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EXPERIMENTAL PROTECTED MILITARY POL INSTALLATION

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13. ABSTRACT

Permafrost either is or can be very easily made impermeable for nonfreezing liquids such as hydrocarbon fuels. Fine-grained, ice-rich permafrost can easily be excavated by application of steam or relatively warm water. An experimental cavity was prepared by melting permafrost and was filled with hydrocarbon fuel. The thermal conditions around the cavity were observed for approximately a year. An artificial heat exchange experiment was conducted. It was concluded that this fuel storage method is suitable for military and civilian needs.

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PREFACE

This report was prepared by Dr. George K. Swinzow, Geologist, Construction Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. The work was performed under DA Project 4A162121A894, *Engineering in Cold Environments*, Task 03, *Expedient Logistic Facilities in a Cold Regions Theater of Operations*, Work Unit 002, *Protected POL Storage*.

The report was technically reviewed by Kevin L. Carey and Edwin J. Chamberlain of USA CRREL.

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by

George K. Swinzow

INTRODUCTION

The consumption of liquid hydrocarbon fuels is subject to seasonal and sporadic fluctuations. Peaks in demand are absorbed by local storage facilities whose capacities are designed so that surges in supply, as well as peaks in demand, may be smoothed out. Usually a small reserve capability exists to cover unforeseen fluctuations. In addition to customary safety precautions the technical requirements for such storage facilities consist of the capability to accept large single fuel deliveries and make frequent small discharges. An example of such a facility is a commercial gasoline station.

A combat type military fuel storage facility differs from a commercial station in the aspect of peak fluctuation, which is neither seasonal nor diurnal but depends upon military action. Furthermore, the military facility must be constructed in a highly expeditious manner. Special requirements are safety and the ability to withstand hostile fire: a military fuel storage and supply installation must be "hardened."

The best way to harden a military installation is to bury it, but this entails much time and effort. An exception is burial in permafrost, where a cavity may be rapidly melted by applying heat in one form or another. This report describes a test in which a cavity was melted in permafrost, instrumented for temperature measurements, filled with fuel and observed for approximately one year.

The fact that frozen soil containers can hold liquid hydrocarbon fuels without any detrimental effects was proven in an investigation by Swinzow (1964) in which a large (500-gal) container was constructed in a permafrost tunnel and filled with fuel. Periodic fuel tests demonstrated the absence of any detrimental effects. Gulikov and Mazurov (1969) evaluated large subsurface facilities for storing refined light petroleum products as well as crude oil. Ananian et al. (1972) performed thermoanalytical studies on small-scale laboratory models. However, previous work was based on elaborate surface construction and could not be seriously considered for military application since the necessary factors of invulnerability, safety and speed of construction could not be applied.

THE PERMAFROST ENVIRONMENT

Permafrost, or perennially frozen ground, is a layer of typically unconsolidated soils material cemented by pore ice into a stratum with mechanical properties similar to those of competent rock. It is distinguished from seasonal ground frost by being perennial; its frozen state exists for many seasons and it is encountered at latitudes higher than the position of the 0°C (32°F) annual isotherm. It occupies approximately one-fourth of all the dry land in the world. One-half of Russia is permafrost. The thickness of the perennially frozen zone generally increases with latitude, while the seasonally thawed zone, as observed toward the end of the summer, increases in depth toward the equator. These are generalities; deviations from them are numerous, and are connected with local geothermal heat flow, type of soil and bedrock, exposure, etc. Distribution, origin and properties of permafrost are treated in great detail by Stearns (1966). It is sufficient to mention that while the temperatures at the surface change over the seasons, and the annual average temperature is significantly below freezing (which is the general condition for permafrost formation), the temperature of the perennially frozen ground increases with depth. The point where it becomes positive (above freezing) is the bottom of permafrost.

The conditions for formation, stability and disappearance of permafrost are, in terms of heat flow, rather straightforward. If the amount of heat arriving at the surface from the inner parts of the earth (geothermal heat) and the summer heat penetrating the surface from above are less in sum than the heat loss in the cold period, then the permafrost stratum grows. In a case of positive heat balance, there is a thinning of the permafrost layer and retreat to the north (in the Northern Hemisphere) of its southern border. Currently there is a slight degradation of permafrost taking place in several geographic regions. It is accompanied by deepening of the maximum summer thaw layer and shallowing of the bottom of the permafrost. Subtle thermal changes at the surface find an immediate reflection in the active layer (seasonal thaw layer) as well as a delayed change at the bottom of the permafrost. For example, systematic removal of snow from an area results in a lower ground temperature, shallower seasonal thaw and eventually thickening of permafrost at the bottom.

The mechanical properties of permafrost are determined by the temperature of its ice content and the actual composition of the frozen soil skeleton. Permafrost and frozen soil material in general might be regarded as competent rock as long as the frozen state persists. Well-graded, gravelly, ice-saturated material might reach an unconfined compressive strength equal to that of concrete. Dry permafrost is incompetent and has the properties of any soil of similar composition. Its strength increases with ice content, reaching a maximum at approximately 90% of saturation in its densest state. When ice content increases beyond 100% of pore space, particles become gradually separated and the strength decreases until it reaches its minimum, the strength of ice. Among single size materials the highest strength would be that of nearly saturated fine gravels and coarse sands. Mixing fine and coarse materials results in increased total contact surface between ice cement and its skeleton. Such materials exhibit the greatest strength (Swinzow 1965). Lower temperatures increase the strength of frozen ground. Higher temperatures are accompanied by a decrease in strength. This relation is regularly measurable between 0°C (32°F) and -17°C (0°F). Below -17°C the strength increase becomes small.

At its southern boundary, permafrost becomes discontinuous, relatively shallow, close to its melting temperature, and has a thick layer of seasonal thaw. This makes the terrain sensitive to any disturbance of the natural surface conditions, which can tip the heat flow balance toward a net heat gain with subsequent melting. Removal of vegetation generally results in degradation and rapid melting of pore ice. Whenever the volume of ice exceeds the volume of pore space in a dense condition, which is very often the case, the results of melting may be catastrophic for any structure erected on such ground because bearing strengths decrease markedly upon thawing. A structure erected on uniform gravel with an ice content equal to or less than its pore volume may not necessarily result in undesirable deformations after thaw. Most often one encounters perennially frozen strata with large amounts of ice segregated in the form of ice lenses, wedges, etc. These situations are the most troublesome if melting should be induced by man's activities.

In common engineering practice, there are two basic approaches to construction on permafrost: either the permafrost is allowed to melt prior to construction, or it is carefully preserved and its strength, bearing capacity and stability are beneficially utilized. The latter practice is less often applicable near the southern boundaries of permafrost (in the Northern Hemisphere).

If a structural design performs well in marginal or warm permafrost, it is reasonable to assume that it will be sound in cold permafrost at higher latitudes. Also, construction methods that are sound in warm permafrost will automatically be applicable and acceptable at higher latitudes with colder permafrost.

Our field experiment was conducted in marginal, discontinuous permafrost near Fairbanks, Alaska, at the Experimental Field Station of CRREL's Alaskan Division. The perennially frozen layer consists of a fine organic silt with excessive ice and is frozen to an approximate depth of 45 m (148 ft). The depth of the active layer is up to 2 m. The temperature at 6 m, approximately 20 ft, is -0.27 C (31.5 F). The ice content is close to 60% by volume. The organic matter is partially or fully decayed and frost-preserved vegetative remnants. The thermal situation at the site is precarious, requiring special measures to preserve the frozen state.

SPECIAL REQUIREMENTS FOR EXPERIMENTAL POL STORAGE FACILITY

It was mentioned earlier that fuel is generally stored to compensate for peaks in supply and demand. Military fuel storage facilities at the operational stage are relatively short-lived, but must be constructed expeditiously and "hardened" against fire and hostile activity. Most operational military fuel storage facilities accept relatively large quantities of fuel and discharge smaller amounts in the process of normal operation.

There are three facts about permafrost that were known prior to development of the present concept of fuel storage. 1) Permafrost either is or can very easily be made impermeable to unfreezable liquids and gases (in cases where some permeability exists) by a light application of water or a water-based slurry of clay. 2) Liquid fuels such as jet fuel, diesel fuel, etc. can be stored in permafrost directly in contact with the soils material; no special lining or other separation from the permafrost is required (Swinzow 1964, 1965). 3) The most expeditious and economic method of excavating permafrost, especially ice-rich, fine-grained permafrost, is by application of warm water.

Based on the general properties of permafrost, together with the above three facts, the set of requirements for the POL storage facility was developed. A military fuel storage installation must require only a small amount of time and effort to construct. It should have maximum protection against fire as well as against hostile air attack and it should not be easily discernible from the air. Since the prospective construction site for this experiment was to be in marginal permafrost, provisions for heat removal from the installation had to be made. Optional possibilities for heat removal for the purpose of preserving the installation were as follows:

1. Refrigerate the fuel in the container.
2. Chill the air space above the fuel in the container so that the general temperature will go down.
3. Utilize cold winter air to chill the fuel and the surrounding permafrost through the fuel.

The third option appeared to be the most advantageous since the cheapest refrigerant in the world is cold winter air.

CONSTRUCTION OF THE EXPERIMENTAL FACILITY

The construction site selected was at the boundary between an area with undisturbed vegetation and another where the brush vegetation had been removed several years before. For this reason, the depth of seasonal thaw varied from 0.6 to 4 m (2 to 13 ft), the deeper thaw occurring under the area with no vegetation. The protective role of vegetation over warm permafrost and the consequences of its removal were described by Linell (1973).

Construction began by moving into position a mobile auger drill with a bit diameter of 122 cm (48 in.). This large diameter was required because there was a need to descend the borehole to examine, sample and study the permafrost in situ along the exposed depth profile. The machine drilled a 6.7-m (22-ft) deep hole, and observations showed that the winter frost had penetrated to about 2.3 m, with 1 m unfrozen at the bottom of the winter frost layer and permafrost below that. The whole layer was constituted of fine, organic-rich, ice-saturated silt.

After excavation to the depth of 6.7 m, 757 liters (200 gal) of +80°C (176°F) water was poured into the hole to induce melting at the bottom. After the silty mud was removed, a cavity approximately 1.8 m (6 ft) in diameter was left at the bottom of the hole. This size cavity was found to be sufficient for the purposes of the experiment. The cavity was still warm after the water was removed and was therefore ventilated. The air temperatures at this time of the year (March) reached about −17°C (0°F) at times and typically it was −10°C (14°F). The ventilation proceeded satisfactorily and in a short time the walls refroze and reached the original temperature. The circulation of outside dry air resulted in some sublimation of the cavity walls. In order to prevent dry dust formation the walls of the cavity were briefly sprayed with cold water which refroze and formed a fine ice glaze, preventing further dust formation in the cavity.

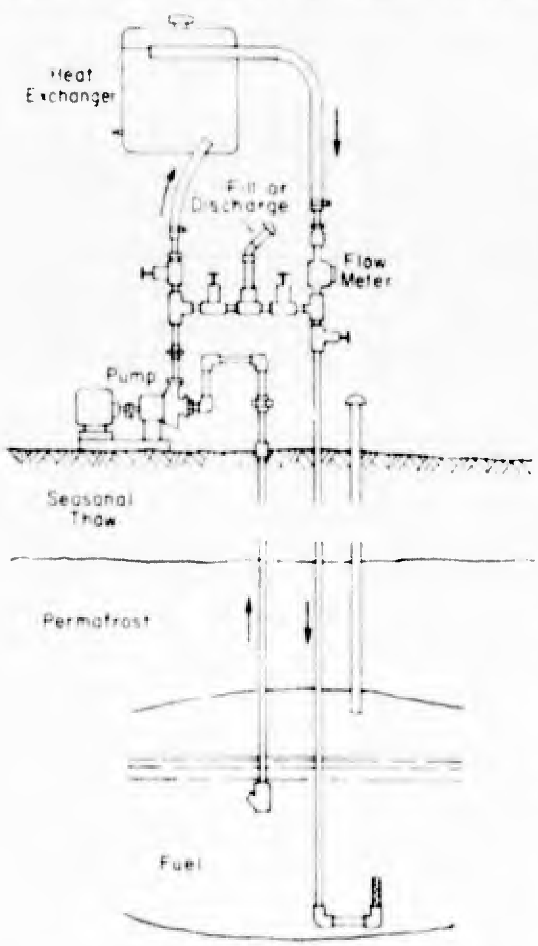

Figure 1. Fuel handling system of the experimental POL installation.

A system of pipes and valves was installed (Fig. 1). The cavity could thus be filled with fuel by gravity flow, and fuel could be removed or circulated through a heat exchanger, using a 5-gal/min centrifugal pump.

The upper surface of the permafrost layer was inclined in the area penetrated by the well; the possibility existed, therefore, that spring thaw water might flow over the permafrost and flood the cavity. To eliminate that possibility, three wooden platforms were installed slightly below and above the permafrost (Fig 2). On top of each platform a 30-cm (1-ft) layer of silt slurry was placed and was allowed to freeze. The mouth of the shaft was lined with wood to prevent possible slump in the summer.

Fifty thermocouples were installed to monitor temperatures within and around the cavity.

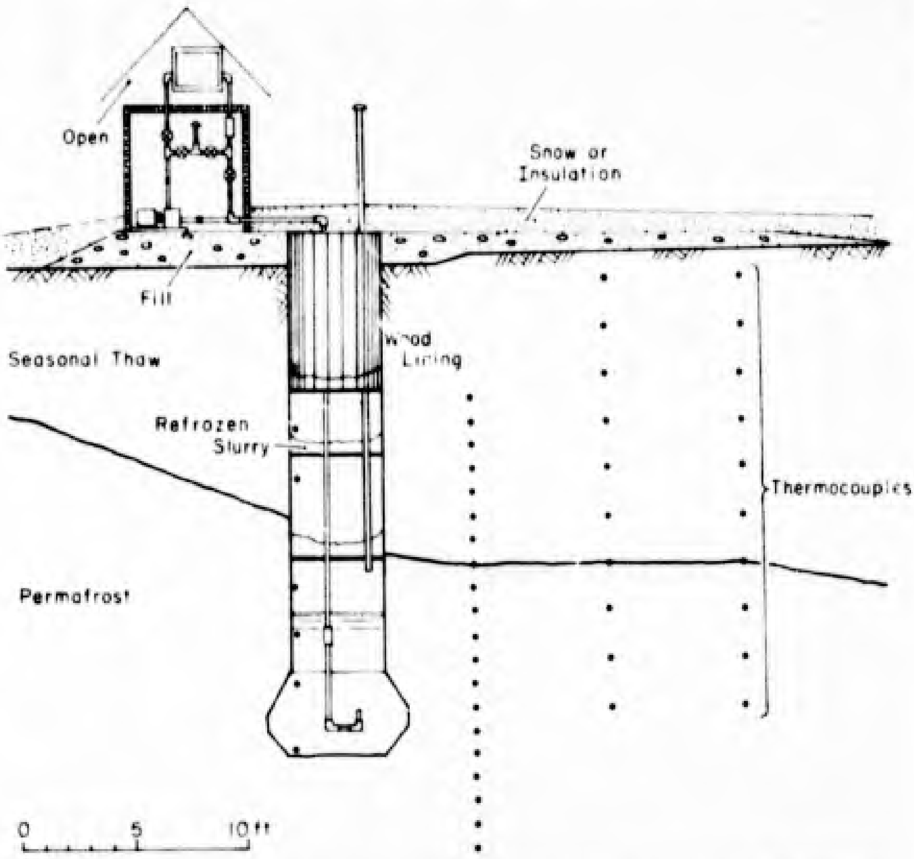

Figure 2. Cross sectional view of the installation showing the temperature measuring points, the method of sealing, and surface detail. (Only return flow pipe shown.)

The vegetation cover was slightly disturbed in the process of construction, and to prevent any detrimental thaw penetration some ordinary fiber glass insulation was placed on the ground around the structure.

Observation during construction indicated that a relatively small amount of effort was required for this type of installation. It is estimated that using a 6- to 8-in.-diameter borehole, which is sufficient for this type of facility if special research observations are not planned, prefabricated equipment and a trained group of personnel, a protected POL installation could be put in operation in 12 hours. The actual initial drilling is, under most conditions, a relatively small part of the total effect. If, therefore, a greater degree of protection against penetrating projectiles was required, the time spent in drilling would increase only slightly. If glazing of the walls is required the cavity could be filled briefly with cold water.

It is felt that 6 m depth of burial in permafrost provides the desired maximum fire protection.

OBSERVATIONS OF PERFORMANCE

As is apparent from the purpose of the investigations, there was a need to see whether or not the installation could survive the warm summer season in the marginal permafrost environment without damage, and if so, what would be the thermal conditions within the fuel and the surrounding permafrost. There also was the need to know what effects an artificial alteration of fuel

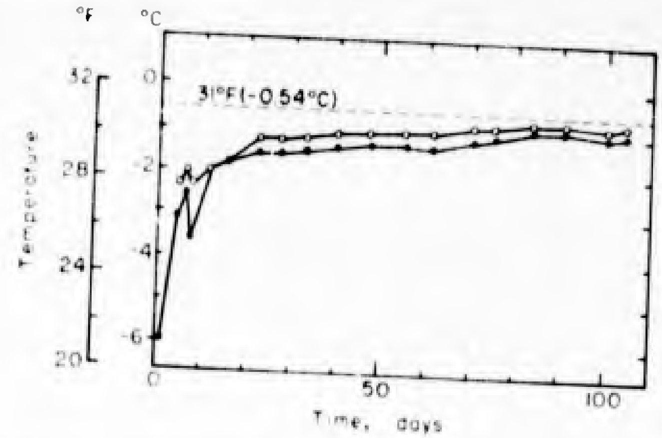

Figure 3. Thermal history over first 105 days after filling. Filled circles: fuel temperatures measured in center of reservoir. Open circles: permafrost temperatures approximately 1 m from reservoir. Dashed line: permafrost temperature away from reservoir's influence.

temperature would have. Of particular interest was the question: To what degree would circulating fuel through the heat exchanger influence the liquid in the cavity and the permafrost walls?

Upon completion of construction and installation of all components, the cavity was sealed and filled with 3800 liters (approximately 1000 gallons) of diesel fuel. This took place toward the end of the cold season (in April) and was followed by weekly temperature measurements made over 50 points (Fig. 2). The temperature of undisturbed permafrost in the locality was approximately -0.54°C (31°F). The construction and subsequent filling lowered the temperature locally. The observations showed that subsequently an asymptotic rise of the fuel temperature took place (Fig. 3). The gradual rise of temperature indicates a thermal condition affording significant changes but not necessarily leading to any detrimental effects. Observations over the remainder of the summer recorded a continuation of the trend disclosed in Figure 3. It is estimated that in about 380 days the difference in temperature between the content of the cavity and the surrounding permafrost would become too small to measure.

No doubt the onset of the cold season introduced another natural change in the thermal condition of the permafrost, but because of the large thawed zone between the seasonal frost and the permafrost, there was no effect upon the cavity. About a year after filling, at the end of the season of severe frost, the pumping experiment was started. The effective circulation of fluid through the heat exchanger was approximately 19 liters/min (5 gal/min) throughout the experiment.

During pumping there were two thermal processes taking place: flow of heat from the fuel to the atmosphere, and flow of heat to the fuel from the surrounding permafrost. The average temperature drop across the heat exchanger throughout the experiment was 0.7°C. Also, due to changing air temperatures the chilling rates of the fuel varied from a low of 0.02°C/hour to a high of 0.33°C/hour. Table I gives some of the observed rates.

The data obtained indicate the relative ease of thermally regulating the reservoir with the existing equipment. Based on these data it was possible to make a detailed analysis of the installation's thermal history (Zehnder 1971). Performed under a series of assumptions the analysis cross checked well with standard thermal data on permafrost and fuel properties.

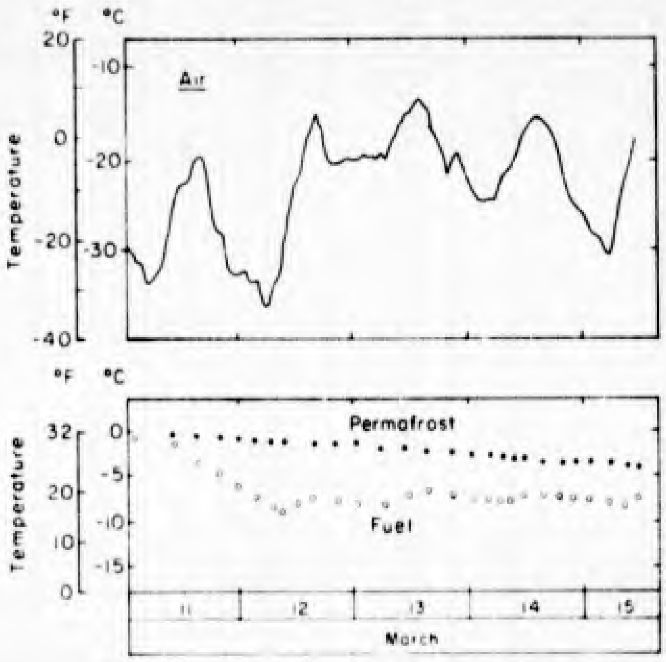

Figure 4. Air, permafrost and fuel temperatures during the heat exchange experiment. Symbols as in Figure 3.

Table I. Some observed cooling rates.

Δt (°C)*	*Rate of cooling* (°C/hr)
15	0.02
18	0.03
19	0.04
22	0.08
24	0.09
27	0.15

* Δt = temperature difference between reservoir and air.

The heat exchange experiment lasted for 96 hours. Figure 4 summarizes the data collected. It shows the air temperature during the experiment together with the changes in permafrost and fuel temperatures. It appears, therefore, that the system shown in Figure 1 is sufficient for a liquid fuel storage cavity, while the principle, satisfying requirements for expeditious construction, simplicity, economy, and military security and safety, appears to be sound. That liquid hydrocarbon fuel is not harmed by contact with permafrost has been amply proven in the past (Swinzow 1963).

The thermal dynamic picture of the whole experiment, beginning with filling the reservoir, continuing through one summer and winter and ending with 96 hours of experimental pump[illegible]s shown in Figure 5 as a series of isotherm drawings. Figure 5 demonstrates that an insta[illegible]on of this type survives a summer season even if placed at the edge of warm permafrost under most

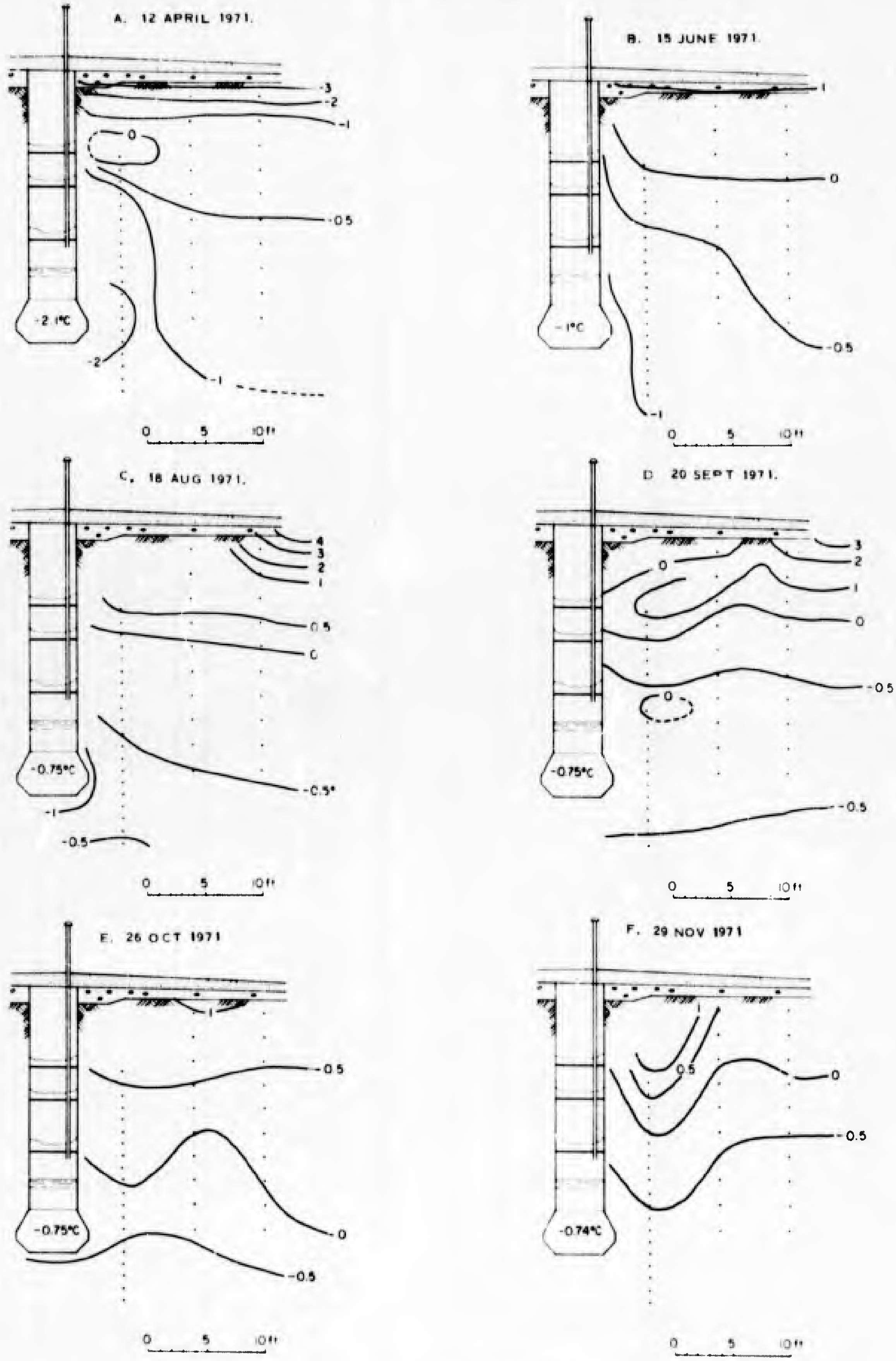

Figure 5. Changes in thermal field during the experiment.

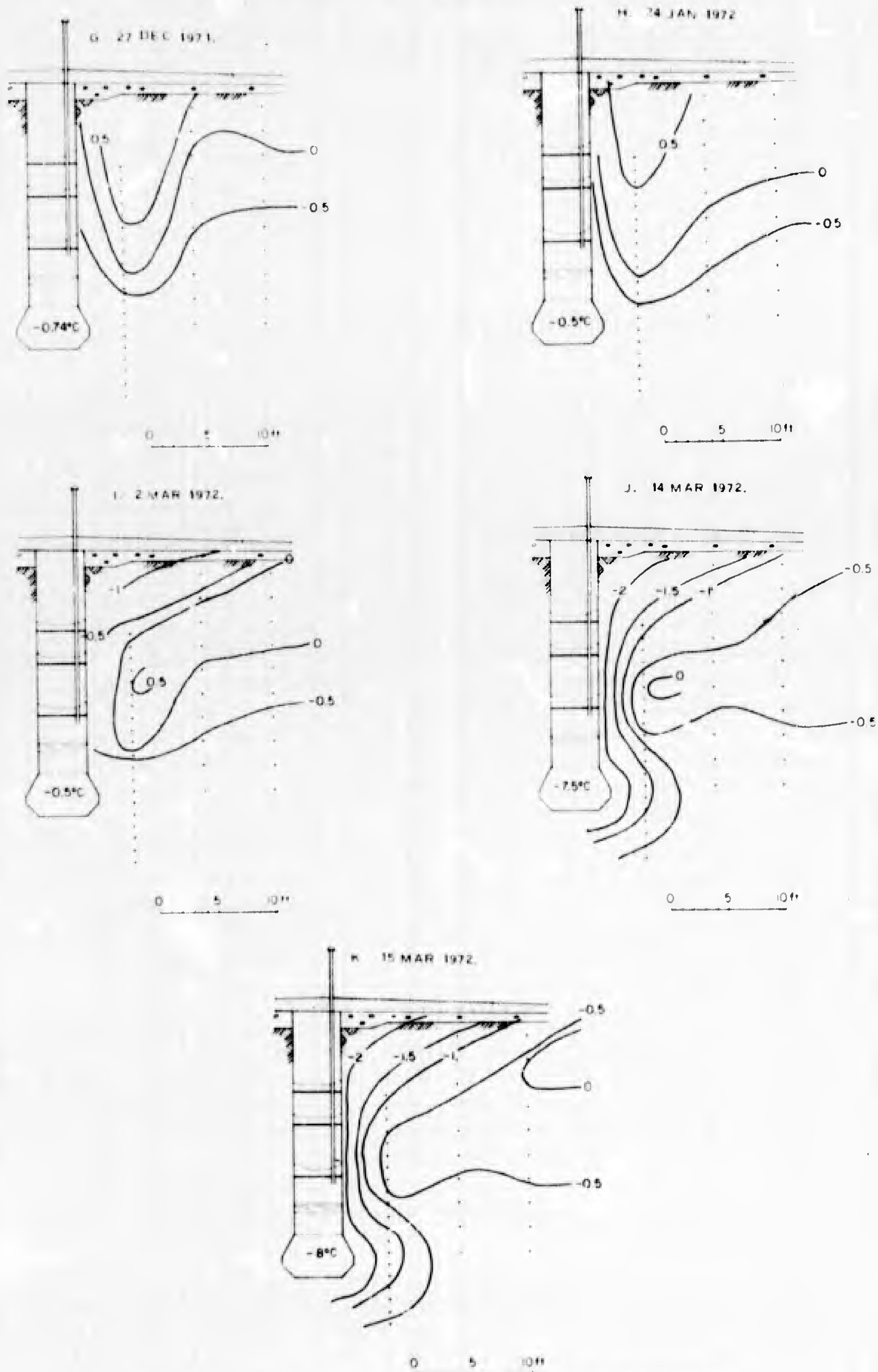

Figure 5 (cont'd). Changes in thermal field during the experiment.

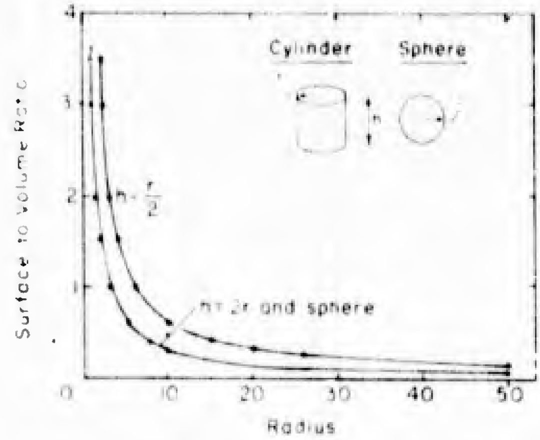

*Figure 6. Changes of surface to volume ratio with changes of radius for the case of a sphere and two cylinders. The h = 2r cylinder plots identical to a sphere. To obtain a nondimensional relation the vertical scale is divided by the surface to volume ratio for a cylinder with r = 1.**

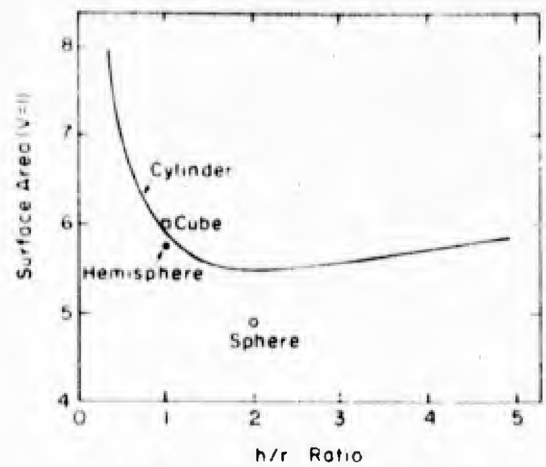

Figure 7. Cylinder of unit volume with varying configuration. Slender cylinders plot to the right, while flat cylinders are to the left of the most advantageous low point. The points for a cube, hemisphere and sphere are shown for comparison.

unfavorable thermal conditions. A question often asked (but not often answered) is that of the size and shape of the experiment. There was a choice between conducting a miniature experiment (1 liter) in the laboratory, a full scale installation (perhaps as high as 400,000 liters) and the present selection. By inspection, the miniature experiment did not allow proper scaling-down of permafrost features such as grain size, ice-filled pore sizes and, most important, the relation of liquid viscosity to gravity (for theory of scale modeling see Soper 1967). The full scale installation would have been mainly a test of the functioning of the system rather than a test of the principle. The admittedly arbitrary round figure for the capacity (1000 gal) was, it was felt, sufficient for the imposed research requirements.

Another reason for selecting the particular size was the role of the surface of the cavity in the process of heat exchange between the liquid and the surrounding permafrost. Regardless of the direction of heat flow, the heat crosses the interface. Surface efficiency, shape efficiency, and the general degree of geometric perfection are the governing factors in selecting the proper cavity configuration. Interfacial or surface heat transfer efficiency cannot be influenced, but it is clear that the geometric form can be controlled to a large degree.

By inspection, a spherical surface is the most efficient and will produce the least thermal disturbance because it will contain the maximum volume for a given surface area. Changing the radius of a sphere changes its volume and surface. Both magnitudes are subject to different changes. One may set up, as a measure of efficiency, a nondimensional ratio of surface to volume (by dividing actual surface area and volume by the surface and volume for a unit sphere with radius equal to one), and see its change with changing radius. Such an analysis, which would be correct for any units in any measuring system, was performed and it demonstrated that with increased radius the surface to volume ratio drops off rather noticeably (Fig. 6), which means that the efficiency of a sphere increases with size.

However, this type of analysis also shows that the sphere, in the framework of Figure 6, is not unique. A cylinder with a height equal to diameter plots identically with a sphere at all sizes and only flattened cylinders (e.g. $h = r/2$) become less efficient. Figure 6 is therefore not a rigorous measure of changing efficiency; yet surface to volume ratio is an expression of efficiency. If

* $(2\pi rh + 2\pi r^2)/\pi r^2 h$ at $r = 1$ the equation cancels out to 3. Divide vertical scale by 3.

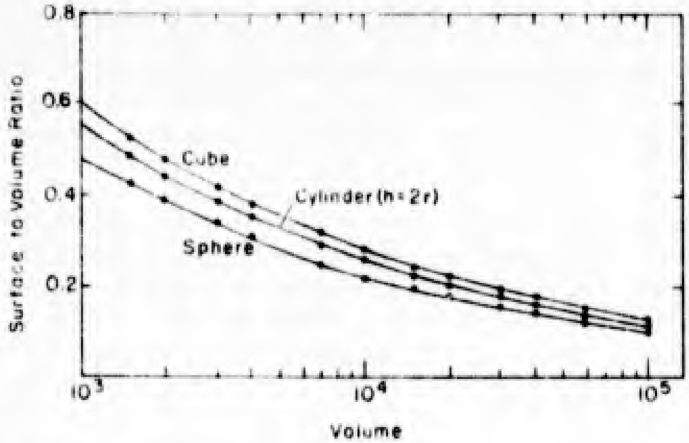

Figure 8. Effect of size upon surface to volume ratios. At large sizes the difference between the different figures has the tendency to diminish.

the axis of a cylinder is its height, then to plot height to radius ratios for various geometric figures one must apply some simple formulism: a cube would have $h:r=1$, a hemisphere would be the same, while a cylinder would vary. A sphere would then have a fixed value of 2. It can be shown then that for a fixed given volume, only the sphere needs the smallest surface to enclose it (Fig. 7). It shows also that the best $h:r$ ratio for the cylinder is 2 and that a hemisphere, a cube and a flat cylinder with $h:r = 1$ are similar. It might also be pointed out that a flat or a slender cylinder becomes increasingly inefficient (left and right side of curve respectively).

How does surface-to-volume ratio, the only measurable shape efficiency factor, change with absolute size? Since surface and volume are magnitudes which change at different rates, total increase of volume will lower the ratio. Furthermore, as shown in Figure 8 the difference between the three most efficient geometric bodies, a sphere, an $h = 2r$ cylinder and a cube, diminishes. Consider that a surface of any kind is, besides being geometrical, also physical; it is always larger than its actual computed or measured value (small deviations from ideal and plain roughness). In other words, the exactness of a selected form is not as crucial for large reservoirs as for small ones. With increased volumes, therefore, heat flow errors due to the difference between computed and created surfaces will decrease. It appears that a spherical or nearly spherical cavity in homogeneous permafrost is relatively easy to produce by the method described.

CONCLUSIONS

To protect a hydrocarbon fuel installation from accidental fire, explosion, etc. it is placed underground. In a military situation, the deeper it is buried, the better it will withstand hostile attacks of all kinds. A buried installation is hardened. A military fuel storage facility must be designed so that it can be constructed quickly, with a minimum of effort. Melting of permafrost is the most expeditious way to make a cavity underground.

While a spherical cavity is the most economical, precise shape is not crucial for realistic sizes. Since the experiment was conducted successfully in discontinuous "warm" permafrost, a fuel storage cavity may be placed in any type of perennially frozen ground. The temperature of the permafrost, its properties (types of ingredients, ice content), and its thickness are the factors affecting the construction of the type of storage facility described.

The principle of fuel storage in permafrost melt cavities is not limited to military applications.

The preceding text describes an experiment which tested the principle. Such a facility withstands considerable thermal disturbance and can incorporate simple means of heat exchange between air, fuel and permafrost. Also important is the relatively low effort required to install the facility in permafrost.

It is concluded, however, that due to unfamiliar technology, some procedural development must precede a standardized routine of construction. The next step would be, therefore, not more research on the principle; the principle was investigated sufficiently and is considered sound. The developmental stage should cover, besides the emplacement process, the adaptation of suitable equipment. Proper technical procedures and equipment will demonstrate the superiority of the installation type.

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Note added in proof. After continuous observation over a period of time had revealed no signs of disturbance in the permafrost, nor any signs of petroleum seepage, the need arose in September 1974 to dismount the installation. The three wooden stages with frozen slurry on top were penetrated one at a time with a 30-in. auger until finally access to the reservoir was established. Visual observation showed that there had been no influx of water from the top of permafrost, and that the measures to prevent it as described above had performed well. The fuel in the reservoir showed no signs of deterioration; a sample tested for compatibility with standard requirements also revealed no signs of deterioration.

The reservoir was filled with several cubic yards of sawdust to absorb the fuel and the shaft was filled with gravel. The experiment was completed and all surface signs of disturbance were obliterated.