1st Quarters trench and one in the Laundry and Dispensary trench) because of the limited supply of electrical power at that time. These two trenches were chosen because they were the only ones closed at both ends. The closed-end trench presents a condition that will exist when the camp is in normal operation. This project was conducted in order to determine the following:

1. The outlet air temperature from the fan as a function of time.
2. The amount of air which can be drawn by the fan under a specific set of experimental conditions.
3. The degree of cold that can be maintained in the trench air and the trench walls during the summer months.

4. How fast and to what extent the snow foundation of the trench will be warmed by the exchange of heat between the incoming air and the snow below the trench floor.

5. The effective area subjected to the air flow and heat exchange by the suction of the fan. This information will be used to determine the optimum placement of air wells for uniform cooling to eliminate the local excessive warming of the snow foundation.

To obtain this information, it was necessary to measure the snow temperature below the trench floor as a function of time, depth, and horizontal distance from the center of the fan, and, similarly, the trench wall snow temperature as a function of height from the trench floor and distance from the fan. Holes 4 in. in diam and 40 ft deep were drilled at various distances from the fans. For the no. 1 fan, thermocouples of 20 ga copper-constantan wire were inserted into the holes at 38, 30, 20, 13, and 3 ft beneath the trench floor and at radii of 5, 10, 20, 30, and 100 ft respectively. To make sure that the thermocouples were not placed in void spaces and were at the exact position desired, the following procedure was followed:

1. A 6-in. length was cut from the snow core obtained by drilling.
2. A hole the size of the thermocouple wire was drilled along the cylindrical axis of the snow core.
3. The tip of the thermocouple wire was inserted through the drilled hole and fastened on the snow core.

The weight of the attached snow core served the purpose of straightening out the thermocouple wire when it was lowered into the 4 in. hole. Some snow powder was poured into the hole before lowering the snow core along with the thermocouple to make a good contact between the thermocouple tip and the snow. This procedure worked out

Table I. Snow-foundation temperature (C) below Laundry and Dispensary trench floor after 42 days of continuous operation of no. 1 fan (5 July - 16 August 1960).

Depth (ft)	Distance from fan (ft)				
	10	20	30	100	0
0	-12.5	-12.5	-12.5	-12.5	-10.5
3	-12.0	-11.9	-11.7	-15.0	-18.3
13	-12.0	-13.0	-14.8	-20.4	-23.5
20	-14.6	-17.5	-20.1	-23.7	-24.5
30	-21.5	-22.9	-23.1	-24.0	-24.5
38	-24.0	-24.0	-24.0	-24.0	-24.5

very successfully and is considered necessary in order to obtain reliable results. No. 1 fan with 5 hp capacity was connected to a 14 in. ID pipe casing, $17\frac{1}{2}$ ft long, by an adaptor. Any possible leak between the pipe and the trench floor was eliminated by covering the fan adaptor with a layer of ice obtained by spraying with water. To assure no channeling flow effect along the holes in which thermocouples were placed, water was also sprayed over a small area about 6 in. in diam. Additional thermocouples were inserted laterally into the trench walls. These measurements are considered to be necessary in order to:

1. Indicate the temperature history (i.e., stability) of the snow walls;
2. Locate the major source of air going into the snow foundation, from measurement of the side-wall temperature of snow.

Before turning on the fan, the temperatures of the air, the trench wall, and the trench foundation were measured using a Rubicon Potentiometer with a precision of 0.1C. Two sets of readings were taken each day after the fan was started. The complete history of the snow foundation temperature in the Laundry and Dispensary trench is shown in Figure 8. It can be seen that snow warm-up is a function of distance from the fan. For example, thermocouple T_{11} , 5 ft away from the fan and 13 ft below the trench floor, showed an 8C rise in snow temperature in only 10 days, whereas thermocouple T_8 , 10 ft from the fan and also 13 ft deep, took about 15 days to show a similar temperature rise, and T_2 , 30 ft away and also 13 ft deep, took 40 days to reach the same degree of warm-up. Thermocouples located 5, 10, 20, and 30 ft away from the fan and 3 ft deep showed a much slower increase in temperature after the first 5 days of fan operation. This is due to the fact that the air enclosed in the trench had been cooling down by the continuous operation of the fan and consequently the upper layer of the trench foundation was also cooling. Table I indicates the results at the termination of 42 days continuous operation. The column beneath 0 represents the original temperature distribution of the snow foundation. A graphical representation of this table (Fig. 9) clearly indicates that the extent of snow warm-up is a function of radius and depth. The snow temperature change at 30 ft depth and at radii of 100, 30, and 20 ft is relatively small and thus it is reasonable to assume that little air passed through this region. The no. 1 fan warmed up the snow foundation about 12C at a 13 ft depth. There was no continuous heat source in the trench at that time. With this particular arrangement, 1700 ft³/min of air at the operating condition was drawn by the fan. The temperature of the outlet air from the fan varied from -22C at the beginning of operation to -18.8C on the 42nd day of operation (Fig. 10). The strong dependence of the trench air temperature on the outside air temperature as shown in Figure 10 is due to the fact that this trench was open to outside air through passageways on both sides of the trench in addition to the small entrance opening connecting to the 1100 ft long main trench. These side openings were about 200 ft away from the fan.

The no. 2 fan was installed in the end of the 1st Quarters trench, which was completed in summer 1959. Thermistors were used instead of copper-constantan thermocouples. The experimental arrangement was similar to that of the no. 1 fan. In addition, thermistors were placed 3, 16, 27, and 100 ft away from the fan center and 3, 13, and 38 ft deep respectively. Thermistors were also inserted into the trench wall to investigate the

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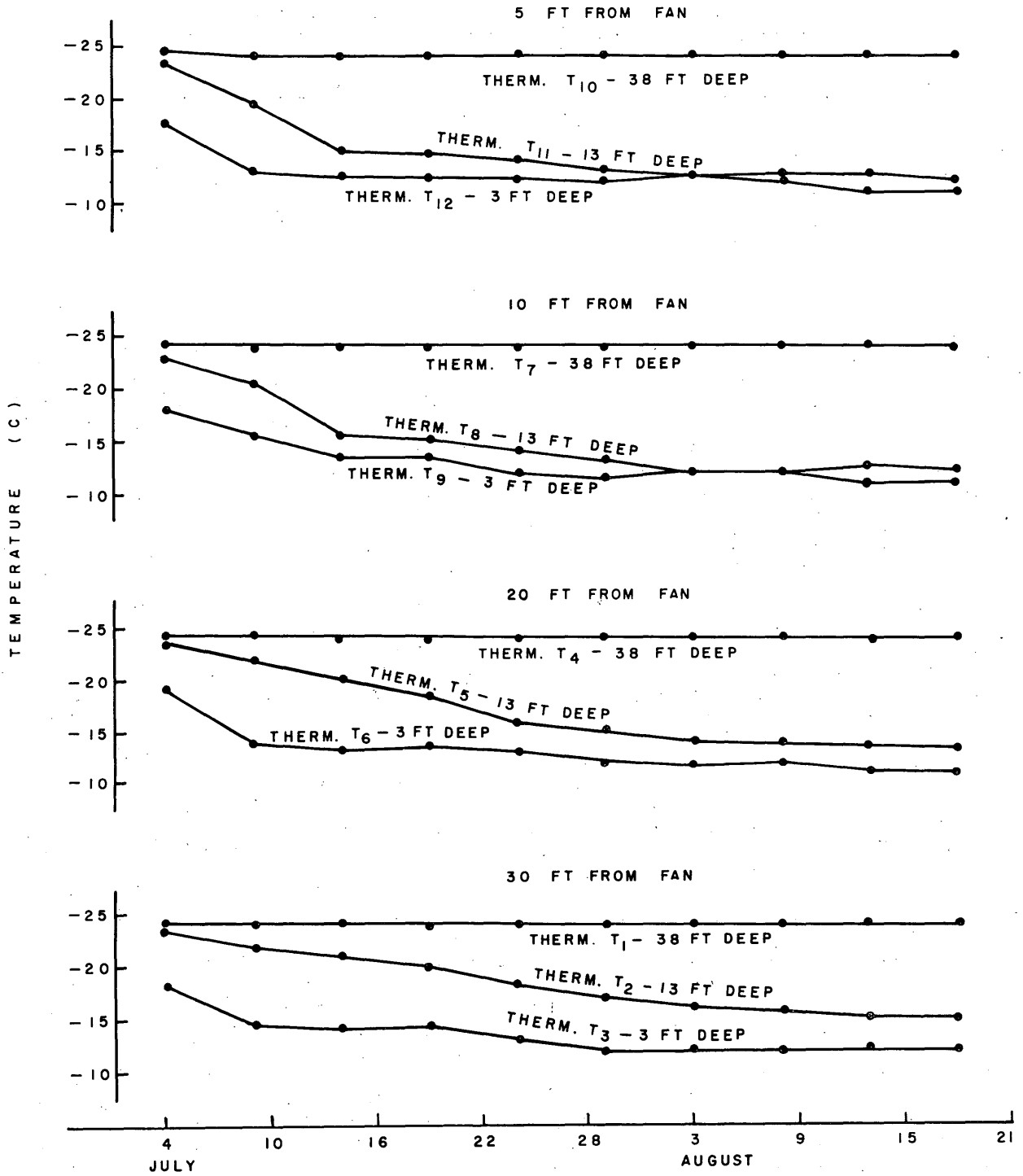


Figure 8. Snow-foundation temperature vs time, Laundry and Dispensary trench.

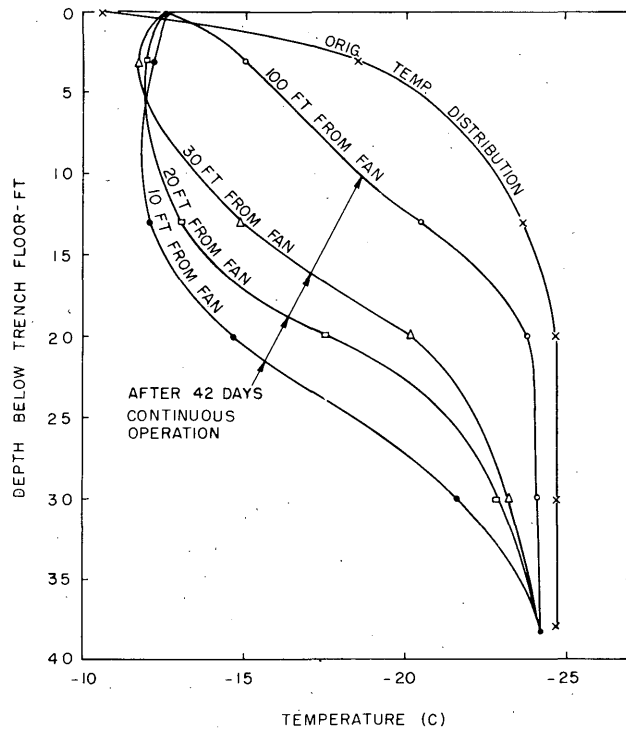


Figure 9. Snow temperature vs depth below Laundry and Dispensary trench floor after 42 days continuous operation of no. 1 fan.

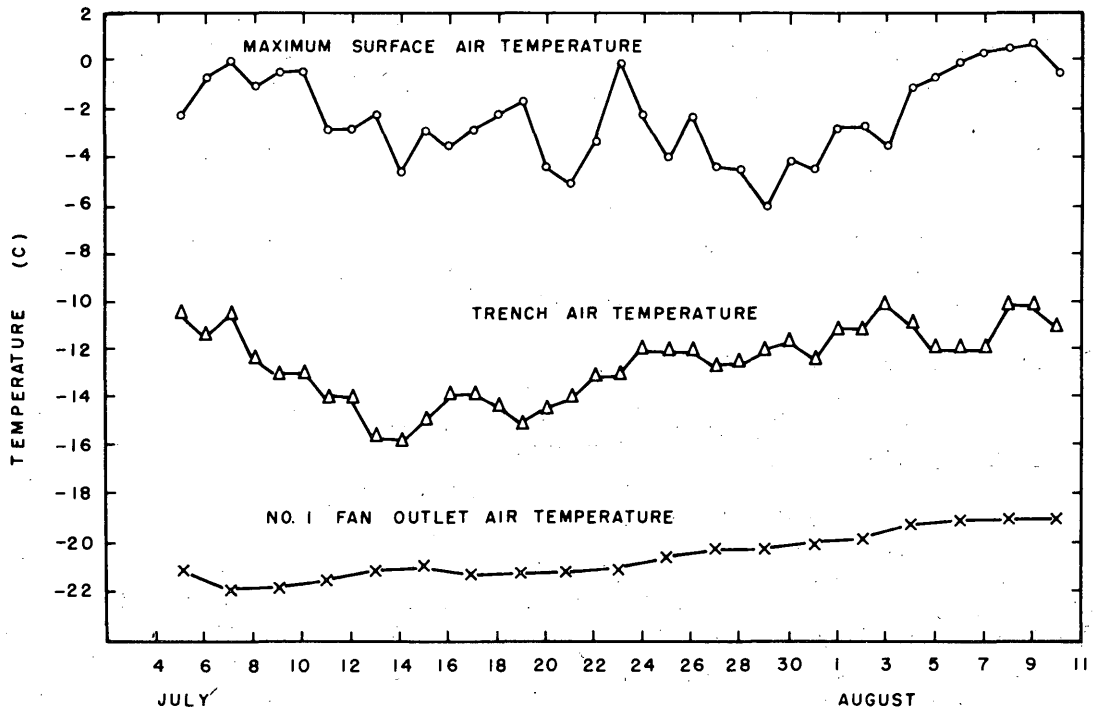


Figure 10. Maximum surface air temperature, trench air temperature, and fan-outlet air temperature vs time, Laundry and Dispensary trench.

temperature profiles longitudinally and vertically in the trench. This air well was also 40 ft deep with a 14-in. diam but was cased down to only 14½ ft. The fan was operated continuously for a period of 55 days at a rate of 1300 ft³/min at the fan outlet conditions, during which time the air outlet temperature changed from -21C to -18C.

In Table II, column 0 indicates the original temperature distribution of the snow foundation. It can be seen that the extent of warm-up was less in this case even though there was a continuous heat source of a 24-kw electrical heater in one of the T-5 buildings. The maximum snow foundation warm-up, about 8.5C, occurs about 13 ft below the trench floor. It can also be noted that the snow foundation temperature at 3 and 13 ft deep was 2 to 3 deg lower than temperatures at corresponding locations in the Laundry and Dispensary trench (Table I). The floor air temperature observed in the 1st Quarters trench (Fig. 11) was more or less constant and was also lower than corresponding temperatures in the Laundry and Dispensary trench. This is probably because the 1st Quarters trench is completely closed except for the small entrance to the main trench.

Table III and Figure 11 show the temperature distribution in the walls as a function of distance from the fan and height above the trench floor. It can be seen that the cold air from the fan was quite localized. In contrast to the snow temperatures away from the fan, the snow temperatures of the trench wall opposite the fan are lower at the highest position and are more or less uniform all up the wall. Except at the end of the trench, there exists about 4C difference between the trench roof and the floor. It is noticed that a slight warm-up occurred in the trench wall opposite the fan at positions of 0, 2.5, and 5 ft from the trench floor. This might be caused by a small amount of trench air passing through this region before going into the trench foundation. Most of the temperature gradient was produced between the fan and 100 ft away as shown in Figure 11. In this space a T-5 had been installed though no heat was discharged from it during the period of investigation.

Effectiveness of the air well

To evaluate the effectiveness of the air well, wall temperatures obtained in the trench with the fan operating were compared with those measured from the Headquarters trench, which has similar conditions except that no fan was operating. The Headquarters trench was occupied by the administrative camp personnel and the buildings had been heated to a comfortable living condition since 10 July 1960. Thermocouples were inserted 1, 4, and 8 ft into the trench wall at about 4, 10, 18, and 22 ft above the trench floor (Fig. 12). Figure 13 shows the snow-wall temperature change in 15 days. During this period, the trench had only a small entrance open to the main trench. It is noted that the snow temperature is raised, but by a smaller amount as the distance from the trench wall surface decreases. Snow 8 ft from the trench wall surface warmed up about 2C as compared to the 0.5C rise for snow just 1 ft from the snow wall. It is also interesting to note that the temperature gradient at 1 and 4 ft in the wall starts to decrease at about 14 ft above the trench floor and finally levels off as the height increases. This is evidently because the thermocouples at 1 and 4 ft depths from the wall surface and about 16 ft above the trench floor are exposed to a more or less uniformly distributed air temperature. For this reason, the temperature increase was smaller for thermocouples nearer the surface of the trench wall than for those deeper in the wall.

A similar study was carried out in the Laundry and Dispensary trench where the no. 1 fan was operating. However, there was no continuous heat discharge in that trench at the time. Figure 14 shows the snow wall temperature change over a 15-day period.

Table IV shows that, at 1-ft depth, the temperature of the walls of the Headquarters trench was increasing while that of the Laundry and Dispensary trench was decreasing after 15 days of operation of the fan. There is a considerable temperature difference between these two trenches, especially at 1 and 4 ft in the trench wall. For thermocouples located 8 ft from the trench wall, this difference becomes apparent only higher on the wall. Without exception, this temperature difference increases with height from the floor.

Data was also taken from the 2nd Quarters trench during a 4-day period. Conditions in this trench were identical with those of the Headquarters trench except that there was no heat discharged from the T-5's in it. Figure 15 compares the temperature readings at 1 ft into the wall for the 1st Quarters, 2nd Quarters, and Headquarters trenches. The readings from the Headquarters trench (curve H) were taken after it had been occupied for

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Table II. Snow-foundation temperature (C) beneath 1st Quarters trench floor after 55-days continuous operation of no. 2 fan (25 June - 18 August 1960).

Depth (ft)	Distance from fan (ft)				
	3	16	27	100	0
3	-14	-14.0	-14.9	-15.0	-17.3
13	-14.9	-14.8	-17.8	-20.1	-23.3
38	-23.9	-23.9	-23.9	-23.9	-24.6

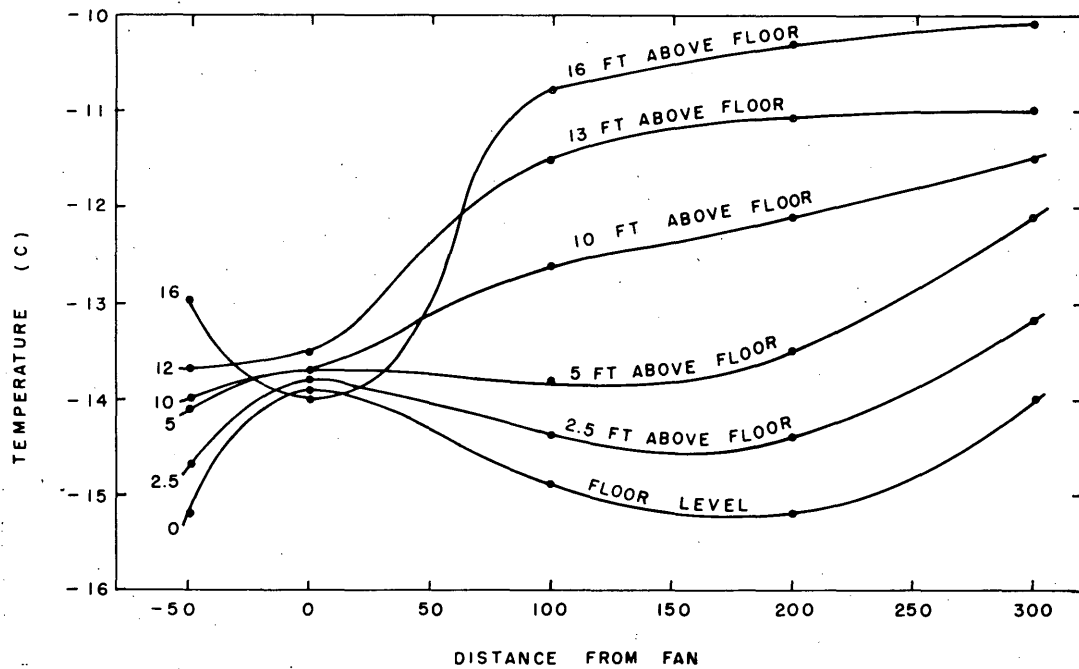


Figure 11. Wall temperature vs distance from the fan, 1st Quarters trench.

Table III. Snow-wall temperature (C) as a function of distance from no. 2 fan and height above the 1st Quarters trench floor (10 August 1960).

Height (ft)	Distance from fan (ft)				
	-31*	0	97	207	313
0	-13	-14	-10.8	-10.3	-10.1
2.5	-13.1	-13.5	-11.5	-11.1	-11.0
5	-14.0	-13.7	-12.6	-12.1	-11.5
10	-14.1	-13.7	-13.8	-13.5	-12.1
13	-14.7	-13.8	-14.3	-14.4	-13.2
16	-15.2	-13.9	-14.9	-15.2	-14.0

* Negative sign indicates position left of the fan.

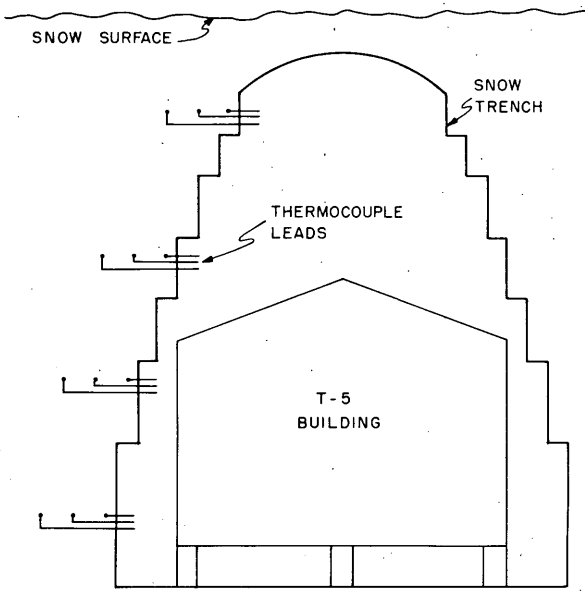


Figure 12. Side view of a typical trench showing the location of the thermocouples along the trench wall.

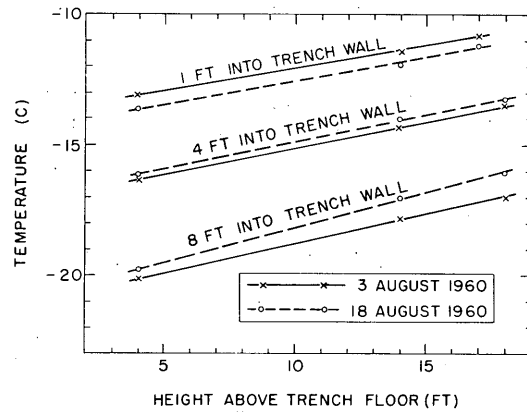


Figure 14. Snow-wall temperature distribution vs height above Laundry and Dispensary trench floor.

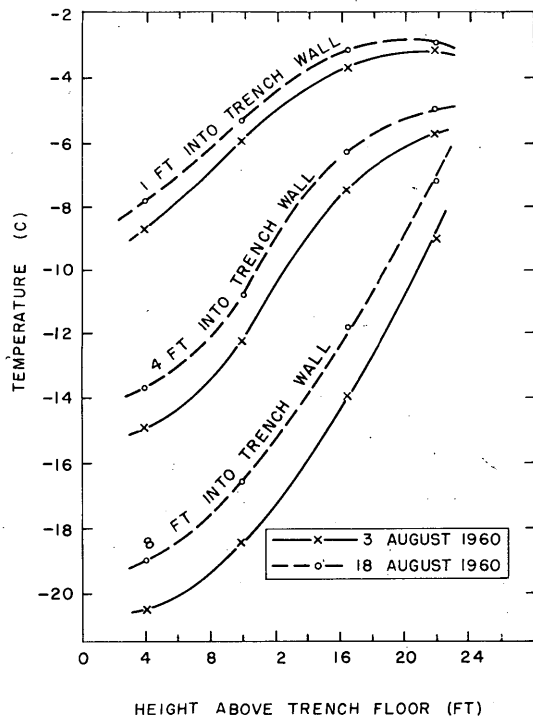


Figure 13. Snow-wall temperature distribution vs height above Headquarters trench floor.

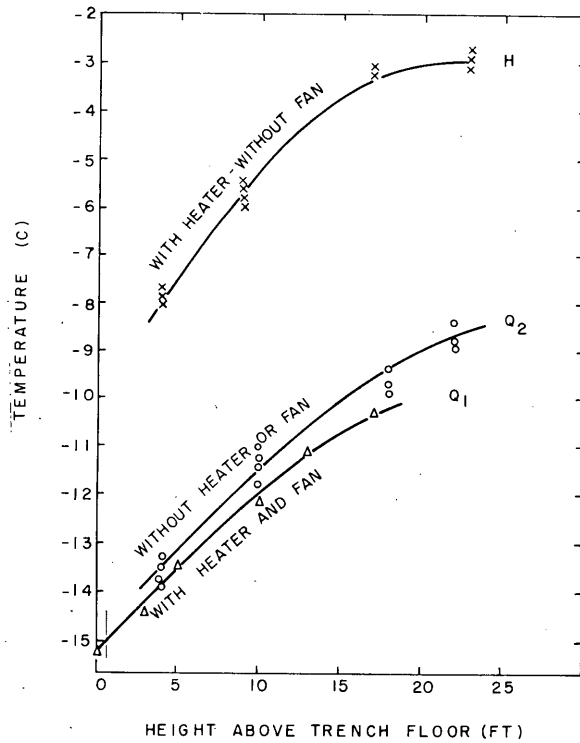


Figure 15. Effect of fan operation on snow-wall temperature distribution.
 H = Headquarters trench
 Q₁ = 1st Quarters trench
 Q₂ = 2nd Quarters trench.

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Table IV. Snow-wall temperature (C) changes in a 15-day period, Headquarters and Laundry and Dispensary trenches, (3 August and 18 August 1960).

Height (ft)		Depth into trench wall (ft)								
		1			4			8		
		LD	H	H-LD	LD	H	H-LD	LD	H	H-LD
4	I	-13.1	-8.7	4.4	-16.3	-15.0	1.3	-20.5	-20.5	0.8
	F	-13.7	-7.8	5.9	-16.1	-13.7	2.4	-19.8	-19.0	0.8
	F-I	-0.6	0.9		0.2	1.3		0.5	1.5	
10	I	-12.1	-6.0	6.1	-15.1	-12.2	2.9	-18.7	-18.3	0.4
	F	-12.6	-5.2	7.4	-14.9	-10.6	4.3	-18.2	-16.5	1.7
	F-I	-0.5	0.8		0.2	1.6		0.5	1.8	
14	I	-11.4	-4.4	7.0	-14.2	-9.5	4.7	-17.7	-16.0	1.7
	F	-12.2	-4.0	8.0	-14.0	-8.0	6.0	-17.0	-14.0	3.0
	F-I	-0.6	0.4		0.2	1.5		0.7	2.0	
18	I	-10.8	-3.5	7.3	-13.4	-7.0	6.4	-17.0	-13.0	4.0
	F	-11.2	-3.1	8.1	-13.2	-5.8	7.4	-16.0	-11.0	5.0
	F-I	-0.4	0.4		0.2	1.2		1.0	2.0	
23	I	-	-3.2		-	-5.8		-	-9.0	
	F	-	-2.9		-	-5.0		-	-7.2	
	F-I	-	0.3		-	0.8		-	1.8	

LD = Laundry and Dispensary trench
 H = Headquarters trench
 I = Data taken 3 August 1960
 F = Data taken 18 August 1960
 F-I = Snow warm-up in a 15-day period
 H-LD = Temperature difference between these two trenches.

about 35 days. They are about 6C higher than comparable readings from the 2nd Quarters trench (curve Q₂) and are dangerously close to the melting point of snow. Operation of the fan caused a 7C cooling effect in the 1st Quarters trench, where heat had been discharging from one of the T-5's (curve Q₁).

Estimation of fan capacity

There are six 4 kw electrical heaters in each T-5 building, and up to three T-5's are installed in each trench. Assuming that the heaters are operating only 10% of the time, then the heat discharge from the T-5's will be:

$$\text{Heat} = 6 \times 4 \times 3 \times 0.1 \times 14,330 = 103,176 \text{ cal/min.}$$

The atmospheric pressure at Camp Century averages about 23.3 in. of mercury and the temperature of the air at the fan outlet is -20C; the air density will be about 0.07 lb/ft³. The specific heat of air is about 0.24 cal/g-C. Thus the heat needed to raise the fan outlet air temperature to that of the trench air will be

$$V \rho_a c_p (t_t - t_f) 453.6 \text{ cal/min}$$

where V = air flow rate, ft³/min
 ρ_a = air density, lb/ft³
 c_p = specific heat, cal/g-C
 t_t = trench air temperature, C
 t_f = fan outlet air temperature, C
 453.6 = g/lb.

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If the desired trench air temperature is -5°C , the above equation becomes

$$V \times 0.07 \times 0.24 [-5 - (-20)] \times 453.6 = 114.3 V \text{ (cal/min)}$$

By equating $114.3 V$ to the $103,176$ desired heat, V is found to be equal to $903 \text{ ft}^3/\text{min}$. The 10% operating time used is only an approximation as no experimental determination of the actual operating time when the camp is under normal conditions has been made.

Table V. Snow-wall temperature ($^{\circ}\text{C}$) changes in a 3-month period, Headquarters and Laundry and Dispensary trenches, (18 August to 25 November 1960).

Height (ft)		Depth into trench wall (ft)								
		1			4			8		
		H	LD	H-LD	H	LD	H-LD	H	LD	H-LD
4	I	-7.8	-13.7	5.9	-13.7	-16.3	2.6	-19.1	-20.1	1.0
	F	-12.8	-12.1	-0.7	-15.1	-13.5	-1.6	-17.4	-15.2	-2.2
	F-I	-5.0	1.6		-1.4	2.8		1.7	4.9	
10	I	-5.7	-12.7	7.0	-10.8	-15.0	4.2	-16.6	-18.5	1.9
	F	-11.3	-11.4	0.1	-13.0	-12.6	-0.4	-15.4	-15.0	-0.4
	F-I	-5.6	1.3		-2.2	2.4		1.2	3.5	
14	I	-4.0	-12.0	8.0	-9.0	-14.1	5.1	-14.6	-17.5	2.9
	F	-10.2	-11.3	1.1	-12.2	-12.4	0.2	-14.2	-14.0	-0.2
	F-I	-6.2	0.7		-3.2	1.7		0.4	3.5	
18	I	-3.1	-11.4	8.2	-6.4	-13.2	6.8	-11.8	-16.4	4.6
	F	-9.7	-11.4	1.7	-11.8	-12.8	1.0	-14.0	-14.7	0.7
	F-I	-6.6	0.0		-5.4	0.4		-2.2	1.7	
22	I	-3.0	-		-5.0	-		-7.2	-	
	F	-10.5	-		-13.1	-		-15.0	-	
	F-I	-7.5	-		-8.1	-		-7.8	-	

I = Initial data taken on 18 August 1960

F = Final data taken on 25 November 1960

F-I = Temperature change (minus for cooling, plus for warm-up)

H = Headquarters trench

LD = Laundry and Dispensary trench

H-LD = Difference in temperature between the two trenches.

Natural cooling in winter

In late November 1960 another set of readings was taken at Camp Century (Table V, Fig. 16). At this time the camp had been completely occupied and in full operation for several months.

There is a general cooling off trend in the Headquarters trench except for a slight temperature increase 8 ft deep at the 4, 10, and 14 ft levels (see Fig. 16). It is worth noting that the temperatures taken nearest the surface of the wall and highest in the trench wall show the greatest cooling. In contrast, the Laundry and Dispensary trench shows a general increase in temperature at all points. The difference between these two trenches, which initially were quite similar, is most likely due to the large amounts of heat released into the trench when the laundry was put into operation during the test.

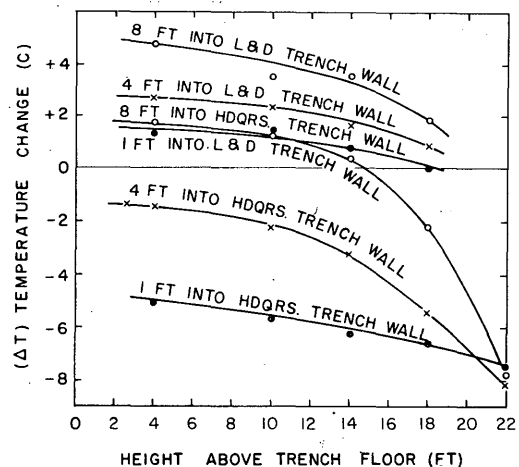
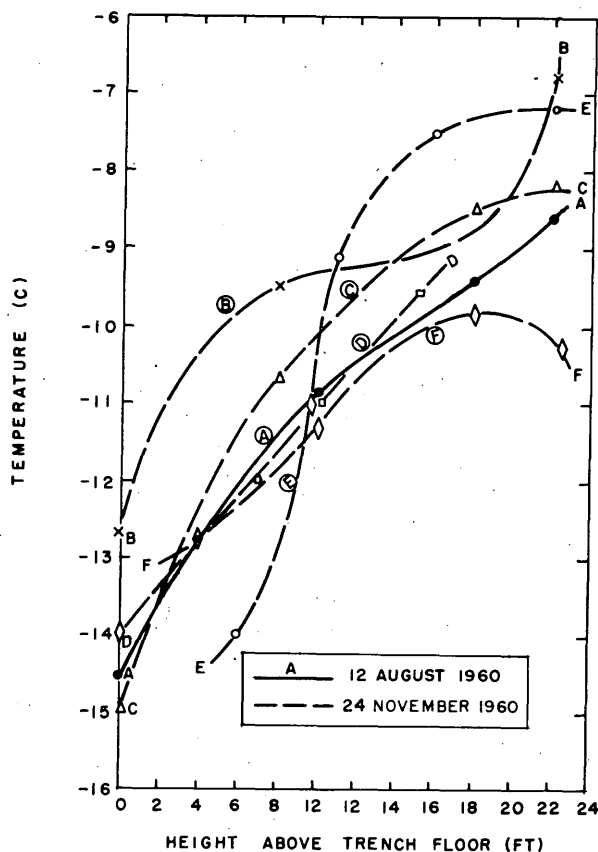


Figure 16. Snow-wall temperature change after 3 months natural cooling (September - November 1960).

Figure 17. Snow-wall temperature vs height above the trench floor after 3 months normal operation of the camp, (12 August - 24 November 1960).

- A. 2nd Quarters trench, 12 Aug 1960
- B. Mess Hall trench
- C. Laundry and Dispensary trench
- D. 1st Quarters trench
- E. 100-man Latrine trench
- F. Headquarters trench.



Change of trench foundation temperature

As indicated previously, the operation of the air well during the summer months causes warming of the trench foundation. The extent of this warm-up is dependent on the distance from the fan, the depth below the trench floor, and the amount of heat released into the trench. It is highly recommended that the trench foundation be allowed to cool down during the winter. If this is not done, there may be a gradual warm-up of the trench foundation from year to year with a resulting loss of cooling ability of the wells.

In both of the trenches shown in Table VI, a fan was operating in the summer. However, these fans were not operating between the beginning of September and the November temperature remeasurement. Therefore, these "F-I" values indicate only the natural cooling rate of the foundation; no attempt was made to increase this rate. It can be noted that the cooling rate is very low. For the 1st Quarters trench, the temperature of the snow increased close to the trench floor and at 38 ft depth. For the Laundry and Dispensary trench, there is a slight general decrease in temperature for all thermocouples except near the T-5 and over 30 ft deep. At the present time there is not sufficient data available to determine whether it will be necessary to provide some artificial means of cooling the snow foundation during the winter months or whether it will cool sufficiently by itself. Cooling could be promoted by allowing the cold surface air to enter the trench directly while the fan is running, either by leaving the escape hatch at the end of the trench open or, if this is not practicable, by installing a separate vent. This cold air would then be pulled through the snow foundation by the action of the fan, cooling the snow as it passed through. Another way would be to reverse the fans and pump cold ambient air from the outside into the foundations. Data are currently being taken at Camp Century to determine whether it will be necessary to increase the cooling rate of the snow.

Trench wall warm-up

Figure 17 shows trench-wall temperature as a function of height above the floor for several trenches. These readings were all taken with thermistors inserted $4\frac{1}{2}$ in. into the trench wall. Curve A represents the data taken on 12 August 1960 from the 2nd Quarters trench before it was occupied and, therefore, before the T-5 was heated. (There is no fan in this trench.) Curves B-F show temperatures obtained on 24 November 1960

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Table VI. Temperature change (C) in the trench foundation as a function of depth from trench floor and distance from fan, (18 August and 25 November 1960).

Depth (ft)	A. 1st Quarters trench									
	Distance from fan, (ft)									
	0	3	3-0	16	16-0	27	27-0	100	100-0	
3	I	-18.3	-14.3	4.0	-14.0	4.3	-14.9	3.4	-15.0	3.3
	F	-18.3	-12.8	5.5	-13.2	5.1	-14.2	4.1	-	-
	F-I		1.5		0.8		0.7		-	-
13	I	-23.5	-14.9	8.6	-14.8	8.7	-17.6	5.9	-20.0	3.5
	F	-23.5	-17.8	6.7	-17.0	6.5	-18.3	5.2	-	-
	F-I		-2.9		-2.2		-0.7		-	-
38	I	-24.5	-23.9	0.6	-23.9	0.6	-23.9	0.6	-23.9	0.6
	F	-24.5	-23.3	1.2	-23.3	1.2	-23.3	1.2	-23.3	1.2
	F-I		0.6		0.6		0.6		0.6	

Depth (ft)	B. Laundry and Dispensary trench.											
	Distance from fan (ft)											
	0	5	5-0	10	10-0	20	20-0	30	30-0	100	100-0	
3	I	-18.3	-11.7	6.6	-11.9	6.4	-12.0	6.3	-12.5	5.8	-14.6	3.7
	F	-18.3	-13.2	5.1	-13.1	5.2	-13.0	5.3	-12.8	5.5	-12.7	5.3
	F-I		-1.5		-1.2		-1.0		-0.3		1.9	
13	I	-23.5	-14.8	8.7	-13.0	10.5	-12.0	11.5	-12.2	11.3	-19.8	3.7
	F	-23.5	-16.8	6.7	-16.2	7.3	-15.8	7.7	-15.8	7.7	-16.5	7.0
	F-I		-2.0		-3.2		-3.8		-3.6		-3.3	
20	I	-24.5	-		-14.0	10.5	-17.5	7.0	-20.1	4.4	-	-
	F	-24.5	-		-18.3	6.2	-20.3	4.2	-19.1	5.4	-	-
	F-I		-		-4.3		-2.8		1.0		-	-
30	I	-24.5	-		-21.5	3.5	-22.9	1.1	-23.1	0.9	-	-
	F	-24.5	-		-		-22.3	1.7	-21.9	2.1	-	-
	F-I		-		-		0.6		1.2		-	-
38	I	-24.5	-24.0	0.5	-24.0	0.5	-24.0	0.5	-24.0	0.5	-24.0	0.5
	F	-24.5	-23.5	1.0	-23.5	1.0	-23.5	1.0	-23.5	1.0	-23.5	1.0
	F-I		0.5		0.5		0.5		0.5		0.5	

I = Temperature taken 18 August 1960

F = Temperature taken 25 November 1960

F-I = Temperature change during this period

0 = Original snow temperature before fan operation in summer

3-0, 5-0 etc. = Deviation of temperature from its original value.

from the trenches indicated. The deviation from curve A indicates the intensity of warming or of cooling during the 3-month period of normal camp operation. Generally speaking, with the exception of the 100-man Latrine trench up to the 8 ft level and of the Headquarters trench, all trenches are warming to various degrees. The 1st Quarters trench shows the least warming with the Laundry and Dispensary, 100-man Latrine, and Mess Hall trenches showing progressively greater amounts of warming. Roughly, during the 3-month period covered by these readings, the temperature of the snow increased up to 2C. Even if the outside atmospheric temperature and other conditions remain the same as they are now, it is expected that the trench roof will be near the melting point by June of 1961. Actually this is a low estimate because the outside air temperature will be much higher during the summer months than it is now. Therefore, if nothing is done to cool down the trenches, especially during the summer, it is expected that the trench roof will be in a very poor condition within a very few months.

Conclusions and recommendations

From the results obtained during the summers of 1959 and 1960, and in late November 1960, the following conclusions and recommendations can be made.

1. The air well is a very practical and economical means of providing cold air to cool the snow structures and thus increase the stability of the trench snow walls and roof. The elasto-plastic deformation of the snow under load will thus be considerably reduced.

2. It is recommended that the minimum distance between two adjacent fans be at least 80 ft to provide a maximum cooling effect over extended periods of time. Fans installed closer together will have intersecting zones of influence with a resultant loss of cooling efficiency.

3. As shown in Figure 9, the warming of the snow foundation is much greater in the first 25 ft below the trench floor than it is further down. Therefore, it is recommended that a longer casing be used in the air wells in order to supply cooler air for longer periods of time.

4. From Figure 11, it can be concluded that the cooling effect of air from the outlet of the fan is localized. A device should be provided to direct the air flow and mix the air inside the trench as homogeneously as possible, thus eliminating localized heating and cooling.

5. The natural cooling of the snow foundation is very slow (Table VI). It is recommended that all the fans should operate continuously all the year around. During the winter season, all the openings to the outside air should be opened to facilitate the natural convective flow of cold air into the trench.

6. It is advisable to discharge all the exhaust air from the T-5's into the outside atmosphere rather than directly into the trench to reduce the heat load on the fan and to maintain a more or less constant fan capacity.

Though precise data on air flow rate from the fan have not been determined because of the limitation of the air well arrangement, it is believed that the capacity of the fan will be a function of time. Most of the high moisture content of the air from the trench will condense as the air flows through the snow foundation. This condensation may eventually reduce the porosity of the snow and thus decrease the flow rate or the capacity of the fan.

7. It can be concluded from Figure 11 that most of the air entering the snow foundation is from the trench floor with only a small portion passing through the trench walls before it penetrates into the snow foundation.

8. A test series should be run with the fan reversed in the winter to pump cold ambient air directly back into the snow.