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EVOLUTION OF CONCEPT
AND
HISTORY OF DESIGN
CONSTRUCTION AND PERFORMANCE

by

Elmer F. Clark

OCTOBER 1965

U.S. ARMY MATERIEL COMMAND
COLD REGIONS RESEARCH & ENGINEERING LABORATORY
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DA Project IV025001A130

PREFACE

The information presented in this report was obtained under the authority of the following projects: Project 8S66-02-001, "Cold Regions Research"; Task 8S66-02-001-01, "Research in Snow, Ice, and Frozen Ground"; Task 8S66-02-001-02, "Experimental Engineering in Snow, Ice, and Frozen Ground"; Task 8S66-02-001-03, "Regional Planning, Cold Regions Research"; and Project 6X61-01-001, "Preventive Medicine"; Task 6X61-01-001-01, "Greenland Waste Disposal".

Camp Century was constructed by the U. S. Army Polar Research and Development Center (now the U. S. Army Research Support Group). The U. S. Army Engineer Research and Development Laboratories, with consultation and assistance from the U. S. Army Cold Regions Research and Engineering Laboratory and guidance from the Chief of Engineers, prepared preliminary design specifications for the camp. The PM-2A Nuclear Power Plant was designed by ALCO Products, Incorporated, Schenectady, New York, under contract to the U. S. Army Engineer District, Eastern Ocean. The Nuclear Power Plant buildings were designed by the engineering firm of Metcalf and Eddy, Boston, Massachusetts.

Lt. Col. Elmer F. Clark, the author, before retiring from active duty in the Army, was in command of the U. S. Army Engineer Arctic Task Force and the Greenland R&D program from 1955 through 1957. In this capacity he was intimately involved in the research efforts described in this report and the development of concepts which led to the construction of Camp Century. Since his retirement in 1958, he has served (first with the Corps of Engineers, and, since the reorganization of the Army, with the Army Materiel Command) as staff action officer for cold regions research and development.

The author gratefully acknowledges the valuable data and consultation provided by Robert W. Waterhouse, Wayne N. Tobiasson, James A. Bender, S. C. Reed, and other members of the U. S. Army Cold Regions Research and Engineering Laboratory staff in the preparation of this report.

The author extends appreciation also to the Chief of Engineers, the Surgeon General, the Commanding Officer of the U. S. Army Engineer Research and Development Laboratories, and the Commanding Officer of the U. S. Army Cold Regions Research and Engineering Laboratory for use of their official records and reports, without which this report could not have been prepared.

USA CRREL is an Army Materiel Command laboratory.

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SUMMARY

This report tells the story of Camp Century, an effort to learn how to construct military facilities on the Greenland Ice Cap. It describes briefly the research done by a number of laboratories, scientists, and engineers in achieving this objective. It discusses the development of concepts, methods, and engineering techniques which made the construction of Camp Century possible. Engineering performance of the camp and its facilities is summarized, and some of the more important reports resulting from the effort are referenced.

It is concluded in the report that subsurface ice-cap camps are feasible and practicable, that nuclear power offers significant advantages in reducing the logistical burden of supporting isolated, remote military facilities, and that the wealth of data and experience obtained from the Camp Century project will be of inestimable value in the development of designs for future ice-cap camps.

CAMP CENTURY—EVOLUTION OF CONCEPT AND HISTORY OF DESIGN, CONSTRUCTION, AND PERFORMANCE

by

Lt. Col. Elmer F. Clark (Ret)

INTRODUCTION

With the advent of such weapons as the atomic bomb, the supersonic long-range bomber, and the intercontinental ballistic missile, it was inevitable that military attention should be drawn to the remote arctic regions which lie athwart the shortest air routes between the major land masses of the Northern Hemisphere (Fig. 1). Thus Greenland, Northern Canada, and Alaska became important in strategic considerations, and led to the construction of such facilities as Ladd Air Force Base, Alaska; Goose Air Force Base, Labrador; and Thule Air Base, Greenland, as well as the extension of the ring of early warning radar stations along the Arctic Circle. At the same time, it became apparent that there was an urgent military requirement to initiate a research and development program which would lead to substantial enhancement of capabilities to conduct sustained military operations in north polar, arctic, and subarctic regions.

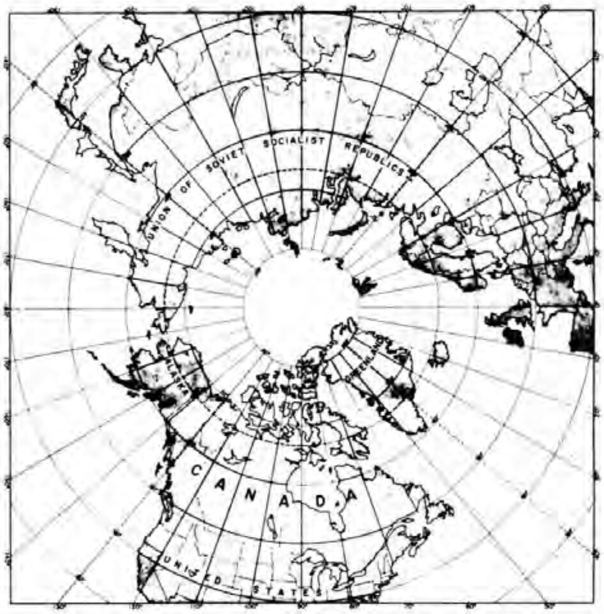

Figure 1. Map of north polar regions.

INCEPTION OF THE GREENLAND RESEARCH AND DEVELOPMENT PROGRAM

For the purpose of identifying problem areas and obtaining information upon which to base an integrated and meaningful Greenland research and development program, Mr. Robert R. Philippe, Office of the Chief of Engineers; Dr. Paul A. Siple, Department of the Army; Mr. Roger Pryor, Department of Defense and Mr. James E. Gillis, U. S. Army Corps of Engineers Snow, Ice and Permafrost Research Establishment, visited Greenland during the summer of 1953. They considered the engineering and associated problems which would have to be solved in order to make possible the military exploitation of Greenland's strategic location. Among other research objectives which resulted from this visit was that of developing concepts, methods, techniques, and equipment required for the construction of camps on the ice cap. Problem areas which were considered to have a direct bearing on camp construction were:

1. Use of snow as a construction material.
2. Foundations in snow.
3. Arctic housing.
4. Control of drifting snow.
5. Sources of power.
6. Water supply.
7. Waste disposal.

As a result of this visit, during the summer of 1954 a modest Corps of Engineers Greenland research and development program was initiated and addressed to these and other problems. In implementing the program, specific research and development tasks were assigned to the following Corps of Engineers laboratories: U. S. Army Snow, Ice and Permafrost Research Establishment (USA SIPRE), now redesignated U. S. Army Cold Regions Research and Engineering Laboratory (USA CRREL); U. S. Army Engineer Research and Development Laboratories (USAERDL); U. S. Army Engineer Waterways Experiment Station (USAEWES); and U. S. Army Engineer Arctic Construction and Frost Effects Laboratory (USA ACFEL), since combined with USA CRREL.

In 1954, to provide logistical support for the program, the 1st Engineer Arctic Task Force (1st EATF) was organized and assigned the Greenland support mission. This mission included construction and operation of necessary camps and related facilities, and providing transportation, personnel, and equipment required by the laboratories to conduct the assigned research (the 1st Engineer Arctic Task Force was redesignated the U. S. Army Engineer Arctic Task Force in 1956). In 1958 it was reorganized as the U. S. Army Polar Research and Development Center (USAPR&DC), which since has been redesignated the U. S. Army Research Support Group.

The 1954 effort was devoted mainly to defining further the construction problems and to the development of promising approaches to the solution of these problems. During the three years that followed, the program was expanded to include more than 30 specific research and development tasks, most of which were related either directly or indirectly to ice cap construction.

EVOLUTION OF THE SUBSURFACE CONCEPT

The subsurface camp concept

The question of whether to construct ice-cap camps beneath or above the surface. is not an easy one to answer, as either choice has distinct disadvantages of major proportions. The severe storms, drifting snow, and extremely low temperatures which prevail on the ice cap are serious disadvantages to above-surface facilities. Further, above-surface structures soon become subsurface as a result of new accumulation and the continuous drifting of snow. This is a condition for which they were not designed; hence, under the stresses of the ever-increasing overburden, ultimately they fail. On the other hand, to construct beneath the surface necessitates tunneling into the snow and erecting buildings and other structures within these tunnels (Fig. 2). The main disadvantage to this concept is that snow is a visco-elastic material which deforms in a relatively slow although somewhat predictable manner as functions of density, temperature, and time under stress*. Hence, in the case of subsurface construction the designer must consider the maintenance price which must be paid in terms of a continuing snow-trimming effort in order to maintain the original geometry and cross section of the snow tunnels. He must consider also the required design life of the camp, since, at some point in time, it becomes buried to a depth where the deformation rate is so great that the trimming task is unacceptably burdensome and costly. However, there is what might be called an optimum zone in which the closure rate is smaller than either nearer the surface or at greater depths. This zone is below the depth where snow densifies rapidly and above the depth of a greatly increased overburden. (Figures 3 and 4 show the densities and temperatures of unprocessed Greenland Ice Cap snow as a function of depth.)† Although, at the

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*Deformation is affected by the complex interaction of these several variables; thus, theoretical calculations are limited to providing reasonable predictions of deformation rates at given depths.

†Data in these figures were abstracted from USA CRREL reports on work accomplished at Site II and Camp Century (see Fig. 21 for location).

Figure 2. Snow tunnel (cut-and-cover type).

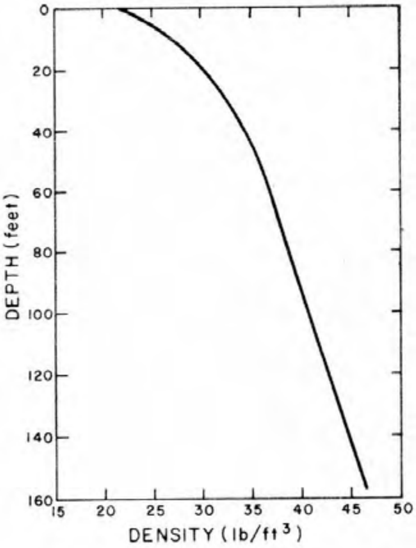

Figure 3. Mean density of unprocessed Greenland snow at Site II (Fistclench) as a function of depth.

time of this writing, there are not sufficient available data to establish the precise limits of the optimum zone, it is deduced from measurements and observations of temperatures, densities, and closure rates as a function of depth at Site II* and Camp Century that it extends from approximately 60 to 120 feet below the surface. Table I shows calculated hydrostatic pressures in Greenland snow as a function of depth.

An alternative to subsurface construction, which has been studied and even put to limited use in construction of the ice-cap DEWline stations, consists of construction on piling (Texas Tower) and installation of jacking systems so that the structures can be raised periodically to keep them above the surface of the snow (Fig. 5). However, the initial cost of this type of construction is far greater than that of constructing beneath the surface and it has the added disadvantage of being readily visible for miles against the white and featureless ice-cap background. For these reasons, except for very special purposes such as cited above, it is not considered practicable for military facilities.

The major advantages and disadvantages of both above-surface and subsurface construction are considered to be:

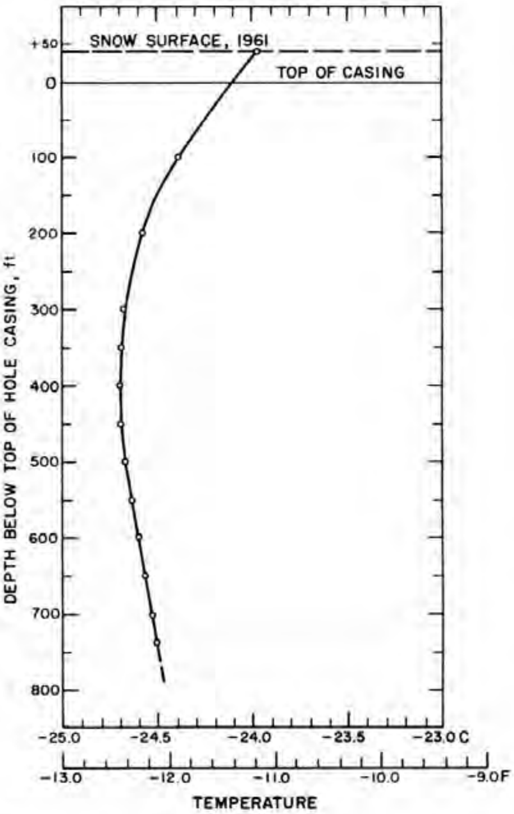

Figure 4. Temperatures as a function of depth in ice cap at Camp Century.

1. <u>Above-surface construction</u>
   a. Advantages:
      (1) Maintenance cost is substantially lower.
      (2) Is more suitable for some types of military facilities (e.g., radomes, radio antennae, meteorological instruments and instrument towers).
      (3) Requires less power for lighting.
      (4) Offers psychological advantages (i.e., many people have an aversion to living in subsurface camps).
   b. Disadvantages:
      (1) Initial construction cost is appreciably higher.
      (2) Is subjected to the severe above-surface environment.
      (3) Requires more imported construction materials.
      (4) Engenders a severe snow-drift removal problem (unless elevated several feet above the surface on columns).
      (5) Only delays eventual burial; hence, provides no permanent solution.

Table I. Site II drill hole measurements, 25 June 1958.

Depth below 1958 surface (ft)	Calculated hydrostatic pressure (kg/cm^2)	Hole diameter (in.)
185	3.58	5.836
235	5.30	5.824
285	6.70	5.780
335	8.10	5.808
385	9.50	5.776
435	10.90	5.758
535	13.70	5.935
585	15.10	5.518
635	16.50	5.470
685	17.90	5.372
735	19.31	5.140
785	20.71	5.000
835	22.11	4.958
885	23.55	4.474
935	24.92	4.410
985	26.32	4.022
1010	27.02	3.786
1035	27.72	3.684
1085	29.12	3.068
1135	30.53	2.704

The flow rates are indicated by hole diameters at successively greater depth after a period of approx 10 months from completion of drilling. Initial diameter of hole was 5.8375". (Abstracted from Hansen and Landauer, 1958).

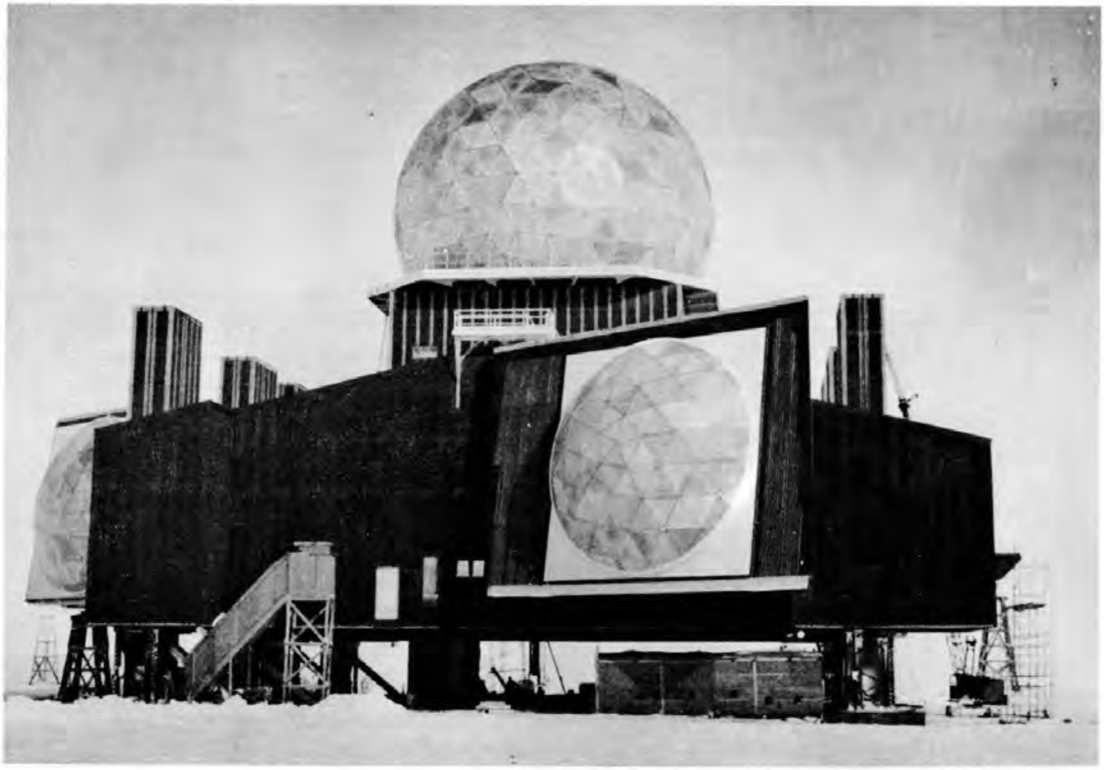

Figure 5. Texas Tower concept used in Greenland Ice Cap DEWline sites. Built-in jacking device permits periodic raising of structure as new snow accumulates.

(6) Is difficult to camouflage.
(7) Is more vulnerable to enemy attack.
(8) Requires more fuel for heating purposes.

2. Subsurface construction:

a. Advantages:

(1) Initial construction cost is lower.
(2) Avoids severe above-surface environment.
(3) Requires less fuel for heating purposes.
(4) Requires less imported construction materials.
(5) Minimizes the problem of drifting snow.
(6) Is easier to camouflage.
(7) Is less vulnerable to enemy attack.

b. Disadvantages:

(1) Maintenance cost is higher.
(2) Requires year-round power for lighting.
(3) Has limited useful life, owing to the fact that it ultimately becomes buried to a depth where the deformation rate is greatly accelerated.
(4) Is psychologically undesirable

After careful consideration of the foregoing, it was decided to address all efforts to the development of techniques, methods, equipment, and design criteria for subsurface camp construction.

The subsurface road concept

Full exploitation of the military potential of the Greenland Ice Cap required reliable year-round access to camps and other facilities located within its boundaries. Summertime access on a fairly reliable basis, by both air and surface means, had been made possible through development by the U. S. Air Force of satisfactory skis for large cargo planes and the development of greatly improved oversnow transport equipment by the U. S. Army Transportation Corps. However, the daily 24-hour darkness (Fig. 6), extremely low temperatures, and violent storms made wintertime transport by either means hazardous and exceedingly unreliable. During three years of operation of the ice cap AC&W stations, Sites I and II*, Thule Air Base was unable for weeks at a time to transport mail, passengers, and needed supplies to these sites by air. The history of wintertime air rescue operations in Greenland is filled with accounts of aircraft crashes and harrowing experiences of near disaster. Wintertime surface transportation, although somewhat less hazardous, is time-consuming and not much more reliable than air transportation.

In view of these limitations of both surface and air transportation, the concept of subsurface roadways was given serious consideration. Such roadways would be independent of weather, would eliminate navigation problems, and would provide reliable year-round access to camps located anywhere on the ice cap. However, it was realized that a system of subsurface roadways would be economically feasible only if major installations were envisioned.

DEVELOPMENT OF METHODS, TECHNIQUES, AND DESIGN CRITERIA

Use of snow as a construction material

The knowledge that snow has excellent insulating properties and can be used for construction purposes is not new. In fact, the Eskimos have used it for centuries to construct igloos and other types of survival shelter. When the requirement for ice-cap camps was established, the possible use of snow as a construction material

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*Respectively 96 miles NNW and 220 miles ENE of Thule.

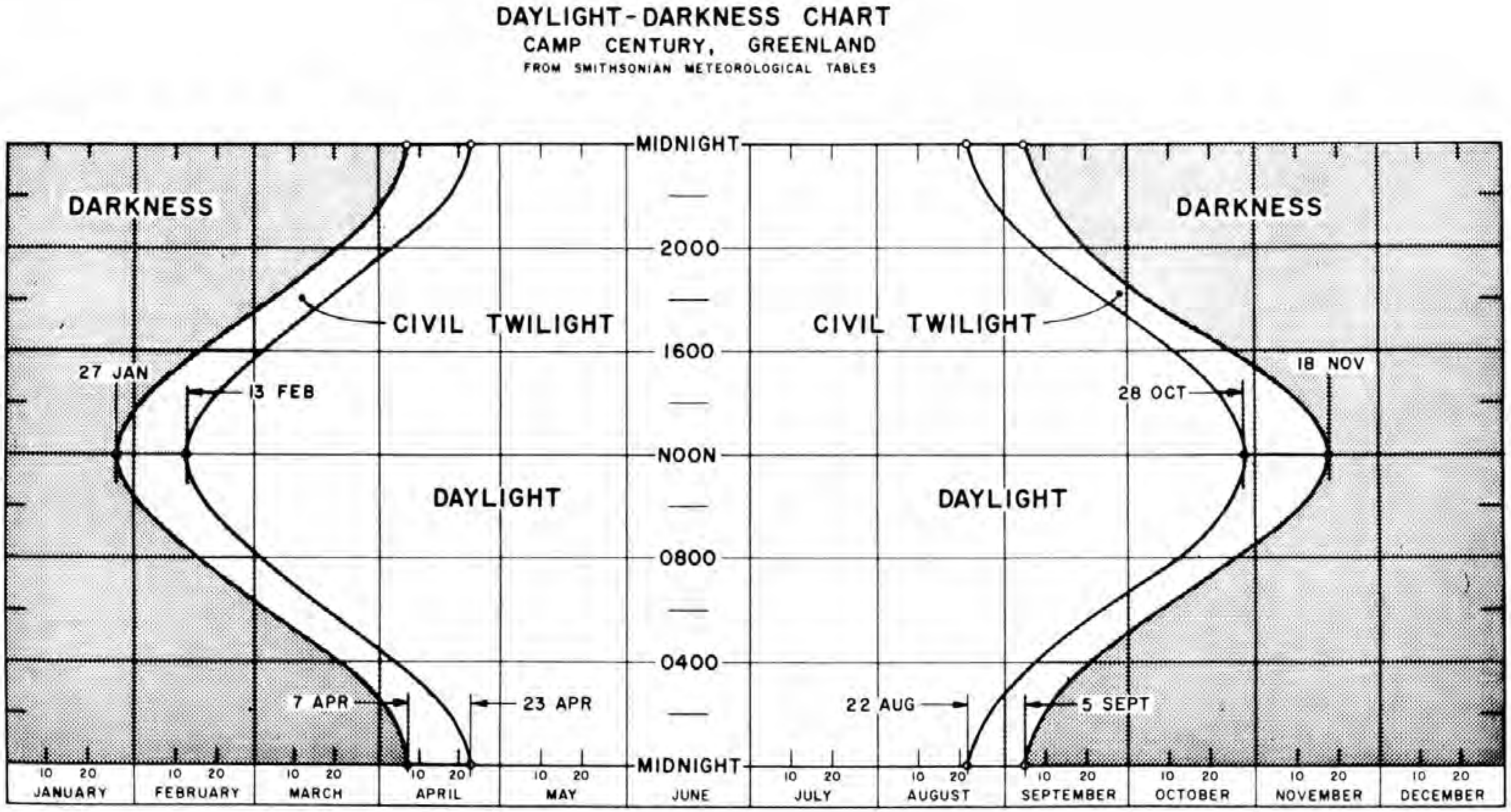

Figure 6. Northern Greenland (Camp Century) daylight-darkness chart. Civil twilight includes the time after sunset and before sunrise when the sun is between the horizon and 6 degrees below the horizon.

became an exceedingly attractive consideration from the point of view of monetary as well as logistical economy. However, to use snow on a massive scale in this type of construction required not only a thorough knowledge of its physical properties, but also development of new techniques and equipment designed to handle it rapidly and in large volumes. Further, as snow has low density and strength in its undisturbed state, it was necessary to develop a means for increasing these property values by some processing technique before its use in construction could be considered seriously.

It had been noted that snow cleared from roads by rotary plows gained significantly in density, hardness, and bearing strength as a result of having been handled by these plows. Hence, it was evident that some type of large rotary plow might provide a solution to the processing problem. Such a plow, the Peter snow miller* (Fig. 7), used by the Swiss to clear roads of avalanche snow in the Alps, seemed to offer promise for this application. It not only possessed a capacity to handle large volumes of snow (approximately 780 yd^3/hr in $0.4\ g/cm^3$ snow), but was also capable of cutting through dense snow containing deposits of ice. Moreover, its milling action produced a high density ($0.55\ g/cm^3$) granular material with a broad range of grain sizes. This snow, called Peter snow, hardens with time into a material of significant mechanical strength.

Figure 7. Peter snow miller in operation cutting a trench.

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*The introduction of the Peter miller for this application in Greenland and the encouraging subsequent developments resulting from its use can be credited to Dr. Henri Bader, who was then Chief Scientist of USA SIPRE.

The trenching capability of the Peter miller was first investigated in 1955 at Site II (Fistclench), a location on the ice cap 220 miles east of Thule at an elevation of 6800 feet. In 1956, under the direction of R. Waterhouse, USA SIPRE, project "Snow Structures" was initiated and the study of snow as a material of construction was incorporated into the program of investigations.

The first 500 feet of trench was produced and covered with an arched snow roof composed of Peter snow, which was deposited by the Peter miller on a specially designed removable metal form. The engineering properties of density, grain size distribution, unconfined compressive strength, and hardness were determined and related to the operating characteristics of the machine, including operation at various speeds and casting over a range of distances. The obvious objective was the production of a material which possessed the highest strength at the earliest possible time after deposition. To this end the investigations continued.

During these early investigations, it was learned that the best material for unsupported snow arches contained a broad grain size distribution (0.1 to 2.0 mm) and that the snow gained strength most rapidly if deposited in layers in which large temperature differences prevailed. It was observed also that this gain in strength, or age-hardening process, was slow when the snow and ambient air temperatures were nearly the same and that the faster rates occurred only when the snow was colder than the air. Butkovich (1962), in his study of the age hardening of processed snow, described the phenomenon as the formation of new bonds between the grains, by both a sublimation and a surface migration process, whereby the material from the grains forms the bonds, and the number of grains in a given cross section decreases with time. He observed that some of the factors which influence the process are heterogeneity of grain size; temperature; temperature gradients between grains; and space between grains, or porosity. He reported also that, when a comparison was possible, the mechanical property of processed snow with time always approached the value for naturally compacted snow of like density but never exceeded it to any great degree. The benefit derived from milling the snow was the faster achievement of high density with rapid age hardening.

Concurrent with these field trials and investigations, physical scientists, working in Greenland and at the USA SIPRE Laboratory in Wilmette, Illinois, were rigorously seeking a better understanding of the properties of the natural snow pack as well as of the processed snow.*

Prior to 1957 all ice-cap installations, including the Air Force AC&W stations (Sites I and II), had been constructed above the surface, and later became subsurface as a result of accumulating snow. In 1957 the first known deliberately designed subsurface camp was constructed at Site II by the U. S. Army Engineer Arctic Task Force (USAEATF), under the supervision of Lt. Col. E. F. Clark, who was then in command of the Army's R&D program in Greenland (Figure 8 shows the layout scheme for this camp).

This camp (Camp Fistclench) exploited the snow structures studies which had been conducted by Waterhouse. The Peter miller was used to cut straight-walled trenches, which were roofed with conventional structures of wood and metal in all cases where the spans were greater than 8 feet (Fig. 9, 10). Systems of measurement were initiated to study the movement of the viscoelastic snow, which continues to densify with time under load. It soon became apparent that, in the design of undersnow facilities of any size and life span, the gradual closure of trenches had to be considered and that some system of trenching was required which would reduce the roof material requirements for trenches 18 to 24 feet wide at the floor.

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*Since 1956, a number of studies of the fundamental properties of snow have been made. For example, Nakaya (1959) measured Young's modulus and viscosity as a function of time; Fuchs (1960) studied the structure of age-hardened disaggregated Peter snow.

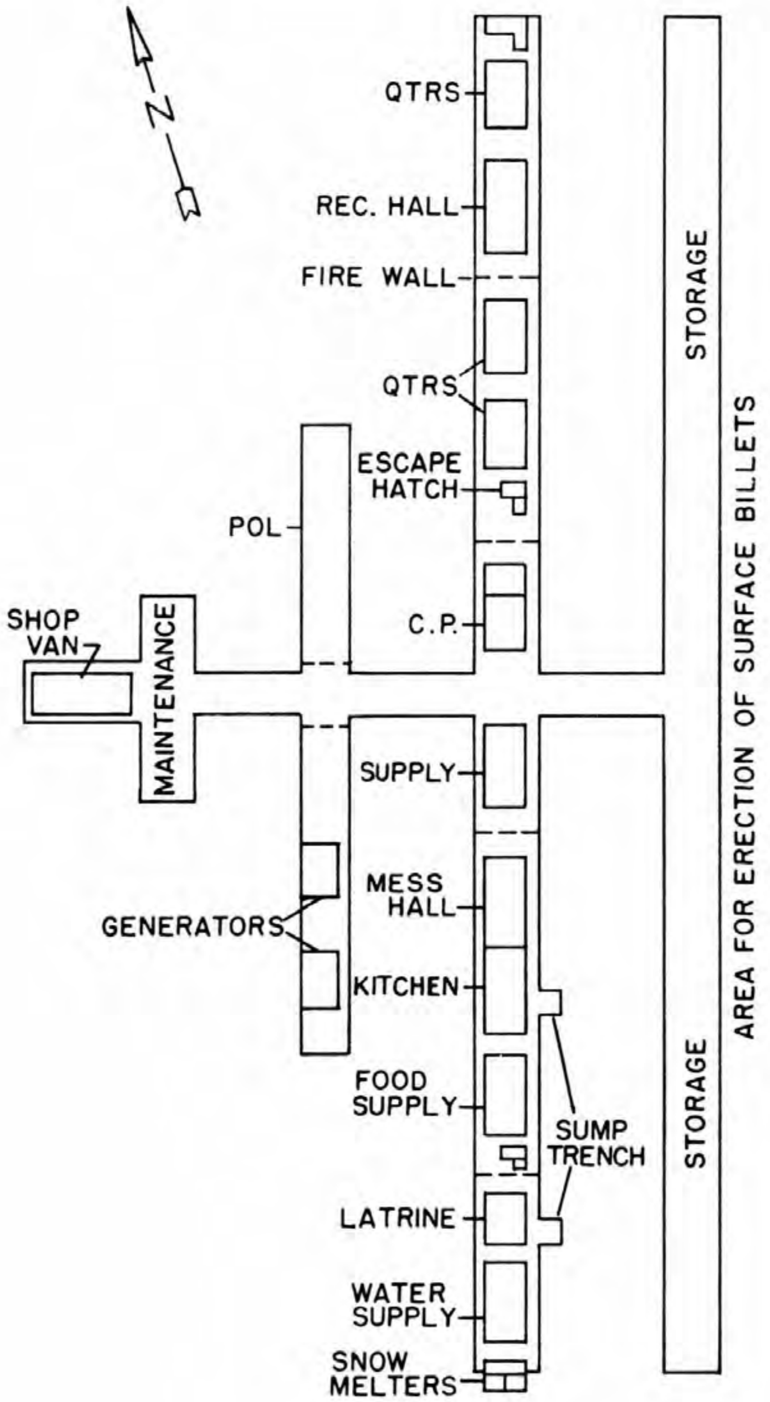

Figure 8. Layout plan for Camp Fistclench.

Figure 9. Peter miller cutting a straight-wall trench.

Figure 10. One of the open trenches covered with timber trusses. Photo taken before prefabricated buildings were installed.

Figure 11. Undercut trench.

To solve this problem, Dr. Bader suggested the undercut trench concept, and the snow structures team built the first undercut trench at Site II in 1958 (Fig. 11). The trench had a width of 8 feet at the top and 18 feet at the floor (Fig. 12, 13). A depth of 20 feet provided sufficient overhead clearance to assure at least a 5-year life before settlement of the roof would begin to crush the enclosed framed structures. The trench was covered with an unsupported snow arch roof. This was accomplished by placing metal forms over the open trench, backfilling over the forms with Peter snow, and then removing the forms as soon as the snow had age hardened sufficiently to be self-supporting (Fig. 14, 15) (Waterhouse, 1960). Data obtained during this construction effort, augmented by studies of the effects of temperature on the strength properties of both unprocessed and Peter snow, and the experience gained from occupation of Fistclench, provided information adequate for the design of subsurface camps with some predictable performance characteristics.

Figure 12. Peter snow miller in operation employing undercutting technique.

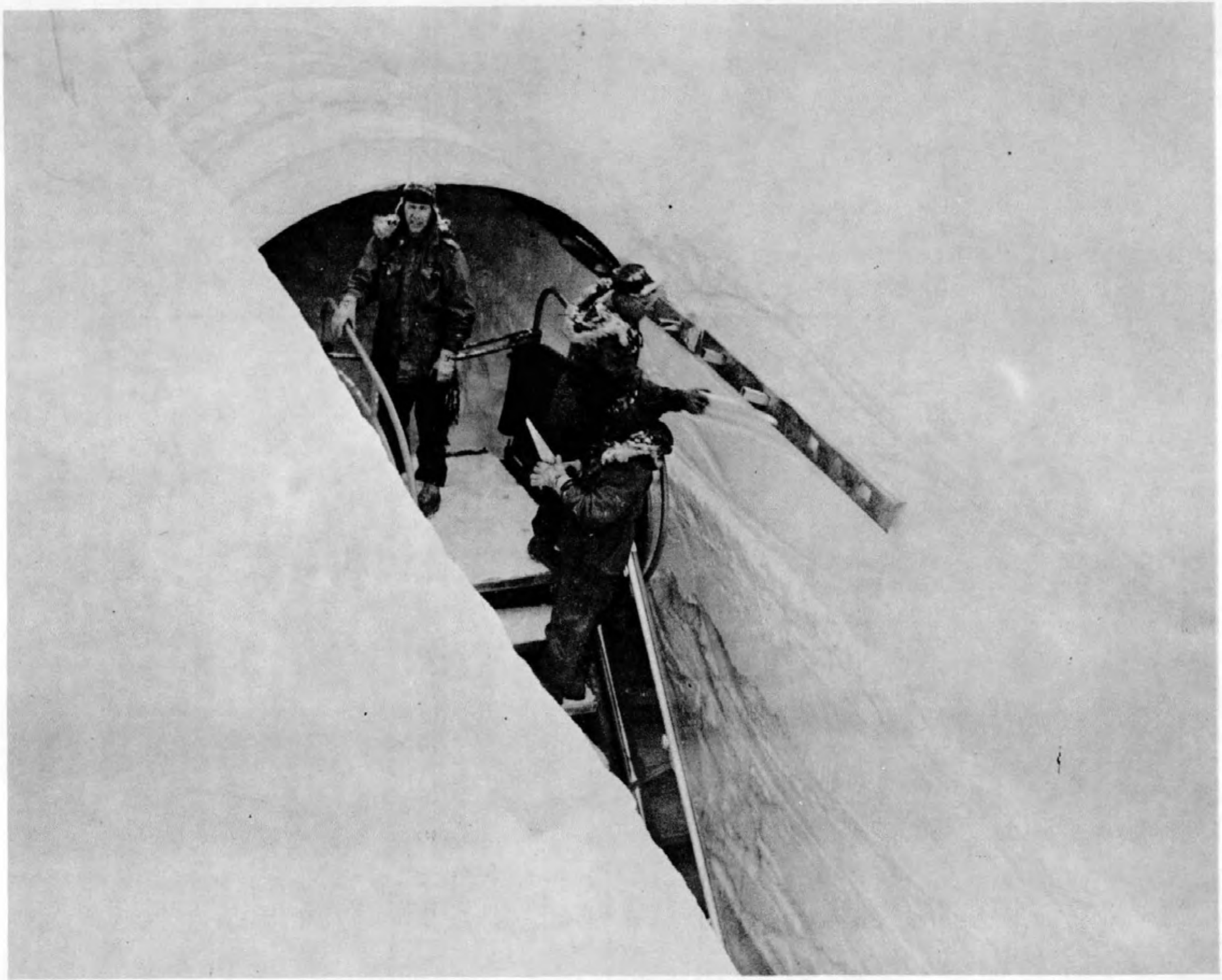

Figure 13. Top view of undercut trench.

Figure 14. Metal arch forms being emplaced over undercut trench.

Figure 15. Unsupported snow arch after metal forms have been removed.

The most important lessons learned at Fistclench were that flat structural roofs over snow trenches were incompatible with the ever-increasing snow load for which they had to be designed, that waste could be disposed of satisfactorily in shafts produced in the snow mass by discharge of station effluent, and that structural supports for buildings must be spaced symmetrically with respect to the trench centerline in order to accommodate an arching of the snow floor as the trench deforms.*

Foundations in snow

Another problem of major concern was that of developing design criteria for foundations in snow. Foundations for ice-cap structures, such as the U. S. Air Force AC&W stations (Sites I and II), had been over-designed because of the lack of reliable data on the bearing strength of snow. To obtain data upon which to base future foundation design, a series of tests, under the supervision of N. Costes, USA SIPRE, were initiated in 1957 at Site II. The program included tests of model and full-scale piles as well as spread footings. Various sizes, spacings, and configurations of piles were incorporated in the plan of test; rates of loading were varied; vertical movements were measured as functions of time and stress. Skin friction and point-bearing values were determined independently.

Several different methods of installing the test piles were employed. These included driving piles into place; augering holes, inserting the piles, and backfilling with snow slush; and a combination of these methods, which consisted of driving the piles several feet after they had been placed in augered holes.

These early tests were not conclusive, although they did provide considerable data on the bearing capacity of piles and spread footings. Costes, after 2 years of pile testing at Site II, concluded that 50 psi (point bearing), with a safety factor of 2, would be a conservative design value for piles, provided they were spaced at least three pile diameters apart, and driven or emplaced to a depth of 30 feet beneath the trench floors. At that time, Costes apparently was convinced that skin friction added little to the bearing capacity of a pile in snow and should therefore be disregarded.† However, additional data obtained at Camp Century in a recent series of tests indicate that skin friction may be the more important factor in pile bearing capacity (A. Kovacs).**

In construction of the Air Force AC&W stations, Camp Fistclench and the ice-cap DEWline stations, spread footings were used exclusively. This decision resulted from the fact that insufficient data were available at that time to provide an adequate basis for reliable pile foundation design. However, since these facilities were constructed, a continuing program of observing the performance of spread footings at these locations has been maintained. Also, several series of tests on the bearing capacity of spread footings have been conducted at other locations in Greenland since 1955. As a result of these tests and measurements, S. Reed, USA CRREL, observed that the settlement of spread footings on snow is strongly dependent on temperature and initial snow density and that an exponential relationship between temperature and the rate of settlement is indicated. He further observed that the relationship between footing settlement and load is linear up to a load intensity of 2000 psf, but that beyond this value the settlement rate increases more rapidly.

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*Trench floor arching is discussed under "Foundations in snow".

†Costes expressed this conclusion in 1958 during a conference on design criteria for Camp Century. Since 1958, as a result of having evaluated additional data which have been obtained, Costes apparently has changed his opinion concerning the value of skin friction and now agrees essentially with the observations of Kovacs.

**Kovacs, who was in charge of the USA CRREL pile testing program at Camp Century in 1964, expressed this view while the author was visiting Camp Century during the summer of 1964.

Dr. A. Assur (USA CRREL) has suggested the following expression for the relationship between settlement and footing size:

$$\frac{S_2}{S_1} = \left[\frac{b_2}{b_1}\left(\frac{1 + b_1/b_0}{1 + b_2/b_0}\right)\right]^n$$

where: S_2/S_1 = ratio of settlement of two footings
b_1, b_2 = width of two footings
b_0 = a factor defining the additional width over which the footing load is assumed to be distributed; i.e., instead of the contact area, width b, the load is effectively distributed over the greater width $b+b_0$
n = exponent dependent upon characteristics of snow under stress.

Reed observed that the adoption of $n=2$ and $b_0 = 1$ (in feet) in the above relationship leads to a very close approximation of observed settlements.

The advantages of piles versus spread footings are debatable and depend largely upon the nature of the structures they are to support. The advantages and disadvantages of each from the point of view of ease of construction, intended use, and logistical economy are considered to be as follows:

1. Piles
   a. Advantages:
      (1) Can extend sufficiently deep beneath the snow surface (trench floor if in trenches) to avoid the adverse effects of heated structures or of solar radiation on the strength of the supporting snow.
      (2) Are more suitable than spread footings for above-surface construction, where the surface snow has relatively low density and strength, or where structures should be elevated several feet above the surface to minimize the snow drifting problem.*
   b. Disadvantages:
      (1) Require more effort and equipment to install than spread footings.
      (2) Are of debatable advantage in cut-and-cover trenches or tunnels, except where heated structures will affect adversely the bearing capacity of the upper layers of the supporting snow.
2. Spread footings
   a. Advantages:
      (1) Require less effort and equipment to install than piles.
      (2) Are more suitable than piles for installation in trenches or tunnels where working space is confined.
      (3) Require less logistical effort in terms of transportation.
   b. Disadvantages:
      (1) Are subject to the adverse effects of heated structures or solar radiation on the strength of the supporting snow.
      (2) Are less suitable than piles for above-surface construction in low-density snow or for structures which should be elevated several feet above the surface to minimize the snow-drifting problem.

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*Pile foundations can be designed to extend from the surface into deeper and denser snow layers, which possess correspondingly greater strength. Hence, in the utilization of a given area, piles would carry a greater load with less settlement than footings placed on the surface, even if a monolithic plate covering the entire area were to be used. If a structure is elevated on piles several feet above the surface, wind action tends to prevent the formation of snow drifts under or around the structure.

The snow floors in trenches tend to become arched within a few months after construction has been completed. This effect is generally believed to result from the stress distribution which concentrates most of the overburden load on the snow directly under the trench walls, thus causing the snow at these points to consolidate at a more rapid rate than elsewhere in the floor. In any event, to compensate for this differential vertical movement, it is considered necessary to space piles or footings symmetrically with respect to the floor centerline (Fig. 16).

Tests and observations of both piles and spread footings in snow which were conducted prior to 1959 did not provide all of the desired solutions to problems of designing ice cap foundations. However, they did indicate that both types were feasible and provided sufficient data to design foundations in snow with reasonably predictable performance characteristics.

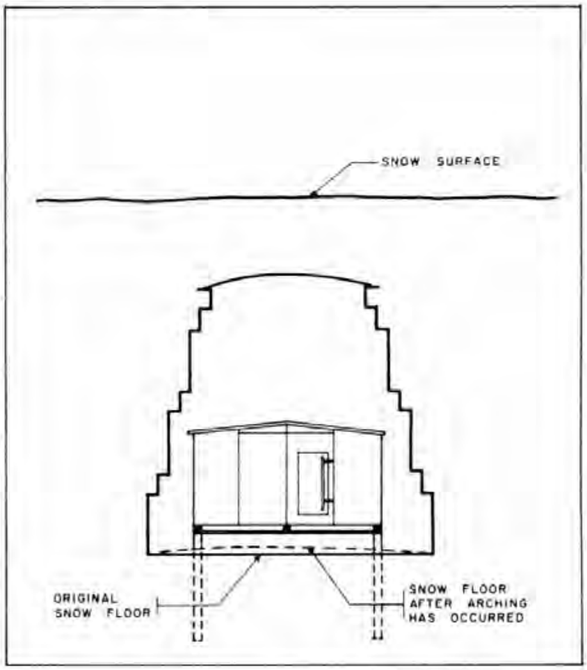

Figure 16. Piles spaced symmetrically with respect to floor centerline.

Arctic housing

With the development of a satisfactory cut-and-cover method of constructing trenches, the requirement for development of lightweight and inexpensive buildings for use in the trenches became important. The then existing family of arctic buildings and shelters were designed for the surface environment, where wind and snow loadings as well as insulation are important design considerations. However, in the trenches there are no wind or snow loads and temperatures remain more nearly constant than on the surface. Consequently, structural members can be made lighter and requirements for insulation can be greatly reduced. The optimum building for use in the trenches would have the following characteristics: very light weight; inexpensive; sufficient structural strength to support only the design floor loads, the necessary insulation, and such appurtenant hardware as might be installed; fireproof; easy to transport and erect or fabricate on-site; and easy to disassemble and remove.

New developments in materials, particularly in organic polymers, appeared to offer promise in the development of such a building. Honeycomb paper, foamed concrete, geodesic domes, inflatable shelters, and many other new developments in both materials and design seemed to merit careful evaluation.

To explore these possibilities, the U. S. Army Engineer Research and Development Laboratories (USAERDL) was assigned the task of studying and evaluating various new materials and design concepts and of designing a prototype building which would satisfy the subsurface construction requirement. In conducting the studies, USAERDL considered a number of new materials, commercially available prefabricated buildings, and fabrication techniques. None fully satisfied all of the above-stated requirements.

Standard off-the-shelf commercial buildings, although generally suited in most respects for semi-permanent surface camps in the arctic, were over-designed for use in the cut-and-cover trenches. Further, without major modification, most were too large for installation in trenches, where width was limited by the construction techniques that had been developed.

Of the materials considered for this application, polyurethane foam appeared most nearly to satisfy all of the stated requirements. Its chief disadvantage was that it could be foamed only in a controlled environment (i.e., 40° to 65°F). Nonetheless, its light weight (2 to 4 lb/cu ft), excellent insulating properties (thermal conductivity, or K factor, of 0.15 Btu/sq ft/hr/°F/in), and a high fire-retardant potential (can be made to be self-extinguishing when specially compounded) more than compensated for this disadvantage. Also, it offered a logistical advantage in that it could be shipped to the construction site as drummed chemicals, which would result in a substantial transportation economy, if on-site fabrication techniques could be developed.

Concurrently with other research on problems relative to ice-cap camp construction, efforts to develop buildings suitable for installation in trenches continued.

Control of drifting snow

Of prime importance in ice-cap construction is the development of methods and techniques for preventing drifting snow from closing the entrances to subsurface camps and rapidly burying above-surface structures (Fig. 17). To solve this problem a number of methods were considered, including the use of portable snow fences, layout configurations, and building geometries which would minimize the problem; inflatable air locks at trench or tunnel entrances; and air curtains in the form of clusters of high-velocity air jets at ramps and portals to prevent the formation of snowdrifts.

Considerable effort was directed to the testing of various snow fence types and fence layout arrangements, but results were generally far from satisfactory. The almost unimaginable mass of snow that is repeatedly shuffled by wind action made the use of portable snow fences ineffective and at best only a temporary expedient. Further, digging them out and reinstalling them frequently, as they become buried in the snow, is a time-consuming task. Another disadvantage of fences is the fact that their continued use around ramps and portals aggravates the problem by the creation of large mounds of snow, which in turn interfere with wind action and thus accelerate the formation of new drifts.

The use of inflatable air locks or air curtains to protect portals and ramps was considered, but was never actually tested in the field. However, it may be that either of these devices would be more effective than snow fences as a solution to the problem of controlling drifting snow. Appendix B describes a method of protecting portals that was tested by USA CRREL at Camp Century in 1964.

The closure of portals is only one of a number of problems involving control of drifting snow which were studied by USA SIPRE during the period 1954-1964.* These efforts were devoted to a broad spectrum of snow-drift problems, including the influences of layout configurations, building geometries, and orientation with respect to prevailing wind directions on control of drifting snow. The investigations and tests which were conducted ranged from theoretical studies on fluid dynamics to actual field tests with full-scale structures as well as scale-model simulation of a blowing snow condition in wind tunnels (Gerdel, 1961). Figures 18 and 19 show an example of the wind tunnel tests.

The most important findings relative to control of drifting snow were: that any object, obstruction, or depression on the surface results in the formation of snowdrifts at a steadily increasing rate; that surface structures must be elevated 10 to 20 feet above the surface on piles, if rapid burial is to be avoided; that snow fences, although useful for some purposes, can be considered only a temporary expedient; and that surface structures should be laid out, oriented, and spaced with respect to prevailing wind directions so that no structure is located in the area of the snowdrift pattern caused by another structure.

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*USA CRREL since 1961.

Figure 17. View of portal to Camp Century showing dozer clearing snowdrifts after a storm.

Figure 18. Wind tunnel test of a model of a composite Dye Site building during stages of construction (Gerdel, 1961).

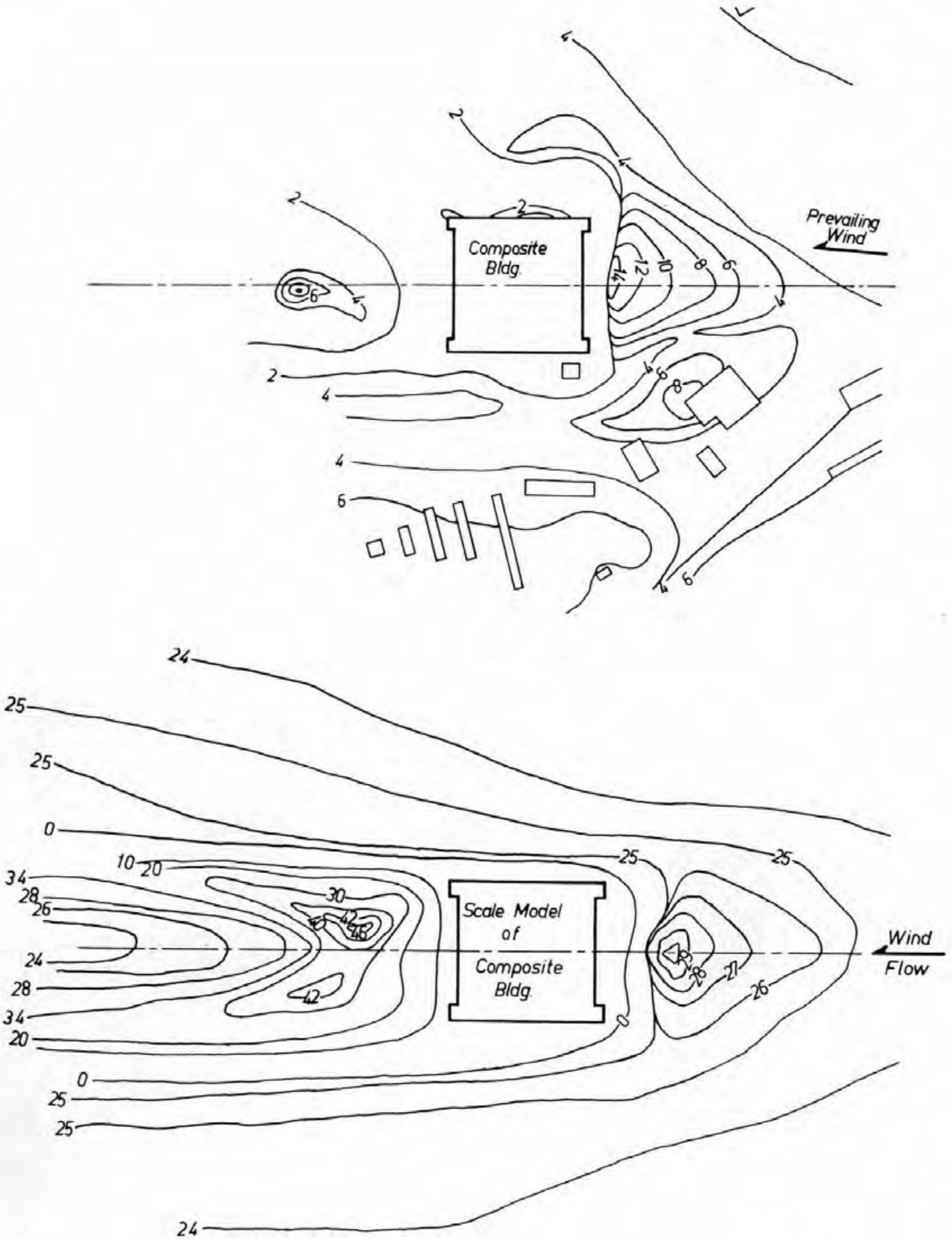

Figure 19. Contours of drift accumulation around the composite Dye Site II building on the ice cap during a 10-month period (upper drawing) and contours showing the accumulation pattern developed in the tunnel on a scale model of the composite Dye Site building (lower drawing). Elevations shown are in feet above the natural surface. (Gerdel, 1961)

Water supply

Dr. Bader in 1955 advocated producing water for ice-cap camps by melting a shaft into the ice to a depth of approximately 100 feet, where the snow has a density of about 0.70 g/cm^3 and is impermeable to water. Then, with the use of steam jets, a pool of water sufficiently large to satisfy camp requirements could be melted and maintained. The water could be pumped into storage tanks by means of a deep well pump (Fig. 20). Bader's concept was based upon his observations of the sewage disposal system at Site II, where water-borne sewage which was dumped into a pit rapidly melted its way down to a depth of about 100 feet. It then ponded and created a pool of ever increasing size which remained in the liquid state as long as the heat input was continued (Bader and Small, 1955).

The advantages of this concept over the conventional snow melter were obvious. Not only would less manpower be required in the production of water but also an abundance of water could be produced at less cost per gallon.

In 1958 a task was assigned to USAERDL to test the ice-cap well concept. In 1959, Mr. R. Rodriguez, USAERDL employee, assembled the necessary equipment (steam generator, flexible steam pipes, steam nozzles, deep well pumps, storage tanks, winch, etc.) and conducted a field test on the ice cap. He developed a water supply system which is now known as the "Rodriguez Well." The equipment consisted mostly of modified commercial items. The success of this test is documented by USAERDL Technical Report No. 1737.

Sources of power

Providing conventional types of fuel (i.e., diesel oil, gasoline, kerosene, etc.) for heat and electricity becomes a logistically burdensome requirement, not only on the Greenland Ice Cap, but also in any remote region. Solar furnaces, wind-powered electric generators, or water turbines may provide partial solutions to this problem, but each has distinct disadvantages and limitations. In the high polar latitudes, solar power is not available at all during the polar night, which lasts from early November to mid-February of each year; wind power is at best sporadic and undependable; and the water-power potential is limited to the two to three months of summer during which streams flow. Further, on the Greenland Ice Cap, sources of water for operation of turbo-electric generators are available only at the very edges, where temperatures rise above 32°F in summer. Hence, nuclear power appeared to be the only feasible solution.

During the summer of 1955, two Corps of Engineers representatives from the Army Nuclear Power Program visited Greenland for the purpose of determining the feasibility of installing a modular-type nuclear power plant on the Greenland Ice Cap. They considered also the advantages, if any, such a plant would offer in comparison to standard diesel-electric plants. After inspecting the Army R&D camps and sites and discussing power requirements and installation problems with USA SIPRE engineers and scientists and the CO, 1st EATF (Lt. Col. E. F. Clark, who was then in command of the Army R&D program in Greenland), they concluded that the engineering problems of installing a plant on the ice cap, although difficult, were not insurmountable and that a tremendous logistical economy in ice cap transportation would be realized.* They recommended that such a plant be designed and installed on the Greenland Ice Cap. The primary reason for selecting the ice cap for this test was that if a plant could be installed and operated successfully there, where engineering problems would be complicated by excessive deformation of the snow trenches housing it, installation and operation of such a plant in other less severe environments would be easy by comparison. Experience with the SM-1 Nuclear Power Plant, then under construction at Fort Belvoir, Virginia, would provide sufficient data upon which to base the design of a small modular-type, skid-mounted plant. Accordingly, plans were formulated to design a plant and install it in Greenland during calendar year 1960.

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*A few pounds of enriched U-235 contains as much energy as thousands of drums of fossil-fuel.

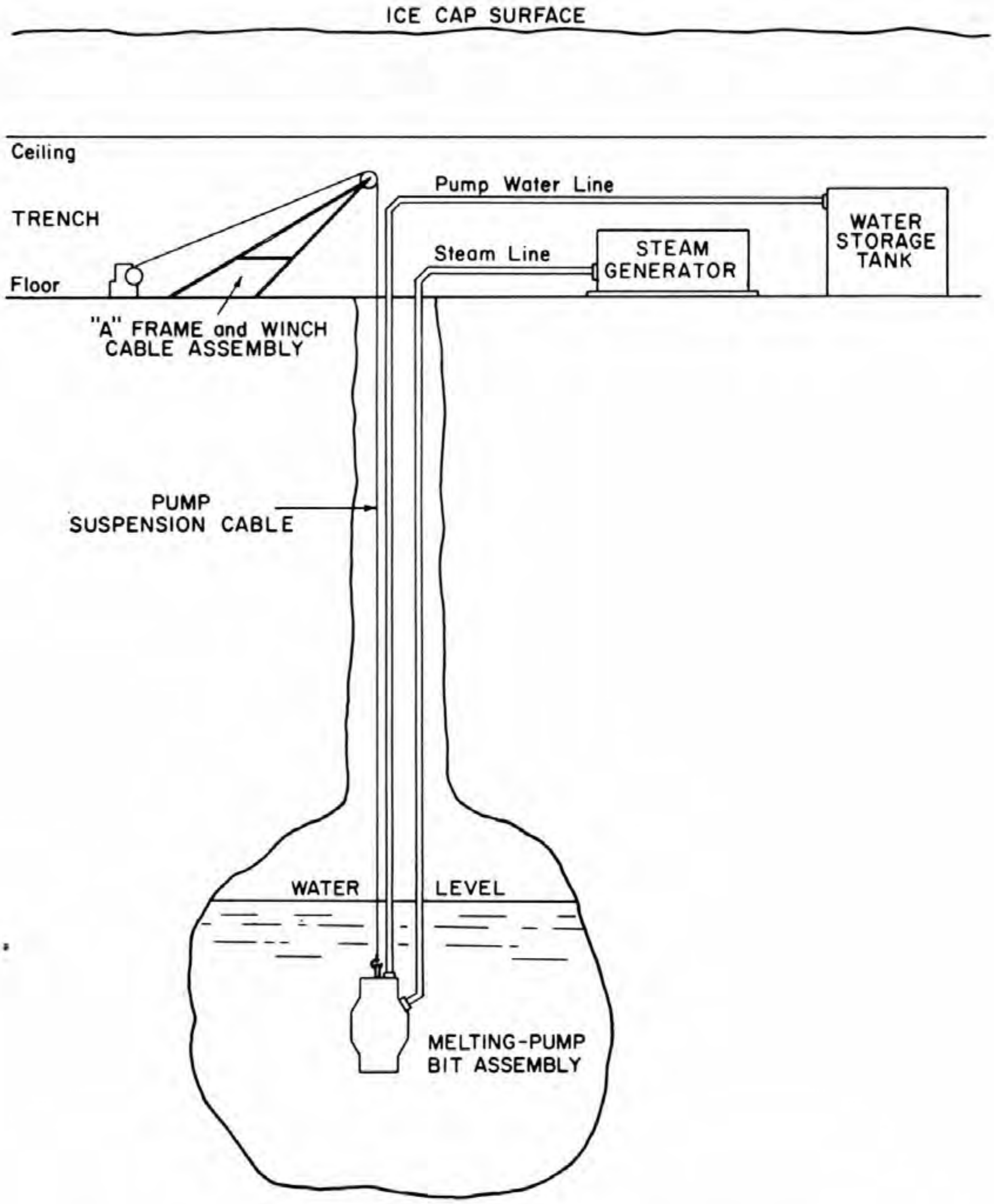

Figure 20. Schematic sketch of water well and equipment.

Waste disposal

A completely satisfactory method of disposing of water-borne waste on ice caps was developed by the Corps of Engineers and incorporated in the design of the Greenland Ice Cap AC&W stations, Sites I and II. This method consisted of dumping the waste into an unlined snow pit, from which it melted a vertical shaft down into the snow to an impermeable layer (approximately 100 feet), where it spread laterally and formed a bell-shaped cavity. The spread of lateral contamination was subsequently determined by coring down through the contaminated zone at consecutively greater distances from the shaft. This provided a basis for determining minimum safe distances between ice cap water wells and sewage pits.

Disposal of trash and other non-water-borne waste was provided by burial in snow trenches in the same manner as in normal sanitary fills in land areas.

DEVELOPMENT OF THE CAMP CENTURY DESIGN

Decision to construct a new subsurface camp

Early in 1958 plans for a modular-type, semi-portable nuclear reactor power plant to be installed on the ice cap had been completed, approved, and funds for its construction had been programmed and promised by the Department of the Army. However, the site for its installation had not been selected. The austere prototype undersnow camp at Site II had not been designed to accomodate such a plant. Furthermore, Site II, located 218 miles from Camp Tuto (Fig. 21), imposed an unnecessary logistical burden in terms of surface transportation, since all of the research and development being conducted there could be conducted nearer to the ice cap edge and much closer to Camp Tuto. Also, from the research point of view, construction of a new camp, which would incorporate all of the methods and techniques that had been developed during the preceding 4 years, seemed highly desirable. Based on these considerations, a decision was made to construct a new camp which would incorporate all of the previously developed ice cap construction methods and techniques.

Selection of a location for the new camp

Considerations of prime importance in selecting a site for the new camp were:

1. A location where the seasonal fluctuations in temperature would not endanger the snow structures through excessive melting or warming of the snow mass.
2. A location free of crevasses.
3. A location which would serve the foreseeable research needs.
4. A location closer to Camp Tuto than Site II.
5. A location that could be served by surface transportation over the existing trail which had been constructed through the crevasse zone extending from Camp Tuto eastward approximately 60 miles.

With these limitations in mind and with the advice of Dr. Bader, a site 138 miles east of Camp Tuto, along the Tuto-Site II trail, was tentatively selected. Subsequent ground reconnaissance verified its suitability. However, with no detailed records of Greenland Ice Cap weather dating earlier than 1952, this selection was made with the knowledge that it was a calculated risk and that surface air temperatures might, on rare occasions, rise above 32°F. This would be serious only if continued for long periods, which was thought to be improbable by Air Force and Army meteorologists, who were most familiar with North Greenland weather.

A name for the new camp

In selecting a name for the new camp, a deliberate attempt was made to avoid naming it after any person living or dead. Danish representatives at Thule Air Base had expressed a distinct aversion to maps which read like an obituary column. Originally, it had been suggested that the new camp be located 100 miles from the ice cap edge. This being so, R. Philippe had suggested that "Camp Century" would be an appropriate name for it. Through usage in correspondence and conferences, this name came to be accepted officially.

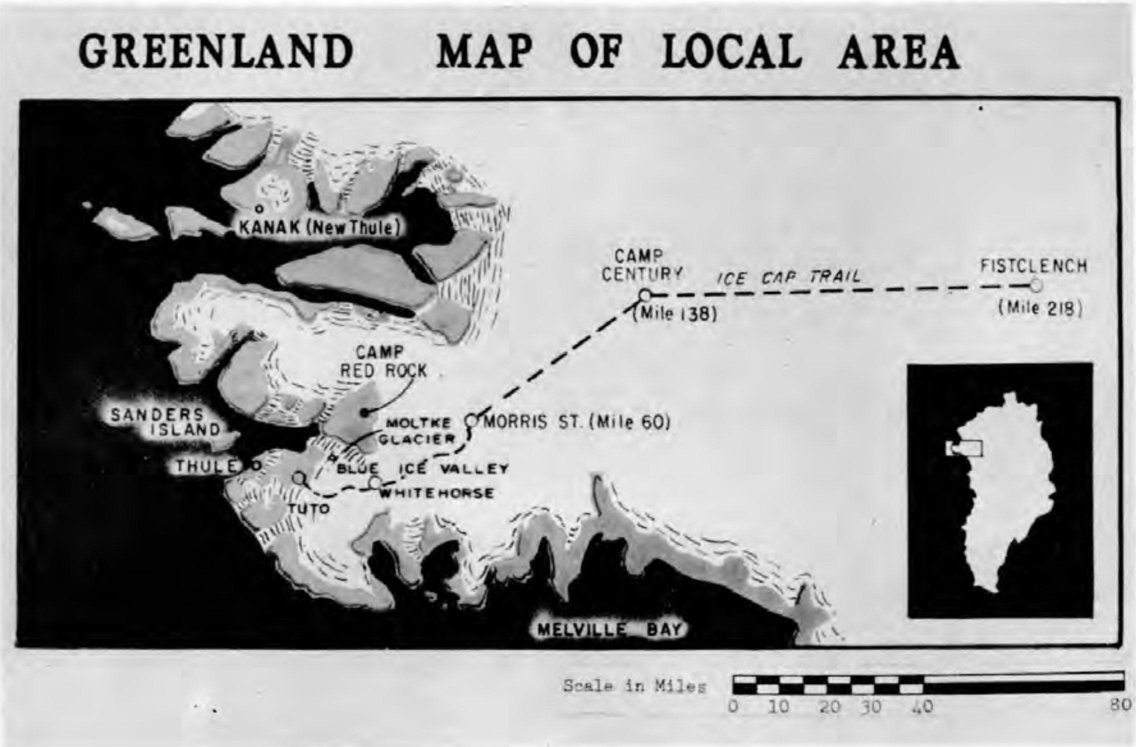

Figure 21. Camp Century location.

Assignment of responsibilities for the construction of Camp Century

After considerable discussion within OCE between the various staff elements which had a direct interest in Camp Century, assignment of responsibilities for its construction were made as follows:

Responsibilities	Unit or Agency
Overall construction, except as otherwise noted	U. S. Army Polar Research and Development Center (USAPR&DC)
Contracting for design and construction of the nuclear power plant (PM-2A), except as otherwise noted	U. S. Army Engineer District, Eastern Ocean (EOD)
Design and supervision of construction of buildings and other structures required for the PM-2A	U. S. Army Engineer District, Eastern Ocean
Design of the camp, including water, power, distribution, and waste disposal systems	U. S. Army Engineer Research and Development Laboratories
Consulting services on snow structures	U. S. Army Snow, Ice and Permafrost Research Establishment
Design of fuel core for the PM-2A	Army Nuclear Power Program, OCE
Supervision of PM-2A installation	Nuclear Power Field Office, OCE

Design criteria

The Chief of Engineers provided the USAPR&DC, USAERDL, USA SIPRE, and EOD conceptual guidance and general design criteria essentially as follows:

1. The facility was to be a subsurface camp (constructed by use of the cut-and-cover trenching technique), with a capacity to house 100 personnel on a year-round basis.

2. Design of the camp was to incorporate the following general features:

   a. A nuclear power plant was to provide electrical power and steam to operate the water well.
   b. Maximum use was to be made of snow as a construction material.
   c. The camp was to have a design life of 10 years (with appropriate maintenance).

3. **Camp facilities were to include:**

   a. Living quarters
   b. Kitchen and mess hall
   c. Latrines and showers
   d. Recreation hall and theater
   e. Library and hobby shops
   f. Dispensary, emergency operating room, and a 10-bed infirmary
   g. Laundry
   h. Post exchange
   i. Scientific laboratories
   j. Cold storage warehouses
   k. POL storage tanks
   l. Communications center
   m. Equipment and maintenance shops
   n. Supply rooms and storage areas
   o. Nuclear power plant (also a standby diesel-electric power plant)
   p. Administrative buildings for office space
   q. Utility buildings
   r. Chapel

4. Layout of the camp was to consist of a series of parallel main trenches in which buildings and other structures were to be housed. A main vehicular access trench, large enough to accommodate tractor-drawn sled trains, was to extend through the center of the camp, perpendicular to the main structure trenches, thus connecting them (Fig. 22).

5. Buildings were to be a prefabricated modular-type, and as light in weight as would be consistent with other requirements.

6. All buildings which were to be heated or contain facilities that would generate heat were to be supported on timber cribs or piles, with approximately 2 feet of unobstructed clearance between the snow trench floor and building floor.

7. Water was to be produced by development of an ice-cap well, located at least 1000 feet from the liquid waste disposal sump. Steam was to be used to melt a shaft down to a depth of approximately 100 feet. At this depth a pool of water of the desired size was to be produced and maintained by use of steam jets. Deep-well pumps were to be used to transport water from the well pool to storage tanks. Storage tanks and distribution lines throughout the camp were to be heated and insulated.

8. Camp ventilation was to be provided by two separate systems, i.e., an inclosed system for ventilation of buildings and a separate system to expel heat and gases from the trenches.

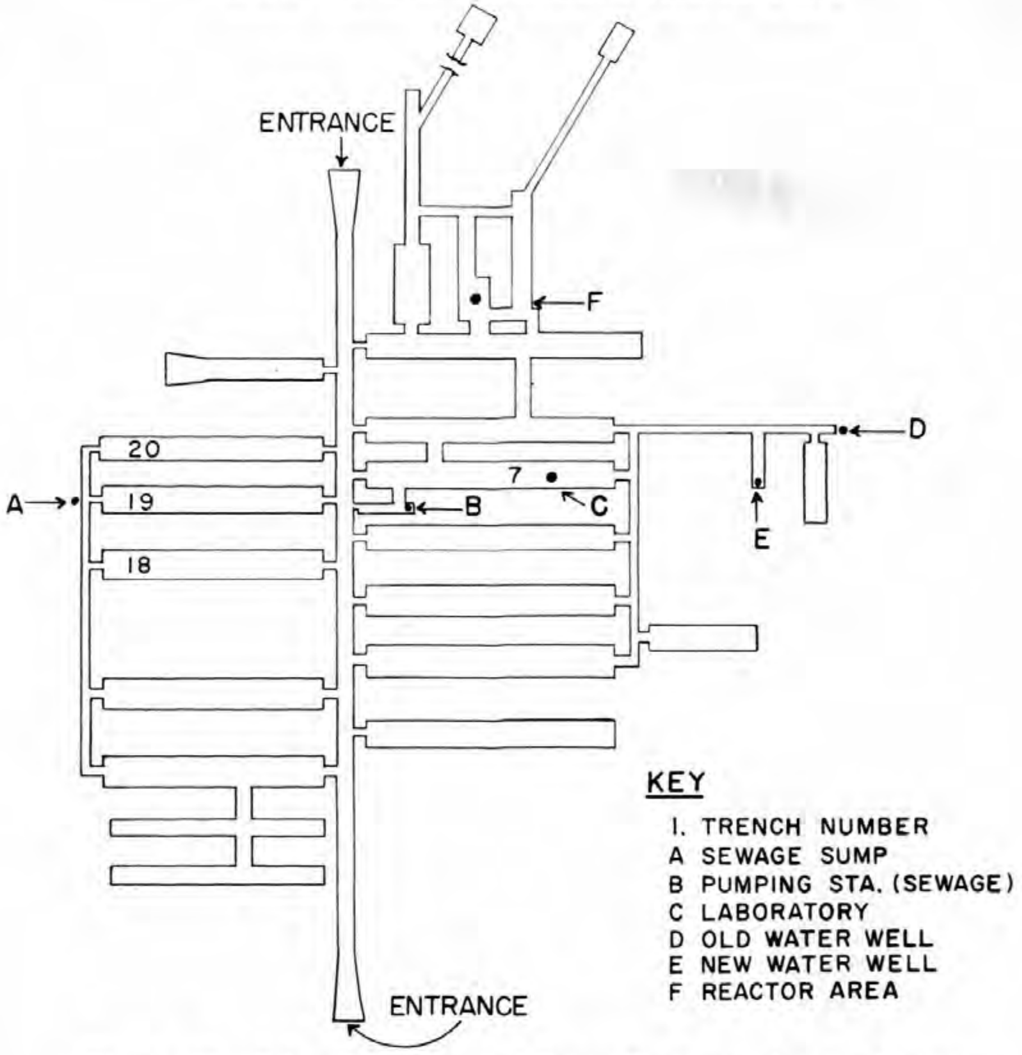

Figure 22. Schematic layout of Camp Century, showing location of sewage sump in relation to water well.

9. Buildings were to be heated electrically.

10. Water-borne waste was to be pumped into well-type sumps, located at least 1000 feet from the water supply source and not less than 500 feet from the nearest building. Solid waste was to be deposited in a separate trench and covered with snow.

11. Cut-and-cover trenches were to be the undercut type. Unsupported snow arch roofs were to be used to the maximum practicable extent. Standard trenches, approximately 24 feet wide at floor level, were to be used to house buildings and other structures throughout the camp. Exceptions to use of the standard type trench were to be limited to maintenance shops.

12. Fire walls were to be installed between buildings.

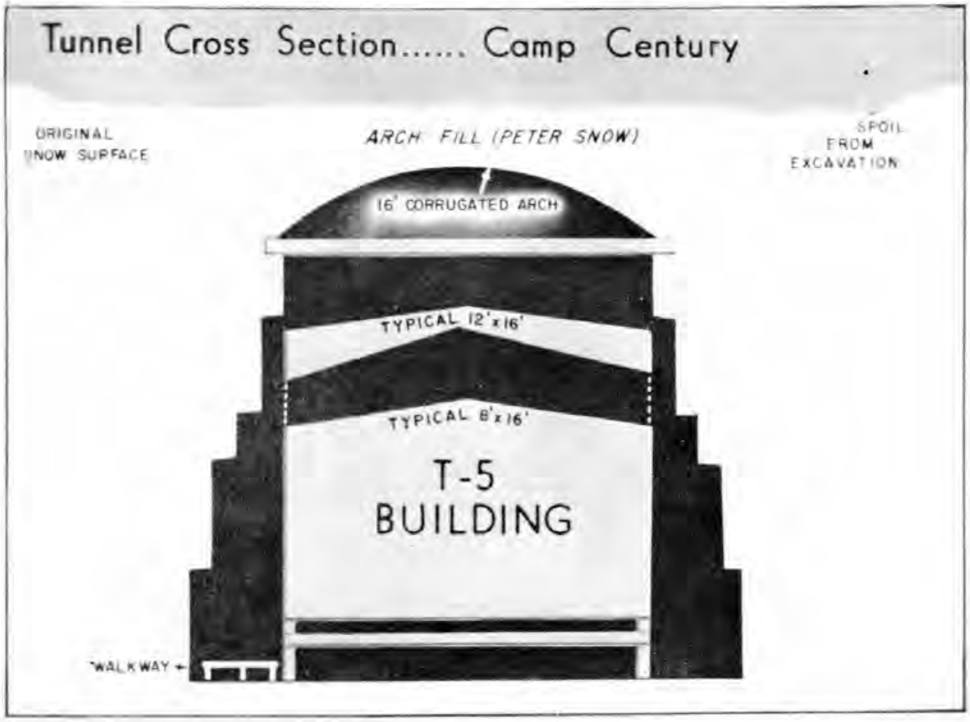

Figure 23. Schematic of modified T-5 building in a standard trench.

Design problems

Very early in the process of preparing plans and specifications for Camp Century, it became apparent that a number of undesirable compromises would have to be made. Specific problem areas and solutions decided upon were as follows:

1. Buildings - USAERDL stated that insufficient time was available to design and test new modular-type buildings such as envisioned, and recommended that the T-5 arctic building be adapted for use in the standard trenches by reduction of its width from 20 ft to 16 ft (Fig. 23). This building was expensive and had been designed to withstand heavy snow and wind loads. Hence, it was grossly over-designed for use in Camp Century. However, there appeared to be no alternative to its use. Accordingly, the USAERDL recommendation was approved, with agreement that only fifty percent of the normal number of laminated plywood roof trusses would be in each building.

2. PM-2A Trenches - ALCO Products had been awarded the contract to construct the nuclear power plant and had agreed originally to a design which could be accommodated in the standard 24-foot trenches. However, before preliminary designs had been completed, they requested relief from the 24 ft trench width restriction for certain portions of the power plant on the basis that the specified configurations and hardware could not be adapted practically to so little space. The EOD held a conference in New York to discuss these and other problems. At this conference R. Waterhouse, USA SIPRE, recommended a solution to the trench width problem which would permit construction of straight-wall trenches up to 40 ft in width. His solution consisted of the use of corrugated metal arches (Wonder Arches) to cover the side trenches (Fig. 24). It was his opinion that 16 gage corrugated metal arches would satisfy the design life requirement, provided the arches acquired a filled spandrel

Figure 24. Wonder Arches being installed over 40-foot wide reactor trench at Camp Century.

load symmetrically, with a limited thickness at the crown, and provided a ventilation system adequate to prevent excessive warming of the snow over the arches was installed. A decision was made to accept Mr. Waterhouse's recommendation. It was realized at the time that this type of construction (i. e., wide, straight-wall trench, covered with metal arches) had not been tested and might not prove to be a satisfactory structure. However, at the time there appeared to be no alternative to this solution.

3. Ventilation - The CO, USAPR&DC requested relief from the requirement to construct convection barriers in the trenches between heat sources (i. e., buildings, etc.) and the snow arch roofs. At a conference held at USAERDL on design problems, it was agreed that the barriers could be omitted from the design plans. It was also agreed at this conference that, instead of an inclosed ventilation system for all buildings, several methods would be used in various parts of the camp in order to evaluate a number of possible solutions to the problem.

CAMP CENTURY COST ESTIMATE

Based upon preliminary plans and specifications, the cost of Camp Century was estimated as follows:

Item	Amount
Prefabricated buildings	700,000
Roofing forms	150,000
Electrical heating system	90,000
Water supply system	70,000
Waste disposal system	50,000
Ventilation systems	200,000
Power distribution system	50,000
Shower and ablution set	100,000

Alarm systems (fire & carbon monoxide)		10,000
Fire fighting system		50,000
Fuel storage tanks		50,000
Misc const materials		200,000
Design costs		100,000
	Subtotal	1,820,000
PM-2A		5,700,000
Standby power plant		400,000
	Total	7,920,000*

*The actual total cost of Camp Century was held to this figure.

CONSTRUCTION OF CAMP CENTURY

Design, plans, and specifications

Detailed design plans and specifications for Camp Century were accomplished during the latter part of 1958 and early 1959. USAERDL, with assistance and guidance from USAPR&DC and USA SIPRE, prepared preliminary design specifications for the camp. Most of this work was done in-house. However, design specifications and drawings for the camp's electrical power distribution system were prepared by the U. S. Army Engineer District of Washington. The bulk of this planning, along with finalized drawings and bills of material, was completed by December of 1959.

In the meantime, planning for the nuclear power plant had progressed rapidly. In October 1958, the Chief of Engineers let a design study contract to ALCO Products, Incorporated, Schenectady, New York, to investigate the feasibility of constructing a nuclear power plant on a polar ice cap. Based upon the favorable conclusions of this study, the Chief of Engineers directed EOD to let a contract for design and fabrication of a plant, the PM-2A, to be installed at Camp Century. In February 1959 ALCO Products was awarded this contract. An additional contract was awarded by EOD to Metcalf and Eddy, Boston, Massachusetts, to design support facilities for the PM-2A, including foundations, buildings, and other utilities. These and subsidiary contracts allowed only 18 months for the fabrication, testing, and delivery of the PM-2A Nuclear Power Plant, together with all materials, buildings, and ancillary equipment necessary for its complete installation.

As previously discussed under design problems, a number of compromises had to be made in the final design plans for the camp, and particularly in providing the wide, straight-wall trenches to house portions of the PM-2A. Hence, the final plans for Century were a composite of tried and proven methods and techniques, which had resulted from 4 years of previous R&D efforts, along with untested and unproven techniques. The plans also incorporated many items of bulky and unnecessarily heavy hardware, such as spiral steel stairways in the escape hatches, standard T-5 buildings, and conventional plumbing systems, because time did not permit the redesign of these items.

Construction of the camp

Camp Century was constructed by the U. S. Army Polar Research and Development Center (USAPR&DC), under the command of Colonel John H. Kerkering. Major Thomas C. Evans was the Project Officer for the non-nuclear portions of the camp, and Major James W. Barnett was Project Officer and Resident Engineer for fabrication, factory testing, transportation, installation, and acceptance testing of the PM-2A Nuclear Power Plant (Barnett, 1961).

Actual construction of the camp was started in June of 1959, and completed in October 1960. Appendix A is a chronological summary of events, abstracted from the USAPR&DC report on the construction of Camp Century (Evans, 1961).

Weather, time available during the two short summer construction seasons, and a number of other minor considerations caused innumerable minor deviations from the original design plans as approved. Most of these were not serious. However, as will be shown in the section of this report on the performance of the camp, some were quite serious and ultimately created problems of major proportions.

Major deviations from the approved design plans were as follows:

1. Steel arch forms were left in place in many of the standard trenches, including the main communications trench which provides vehicular access to the camp. This change was made by the CO, USAPR&DC based on observations of the behavior of some of the unsupported snow arches in which the metal arch forms had been removed before sufficient age hardening had occurred (Fig. 25). In these instances, as might have been predicted, the unsupported snow arches deformed rapidly.

2. The original plans called for the installation of sliding overhead-type doors. However, the dark winter season came in 1960 before this had been accomplished, and snowdrift problems encountered during the first winter of occupancy indicated that the original plans were not feasible. Hence, installation of closure means was deferred until more studies could be undertaken. The problem of portal closure will be discussed in the performance section of this report.

3. Although not specifically stated in the approved plans, it was agreed that the waste disposal sump would be at least 1000 feet from the water well and at least 500 feet from the nearest building. As the camp was constructed, the sewage sump was located only 150 feet from the nearest building. Time again prevented adherence to the original plans.

4. The ventilation systems called for in the original plans were not installed. In the case of ventilation of the interior of buildings and other structures, this was not serious. Convection and the natural air permeability of snow provided adequate fresh air in the tunnels to prevent dangerous carbon monoxide levels from accumulating. The buildings were designed so that fresh air was drawn into living quarters and other structures by a system of louvers and fans. However, failure to install a system to expel heat from the trenches became a serious problem, which will be discussed later in this report.

5. Fire walls between each set of structures were not installed, owing to shortage of time and funds. It was planned to install these in 1961, but these plans were later cancelled, as it was considered that the installed sprinkler systems and other fire fighting equipment were more than adequate to isolate any fire which might occur.

The construction of Camp Century required an impressive logistical effort in terms of transportation of heavy cargo by tractor-drawn sled train. Materials hauled from Camp Tuto to Century, a distance of 138 miles, approximated 1000 short tons in 1959 and 4600 short tons in 1960. Some of the cargo transported consisted of items too heavy or bulky to be carried on the 20-ton cargo sleds. Accordingly, special sleds had to be fabricated in Greenland.

Details of the construction of Camp Century are provided in the U. S. Army Polar Research and Development Center report, dated 31 December 1961, entitled "The Construction of Camp Century." This report documents the construction techniques used, organization and employment of the construction force, the sequence of construction, pertinent logistical data, and the major construction problems encountered. It does not, however, include "as built" plans, which are available at the U. S. Army Engineer Research and Development Laboratories, Fort Belvoir, Virginia.* Figure 26 is a plan view of Camp Century as it was actually constructed. The sewage sump was located 150 feet from the end building in Trench 19.

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*USAERDL was designated the official office of record for all drawings of Camp Century, except those pertaining to the nuclear power plant and buildings.

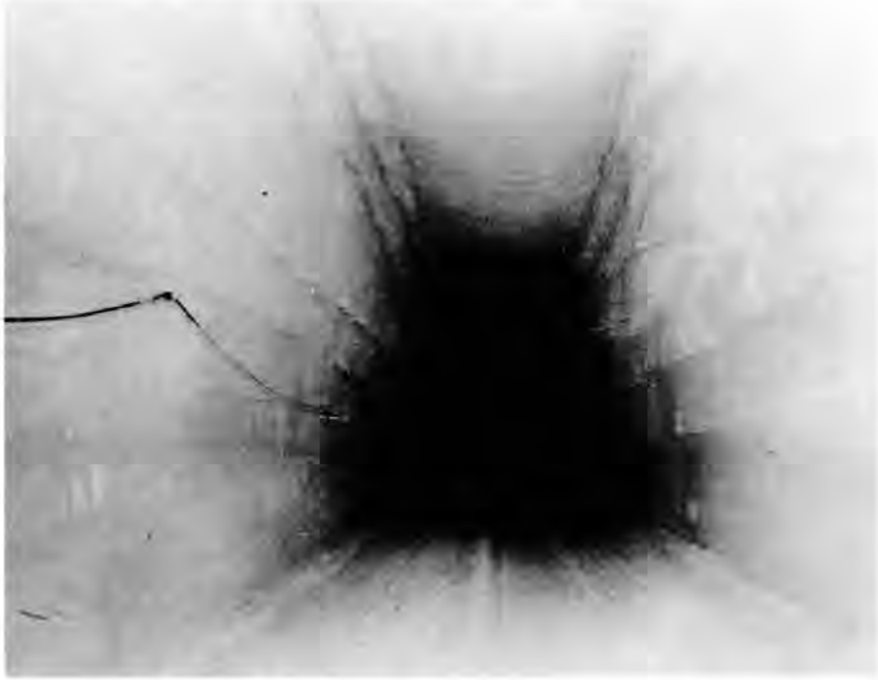


Figure 25. Example of a cut-and-cover which deformed rapidly because the forms were removed too soon.

PERFORMANCE OF THE CAMP

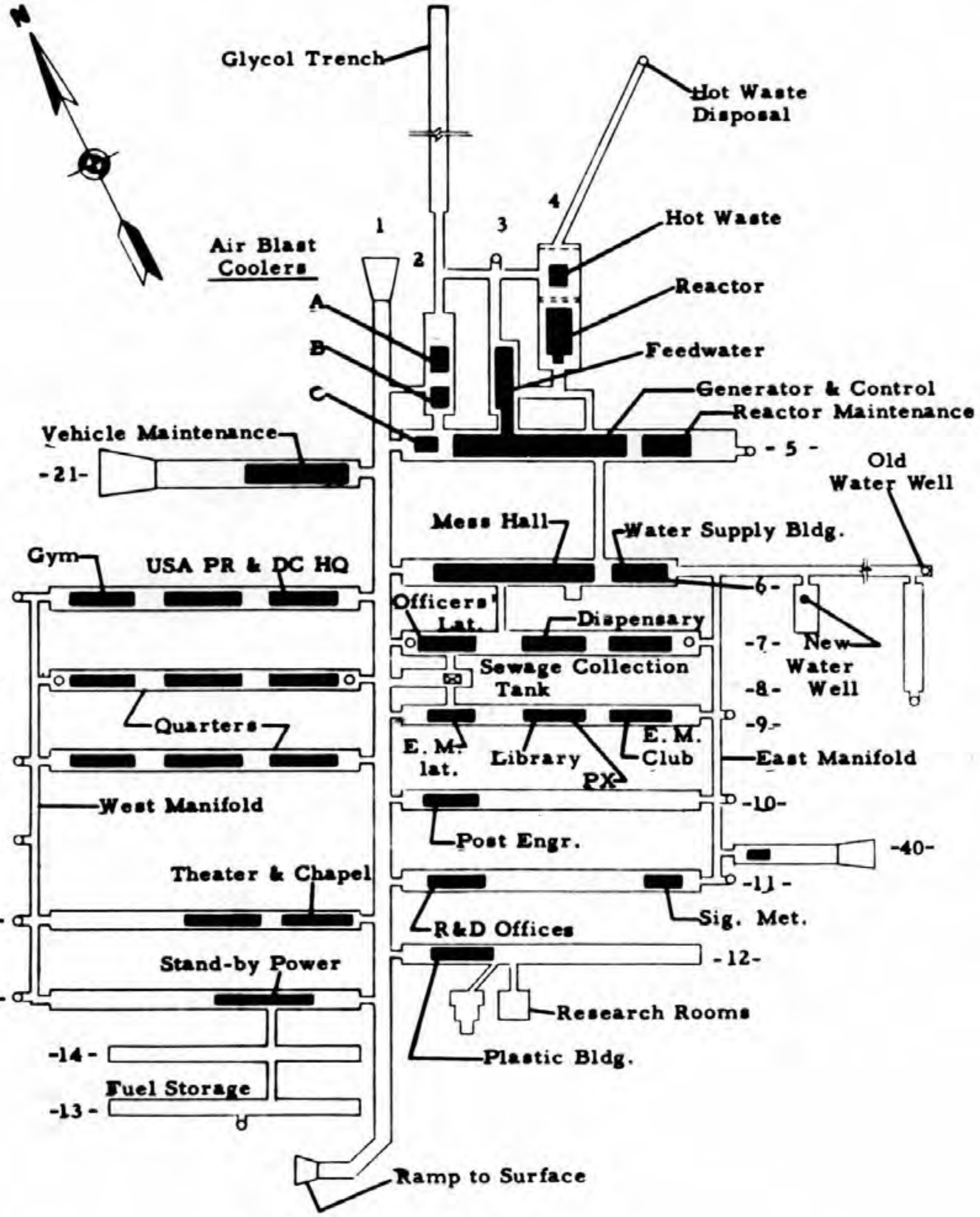
General

It is apparent, in the light of 4 years of Camp Century performance data, that in general the subsurface concept is sound. In most cases the engineering design of foundations, buildings, cut-and-cover trenches, and other structures has satisfied stated requirements. Data which have been obtained through careful measurements and observations at Camp Century will be of the utmost significance in improving and perfecting the engineering design of future undersnow facilities. Both design and construction deficiencies which have been observed during the past 4 years are discussed in subsequent paragraphs. Figure 27 compares monthly mean ambient temperatures on the surface of the ice cap with those in two unheated trenches at Camp Century. This comparison provides a basis for judging the value of subsurface ice cap construction in terms of protection from extreme cold.

Deformation rates

Of the engineering studies which have been made of the performance of Camp Century, the one that, understandably, has received the most attention is that of tunnel (cut-and-cover trench) deformation and the resulting loss of vertical and horizontal clearance.

There are several possible modes of adverse structural behavior of snow under load, and there are a number of factors which determine which mode, or modes, will occur in a specific case. Under rapidly applied loads which grossly exceed the yield strength of the snow, either complete disaggregation or tensile rupture of the snow may occur, resulting in collapse of the structure. Under lesser loads, distress is generally evidenced by viscous flow (plastic deformation). At Camp Century only the latter has been observed.



Camp Century - Plan View

Figure 26. Schematic layout of Camp Century.

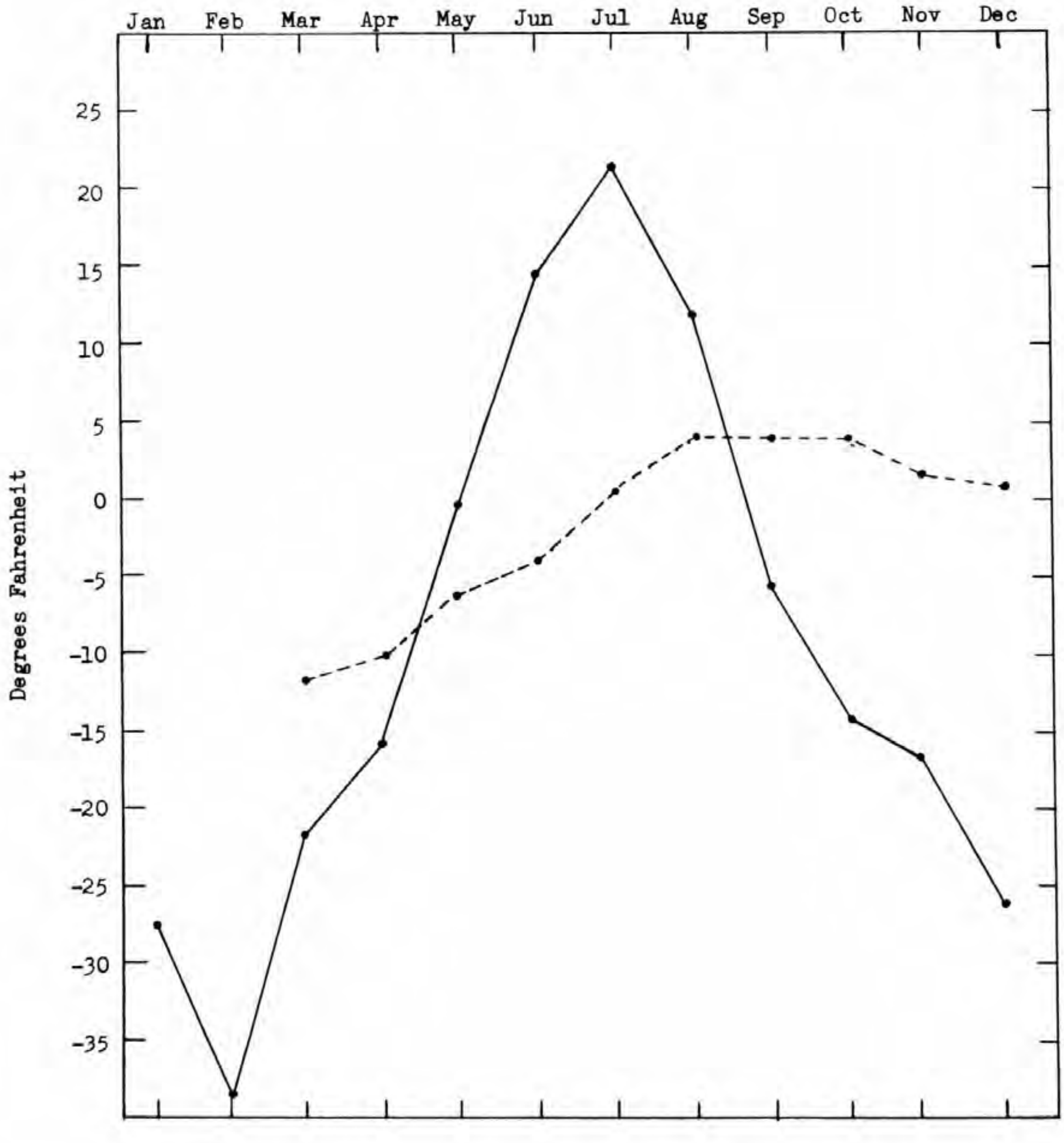


Figure 27. Monthly mean temperatures (Camp Century - 1962).

—Monthly mean air temperatures on the surface at Camp Century.
---Monthly average mean temperatures in two trenches (13 and 14) which contain no heated structures. Data was obtained from USA CRREL records.

In most cases the rates of deformation have approximated closely those which had been predicted. However, flow rates are highly temperature dependent, and where concentrations of heat have persisted in the camp, the temperature of the adjacent snow mass has risen several degrees. As a result, the snow has deformed more rapidly than predicted by several fold.* Although there is considerable variation, the average approximates 30 inches of gross vertical closure a year.

Table II (abstracted from an unpublished report by W. Tobiasson, 1963) provides examples of deformation data which were collected during 1962 and 1963.† It is of interest to note that the closure rates have been appreciably lower in the trenches in which the metal roof forms were left in place. Judging from this fact alone, it might be deduced that the in-place metal arches were responsible for the lower rates, and there can be little doubt that they were of some value in this respect. However, the fact that most of the trenches retaining the in-place metal arches contained no buildings or other sources of heat is considered a more significant factor in retarding the flow rates. Figures 28 and 29 show deformation in the Main Trench and Trench 20 during a period of approximately 18 months. The Main Trench contained no heated structures; Trench 20 housed the camp headquarters buildings and the gymnasium. In both trenches the metal arches were left in place initially. However, the arches in Trench 20 were removed in 1963 to permit overhead trimming of the encroaching snow.

In Trenches 3, 4, and 5 (trenches up to 40 ft in width, which contained the major PM-2A Nuclear Power Plant modules) Wonder Arches were installed but were not covered uniformly with Peter snow. In fact, in places they were left partially uncovered, owing to the haste which had to be exercised in completing construction of the camp before fall of the long arctic dark season. As a result, the Wonder Arches acquired non-symmetrical loads and by the end of the first year of occupancy showed severe distress in a number of places (Fig. 30, 31). It was apparent that expeditious rehabilitation action had to be taken. Twice during the 3-year life of the PM-2A at Century, sections of these arches were raised approximately 6 feet to prevent damage to the inclosed buildings and other structures.

Wide, straight-wall trenches, covered with Wonder Arches or timber trusses, similar to those used in the undersnow camp at Site II, are considered feasible for certain purposes. However, if Wonder Arches are to perform satisfactorily they must be seated on and covered with Peter snow so that they acquire a symmetrical load.

The chief disadvantage of Wonder Arches, or of leaving short-span metal arches in place, is the great increase in cost as well as the requirement to import many additional tons of construction materials. The primary objective of developing the under-cut trenching technique was to economize on imported materials by reducing arch span width so that unsupported snow arches could be used.

Accumulation of heat in the trenches

During early stages of the research and exploratory development which led to the design of Camp Century, it was realized that buildings, the PM-2A Nuclear Power Plant, and other sources of heat including vehicles, electric lights, and even people would raise air temperatures and present serious problems in regard to heat dissipation. Data on the detrimental effect of heat on the stability of snow structures, as previously discussed in this report, resulted in the initial design criteria which specified the use of convection barriers to protect the snow trenches. However, in the final construction plans, as approved by the Chief of Engineers, convection barriers were not included. Their removal would have been necessary whenever

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*It has been observed that the creep rate is twice as fast at 14°F as at 2°F and one hundred times as fast at 28°F as at -40°F.

†Detailed and comprehensive data on deformation rates are contained in Waterhouse, Tobiasson, and Scott (1963).

Table II. Deformation data—Camp Century; arch movement, 1962-1963.

Trench numbering system is shown in Figure 25

Heights measured on centerline of trench from floor to arch apex

Stationing: Main Trench, 0+00 at north end
Side Trenches, 0+00 on Main Trench centerline

Legend: (M) Metal arch still in place
(S) Metal arch removed - measured to snow

Trench	Station	1962 height	1963 height	Yearly change
Main	0+21	15.80 ft	14.70 ft	1.10 ft
	Tr. 5	14.35	12.70	1.65
	Tr. 21	14.85	12.80	2.05
	Tr. 6	15.45	14.10	1.35
	Tr. 20	15.30	13.85	1.45
	Tr. 7	14.85	13.65	1.20
	Tr. 19	14.55	13.10	1.45
	Tr. 9	14.95	13.70	1.25
	Tr. 18	16.90	13.65	3.25
	Tr. 10	15.35	14.10	1.25
	Tr. 11	15.10	13.90	1.20
	Tr. 16	14.90	13.70	1.20
	Tr. 12	15.10	13.90	1.20
	Tr. 15	15.45	14.50	0.95
	Metal arch in place along entire Main Trench			
6	0+50	15.7 (S)	13.2 (S)	2.5
	3+50	15.4 (S)	13.5 (S)	1.9
	4+00	15.7 (M)	14.6 (M)	1.1
7	0+57	17.1 (M)	14.8 (S)	2.3
	1+50	16.8 (M)	12.9 (S)	3.9
	2+60	16.6 (M)	12.9 (S)	3.7
	3+65	19.0 (M)	15.7 (M)	3.3
	3+95	20.0 (M)	17.3 (M)	2.7
9	0+50	19.2 (M)	16.4 (S)	2.8
	1+50	20.4 (M)	17.1 (S)	3.3
	2+50	20.4 (M)	17.1 (S)	3.3
	3+70	19.7 (M)	16.4 (S)	3.3
10	0+50	20.1 (M)	17.6 (M)	2.5
	1+60	20.0 (M)	17.9 (M)	2.1
	2+00	20.3 (M)	17.7 (M)	2.7
	2+50	20.4 (M)	17.5 (M)	2.9
	3+00	19.4 (M)	16.2 (M)	3.2
	3+70	18.5 (M)	15.3 (M)	3.2
	3+95	20.7 (M)	17.9 (M)	2.8
11	0+50	20.2 (M)	17.8 (M)	2.4
	1+50	20.4 (M)	17.6 (M)	2.8
	2+00	20.0 (M)	17.2 (M)	2.8
	2+65	18.9 (M)	15.8 (M)	3.1
	3+30	18.7 (M)	15.8 (M)	2.9
	3+70	18.4 (M)	15.0 (M)	3.4
	3+95	19.6 (M)	16.6 (M)	3.0
12	0+50	21.0 (M)	17.8 (M)	3.2
	1+50	20.8 (M)	17.2 (M)	3.6
	2+00	26.8 (M)	23.4 (M)	3.4
	2+50	25.8 (M)	22.5 (M)	3.3

Table II (Cont'd). Deformation data—Camp Century; arch movement, 1962-1963.

Trench	Station	1962 height	1963 height	Yearly change
15	0+50	19.3 (S)	17.0 (S)	2.3
	2+50	18.3 (S)	14.7 (S)	3.6
	2+90	19.3 (M)	15.9 (M)	3.4
	3+65	19.3 (M)	15.4 (M)	3.9
16	Trench roof cut during June-July			
18	0+50	18.0 (M)	14.5 (S)	3.5
	1+50	17.3 (M)	13.7 (S)	3.6
	3+75	20.0 (M)	16.8 (M)	3.2
19	1+60	11.8 (S)	8.4 (S)	3.4
	2+60	12.6 (S)	9.6 (S)	3.0
20	0+50	18.9 (M)	15.4 (S)	3.5
	1+50	19.4 (M)	15.3 (S)	4.1
	2+50	19.8 (M)	15.9 (S)	3.9
	3+60	19.8 (M)	15.7 (M)	4.1
	3+80	21.0 (M)	18.0 (M)	3.0
21	0+30	25.1 (M)	24.1 (M)	1.0
	1+50	21.8 (M)	21.5 (M)	0.3
	2+00	23.8 (M)	21.9 (M)	1.9
	2+50	24.1 (M)	21.5 (M)	2.6

Metal arches in Trenches 7, 9, 16, 18 and and 20 removed during June-July 1963

Summary:

Main Trench: 16 in./year (average)
Side Trenches (between station 1+00 and 3+00 where end effects are not present): 34 in./year (average)
Side Trenches (near front and back where endwalls act to decrease movement): 34 in./year (average)
Overall average throughout camp: 29.66 in./year.

snow trimming of roof arches became necessary, but there can be little doubt that the use of convection barriers would have retarded the closure rates significantly. It may be concluded also that the non-uniform rates of closure shown in Table II resulted from accumulations of heat and that any system which would have dissipated or otherwise expelled the heat from the trenches would have extended their useful life span, without extensive maintenance.

During 1959-1960 USA SIPRE experimented with a unique method of cooling the Camp Century trenches (Yen and Bender, 1962). Simple in concept, it consisted of drilling 14-inch diameter holes (air wells) approximately 40 feet into the snow mass beneath the trench floors. Air pumped from these holes into the trenches by means of electrically driven fans was drawn through the colder and permeable underlying snow mass, and thus cooled several degrees (Fig. 32). Yen and Bender concluded, as a result of this experiment, that the air wells provided a practical and economical means of cooling snow trenches, but only if the wells were spaced at least 80 feet apart and were operated on a year-round basis in order to take maximum advantage of the cold outside air temperatures in wintertime. They also recommended that all portals and ventilation shafts leading to the outside be left open during the winter season to facilitate the natural convection flow of wintertime cold air through the trenches and thus reduce the rates of closure.

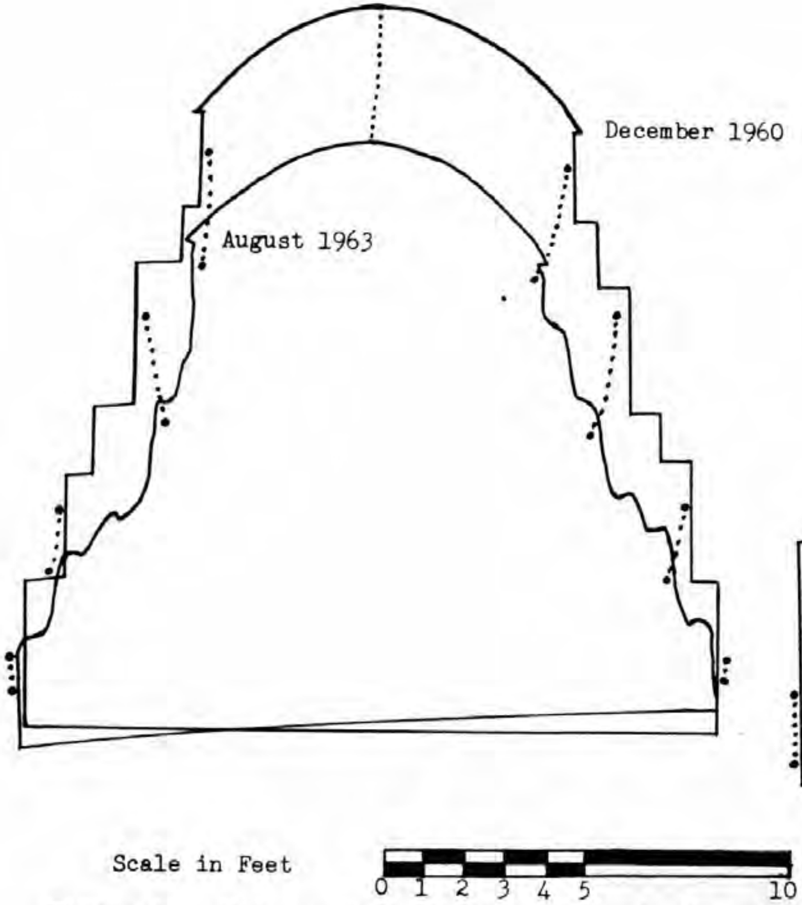
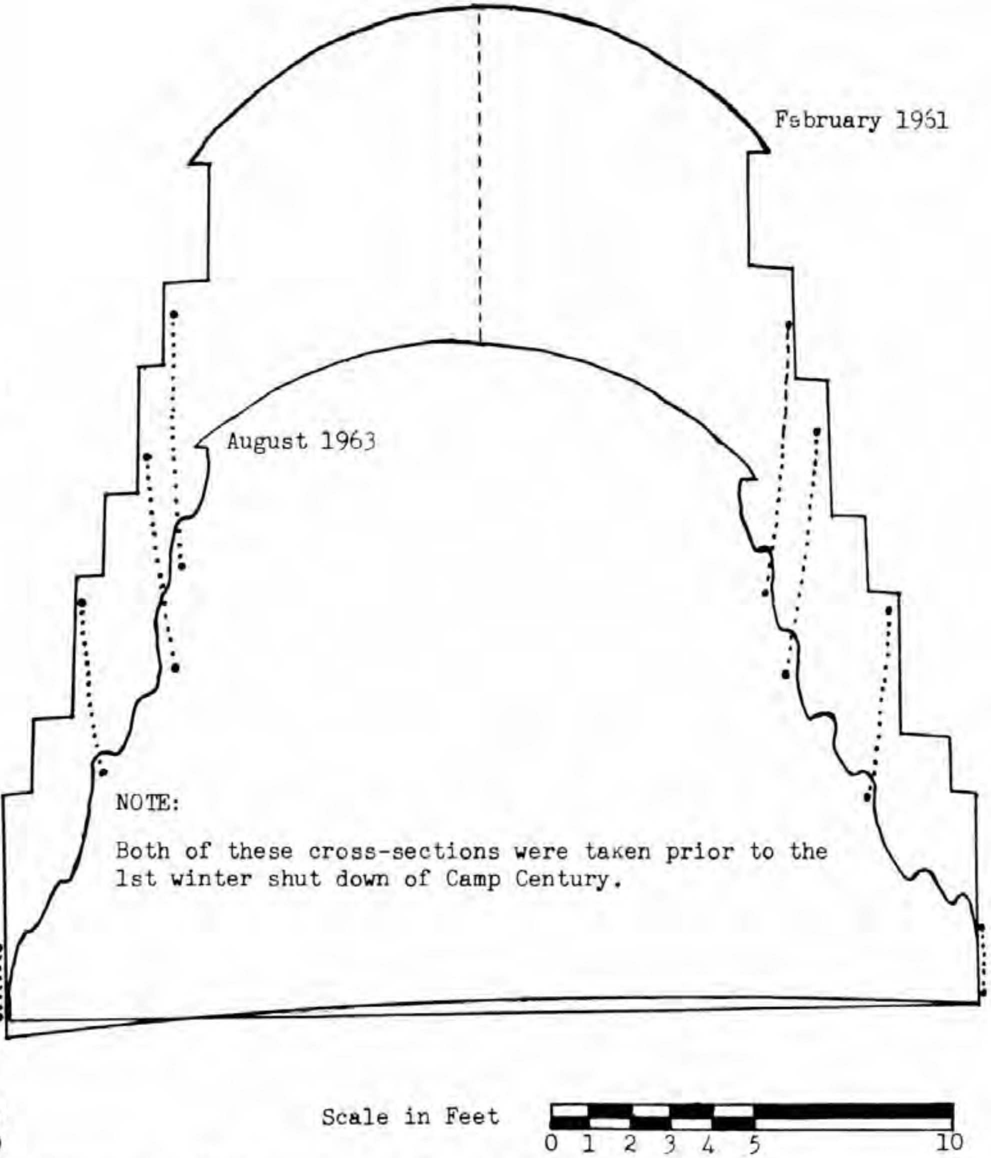


Figure 28. Deformation in the Main Trench, Camp Century, Station 6+00. Looking south. Temperature varies with season between 14°F and -40°F. Reduction in cross sectional area=12% per year (Tobiasson, USA CRREL).



NOTE:

Both of these cross-sections were taken prior to the 1st winter shut down of Camp Century.

Figure 29. Deformation in Trench 20, Camp Century, Station 2+60. Looking west. Temperature has varied between 23°F and 5°F, depending upon the time of year. Reduction in cross sectional area=17% per year (Tobiasson, USA CRREL).

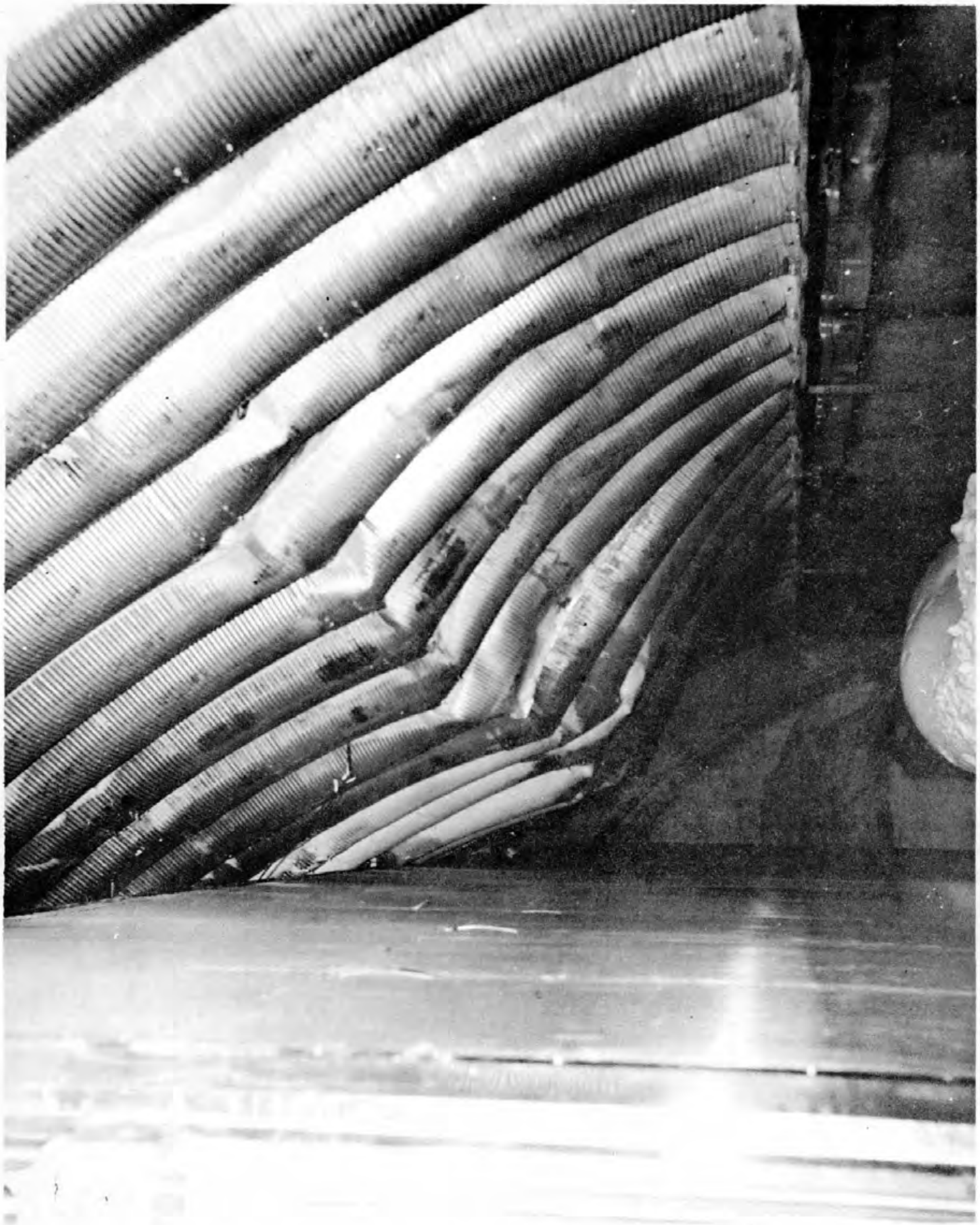


Figure 30. Severe distress manifested by Wonder Arch buckling and coming into contact with the roof of one of the PM-2A buildings.

Figure 31. Deformation of Wonder Arch over one of the PM-2A buildings.

The snow trimming problem

Based on past deformation rates, the amount of snow which has to be trimmed and removed from Camp Century each year in order to maintain the original cross section of the trenches is estimated to be on the order of 20,000 cubic yards. Assuming a work-year of 240 days of 8 hours each, snow trimming and removal would have to be at the rate of approximately 0.173 cu yd/min. Hence, even for a camp no larger than Century, the snow trimming effort is burdensome, and particularly so if done with hand tools alone (Fig. 33). Efficient mechanical equipment systems capable of trimming the trenches and transporting the snow out of the camp could be developed. However, the cost would be high (estimated 0.4 million dollars), and this expensive development effort would not be justified unless a number of subsurface installations such as Century were planned.

Sewage disposal

The liquid disposal system which had been developed by the Corps of Engineers for use at ice cap AC&W Sites I and II was incorporated in the Camp Century design (i.e., dumping into a snow pit and letting it melt its way down into the ice cap). However, experience at the abovementioned stations indicated that the sewage sump should be vented and should be located at least 500 feet from the nearest occupied building to prevent accumulation of odious fumes in living or working areas. As Century was nearing completion in September of 1960, the approach of the winter dark season and the great amount of work remaining to be done resulted in locating

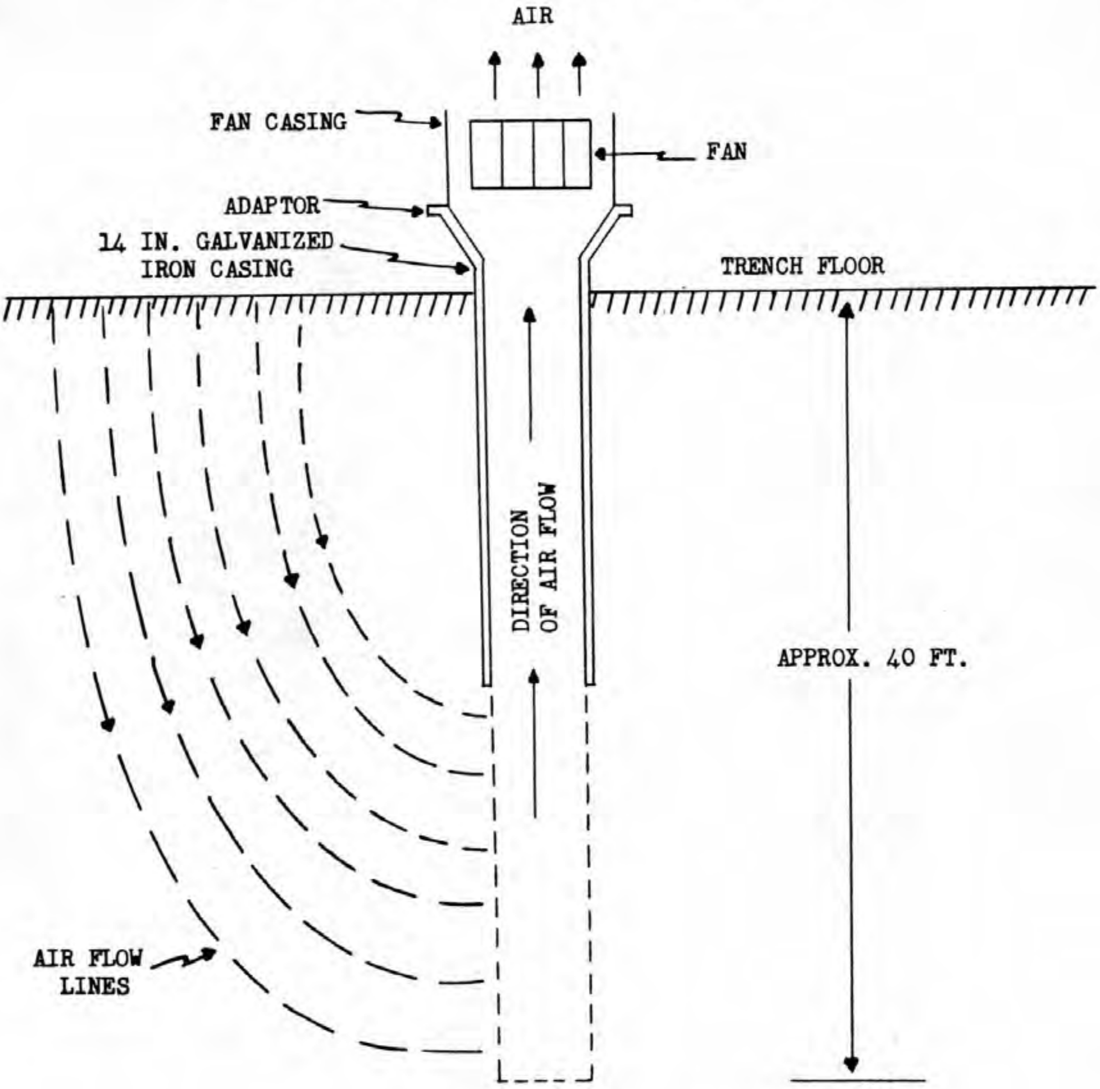


Figure 32. Schematic sketch of air well.

the sewage sump within 150 feet of the nearest T-5 building which was to serve as living quarters. The sump was not vented. As a result, the odor of sewage became almost unbearable in the nearest quarters by the following summer and traces of sewage odor were detectable throughout Trenches 18, 19, and 20. Subsequent venting of the sump reduced the odor to a more tolerable level but did not completely eliminate the condition.

To determine the extent of sewage contamination of snow at Camp Century, a research project was initiated by the Surgeon General in 1962. Some prior research on this problem had been conducted in 1960 by Major Thomas Ostrom, MSC, of Walter Reed Army Institute of Research at the abandoned Site II AC&W Station. However, the results of the 1960 investigation were inconclusive and, furthermore, the volume of water-borne sewage at Century was much greater than at the Site II installation. Hence, it was considered necessary to reinvestigate the problem.

Figure 33. View from top of one of the T-5 buildings in a standard trench, showing a soldier using an electric chain saw to trim snow away from the building eave.

The 1962 investigation was accomplished under the supervision of Major Ostrom, Walter Reed Army Institute of Research and 1st Lt. John Wilson, U. S. Army Environmental Hygiene Agency. 2nd Lt. Terry Orr, DeWitt Army Hospital, was assigned as Project Engineer.

Holes were drilled in the snow mass surrounding the sump. Ice core samples were obtained from the holes and analyzed. Figure 34 shows the limits of the contaminated snow as determined during this investigation. The farthest lateral penetration of the liquid waste from the sump was about 170 feet. However, this had occurred in a period of less than 2 years. How far such contamination will ultimately spread with time is a matter of conjecture. Undoubtedly, as additional heat and liquid are deposited, the lateral penetration will continue until a state of near equilibrium is reached after many years.

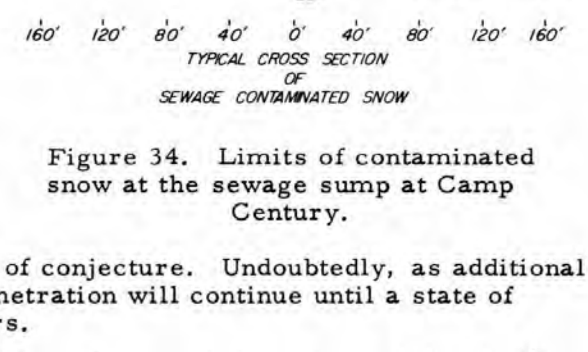


Figure 34. Limits of contaminated snow at the sewage sump at Camp Century.

During the first 2 years of operation of Camp Century it is estimated that 3.26 x 10^6 gallons of liquid waste were pumped into the sewage sump. The temperature range of this discharge varied from 60 to 88°F. The sewage mass in the sump in August 1962 had a liquid volume of 1.3 x 10^6 gallons with a mean temperature of 33°F. This liquid state had been maintained by the daily addition of 4650 gallons of liquid waste with a temperature range of 60 to 88°F, thus adding daily approximately 1.0 to 2.0×10^6 Btu. This quantity of heat (365 to 730×10^6 Btu/yr), during the first two years of operation, warmed the surrounding snow mass several degrees and greatly accelerated the rate of deformation of the trenches. As a result, the snow floor in the end of Trench 19 settled about four feet, necessitating removal of the two T-5 buildings nearest the sump.

In view of the data obtained at Site II and Camp Century, it appears that locating the sewage sump 1000 feet from the water well and 500 feet from the nearest building is sufficient. However, as observed by Ostrom (1962), the shape and volume of the contaminated area are functions of sewage temperature, frequency of waste discharge, daily volume of discharge, and density of the névé. Hence, accurate records of the volume, frequency, and temperature of the discharge into the sump should be maintained. This would permit use of the Bader and Small (1955) procedure in estimating the volume and probable lateral spread of the contamination.

The water well

The subsurface water well, which has been discussed previously in this report, was installed at Camp Century during the summer of 1960. The major items of equipment for the well consisted of a diesel-fired steam generator* capable of producing 165 psi of saturated steam at 373°F and at a rate of about 800 pounds per hour; a melting-drill bit assembly for melting a well shaft into the ice; a melting-pump bit assembly for melting the glacial ice and pumping the melt to the surface; a gasoline engine-powered cable winch for raising and lowering the bit assemblies; an A-frame and two wanigans; a 5000-gallon insulated and heated water storage tank; and necessary rubber hose to convey the steam from the generator to the bit assemblies, and to convey the melt from the pool to the storage tank (Fig. 35).

This equipment functioned efficiently and easily produced sufficient water to satisfy all camp requirements, including those of the PM-2A Nuclear Power Plant. Owing to the fact that the well had reached a depth of over 500 feet, which was nearing the maximum head for the type of deep well pump in use, the well was relocated in May 1962 after approximately 3.5×10^6 gallons of water had been produced. More than 5×10^6 gallons have been pumped from the new well as of September 1964. The overall average monthly consumption rate has been slightly more than 230,000 gallons.

The quality of the water obtained from the well was excellent and suitable for drinking without filtration or chlorination. R. Rodriguez, during his installation and testing of the well equipment, obtained several water samples which he shipped to the Sanitary Engineering Branch at USAERDL for analysis. The results of these analyses indicated that the ice melt was better in quality than water obtained by triple distillation in glass (Rodriguez, 1963). Table III shows the results of the tests conducted by USAERDL at Fort Belvoir, Virginia.

The 12-foot wall T-5 buildings

During the finalization of building designs for Camp Century a decision was made to use 12-foot wall T-5 buildings instead of the standard 8-foot wall type for some of the facilities. As all of the buildings, except in the maintenance and PM-2A trenches, were to be fitted into standard trenches (approximately 24 ft x 24 ft) this decision resulted in a 4-foot reduction in overhead clearance between the building roofs and the snow arches above them. The consequence was that trimming of the snow arches above the 12-foot wall buildings had to be commenced even before the rest of the camp had been completed.

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*The diesel-fired steam generator was installed as a standby heat source. The primary source of heat for the water well at Century was the 10^6 Btu/hr produced by the Nuclear Power Plant.

Figure 35. View of water well from top looking down.

Table III. Well water analysis performed at Fort Belvoir, Virginia - 1960.

Sample	Date taken	Depth of well (ft-in.)	Temperature of water in well (°F)	pH	Resistance (ohm)	Specific conductance at 25°C (micromho/cm)	Concentration (mg/l)					
							Na	K	Ca	CL	SO_4	NO_3
1	21 May	174-10	42	6.1	600,000	0.17	0.02	0.04	0.1	----	---	0.02
2	28 May	176-4	41	6.1	590,000	0.17	0.02	0.02	0.1	0.10	---	----
3	11 Jun	183-0	35	6.1	680,000	0.15	0.01	0.02	0.1	----	0.1	----
4	18 Jun	185-0	34	6.1	720,000	0.14	0.02	0.02	0.1	----	---	0.04
5	25 Jun	185-11	32	6.1	680,000	0.15	0.02	0.04	0.1	0.02	---	0.03
6	2 Jul	191-6	46	6.0	700,000	0.14	0.01	0.03	0.1	----	0.1	0.02
7	9 Jul	194-6	40	5.8	750,000	0.13	0.01	----	---	0.03	---	0.03
8	16 Jul	197-5	39	5.8	700,000	0.14	0.02	----	---	0.03	---	0.03
9	23 Jul	199-8	34	5.8	700,000	0.14	0.02	----	---	0.03	0.1	0.00
10	30 Jul	203-6	39	5.8	720,000	0.14	0.01	----	---	----	---	0.00
11	6 Aug	207-0	40	5.9	850,000	0.12	0.02	----	---	0.04	---	0.00
12	13 Aug	208-8	39	6.0	800,000	0.12	----	----	---	----	0.1	0.00
Average			38	6.0	708,000	0.14	0.02	0.03	0.1	0.04	0.1	0.03

(Abstracted from USAERDL Technical Report 1737-TR)

Figure 36. View of main communication trench showing overhead utility lines.

Overhead utility lines

In the main communications trench utility lines were placed overhead (Fig. 36). Also, to provide a trench floor which would accommodate tracked vehicles without serious deterioration, a 3 in. x 12 in. plank wearing surface was installed in this trench. The result was that, as the trench deformed, snow trimming to maintain the required vertical clearance could not be accomplished without removing either the utility lines or the plank floor. During the summer of 1963 the floor was removed and an additional 4 feet of snow was excavated.

Disaggregation of snow in trench floors

Under vehicular traffic, the snow floors in the trenches soon deteriorated unless wood or metal wearing surfaces were installed. This deterioration consisted of progressive disaggregation of the snow to depths of 12 or more inches. This loose and coarse granular snow made walking difficult. Further, oil, grease, and fuel drippings from vehicles made recompaction of the disaggregated snow virtually impossible.

In the construction of Century, this problem had been recognized and a wood wearing surface (3 in. x 12 in. planks, nailed to 6 in. x 6 in. timber stringers) had been installed in the main communication trench. However, no such precautions were taken on the ramp entrances to the camp. As a result these ramps were difficult to negotiate by men on foot and in time could have become virtually impassable even to tracked vehicles. Maintenance efforts consisted of removing the loose, granular snow with a bulldozer, but this was only an expedient solution. The new surface, under traffic, again rapidly deteriorated. Further, with each removal of the surface layer of loose snow, the ramp was made deeper and had to be extended in length in order to maintain a proper slope.

USA CRREL conducted considerable research on this problem (Abele, 1963). Efforts included processing the snow floors with the Peter miller and mixing several types of additives, such as wood shavings or sawdust, with the snow and sprinkling the mixture with water which froze, forming a binder. None of the measures provided a satisfactory solution of the problem for tracked vehicles. However, the Peter snow pavement held up well under wheeled vehicles mounted on smooth (without tread) low pressure tires. Of the problems associated with the construction and maintenance of Camp Century, this one and the control of snow drifting in ramp entrances are the only two for which reasonably satisfactory solutions have not been developed, although studies have been made on ramp protection (see App. B).

Snowdrift problems and portal closure

The almost continuous drifting of snow created a problem of major proportions at Century. Portal ramps to the camp filled with drifting snow within a few hours during frequent storms. Structures which protruded above the surface created snowdrift patterns that accelerated the rate of accumulation. Thus the overburden was increased proportionately and, in turn, it may be assumed that the deformation rates of the snow trenches beneath become correspondingly greater.

Various approaches to a solution of this problem were tried without any appreciable degree of success. Tests involving the use of snow fences to control drifting around portals and ramps were conducted during the first 2 years the camp was occupied. However, the tremendous volume of drifting snow during severe storms soon covered the fences and thus rendered them ineffective. Further, the fences created large drifts adjacent to the portals and ramps which tended to aggravate the problem by trapping even greater volumes of snow.

A system of air locks made of nylon, polyurethane film, or some similar material which could be installed quickly in the ramps and portals during storms seems to offer promise, but to date the concept has not been tested.

The PM-2A Nuclear Power Plant

The PM-2A Nuclear Power Plant, which was constructed by ALCO Products, Inc., under OCE contract, was installed at Camp Century during the summer of 1960. The plant achieved initial criticality and became operational on 2 October 1960, and, except for down-time to accomplish routine maintenance or repairs, it operated continuously until 9 July 1963 at which time it was closed down pending a decision to relocate it. Figure 37 is a cutaway sketch of the PM-2A as it was installed at Century. Major characteristics of the plant are as follows:

PM-2A Characteristics

Gross thermal power	10,000 kw
Gross electric power	2,000 kw
Net electric power	1,560 kw
Process steam	1,000,000 Btu/hr
Plant weight	310 ST
Number of packages*	27
Core life (at full power)	17 Mo
Crew size	18 Men
Generator rating	2,000 kw
Generator voltage	4,160 v
Generator frequency	60 CPS
Phases	3
Plant cost (through FY 61)	$5.7 Million
Operator and maintenance cost (0.8 PF)	65 Mills/kwh
Relocation and reinstallation cost (estimated)	$2.5 Million

*9 ft x 9 ft x 30 ft or less, 30,000 lb or less.

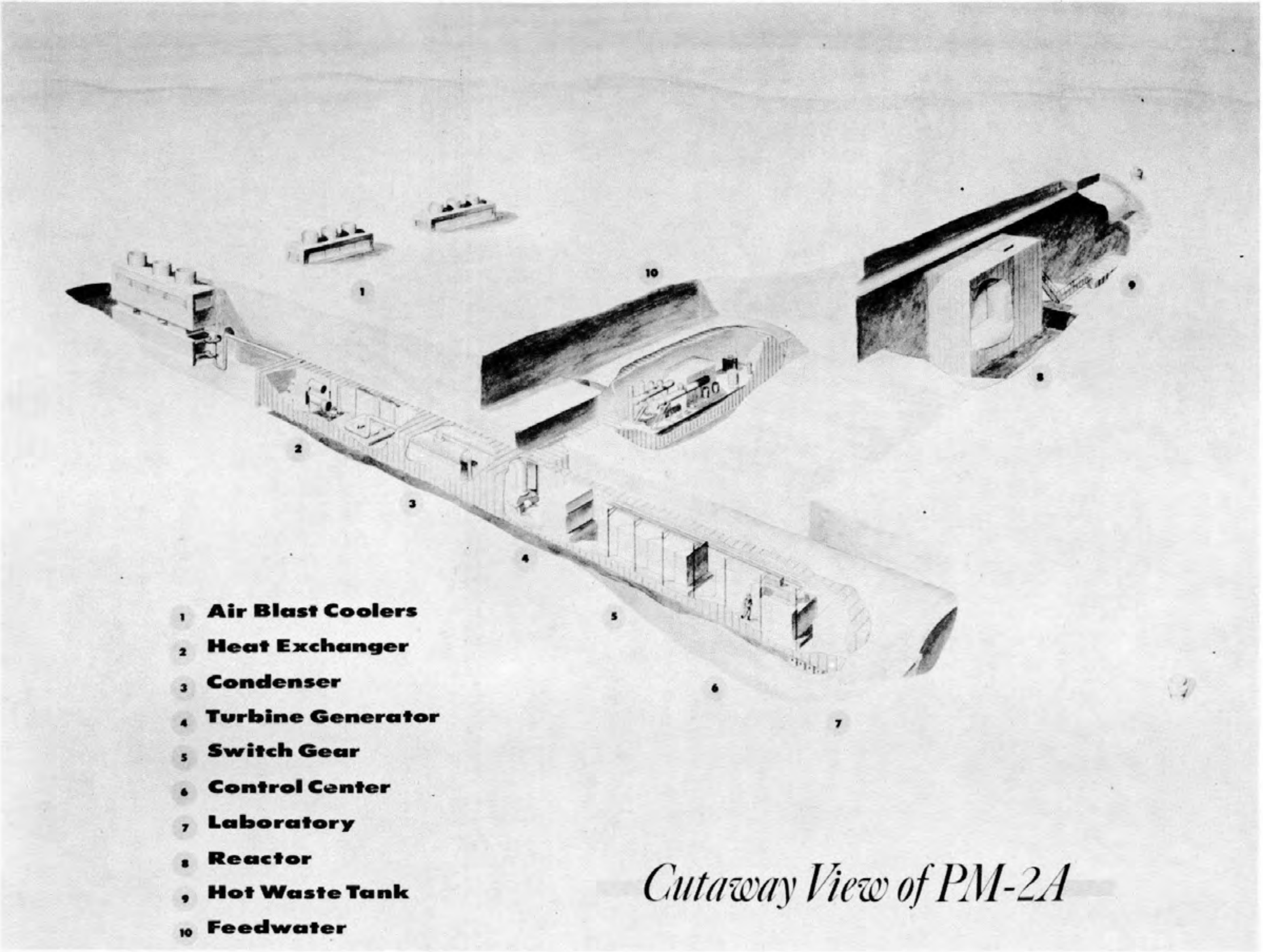

Figure 37. Cutaway view of PM-2A layout.

The only serious difficulty experienced during the first year of operation of the PM-2A was a series of malfunctions of the turbine-generator. In each case similar symptoms were manifested, i.e., excessive noise and vibration in the vicinity of the reduction gears and turbine oil pump, loss of turbine governor control (frequency hunting), and deposition of metallic particles in the turbine oil system. During each such period, maintenance on the turbine-generator unit was performed by the normally assigned crew, under supervision of one or more of the manufacturer's representatives. As a result of these difficulties the PM-2A produced no electrical output during the following periods: 26 April through 14 May 1961, 10 June through 6 July 1961, and 2 August through 31 August 1961.

Indications are that these difficulties resulted from a thrust bearing failure early in November of 1960 which contaminated the entire turbine oil system with metallic particles. However, the condition was aggravated by a poorly designed turbine oil filter system, which was ultimately corrected by installation of a centrifuge type of filter.

The only significant modification of the PM-2A equipment during approximately 33 months of operation was that of providing additional shielding to supplement that required by the original plant design.

The following summary of PM-2A Power Plant operation is abstracted from the official records of Corps of Engineers and covers a typical period of 1 year (1 January - 31 December 1962):

Output data

Gross electrical output	5,388,900 kwh
Net electrical output	2,663,544 kwh
Steam output	2080×10^6 Btu
Core burnup	4,712 MWY
Time on line	6,491 hr
Time off line*	2,269 hr
Percent of time on line	74.1
Average gross electrical demand while on line	830 kw

*The greater percentage of the time off the line was caused by the necessity to cease operation of the plant for several weeks while USAPR&DC crews rehabilitated the metal arch roofs covering the reactor building trench.

Miscellaneous statistics

Average core burnup rate	0.265 MWD/hr (at power)
Average radiation dose per crew member	50 mrem/mo gamma 40 mrem/mo neutron
No. of personnel overexposures	None
Primary water before demineralizer:	
Normal resistivity	2.2 megohm-cm
Normal activity	5.08×10^{-5} mc/cc
Primary water after demineralizer:	
Normal resistivity	2.4 megohm-cm
Normal activity	1.50×10^{-5} mc/cc

Waste disposal*

Date of disposal	Quantity discharged (gallons)	Specific activity (mc/cc)	Activity discharged (mc)	Cumulative (mc)
3 Jan 62	2755	1.11×10^{-7}	1.115	1.115
22 Jan 62	2613	1.81×10^{-7}	1.790	2.905
9 Feb 62	3025	1.33×10^{-7}	1.525	4.430
25 Feb 62	2850	1.15×10^{-7}	1.240	5.670
11 Mar 62	1812	1.74×10^{-8}	0.118	5.788
2 Apr 62	2205	2.72×10^{-8}	0.227	6.015
26 Apr 62	2350	3.00×10^{-8}	0.267	6.282
26 May 62	3250	1.29×10^{-7}	1.530	7.812
8 Jun 62	3468	9.97×10^{-8}	1.310	9.122
24 Jun 62	2400	6.65×10^{-8}	0.605	9.727
28 Jun 62	2325	2.43×10^{-8}	0.214	9.941
11 Jul 62	1950	8.71×10^{-9}	0.064	10.005
1 Aug 62	2375	4.08×10^{-9}	0.037	10.042
28 Aug 62	1850	4.70×10^{-8}	0.330	10.372
24 Sep 62	1950	1.57×10^{-9}	0.012	10.384
10 Oct 62	2050	1.80×10^{-8}	0.410	10.524
26 Oct 62	2000	2.16×10^{-9}	0.016	10.540
14 Nov 62	1850	1.80×10^{-8}	0.126	10.666
4 Dec 62	1625	1.70×10^{-8}	0.105	10.771
18 Dec 62	2375	6.25×10^{-8}	0.562	11.333
	47,078	Avg. 6.55×10^{-8}	11.333	11.333

*Radioactive liquid waste which was discharged into the Greenland Ice Cap. Danish-American agreement permits up to 50 millicuries per year of radioactive liquid waste disposal in the ice cap. In accordance with this agreement all solid waste must be removed from Greenland and disposed of in accordance with AEC regulalations, i.e., placed in concrete casks and dumped into designated locations in the ocean or buried in one of the designated land area burial grounds in the United States.

An auxiliary power plant, which consisted of three 300-kw diesel powered generators, was installed at Camp Century in 1960. Its function was that of providing necessary power when the PM-2A had to be shut down for routine maintenance or repair. During the period when the PM-2A was undergoing shakedown testing, the diesel plant provided power for the entire camp for more than fifty percent of the time.

On 2 August 1963, a U. S. Army Materiel Command plan to remove the PM-2A Nuclear Power Plant from Camp Century was approved by the Chief of Research and Development, Department of the Army. This decision stemmed primarily from plans to discontinue year-round operations at Camp Century in order to reduce Greenland R&D support costs. The fact that closing down the PM-2A and leaving it unattended during part of the year posed a number of technical difficulties of major proportions, plus the poor utilization factor resulting from operating it part time, made its removal the only practicable alternative. Further, it was considered that the research and development objectives of installing and operating a modular-type, air-transportable nuclear power plant on the Greenland Ice Cap had been achieved. The project had demonstrated conclusively that nuclear power is feasible at remote military installations and that these plants can be operated efficiently with military personnel had been the primary objective in choosing the ice cap for testing the first modular type plant. It was obvious that if it could be done successfully in an ice cap environment, where foundations of snow, extremely low temperatures, and the confined space in trenches magnified design, construction, and operating difficulties, the feasibility of employing nuclear power at isolated military installations would be established.

During the summer of 1964, the PM-2A Nuclear Power Plant was disassembled, removed from Century, and shipped to the United States.* No unforeseen major difficulties were encountered during this operation. However, residual radiation levels around the primary unit (i.e., reactor and hot waste tank) were considerably higher than had been anticipated. Hence, daily permissible exposure of crew members disassembling these components was shorter than had been calculated, and, as a result, more personnel were required to accomplish the task in time to meet scheduled shipping dates than was planned originally.

The glycol heat sink, after its installation in 1961, worked efficiently.† It is interesting to note that, during the period of approximately 2 years it was in operation, a subsurface cavity containing approximately 20,000,000 gallons of water was produced (Fig. 38). This pool of water was determined to be entirely suitable for drinking and other camp needs. It contained no radioactive contamination above the normal ice-cap background level and was as pure chemically as that produced in the ice-cap water well. Hence, in future designs for ice cap camps which are to be powered by nuclear plants, the heat sink offers a most economical means of supplying water and cooling the plant with a single system.

A complete technical analysis of the glycol heat sink is contained in USA CRREL Research Report 60 (Tien, 1960).

SUMMARY OF RESULTS

Results of the Camp Century project considered to be significant are:

1. The capability to construct both surface and subsurface military facilities on ice caps has been demonstrated.

2. The methods and techniques employed in the construction of Camp Century have been determined to be feasible and fundamentally sound.

3. The following distinct advantages of subsurface over above-surface camps have been demonstrated:

    a. The initial construction cost is lower.
    b. The severe above-surface environment is avoided.
    c. Less fuel is required for heating purposes.
    d. Less imported construction materials are required.
    e. The problem created by drifting snow is minimized.
    f. Effective camouflage is made easier.
    g. Vulnerability to enemy attack is greatly reduced.

4. Foundations in snow capable of supporting very heavy and large structures can be designed with confidence.

5. Substantial economy can be realized by use of lightweight materials in design of buildings.

6. The "Rodriguez Well" is a very efficient ice-cap water supply system.

7. Nuclear power plants offer significant advantages in reducing the logistical burden of supporting isolated, remote military outposts. They provide a reliable source of power and are able to respond instantaneously to changing power

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*The primary unit was shipped to the AEC for destructive testing (i.e., determining rates of embrittlement and maximum safe service life of metal components, such as the pressure vessel, which are subjected to neutron bombardment). The secondary unit is stored at a depot in the United States pending determination of a relocation site.

†A system for removing waste heat from the reactor system. Water, pumped into a heat exchanger from a pool within the ice cap, removes heat from the glycol. Glycol, in a closed loop, is used as the condensing medium for the turbine exhaust steam.

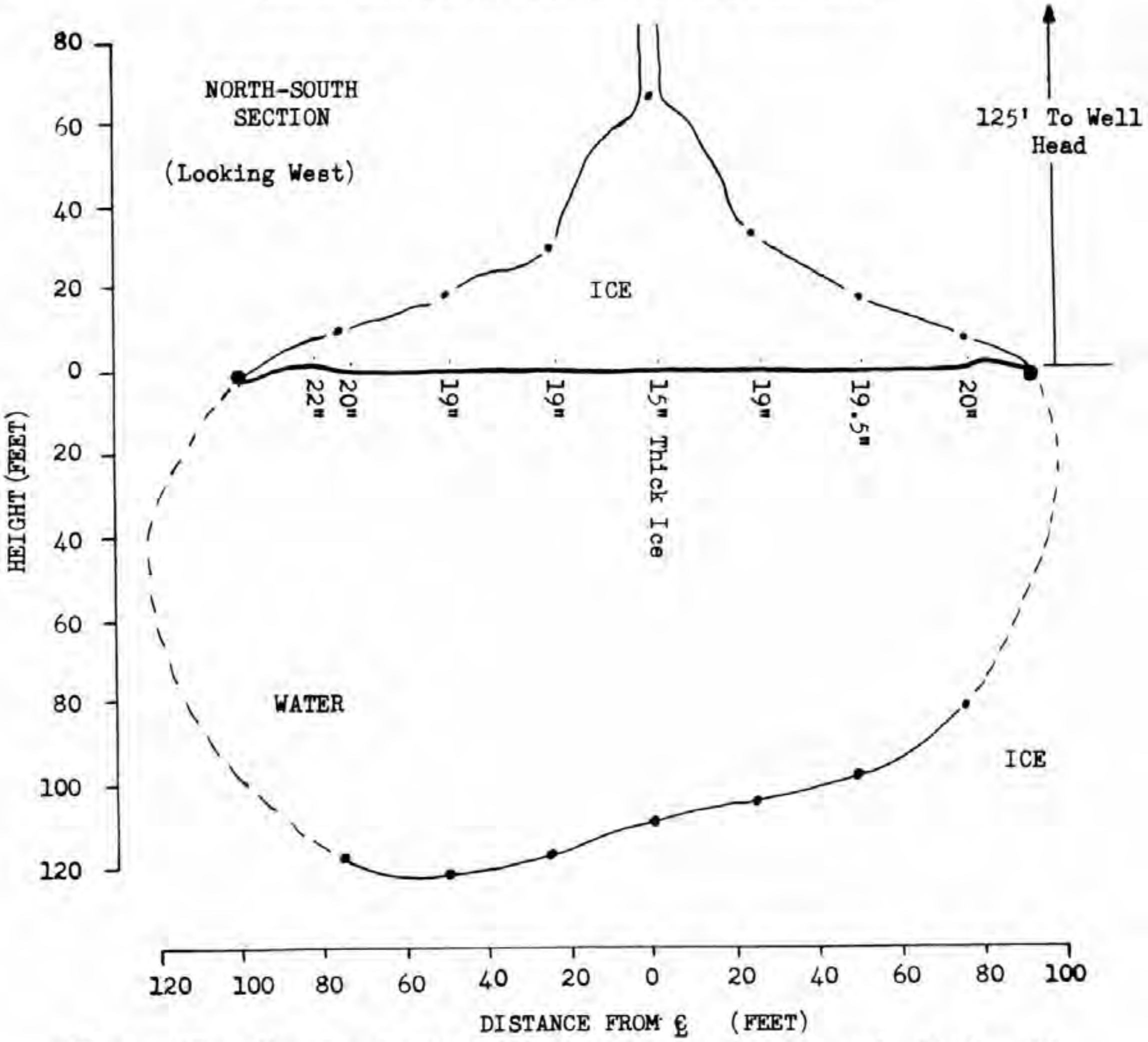

Figure 38. Glycol well cavity, Camp Century. Measured: 20 June 64. Depths obtained by direct taping; diameters estimated from sonar data.

conditions. However, to achieve these advantages, a high initial cost must be paid, much higher than for comparable fossil-fueled plants.

8. The sewage disposal system developed for Century is efficient and economical.

9. Only two serious problems pertaining to operation and maintenance of subsurface camps do not have reasonably acceptable solutions; namely, stabilization of snow trench floors for tracked vehicles and prevention of drifting snow from closing ramp entrances. However, Appendix B describes a covered entrance concept, devised by USA CRREL in 1964, which appears to offer promise as a solution to the problem of drifting snow closing ramp entrances.

CONCLUSIONS

Based upon the foregoing discussions, it is concluded that:

1. The main objectives of the Camp Century project were achieved.

2. Subsurface camps on ice caps are feasible and practicable, but only in environments as cold or colder than Century.

3. Both undercut trenches, covered with unsupported snow arch roofs, and straight-wall trenches, covered with metal arches (such as the Wonder Arch) or timber trusses, are feasible and perform acceptably well, if properly installed. Each serves a specific purpose.*

4. The cost of future subsurface ice cap camps, such as Century, can be reduced appreciably by:

a. Removal, during construction, of all metal arch forms in which the span does not exceed 12 ft in width.

b. Use of foam plastic or other very light weight materials for all buildings.

c. Simplification of utility systems, i.e., avoidance of overhead utility lines and unnecessarily sophisticated power distribution systems.

5. Modular-type, semi-portable nuclear power plants are feasible and practicable for remote military facilities as large or larger than Camp Century. They can be operated and maintained efficiently by trained soldier crews.

6. Means for a continuous program of trimming the snow trenches should be provided in initial planning for any undersnow camp.

7. Roughly 10 years is the maximum feasible design life for an undersnow camp in environments similar to Century.† This presupposes an adequate maintenance program.

RECOMMENDATIONS

For the design of undersnow camps, the following specific recommendations are made:

1. Site should be selected where the annual mean temperature does not exceed 25°F for more than a few hours at a time. The selected location should be free of crevasses.** Allowable surface slopes should not exceed two percent, as greater slopes could be indicative of rapid visco-elastic flow rates.

2. Metal arch roof forms should be removed from trenches in which the arch span does not exceed 12 ft in width.

3. In the construction of unsupported snow arch roofs, Peter snow should be backfilled over the metal forms, in approximately 1-foot lifts, until the arch has acquired a filled spandrel load symmetrically. Forms should not be removed until the age-hardening process is well advanced.††

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*For trenches wider than 24 ft at the floor, straight-wall trenches, covered with metal arches, are preferable; for trenches up to 24 ft wide at the floor, undercutting and covering with unsupported (metal forms removed) snow arches is considered preferable, since both a dollar and a logistical economy are realized (i.e., procurement cost and transportation of metal arches to the site).

†The average annual accumulation at Century is approximately 4 feet of snow; the average annual mean temperature is around -10°F. In a colder climate, with less precipitation, a proportionately longer design life may be feasible. For example, at Byrd Station in Antarctica, a design life of 20 years is not unreasonable, provided adequate maintenance is accomplished.

**It is the consensus of glaciologists that crevasses normally do not occur where ice cover is at least 1000 feet thick. The presence of crevasses is often indicative of relatively fast flowing ice.

††Bender (1957) reports that snow with a ram number (Rammsonde) of less than 57 has no compressive strength. Hence, it is recommended that arch forms be left in place until a ram hardness number of 100 is reached at a depth of 15 cm below the surface.

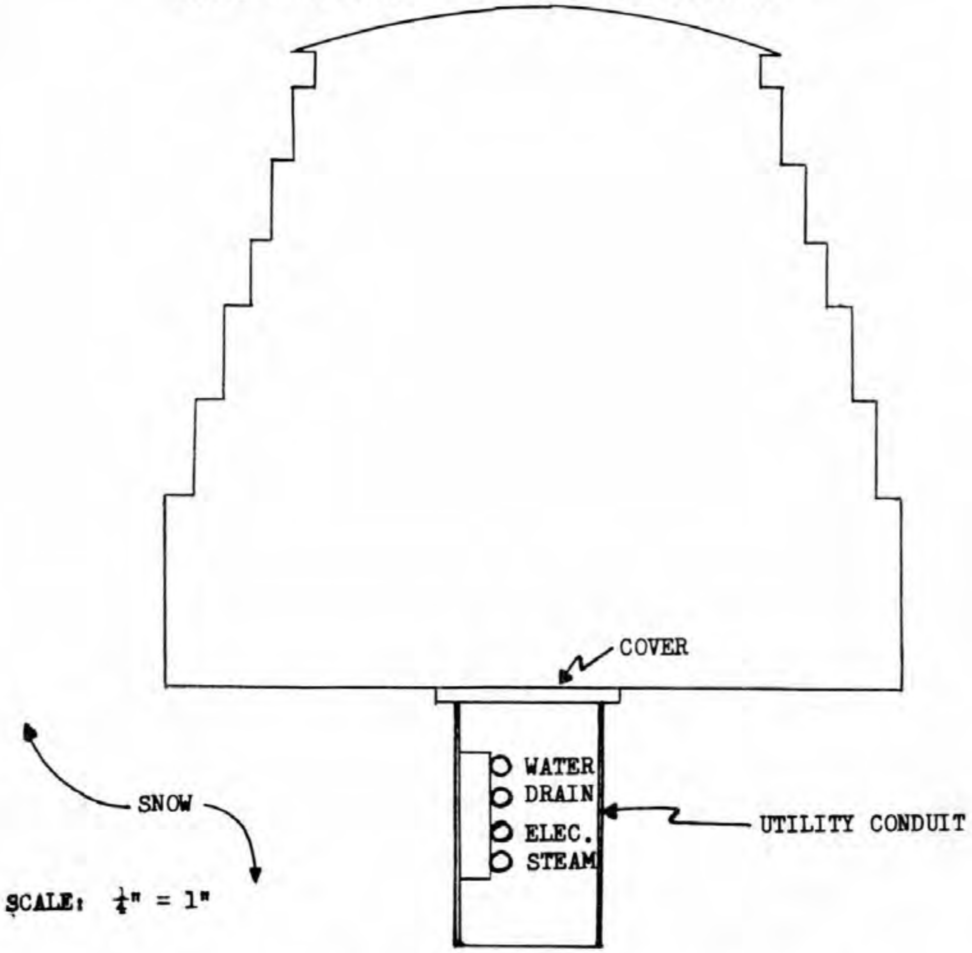

Figure 39. Proposed location of conduit in trench floor.

4. Lightweight, modular-type prefabricated buildings, which are easy to erect or disassemble, should be used throughout the camp.

5. Design criteria should emphasize simplicity, dependability, and maximum use of indigenous materials (i. e., snow and ice).

6. Utility lines should be located in a sub-floor utility duct (Fig. 39). This permits trimming of the snow roof without removal of a great amount of hardware and the resulting disruption of power and sewage services.

7. Sewage sumps should be in a separate and sealed trench, vented, and located a minimum distance of 500 feet from the nearest building.

8. The water well should be located a minimum distance of 1000 feet from the sewage sump.

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APPENDIX A: CHRONOLOGICAL SUMMARY OF EVENTS

Event	Dates
Initiation of project	1 Sep 58
Preliminary design of Camp Century	1 Sep - 15 Nov 58
Study contract for PM-2A Nuclear Plant	14 Jun 58 - 31 Jan 59
Final design of those portions of Century to be constructed in 1959	15 Nov 58 - 15 Feb 59
Procurement of construction materials to be emplaced in 1959 and portions of those required for 1960	1 Dec 58 - 20 May 59
Letting of contract to ALCO Products, Inc. for design, fabrication, and testing of PM-2A Nuclear Plant	23 Jan 59
Letting of contract to Metcalf and Eddy, for design of support facilities for PM-2A	26 Feb 59
Departure of 1959 construction force to Greenland	15 Apr - 15 May 59
Selection of site for Century	17 May 59
Organization of materials at Tuto and buildup of stockpiled supplies at Century	13 May - 14 Jun 59
First construction troops arrive at Century	14 Jun 59
Construction of temporary surface camp at Century to house construction troops	14 Jun - 10 Jul 59
Experimentation to develop practical trenching techniques*	25 Jun - 15 Jul 59
Construction of 10% of the permanent camp (5 trenches and 5 buildings)	5 Jul - 1 Sep 59
Closing of Century for the winter of 1959-60	1 Sep 59
Return of construction troops to the United States for the winter of 1959-60	2 - 7 Sep 59
Final design of remainder of Century	1 Aug - 1 Sep 59
Procurement of remainder of materials	1 Oct 59 - 1 Apr 60
Training of Peter miller operators at Houghton, Michigan	1 Dec 59 - 1 Jan 60
Training of reactor crew at ALCO Products plant during test assembly of the PM-2A	5 Jan - 20 May 60
Departure of 1960 construction force to Greenland	7 Apr - 7 May 60
Organization of materials at Tuto and buildup of stockpiled supplies at Century	10 Apr - 10 May 60
Reopening of temporary surface camp at Century	17 Apr 60
Arrival of bulk of 1960 construction troops at Century	1 - 20 May 60

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*Consisted mainly of training Peter miller operators.

Event	Dates
Expansion of temporary surface camp to accomodate increased construction force	10 - 25 May 60
1960 start of construction on Century	12 May 60
Disassembly, packing, and loading of PM-2A Nuclear Power Plant on USNS Marine Fiddler at Buffalo, N. Y. for shipment to Greenland	28 Apr - 27 Jun 60
Shipment of one PM-2A airblast cooler to Greenland by C-124 aircraft to demonstrate its air transportability	27 May 60
Arrival of USNS Marine Fiddler with PM-2A at Thule, Greenland	10 Jul 60
Transport of PM-2A components and materials to Century	11 Jul - 1 Sep 60
Installation of PM-2A at Century	15 Jul - 1 Oct 60
Arrival of crew to operate completed camp	9 Sep 60
Departure of Century construction troops	12 Sep - 15 Oct 60
Completion of non-nuclear portions of Century	1 Oct 60
Completion of installation of PM-2A (including additional shielding)	6 Feb 61
Acceptance of PM-2A by USAPR&DC	8 Mar 61

APPENDIX B: ABOVE-SURFACE COVERED ACCESS TO CUT-AND-COVER TRENCHES

by

Wayne Tobiasson

Figures B1-B4 illustrate the above-surface covered entrance concept devised by USA CRREL to provide a year-round access to ice cap facilities.

Using plywood forms, two 14-ft high processed snow abutments were erected 12 ft apart. The abutment snow consisted of backcast Peter miller snow picked up by a traxcavator and dumped between the forms. A vibratory compactor was used to break up lumps of snow. After 24 hours the forms were removed and reerected for the next pour. Each abutment was poured in three sections.

A timber arch seat was placed on each abutment and 14 ft span corrugated metal arch used to cover the trench. A standard Peter miller blew 6 to 12 inches of processed snow over the arch.

A timber door frame was constructed at the open end of the ramp and a three-piece plywood door erected to provide personnel and vehicular access while preventing drift snow from depositing in the end of the ramp.

The abutments have been instrumented for deformation.

Figure B1. Erection of 14-ft high plywood forms.

Figure B2. Traxcavator filling plywood forms with Peter-miller snow.

Figure B3. Peter miller covering arch.

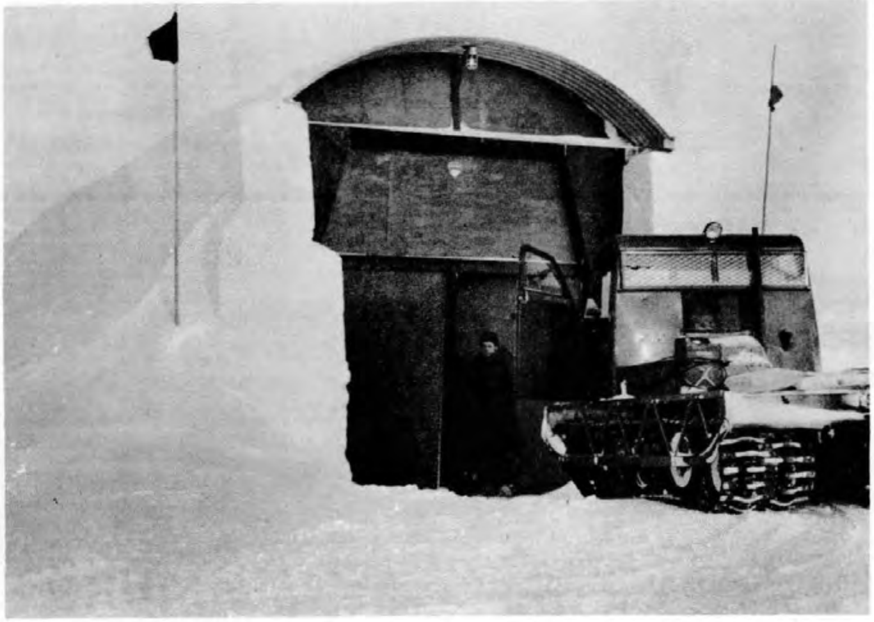

Figure B4. Vehicular access door.

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1. ORIGINATING ACTIVITY *(Corporate author)*
U. S. Army Cold Regions Research and
Engineering Laboratory, Hanover, N. H.

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

3. REPORT TITLE
CAMP CENTURY—EVOLUTION OF CONCEPT AND HISTORY OF DESIGN, CONSTRUCTION, AND PERFORMANCE

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Technical Report

5. AUTHOR(S) *(Last name, first name, initial)*
Clark, E. F.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
Oct 1965	66	31

8a. CONTRACT OR GRANT NO.

b. PROJECT NO.

c. DA IV025001A130

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
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13. ABSTRACT

This report tells the story of Camp Century, an effort to learn how to construct military facilities on the Greenland Ice Cap. It describes briefly the research done by several laboratories, scientists, and engineers in achieving this objective. It discusses the development of concepts, methods, and engineering techniques which made the construction of Camp Century possible. Engineering performance of the camp and its facilities is summarized, and some of the more important reports resulting from the effort are referenced. It is concluded that subsurface ice-cap camps are feasible and practicable, that nuclear power offers significant advantages in reducing the logistical burden of supporting isolated, remote military facilities, and that the wealth of data and experience obtained from the Camp Century project will be of inestimable value in the development of designs for future ice-cap camps.

DD FORM 1 JAN 64 **1473**

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	ROLE	WT	ROLE	WT	ROLE	WT
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Snow (construction material)						
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