Construction And Operation Of Underground Cold Storage Facilities In The North And North-east Of The Ussr

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CONSTRUCTION AND OPERATION OF UNDERGROUND COLD STORAGE FACILITIES IN THE NORTH AND NORTH-EAST OF THE USSR

by N.G. Mironov

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This monograph examines questions relating to the construction and operation of underground cold storage facilities in permafrost areas. It makes practical recommendations concerning the design, construction and operation of such facilities which will make it possible to achieve considerable financial savings and simplify and improve storage conditions for a variety of food products. A description is given of the experience gained in building and operating cold storage facilities in Chukotka.

This publication intended for designers, builders and other specialists engaged in developing permafrost regions.

INTRODUCTION

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The natural resources of the Far North are being rapidly exploited and there has been a corresponding growth in population. As a result the question of the supply and prolonged storage of perishable goods has become particularly acute. Some way must be found of building large cold storage facilities.

The Far North is, of course, a region of continuous permafrost with temperatures in the layer of zero annual temperature fluctuations ranging from minus 2 to minus 10°C.

Shallow-lying cellars have long been used for the storage of food products. Many years ago someone had the idea of utilizing the local natural conditions to build underground cold storage facilities. As early as 10927, M.I. Sumgin had suggested building a huge combined museum and cold store. Since then underground food warehouses have been constructed in various parts of the Far North.

M.M. Krylov (Tumel' , 1945) was the originator of the first design for an underground cold storage facility and this was used in the construction in 1932 of a fish storehouse in the village of Ust'-Port on the Yenisei River. However, according to V.F. Tumel' (1945) , the design was modified somewhat in the course of construction.

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*Page number in the Russian Text. - Translator.

In 1936 two underground storehouses were built for scientific purposes at the Igarka permafrost research station, under the direction of P.I. Mel'nikov.

In 1942 underground cold storage facilities were constructed at Kyusyur on the Lena River and near Anadyr' in Chukotka. The second of these was designed by I.F. Sidorov of the Anadyr Permafrost Research Station (Tumel', 1945).

During construction and the subsequent period of operation the Igarka underground storehouses were used first by P.I. Mel'nikov and then by L.A. Meister and V.F. Tumel' as underground laboratories for various scientific research projects. Mel'nikov succeeded in determining the structural and watertightness characteristics of such buildings in permafrost conditions and also in elucidating the /4
conditions under which the roof would be stable. Later, first Mel'nikov and then Meister and Tumel' studied certain aspects of the thermal regime of the frozen ground around the facilities.

The 1960S saw a boom in underground cold storage construction. Large numbers of projects were begun on collective and state farms in the Chukchi National District, and various scientific research organizations were asked by party and state agencies to undertake scientific feasibility studies prior to the construction and operation of underground cold stores in certain areas. In response to a request from the Council of Ministers of the Yakut ASSR a senior scientist at the Geocryological Institute of the Siberian Division of the USSR Academy of Sciences, K.F. Voitkovsky, produced a design for an underground storage facility suited to conditions in Yakutia.

Similarly, a scientist at the Anadyr permafrost research station, N.G. Mironov, was commissioned by the Chukotka district executive committee and district committee of the Soviet Communist Party to design a cold store for service in Chukotka.

The author of the present work investigated the temperature conditions of some of the existing underground storage facilities, devised solutions to various design and engineering problems, and developed equations for use in thermal calculations.

Notwithstanding the obvious technical and economical advantages of building underground cold stores in frozen ground and underground ice, construction is still being delayed: engineering feasibility studies have not been done, themal equations have not been developed, and the experience that has been acquired in construction and operation has not been made generally available to engineers and technicians.

The author has set himself the task of filling this gap in the engineering literature.

The author wishes to express his sincere gratitude to R.M. Sarkisyan for his work in editing the manuscript and to thank all his colleagues at the laboratory and station who helped him in his task.

Chapter I

UNDERGROUND COLD STORAGE FACILITIES

Structural properties of frozen soils and underground ice

Experience in developing the Far North, and particularly Chukotka, has shown the desirability of constructing cold storage facilities in underground ice and frozen ground.

Practice has demonstrated that the various kinds of deformation undergone by soil used as a building material are caused mainly by the thawing of the permafrost during construction or operation. Lengthy observation of cold stores and shafts in frozen soil and underground ice has shown that frozen very fine-grained icy soil and underground ice are quite strong enough to ensure the stability of the excavations.

The underground cold stores studied in Chukotka, which have been built in loam, loam-sand, silty clayey and icy soils and underground ice, have rooms with spans ranging from 2 to 5 m and an unsupported semicircular dome under rock varying in thickness from 3 to 30 metres. They have been in service for periods ranging from 3 to 10 years and no cases of roof collapse have yet been recorded.

The results of observations of the behaviour of the roofs of underground cold storage facilities constructed in icy clay, loam, and silty loam sand soils and underground ice with temperatures below - 2°C* show that it is possible to make unsupported underground excavations with a span of 4–6 m.

Data on the mechanical and strength properties of frozen soils as a function of their state can be found in the works of geocryologists (Tsytovich, 1958a,b; Vyalov and others, 1962; Velli and others, 1963). /6

The mechanical properties of frozen soils depend chiefly on temperature, structure and texture, the amount of unfrozen water, the

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*Except for saline soils, in the case of which the freezing point of the interstitial water is well below 0°C.

chemical composition of the ice, and so on. The mechanical properties of the soil at the selected site can be determined experimentally or be taken in accordance existing standards and specifications (CH315-65). The magnitude of the design compressive strength (allowable pressure) for frozen ground as a function of temperature and particle size distribution can be judged from the data in Table 1 (Tsytovich, 1958a).

Table 1 Calculated strength values for frozen soils, kgf/cm^2

soil	Maximum soil temperature		
	-0.4°	-1.2°	-4.0°
Medium- and fine-grained sand	6.0	10.0	14.0
Silty loam sands, W ≤ 35%	3.5	7.0	10.0
Silty loams, W ≤ 45%	3.0	5.0	8.0
Ice-saturated silty, sand loam-loam and clay soils and soils with a high content of ice layers and inclusions (over 5 mm thick)	2.5	4.0	6.0

Frosty (unbended) sandy, loam sand soils are characterized by lower strength and significantly lower heat capacity, so they should not be used for the purpose under discussion.

ACCUMULATION OF COLD BY THE FROZEN SOIL AROUND THE COLD STORAGE FACILITY

The main advantage of underground cold storage facilities as opposed to surface ones is that a "reserve of cold"* may be created in

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*This term is taken from refrigeration engineering.

the surrounding soil because of the high heat capacity of the latter. /7 The source of this cold may be cold air from outside circulating through the rooms in winter. The reserve of cold accumulating in the soil depends mainly on the difference in temperature between the source of the cold (air temperature) and the soil, and on the heat capacity of the latter and the conditions and length of cooling.

In the vast territories of the Far North, cold winter air may be used as the cold source, and the higher temperatures in the underground excavations make it easier to use for this purpose.

The minimum average monthly ground temperature increases with depth and it occurs much later than the minimum average monthly air temperature. In the Far North, for example, where the seasonally thawed layer freezes during December and early January, the minimum temperature at a depth of 7 m occurs in July-August (a delay of 5-6 months), and at a depth of 10 m it is reached in September-November (a delay of 8-9 months). The maximum mean monthly ground temperature occurs in November-December at 3 m and in March of the following year at a depth of 10 m, thus lagging eight or nine months behind the maximum mean monthly air temperature.

The annual fluctuations in ground temperature diminish with depth. Already at a depth of 5–7 m the variation is no more than 1-3°C, and deeper down it is only tenths of a degree (Table 2). In most cases the annual zero fluctuation zone for the very fine-grained soils of the Far North lies at depths ranging from 12 to 20 m. These circumstances created favorable conditions for the accumulation of additional reserves of cold through the injection of cold winter air into the underground storage areas.

The above-noted patterns in the time and depth distribution of ground temperature in natural conditions are reflected in Table 2 and Fig. 1.

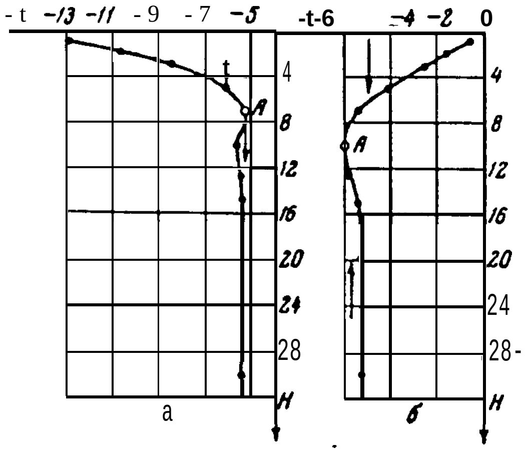

Fig. 1. Depth distribution of ground temperature
a - in winter; b - in summer

Table 2

Mean monthly ground temperatures in 1954 measured at the Soviet Academy of Sciences Permafrost Research Station
(in 'C)

	I pth, m										
	1.0	1.5	2.0	3.0	5.0	7,0	10.0	12,5	15.0	20.0	30,0
Jan. " -	-11,8	—10,5	—9,4	—6,3	—5,1	–5, t	-5,7'	-5,7	—5,6	-5,4	-5,2
Feb.	—12,9	—11,3	—10,6	—8,5	–6,1	-5,3	-5,6	—5,5	-5,4	—5,4	-5,4
March	—15,0	—13,3	—12,2	—10,1	–7,0	-5,7	-5,4	—5,4	-5,2	—5,5	-5,7
April	–10,1	—10,8	-10,7	—10,3	—8,0	—6,2	-5,6	—5,6	-5,5	—5,4	-5,3
May	–5,6	-6,8	—7,6	–8,5	-8,0	—6,7	—5,9	—5,6	-5,6	—5,4	-5,2
June	–2,8	—4,0	—4,9	—6,4	—7,3	—6,8	—6,i	-5,7	-5,5	—5,4	-5,2
July	–2,1	—3,2	—3,9	—5,3	-6,1	-6,6	-6,2	—5,7	—5,6	—5,4	-5,2
August	—0,9	—	—2,4	—3,6	-5,2	—6,3	-6,3	—5,7	—5,6	-5,4	-5,2
Sept.	—0,6	—	—2,0"	—3,1	—4,5	—5,8	—6,1	—5,9	—5,6	-5,4	-5,2
Oct.	—0,6	—	—1,6	—2,6	—4,0	—5,5	—6,0	—5,8	—5,5	-5,4	-5,2
Nov.	'—3,9	—	—3,5	—4,5	—3,7	—5,1	-5,9	—5,8	-5,5	—5,4	-5,2
Dec.	—12,2		—5,4	—6,7	-3,8	—4,0	-5,6	—5,8	—5,6	-5,4	-5,2
Annual mean . . .	—6,5		—6,2	—6,3	— 5,7	-5,7	-5,8	—5,7	—5,5	-5,4	-5,3

Figure 1 shows the ground temperature distribution in winter (February) and at the end of summer (October). The arrows on the graphs indicate the direction of heat flow.

In February the heat accumulated in the soil during summer is dissipated - most of it into the atmosphere and the rest into the underlying soil. The temperature gradients are quite high (1.23 degrees per metre) down to a depth of 7 metres. Beyond that point there is a sharp drop, and at depths of 15-30 metres the gradient is zero, i.e. there is no heat flow.

In October the heat in the upper layers (from 1 to 10 m) flows into the ground. The gradient near the surface is once again quite /9 high and in our case averaged 0.82 degree/m at depths of 1-7 metres, whereas at 15-30 metres the heat flowed in the opposite direction and the gradient was only 0.02 degree/m.

The natural flow of heat per unit from the lower layers can be calculated using the formula

$$q = -\lambda_m \operatorname{grad} t, \qquad (1)$$

where λ_m is the thermal conductivity of the frozen ground; grad t is the temperature gradient, degrees/m.

At grad t = 0.02 degree/m and $\lambda_m = 1.5$ kcal/m^2-hr-degree, the heat flow rate q = 1.5X0.02 = 0.03 kcal/m^2-hr = 0.03X24 = 0.72 kcal/m^2-day.

Since the temperature gradient near the annual zero fluctuation zone is far lower in most areas of the Far North (0.005-0.2 degree/m) than the temperature gradient averaged over the entire depth of the frozen zone, the flow of heat from within the earth will be still lower, by approximately one order of magnitude. This amount of heat is enough to increase the temperature of a layer of soil 1 metre thick by 0.03°C per year provided there is no heat loss from the surface. /10

These calculations are rough estimates and merely show the order of magnitude of the heat flow.

As noted above, the range of temperature variation diminishes with depth. At depths of 3-4 m the maximum heat flux from the atmosphere into the ground in the first and second zones occurs in August-October, whereas at depths of 7-10 m it is observed in November-December. Thus, in August-October the temperature gradient at Anadyr is 0.7-0.8 degree/m at a depth of 3-5 m and 0.2-0.25 degree/m at 7-10 m. Using the above formula to recalculate the heat flow from the atmosphere into the soil, we get a figure of 25-30 kcal/day per square metre for the 5 m horizon and from 7 to 10 kcal/day per square metre for the 10 metre horizon.

From this we can judge the optimum depth down to a cold storage facility at which cooling losses into the atmosphere through the roof and into the underlying soil will be minimal. The appropriate depth in Chukotka is the zone of annual zero temperature fluctuation, i.e. 10-15 m.

At first glance it would seem that the depth of the cold storage facility could be reduced in view of the lateness of the wave of heat from the atmosphere. This is a common error, but it should always be borne in mind that the depth must in all cases exceed the radius of artificial cooling of the frozen soil around the excavation, which is estimated at 4-5 m. If the depth down to the roof is strictly equal to the cooling radius, by the end of winter there will be a relatively low negative temperature, and this will mean an increase in the flow of heat from the atmosphere into the soil in summer. Therefore the depth from ground surface to roof must exceed the cooling radius by at least a factor of two. This will give us the optimum depth cited above, i.e. 10-15 m.

Hence, as already stated, it is best to build underground storage facilities in the zone of annual zero temperature fluctuation (at a depth of 10-15 m).

The creation of a reserve of cold in the surrounding soil in /11 winter depends on the rate of air flow through the rooms, the air temperature, the duration of flow and the thermophysical constants of the surrounding soil. The higher the rate of flow, the higher the heat transfer coefficient and the smaller the temperature difference between the points of entry and exit of the current of air. A low negative air temperature helps to cool the surrounding soil down to a considerable depth.

In order to create a large reserve of cold the passage of air can be speeded up by forced ventilation during the cold season. Care should be taken to ensure that the direction of movement of the forced draught coincides with that of the natural draught.

This is necessary in order to be able to switch from forced circulation to natural circulation, which is much more intense when there is a low-temperature field in the surrounding soil.

CONSTRUCTION ZONES FOR UNDERGROUND COLD STORAGE FACILITIES

Any attempt at zoning is always beset by the difficulty of assessing the principal factors defining the zones. For purely practical purposes we based our zoning of the Soviet North on the following factors: the temperature of the frozen ground, the duration of negative air temperatures in winter, and soil strength. The sample scheme proposed (Fig. 2) is based on I.Ya. Barabanov's geocryological map (1960).

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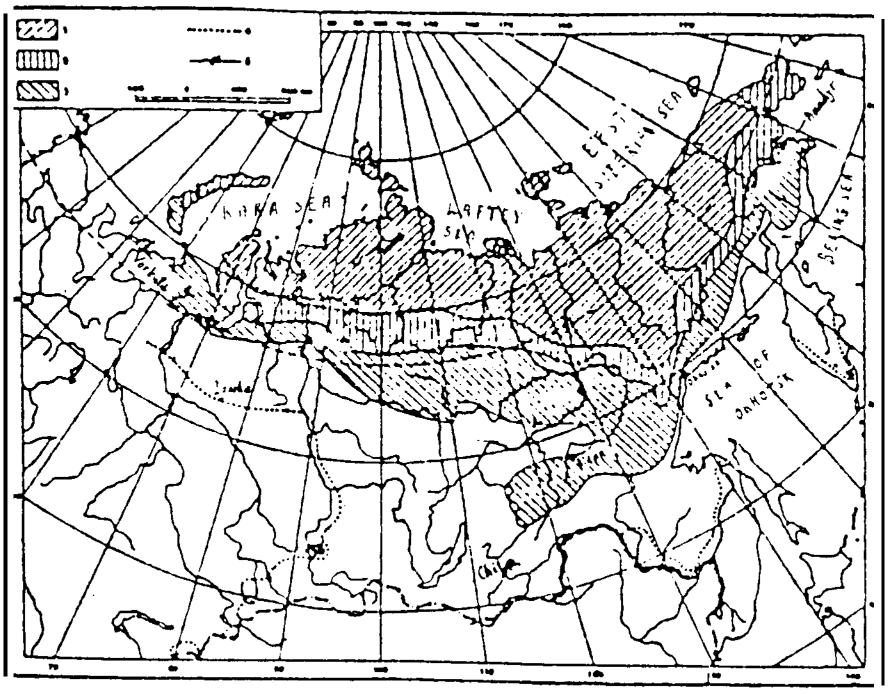

Fig. 2. "Map of the Soviet North showing the zones where it is feasible to construct underground cold storage facilities. 1 - Arctic and Subarctic zone; 2 - temperate zone; 3 - zone of stable cold winters; 4 - limit of permafrost region; 5 - minimum soil temperature near base of layer of annual temperature fluctuations.

In theory, underground cold storage facilities could be built anywhere within the permafrost region, but it makes better economic sense to narrow the choice down to areas with a negative soil temperature below minus 2°C where the winter is long. In the permafrost areas of the North which meet these criteria, both the

the construction costs and operation costs are lower than for surface facilities.

For our purposes we have divided the Soviet North into three zones (see Fig. 2).

Zone I - The Arctic and Subarctic permafrost zone is characterized by low soil temperature below minus 7°C at the zero fluctuation level. /13

The climate is marked by stable cold winters with more than 100 days of temperatures below minus 15°C. The areas concerned lie along the Asian shore of the Arctic Ocean. The western boundary passes along Ob Bay, the southern one around the Arctic circle, swinging north-eastward as far as the 65th parallel, along the minus 7°C isotherm of the soil at the zero annual fluctuation level.

In this zone a reserve of cold can be created in the walls of an underground storage facility in winter by using outside cold air as a cold source. With correct handling, meat, fish and other food products can be chilled, frozen and stored without mechanical aids, relying entirely on the natural cold reserve in the surrounding frozen ground created by the winter. In these circumstances, of course, freezing take's longer than if mechanical refrigeration had been used.

Zone II - This temperature zone is characterized by constant negative soil temperatures ranging from minus 7°C to minus 5°C at the zero fluctuation level. The climate in this zone is marked by stable cold winters with over 100 days of temperatures below minus 10°C. The zone includes the areas to the south of zone I. Its southern boundary passes along the minus 5°C isotherm of the soil at the zero fluctuation level (see Fig. 2).

In this zone a reserve of cold can be built up in the surrounding soil by using additional forced circulation of cold air from outside throughout the entire cold season. The cold accumulated during the winter is enough to store meat and fish for the whole of the warm season. A small amount of produce can be frozen relying principally on the coldness of the soil and on ice-salt cooling. For larger quantities prefreezing in a mechanical refrigerator is necessary. If the span is correctly calculated, the rooms and corridors can be left unsupported.

Zone III. This zone is marked by stable and long cold winters. /14 It lies south of the second zone. Its southern boundary passes along the minus 2° isotherm of the soil at the zero annual fluctuation level. Geographically speaking the southern boundary lies roughly along the line connecting Vorkuta, Salekhard, Igarka and Aldan. In the southern areas of the zone the cold reserve accumulated in winter due to the circulation of could outside air through the rooms will be insufficient for the storage of meat and fish throughout the warm season. In autumn additional cooling will be required - salt-ice or mechanical refrigeration.

In the remaining parts of the USSR, underground cold storage facilities are economical only if ready-made near-surface excavations are used. Mechanical cooling is necessary to provide the right negative temperatures for storage, chilling and freezing. The most economical cold storage facilities under these conditions are M.M. Krylov's ice stores which use mechanical refrigeration.

TYPES OF UNDERGROUND STORAGE FACILITIES AND THEIR DEFICIENCIES

In the Far North several dozen underground cold storage facilities have been constructed which differ in design, layout and operating technology. The differences in vertical and horizontal layout are due to the particular method of ingress used. It has been suggested that underground facilities with (vertical) ingress via a shaft should be called shaft facilities, and those with an entrance at floor level adit facilities. This arbitrary division into two types makes it easier to describe their design and demonstrate the advantages and disadvantages of each type.

Most of the underground cold stores that have been built so far suffer from many substantial defects affecting the temperature regime and operating technology. So far not a single work has been published which deals adequately with the constructional and operating features and defects of underground cold storage facilities. Some of these are described below.

1. Siting too close to the surface. As a rule this results in /15 large unproductive losses of cold from the surrounding soil to the atmosphere. 'l'he air temperature is elevated even in autumn, when there is no natural compensating source of cold (i.e. cold air).

Such a facility was built at the XXII CPSU Congress collective farm in the vicinity of Tavaivaam in the Anadyr district. The depth from ground surface to the roof of the rooms and corridor in this shaft-type facility ranges from 3.5 m at the entrance to 4.5 m at the end.

The facility is built mainly in vein ice and only at three points do the ends of the rooms extend into frozen ground, which is silty loam sand, with a low ice content. In autumn, when the outside air temperature is around 8-10"C, the air temperature inside the ice store often rises to minus 3° .

2. <u>Making the roof of the corridor and rooms slope towards the exit in cold storage facilities of the adit type</u>. The author investigated a facility of this type at the "Kanchalansky" state farm in the Anady district. It is situated 100-150 m from the settlement of Kanchalan, downstream of the river of the same name. The adit was driven in the slope of the first river terrace above the floodplain in frozen silty loam sand. The entrance faces the river (Fig. 3).

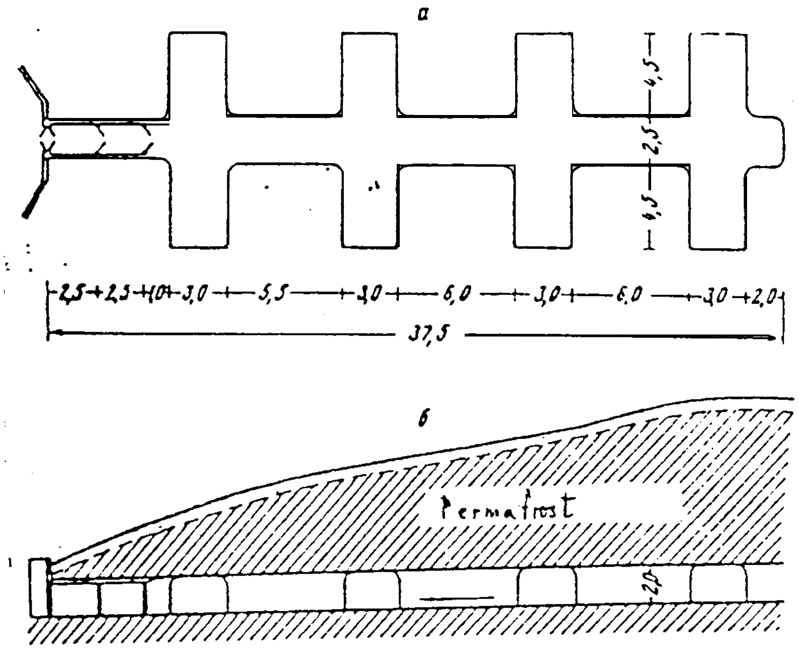

Рис. 3. Подземный холодильник типа штольни в пос. Канчалан Анадырского района Магаданской области

а — план; б — разрез

Fig. 3. An adit-type underground cold store at Kalanchan in the Anadyr district of the Magadan Region
a - plan view; b- cross- section

Because the roof slopes towards the exit, every time the entrance doors are opened warm outside air rushes into the facility and rises to the highest point of the roof at the end of the corridor. This leads to considerable losses of cold and fluctuations in the air temperature inside the facility. When the relative humidity is high in autumn, the temperature fluctuations cause condensation to form on the walls of the chambers and on the produce, so that the latter turns mouldy.

3. The infiltration of surface and ground water leads to a considerable rise in the temperature and humidity of the air inside. At fairly high air temperatures the roofs of the rooms and corridor become much less stable. In the adit-type of facility most of the /16 water seeps in where the entrance joins the corridor and also straight through the ceiling and walls of the entrance area. The water comes in when the ground thaws above the entrance, either because the overburden is not thick enough or because the waterproofing is inadequate. In facilities of the shaft type, the water usually penetrates through the lining of the service and ventilation shafts due to defective sealing.

4. The absence of a lining of ice on the walls of the rooms and corridor leads eventually to drying out of the soil, which then begins to crumble on the lightest contact, or even under the weight of frost. An investigation of existing underground cold storage facilities revealed that soil unlined with ice absorbs the specific odours of the food products being stored, and even ventilation is unable to dispel them completely. It should also be pointed out that /17

lining the walls with wood does not help to remove the odours. Furthermore, voids forming behind the woodwork on the ceiling and walls Increase thermal resistance on the one hand, and on the other promote breeding by rats and mice. It is very difficult to take preventive measures in such facilities. The disadvantages listed can be remedied by lining the walls with ice, making sure that there is no gap between the ice and the soil.

5. The absence of ventilation shafts in all types of underground cold store makes it difficult to create a reserve of cold in winter. This defect was discovered in most of the facilities investigated.

Chapter II /18

CONSTRUCTION OF UNDERGROUND COLD STORAGE FACILITIES

Until now the technical literature has contained very little information on the construction of underground cold storage facilities. Moreover, the works published earlier (Tumel', 1945; Chekotillo, 1945, 1946) are hard to come by and unavailable to most specialists in the field.

Underground cold storage facilities have been built on the basis of individual and imperfect designs. The unsatisfactory performance of some of the above-described facilities in Chukotka (on the XXII CPSU Congress collective farm, the "Kanchalansky" state farm and others) is due to engineering errors of the sort mentioned earlier

(Mironov, 1959). The recommendations given below concerning the planning, construction and operation of cold storage facilities are based on the author's observations of newly built facilities in service in Chukotka, and also on analysis of the results of engineering computations made by the author.

Successful operation of an underground cold store depends largely on correct siting, appropriate scaling, rational layout and other factors.

Selecting the construction site

The choice of site should be governed by' the following considerations.

1. The site should be located in soil with a high content of of ice, including underground ice. It is easier to excavate the rooms and corridor in such soils than in plastic soils with a low ice content. Their heat capacity is considerably higher than that of the /19 latter, and this permits the accumulation of a large reserve of cold in the walls of the facility.

2. A shaft-type facility should be located on a local rise in a generally level area, whereas an adit-type facility should situated on a slope. The surface gradient should ensure natural drainage of surface water without disturbing (eroding) the soil.

3. The facility should be sited close to a population centre in order to derive the benefit of already existing access roads and transmission lines, and to reduce trucking and other costs.

4. Adit-type facilities should be built in permafrost with a depth from surface to roof of the first rooms of not less than 10 m. Underground facilities should not be built on gentle slopes since this would necessitate a long corridor between the entrance and the first rooms.

4. Underground facilities to be equipped with mechanical cooling should be located close to natural water bodies or a water-supply line providing enough water to operate the facility.

The siting, heat engineering calculations and design work will be fruitless without a knowledge of the geological and geocryological features of the area concerned. A design and planning engineer planning a facility in the Far North must have a clear idea of the geology and geocryology not only of the site selected, but also of the adjoining areas, so that if necessary he can make a sound choice based on technical and economic comparisons. A knowledge of the geocryological and geological structure of the site area makes it possible to determine in advance the direction and scope of the surveys that have to be done at each planning stage.

Engineering geologists performing surveys and planners responsible for siting the installation have difficulty identifying /20 underground ice on the basis of external characteristics and general geological structure.

Large accumulations of underground ice were recorded long ago (Shvetsov, 1938; Solovyev, 1947) in Chukotka, but their origin and hence their distribution pattern have long remained uncertain. This applies not only to the ice discovered in Chukotka but also to the underground ice in other parts of the North such as the Yana-Indigirka (Maritime) lowland, the Novosibirsk and Lyakhovsk islands, Eastern Siberia, and others.

It was long thought that large accumulations of underground ice were relics of the ice age, that they were buried glaciers, firn or snow fields. In recent years, however, it has been ascertained that most deposits of underground ice are a natural product of underground ice formation in permafrost conditions. They are either ice veins forming in frost fissures, or layers and lenses of injection ice formed as the result of redistribution of water in the soil.

Thus, wedge-ice is usually encountered in very fine soils and organogenic sediments (clay, loam, loam sand, and, less often, sand). The densest network of wedge-ice is observed in the very fine soils of floodplain alluvial facies, in ice-saturated marine, glacial-marine and glacial sediments.

In cross-section wedge-ice has the shape of a regular or irregular wedge.* The width of the veins at the top has been measured at 3-5 to 10-12 m (Vtyurin, Mironov, 1961; Vtyurin, 1964; Gasanov, 1964). The vertical extent of epigenetic ice veins ranges from 2-8 m, whereas that of syngenetic ice veins is 40-50 m or more. On the surface the wedge-ice system is sometimes associated with fissure polygons.

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*<u>Translator's note</u>: This statement is less self-evident in Russian than in English, since the Russian term for ‘wedge-ice’ translates literally as “‘repeated vein ice’”.

In nature a fissure polygon topography goes through three stages of development: 1) an ice veing growth stage; 2) a destructional stage; 3) a residual stage.

The growth stage is marked by intersecting pairs of low ridges on the surface forming a network of polygons (Fig. 4) .

A change in the heat exchange conditions at the surface (flooding or desiccation due to intesive drainage) increases the depth of seasonal thawing of permafrost and this results in melting and decay of the vein ice and settling of the ground, i.e. to the process known as thermokarst. Thermokarst polygons of destruction are formed. Unlike the growth polygons they are characterized by troughs around the edges and convex surfaces int he centre of the polygon, instead of ridges and boggy depressions. Thus , the destructional stage of wedge-ice at the surface corresponds to a polygonal thermokarst microrelief (Fig. 5). /21

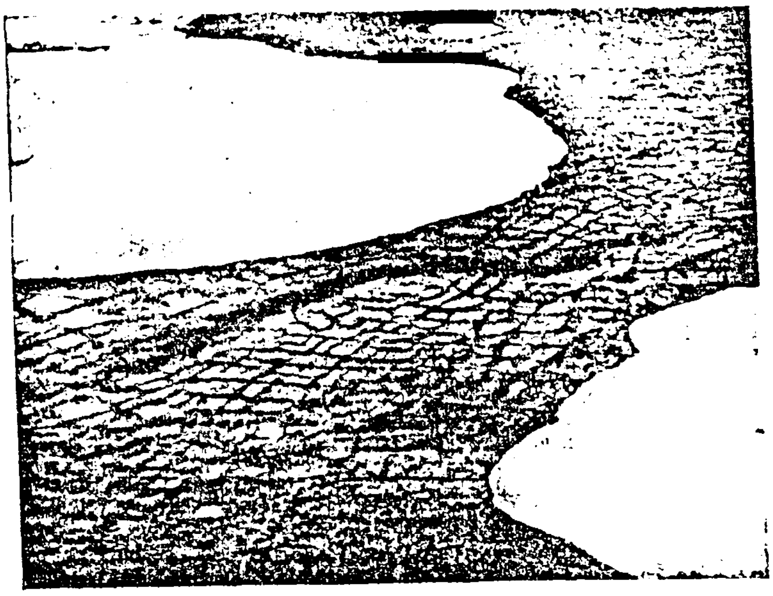

Fig. 4. Ridge polygon microrelief in the Anadyr tundra.

Fig. 5. Thermokarst polygonal microrelief in the Anadyr district

The residual stage is marked by complete or almost complete melting of the wedge-ice and the formation of a residual polygonal relief.

It should be noted that wedge-ice is not invariably associated with these surface landforms. Yet another developmental stage intervenes - the conservation stage, in which for some reason or other /22 the wedge-ice fails to grow and the surface tends to be levelled out. Often it becomes completely flat and loses the appearance of a vein-polygon relief. In such areas as these the wedge-ice can be detected by geophysical methods of exploration or by trenching and drilling.

When conducting the geocryolocial and geological investigations prior to constructing an underground cold storage facility, the network of wedge-ice should be carefully mapped. The plotting of this network can be simplified and speeded up by making excavations at those drilling points where the thickest layer of ice is to be found. The dimensions of the icc body and its strike can be determined by studying its mode of occurrence and the direction of its bedding. Once the strike has been ascertained, it is an easy matter to trace the ice vein all over the area by drilling small test holes. When the second vein has been located, the same method can be used to determine its dimensions and strike. It will then be possible to predict roughly the entire network, since for small homogeneous areas we can assume a regular net in which the polygons will be much the same size and shape.

For this purpose it is sometimes advisable to use artificially induced thermokarst to "develop" a network on areas similar to the one /23 selected (Shumsky, 1955; Vtyurin, Mironov, 1961). This can be done quite simply by removing or flattening the plant cover with a bulldozer in strips 2.5-3 m wide. It should be pointed out, however, that once begun the thawing process will progress and extend to neighboring areas, especially on slopes with intense surface drainage. The experimental areas should therefore be chosen some distance away from the construction site and in locations which are not earmarked for future development. Relatively shallow-lying wedge-ice can be used as a site for a cold store (Vtyurin, Mironov, 1961) as long as additional soil is heaped on top of the facility (the total thickness should be 10 m). In the Siberian North, however, many investigators (E.M Katasonov, B.I. Vtyurin and others) have encountered wedge-ice which could house cold storage facilities without additional soil on top. Such a facility would be roughly three or four times cheaper to build than one in permafrost.

Of the utmost interest for the construction of underground cold stores are the thick deposits of injection ice which are fairly widespread in the Far North.

Depending on the mechanism by which it is formed Sh.Sh. Gasanov (1964) recognized two types of perennial injection ice: injection ice proper and repeated injection ice. The first type is generally lenticular with a round wavy top. The examples of this type of injection ice that have been found measure as much as 60-80 m along the strike. With thicknesses of up to 10 m this type mainly lies at depths of 10-20 m.

Two varieties of repeated injection ice - folded and block injection ice - are fairly common in Chukotka in glacial marine sediments and at the contacts of these sediments with ingressive marine sediments. This type of ice may extend over fairly large areas. The photograph in Fig. 6 gives a clear indication of its extent.

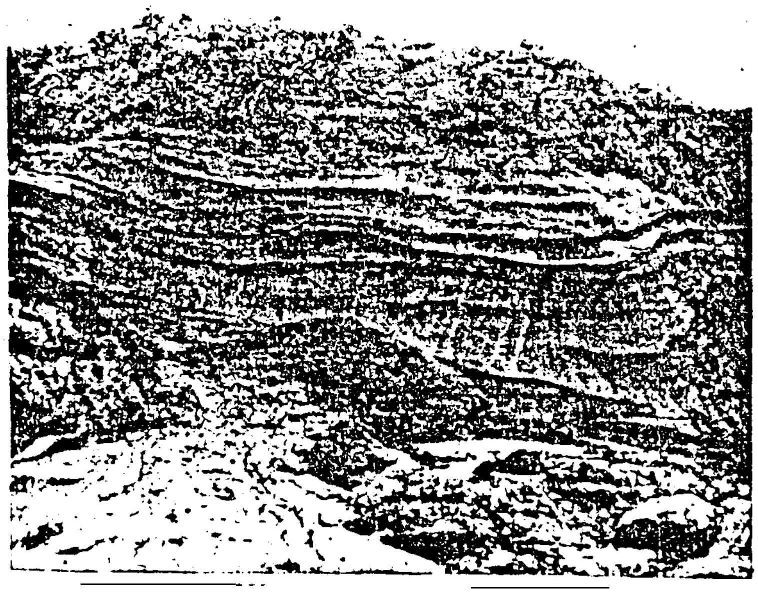

Fig. 6. Fragment of an outcrop of repeated injection ice on the east coast of the Chukchi Peninsula (photo by Sh.Sh. Gasanov)

This kind of ice sometimes stretches for 280-300 m, while its thickness, which fluctuates widely, is often as much as 5-9 m. The upper surface of the ice body is frequently wavy and occurs at depths /24 ranging from 4-5 m to 10-15 m.

The search for occurrences of injection ice in which to build cold stores should be based on general geological and lithological characteristics determined by drilling or the application of geophysical methods. The cost of searching will be more than recovered once the cold store is built and in service.

DETERMINING THE SIZE AND CAPACITY OF THE COLD STORE

The choice of underground cold store depends on local conditions. The key factors are the presence of buried ice suitable for accommodating a cold store, the hydrological, hydrogeological and topographical conditions at the building site, ease of access, snow accumulation, and others.

All cold stores, no matter their type, are made up of several /25 individual arched rooms arranged on either side of a common corridor (adit), or simply of separate rooms. The number of rooms depends on the amount of storage space required.

The size of the rooms, and especially their width, is dictated by the stability of the roof. Room length is predetermined by the method used to store the food and by the way in which transport is organized within the store. As shown by operating experience with ice warehouses (Chekotillo, 1946) and underground cold stores (Mironov, 1965), the rooms should be 4-5 m wide, 10-15 m long, and 2.5-3 m high.

This sort of width for rooms with arched roofs will ensure roof stability without support in the loam and ice-rich loam sand soils in construction zones I and II.

The rooms in the cold store design proposed are divided into three groups according to their intended function: storage rooms, chilling rooms and freezing rooms. The minimum number of each type of room will be determined by thermal calculations taking into account the reserve of cold in the frozen soil around the store.

Larger underground cold stores are cheaper to build and operate. With increase in capacity the cost of installing the entrance per square metre of usable area diminishes. It is undesirable to build a facility with only one or two rooms because chilling, freezing and storing should be done in separate specially equipped rooms. Moreover, the rooms should be adapted to each individual type of food product (meat, fish, butter). Thus the store should have at least 3-4 rooms.

The handling capacity of the prechilling and freezing rooms can be calculated using the formula

$$A = 1.5\,\frac{'\mathrm{max},}{30} \qquad (2)$$

where 1.5 is a coefficient allowing for unevenness in the inflow of produce; G_{max} is the net weight of the produce entering the cold store every month; 30 is the number of days in the month.

The cooling room capacity ensuring the required level of /26 production is a funtion of the time taken to chill and the allowed density of stacking per square metre of room space. The chilling time depends on the temperature, the thermophysical characteristics and other factors.

The stacking density of the freezing rooms is also dependent on the temperature and thermophysical characteristics of the surrounding soil and the produce. The density can be determined by heat engineering calculations or by experiment. It should always be borne in mind that the air temperature inside the rooms must not rise above minus 2-4°C, otherwise the roof may cave in.

The useful area of the freezer rooms is a function of the daily output A, the stacking density per square metre a, and the chilling time τ_3

$$S = \frac{A\tau_з}{a}.$$

The freezing time for meat and fish arranged in a single layer is estimated using Ryutov's empirical formula

$$\tau_з = \frac{\gamma_п}{\lambda_п}\left[\frac{q_п(1 + 0,0057\,t_н)}{8(t_{кр} - t_0)} + \frac{mC_0}{9,86}\left(\ln\frac{t_{кр} - t_0}{t_{к.ц} - t_0} + 0,21\right)\right] \times$$
$$\times \Delta\left(\Delta + 4\frac{\lambda_п}{\alpha_п}\right), \qquad (3)$$

where γ_π is the specific weight of the frozen produce, kg/m^3; and

λ_π is the thermal conductivity coefficient of the produce, which is a function of its final temperature; for meat and fish, the following values can be taken (Chizhov, 1956):

Final temp. of produce, 0°C	0	-1	-5	-10	-20
Thermal conductivity, kcal/m-hr-degree		0.6	1.0	1.2	1.4

q_π is the latent heat of ice formation per kg of produce (kcal/kg); it is taken from Table 3 using the final temperature and moisture content of the produce as coordinates;

Table 3

Latent heat of ice formation q_{π} per kilogram of meat and fish /27
(in kilocalories per kilogram; formula 3)

Final temperature of produce	water content of produce, %					Amount of water frozen solid, %
	60	65	70	75	80	
-6	36	39	42	45	48	75
-8	38	41	44	47	50	78
-lo	39	42	45	48	51	80
-12	40	43	46	49	53	83
-18	41	44	48	51	55	85
-20	43	47	51	-54	58	90

$\alpha_{П}$ is the coefficient of heat transfer from the surface of the produce to the cooling environment, kcal/m^2-hr-degree ;

co is the heat capacity of the frozen produce, kcal/kg-degree ;

A. is the stack height, m;

$'_{H}$ is the initial temperature of the produce;

t_{Kp} is the initial cryostatic temperature of the produce, "C;

$t_{КЦ}$ is the final temperature in the centre of the produce, 0°C;

t_0 is the temperature of the cooling environment, 'C;

m is a correction factor dependent on the ratio $\Delta:\delta$ (here $\delta = \lambda_{П}:\alpha_{П}$); below we give the magnitude of the factor based on the data of Chizhov (1956):

$\Delta:\delta$	0.1936	0.3475	0.590	0.988	1.710	3.412	5.85	8.25	10.63	16.0	∞
m	1.217	1.200	1.183	1.157	1.112	1.074	1.074	1.027	1.019	1.01	1.00

$1 + 0.0057\, t_H$ is a correction binomial allowing for the initial drop in temperature.

For products of a cylindrical shape (certain kinds of fish) the freezing time can be estimated to within 10-15% using the formula /28

$$\tau_з = \frac{q_з \gamma_п d \alpha_п}{4(t_{кр} - t_0)} \left(\frac{\alpha_п}{4\lambda_п} + \frac{1}{\alpha_п} \right), \qquad (4)$$

where d is the diameter of the cylinder, m;

q_3 is the specific heat of freezing of 1 kg of the product, kcal/kg equal to

$$q_3 = C_T(t_H - t_{KP}) + (W - W_{H3})\rho + C_{\theta}(t - t_{C.K});$$

here CT is the heat capacity of the thawed produce, kcal/kg-degree;

W is the water content of the produce, kg/kg;

W_{H3} is the quantity of unfrozen water in the produce in relation to its final temperature;

ρ is the heat of crystallization of the water, equal to 80 kcal/kg;

$t_{C.K}$ is the average final temperature,

$C_0 \cdot 0.5\,(W - W_{H3}) + C_{C.K}\, W\,(1 - W_{H3}) + C_C(1 - W)$ is the heat capacity of the frozen produce, kcal/kg-degree;

C_C is the heat capacity of the dry parts of the produce;

$C_{C.K}$ is the heat capacity of the unfrozen juices of the produce.

The freezing of the produce can be considerably speeded up if we increase the surface heat transfer coefficient by boosting the circulation of air in the chamber and lowering the temperature of the refrigerating environment. The freezing time can be cut by 10-30% by doubling the heat transfer coefficeint and by 5-7% by lowering the temperature of the refrigerating environment by 1°C.

The freezing load per square metre of floor space depends on the heat capacity and temperature of the surrounding soil. In spring, when the temperature of the surrounding frozen soil is fairly low, the produce freezing speed will be at its maximum. In autumn the soil temperature is much higher and freezing takes place more slowly.

PLANNING AND EXCAVATION WORK

Where necessary the selected construction site must be prepared by filling in and turfing over all breaks in the moss-tundra cover, such as thaw depressions, sinks, artificial trenches and other similar /29
features. This work is normally done in early spring. Special attention must be paid to surface and flood water drainage. The method to be used is as follows.

1. Surface water, i.e. rain water and snowmelt, must be drained off so that no erosion takes place. Surface water should be intercepted by berm ditches situated more than 150 metres above the site. It should be remembered that rain channels may form along ice veins. If the site contains wedge-ice, the surface water should be intercepted by levees to avoid disturbing the moss-tundra plant cover. These levees should be turfed over and reinforced if necessary.

2. Places where the moss-tundra cover has been disturbed

should be carefully repaired. This must be done in such a way that there is no possibility of thermokarst forming or, where already present, progressing still further.

3. Before the excavation work is embarked upon the ground should be carefully prepared: the approach roads should be constructed, drains and water by-passes installed, layout completed, and measures taken to prevent the formation and development of thermokarst.

It is desirable to begin the actual excavation work in the autumn-winter period, when it can be combined with artificial cooling of the frozen ground. When working in autumn precautions should be taken to keep out surface water. The entrance should be constructed at the same time work begins on the excavation. Special attention must be paid to the waterproofing of the entrance.

In the case of shaft-type underground storage facilities the best way to keep out water is to line the mouths of the loading shaft and ventilation shafts with sheet metal down to a depth equal to twice the thaw depth. Figure 7 shows the design of a loading shaft with a staircase.

In plan the shaft measures 320 X 320 cm. Around the edge of the shaft there are four flights of stairs descending at an angle of 45°. The height and width of the steps is taken as 20 cm. The flight /30 width is 90 cm. The 90 X 90 cm landings rest on beams with their ends embedded in the frozen ground to a depth of 50 cm. The embedding is done as follows: 1) line the beams up with the level marks shown on the plan; 2) wedge their ends into the holes; 3) fill the holes in around the ends with damp soil; 4) freeze the soil. The beams should preferably be installed during the cold season, when it is much easier

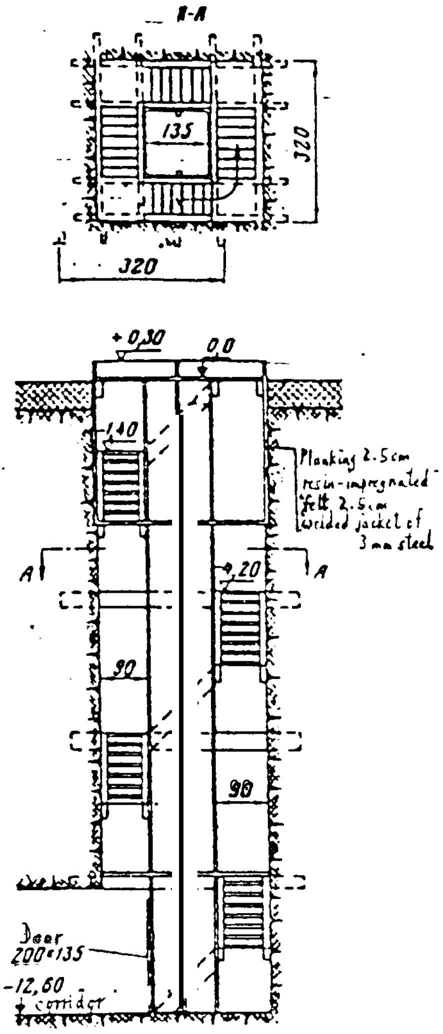

Fig. 7. Loading shaft of shaft-type underground cold storage facility

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to freeze them in place. Resting on the stair beams is a plank lining extending for the entire height of the shaft. Nailed to the lining are the guides for the loading cage or platform.

To restrict the amount of heat entering the excavation, the shaft has three boarded warm air barriers at different levels: the first at the mouth, the second in the middle, and the third at the level of the arched roof of the corridor. The barriers must be fitted carefully and without any gaps. A hatch (door) must be left for the passage of workers, and a double door for the passage of goods fitted with an automatic opening and closing mechanism (Fig. 7). The shaft lining protrudes 20-30 cm above the planned surface of the collar of spoil. Over the shaft there is a frame-and-fill shaft house measuring /31 5.5 X 6 m in plan and 2.5-3 m in height. Near the ceiling there should be a telpher system or single-girder overhead traveling crane. If there is no telpher or electric hoist, the goods must be raised and lowered with a hand winch.

The entrance to an adit underground cold store (Fig. 8) consists of U-frames spaced 0.5 m apart. The entrance is lagged on top and at the sides with a prop wall composed of half-rounds* measuring 20/2 - 25/2. The portal itself consists of half-rounds of the same size. The portal serves as a retaining wall for the fill on top of the entrance, and it must be carefully anchored and secured to the entrance.

There are two sets of double doors leading into the entrance. The outer doors are insulated and made of boards. The inner ones are /32 latticed and may be made of rod iron. Where iron is not available, they can be made of bars measuring 5 X 5 cm in cross-section. The entrance should be carefully sealed to keep out ground and surface water. When building the entrance and waterproofing it, particular attention should be paid to where it joins the corridor of the cold

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*Translator's note: No convincing meaning for the Russian term "polovinka" could be found. The only dictionary in which it occurred gave "half-bat'" or "half-brick", but it seems more likely to be timber.

store, since in most of the facilities investigated by the author that was where water usually penetrated. The best waterproofing material for the entrance is a layer of ice-filled loamy or clayey soil kept in a permanently frozen state. The damp material is spread on top of the entrance in a layer twice as thick as the seasonally frozen layer.

After installing the entrance and waterproofing it, the excavation work can begin. The necessary safety precautions must be taken during the drilling, blasting and mucking operations. It is particularly important to ensure that no overhangs or areas of fractured rock remain on the roof to endanger the safety of the workers. The roof should be inspected carefully after each series of blasts, not only near the face but all over the chamber.

When the driving is complete there should be another careful inspection of the roofs of the rooms and any scaling should either be removed or shored up.

STRUCTURAL FEATURES OF COLD STORAGE FACILITIES

The internal layaout of an underground cold storage facility should meet the following requirements:

a) a conventional operating plan, ensuring preservation of quality and original taste properties of the products;

b) economy (the construction and operating costs must be minimal);

c) industrial hygiene: appropriate measures must be taken to ensure that the personnel operating the facility have all the necessary conveniences.

The designs recommended satisfy the above requirements.

Construction costs per unit of usable space depend on the capacity and type of the facility, on geographical location (the regional factor), soil category and so on. /33

It is advantageous to build the facility in underground ice or soils with a high content of ice, since it is 4-5 times less difficult to excavate in them than in frozen soils with a low ice content. The cold capacity of the frozen walls of the cold store depends on their heat capacity and the amount of material participating in the accumulation of cold. The cold capacity of buried ice and icy soils Is virtually the same because ice has a somewhat higher heat capacity but lower heat conductivity than frozen soil; hence a smaller volume of ice is taking part in the accumulation of cold. This should be borne in mind when planned the facility: the usable area of the chilling, freezing and storage rooms must match the flow capacity of the facility and the type of food product, which ultimately determine the power of the heat source and the thermophysical possibilities for the accumulation of cold in the walls of the store.

As already noted, the capacity of the underground cold store can be determined by thermal and heat engineering calculations. We can estimate the space requirements for chilling, freezing and storage, and the time required to cool the frozen soil when outside air is passed through the rooms in winter.

The freezing and storing of the food products are done in separate rooms. Any decision concerning joint storage of different products in the same rooms must be made in each case on the basis of hygienic and temperature considerations.

The temperature regime of the cold store predetermines its cooling ventilation plan. In underground cold storage facilities

(Fig. 8, 9) the rooms are ventilated by a current of cold air whose direction is controlled by a system of doors or draught barriers.

In Fig. 8b the stream of air enters the cold store through the entrance, then passes through the doors of rooms 1 and 2, flows round via the connecting passage at the ends of these two rooms into rooms 3 and 4, out into the corridor, then into rooms 5 and 6, through the connecting passages into rooms 7b and 8, then up the corridor again and into the ventilation shaft. The air can be made to move in this way by closing the doors in the corridor between rooms 1 and 2 and 3 and 4 and between rooms 5 and 6 and 7 and 8. Operating on this plan the ventilation system is designed for the maximum pressure drop in a stream of outside air moving through all the rooms at the proper speed. /34

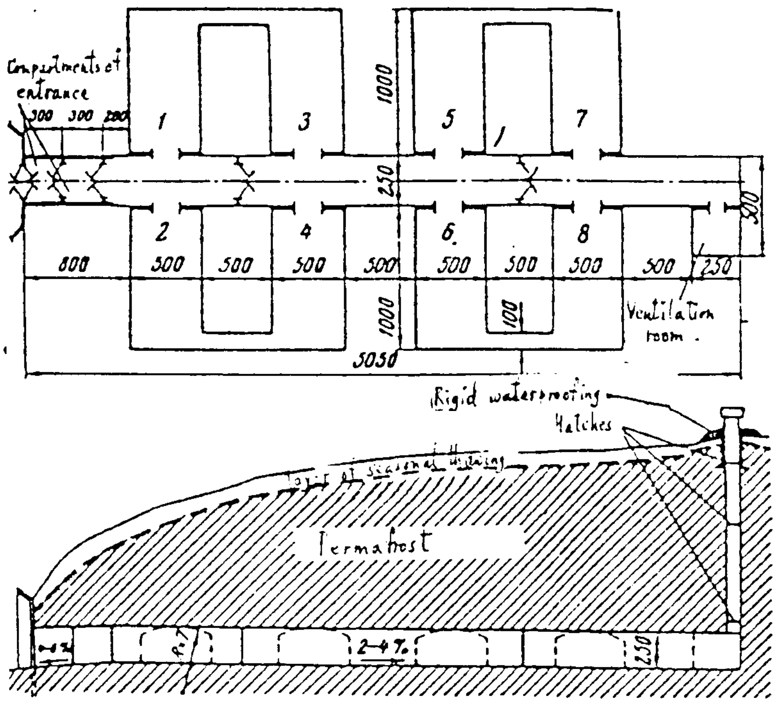

Fig. 8. Adit-type cold storage facilities
1,2 - chilling rooms; 3-6 – freezing rooms; 7,8 - storage rooms

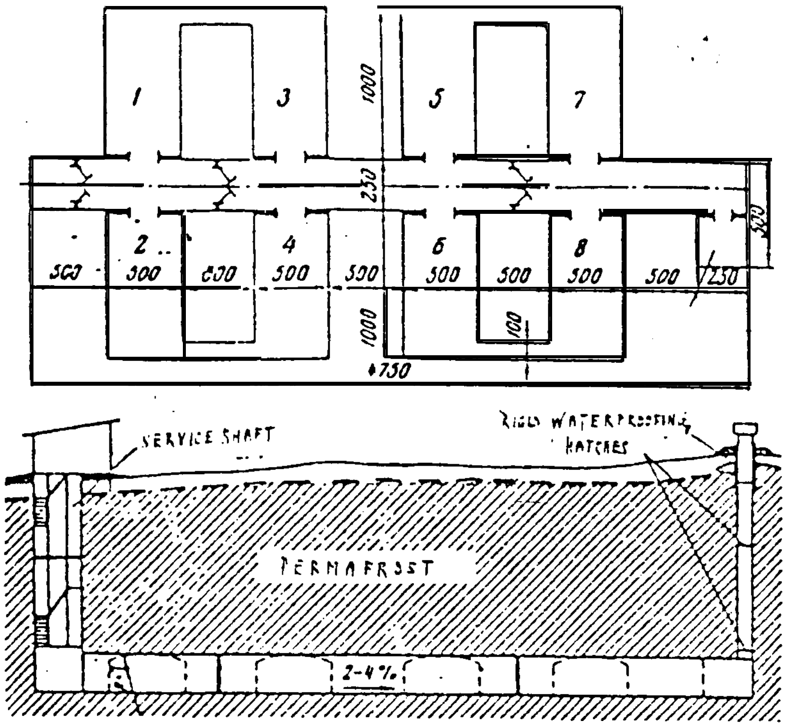

Fig. 9. Shaft-type underground cold storage facility
1,2 - chilling rooms; 3...6 - freezing rooms; 7,8 - storage rooms

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In Fig. 10 (an underground cold store with a fan-shaped layout) the winter forced cold air circulation system is either individualized, with air being blown (sucked) through a special ventilation duct located at the end of each room and leaving via the loading hatch, or else unified, with the chambers being connected by -ventilation ducts leading to the same ventilation shaft, which may be the loading shaft.

The installation of ventilation shafts at the end of each room greatly simplifies the ventilation system, but it involves more excavation and construction work and is therefore more expensive.

Underground cold storage facilities built in frozen soil are much cheaper to operate than surface facilities: the reserves of cold created for chilling and storing the produce are much higher, and the /36

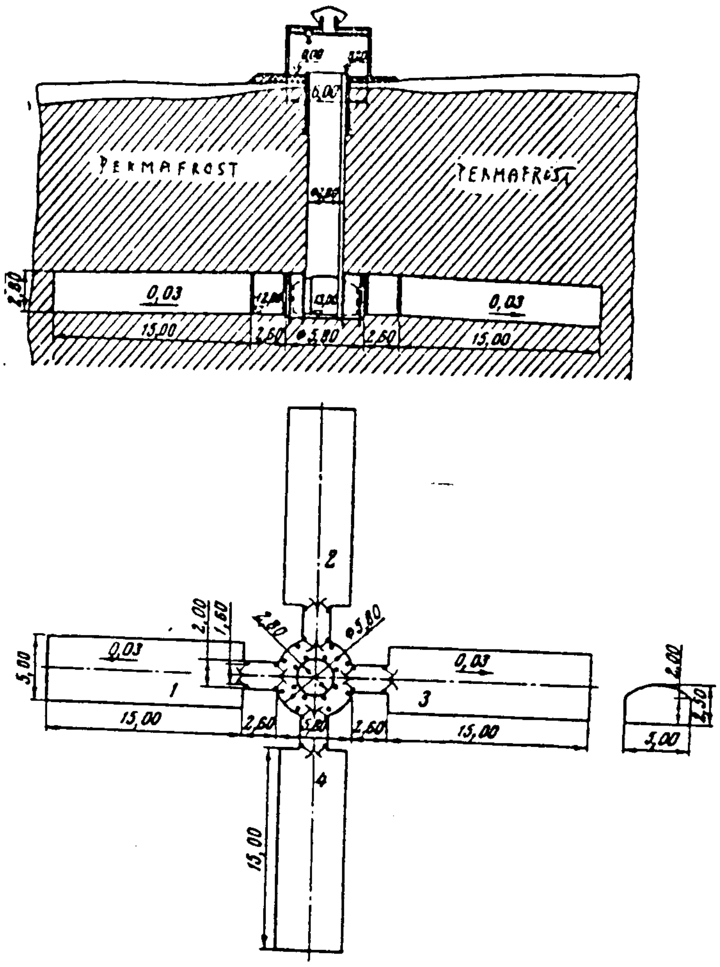

Fig. 10. A shaft-type underground cold storage facility with the rooms arranged in the shape of a fan
1 - chilling room; 2,3 - freezing rooms; 4 - storage room

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amount of heat entering surface cold stores through the structures often accounts for 60% of the total organized heat flow.

Other operating factors to take into account are the outflow of cold resulting from the opening of doors, air leaks through the walls, floor and ceiling, the presence of personnel in the rooms, lighting and so forth. In surface facilities these losses amount to 24% of the organized heat flow (Komarov, 1962). They are greatly reduced by the airtight barriers in Underground warehouses.

The size of the ventilation shaft must be calculated, but its cross-section should not be less than 0.8 X 0.8 m. The top of the duct should be additionally insulated with layers of moist loamy soil and a covering of tundra moss. Water can be kept out of the duct by installing a rigid moisture barrier extending for a height equal to twice the depth of seasonal thawing of the soil. The rigid barrier may be made of sheet metal or metal cylinders with their ends welded together. Three holes must be made in the ventilation shaft at different heights: the first at ground surface level, the second 2.5-3 m below the ground surface, and the third at the level of the roof of the ventilation room.

The ventilation room is located on one side of the corridor and must be large enough to accommodate the ventilation plant. The room is separated from the corridor by a door. In cold storage facilities with the fan-shaped layout the ventilation shaft should be placed in the furthest corner of each of the rooms.

The forced ventilation system may operate by blowing or by suction. The forced air must move in the same direction as the natural air flow. In some cases this results in self-ventilation of an underground cold store. In the shaft type of facility the current of ventilating air should come in through the entrance and leave via the /37 ventilation shaft, which projects far above the mouth [of the main shaft].

The control panel for the ventilation system should be located at the surface and have an automatic thermal relay for switching the system on and off.

CALCULATION OF ROOM AND CORRIDOR ROOF STABILITY

The physicomechanical and strength properties of frozen soils are closely dependent on their temperature, lithology, cryogenic composition, moisture content (ice content), internal relations and other factors.

The internal relations - the combined effect of the cohesive forces and internal friction - depend mainly on the strength of the bonds between the mineral particles of the soil and the ice and on the friction between the soil particles and the presence of unfrozen water. The cohesion between the mineral particles and ice depends on the type of ice-cement (contact, film, pore, basal) and on the amount of unfrozen water, which is governed by the particle size distribution, temperature of the rocks, salt content and other factors.

Soil containing the basal type of ice-cement is stronger than that containing the contact type. The deformability of frozen soils depends chiefly on temperature and the amount of unfrozen water, which determines their plasticity. The strength, deformability and plasticity of frozen soils are discussed in the works of N.A. Tsytovich (1958a,b), K.F. Voitkovsky (1960), S.S. Vyalov et al. (1962) and many others. Those interested should refer to them.

The example we give of chamber roof stability calculation, which is based on the maximum roof exposure method*, is taken from the work of K.F. Voitkovsky and A.F. Zil'berbord (1959). In this method the roof is regarded as a slab supported at the edges.

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*Translator's note: This may be the maximum-pressure arch method, but no confirmation could be found.

The maximum moment for a rectangular slab with a short edge 1_m is in the centre of the span and is determined from the formula /38

$$M_{max} = БPl^2,$$

where P is the load per unit area, in kg/cm^2; Б is a numerical coefficient which depends on the length/span ratio of the slab L/l, and it has the following values

L/l	1	1,2	1,5	2,0	3,0	∞
Б	0,0460	0,0009	0,0798	0,1008	0,1186	0,1250

The load per unit area of the slab is determined from the formula

$$P = \frac{\gamma_{гр} H}{10}, \qquad (5)$$

where $Y_{гр}$ is the average unit weight of the rock, in t/m^3; H is the thickness of the overburden.

The maximum span $1_{пр}$ of a stable slab is determined from the formula[1]

$$1_{пр} = \sqrt{\frac{G_{сж} G_p}{2(G_{сж} + G_p) БP}}\, h, \qquad (6)$$

where $G_{сж}$ is the ultimate long-time compressive strength at negative temperatures of the frozen soil;

G_p is the ultimate long-time tensile strength

$h = H - h_{от} - 1$ is the design thickness of the slab in m

(here $h_{от}$ is the depth of seasonal thawing of the soil, in m; 1 is the possible reduction in the thickness of the slab when the roof weakens as the result of fracturing and spalling).

<u>Specimen calculation of the maximum span.</u> H = 8 m ; $h_{от}$ = lm;

$\gamma_{гр}$ = 1.8 t/m^3; G_p = 2.5 kg f/cm^2 (for loams with a temperature of -4 degrees).

$G_{сж} = G_p$ X 2 = 2.5 X 2 = 5 kg f/cm^2 (for loams, the ultimate long-time compressive strength is z-3 times greater than the ultimate long-time tensile strength G_p).

L = 10 m; 1 = 5m; L/l = 10:5 = 2; Б =01008 (the value of Б is taken from its aforementioned relation to the ratio L/l).

Let us specify h = 8-1-1 = 6 m; $P = \frac{1.8X8}{10}$ = 1.44 kg/cm^2. /39

Then

$$l_{пр} = \sqrt{\frac{5\cdot 2,5}{2(5+2,5)\cdot 0,1008\cdot 1,44}}\cdot 6 = 15,7 \text{ м}.$$

Given a safety factor of 2.5, the maximum room span will be 15.7:2.5 = 6.3 m.

From the above example it can be seen that a span of 4-5 m is quite stable and requires no support.

In cases where the rooms are excavated by blasting, U-frames will have to be inserted to" stop the rest of the roof collapsing. The frames are designed to withstand the load of spalling layers of rock up to 1 metre thick. U-frames can be incorporated in the design of the cold storage facility to provide a structure from which to suspend the telpher beam needed to mechanize product transport; the frames can also be used for other purposes.

The safety factor will be much higher for an arched roof.

Chapter III

THERMAL CALCULATIONS IN UNDERGROUND COLD STORE DESIGN

The thermal calculations for underground cold storage facilities differ somewhat from those for surface facilities, so readers should be given a brief outline of the methods used.

The thermal calculations must determine the refrigeration requirements for chilling, freezing and storage and ventilation during the warm season, the operating losses, and also the minimum reserve of cold accumulated by the frozen soil when cold outside air is passed through the corridor and rooms of the facility during winter. The design calculations should give the loading rate per square metre of room space for product chilling, freezing and storage, depending on type, thermal properties etc.

The initial design data required are the plan view configuration and dimensions of the facility, the thermophysical characteristics of the frozen soil and the local climate parameters.

The quantity of cold accumulated in the walls of the chamber

$$Q \geqslant Q_1 + Q_2 + Q_3 + Q_4, \tag{7}$$

where Q_1 is the amount of cold used to chill the produce to $t_{\text{кр}}$; Q_2 is the amount of cold used to freeze the produce; Q_3 is the amount of cold used to cool the produce from $t_{\text{кр}}$ to the storage temperature; Q_4 is the amount of cold lost during operation (due to opening of outside doors, the presence of personnel in the rooms, lighting, etc.).

During the first few years of operation the amount of cold accumulated should be much greater than the freezing and chilling requirements and operating losses. This is due to the artificial cooling zone formed around the cold store. In later years, when the configuration of the zone has stabilized, the amount of cold accumulated will balance the amount expended. /41

The amount of cold needed to chill and freeze the produce depends on the thermophysical properties of the latter and can be determined from the following equations:

$$Q_1 = \sum P_i C_i (t_1 - t_{кр}); \qquad (8)$$

the refrigeration requirement for freezing

$$Q_2 = \sum P_i W_i \omega_i 80; \qquad (9)$$

the refrigeration requirement for cooling from $t_{кр}$ to the storage temperature t_2

$$Q_3 = \sum P_i C_0 (t_{кр} - t_2); \qquad (10)$$

where P_i is the weight of the produce and containers, in kg/day; C_i is the heat capacity of the produce and containers; t_1 is the initial temperature of the produce when delivered to the facility; $t_{кр}$ is the freezing point of the juices in the produce (minus 0.6-1.2 degrees for meat); t_2 is the final temperature of the produce; W is the water content of the produce, in kg/kg; $\omega = W_л / W$ is the ratio of frozen juice to water at t_2; Co is the heat capacity of the frozen produce.

Observations show that most of the heat generated by the produce stacked on the floor of the room is transmitted to the ground under the room. During the first few years of operation of the facility, before the cold zone has stabilized, the amount of heat involved represents roughly 50% of the entire amount of cold accumulated in the walls.

The amount of cold used to ventilate the cold storage facility for hygienic purposes and make good operating losses cannot be calculated accurately and must be determined experimentally.

Experience in the operation of adit-type underground storage facilities in Chukotka has shown that they are thoroughly ventilated when the doors are open during the daily loading and unloading /42 operations, even when the ventilation shaft is closed. When the frequency of such operations is less, the facility should be aired by opening the entrance doors for 15-20 minutes every day. The minimum amount of daily ventilation for all types of underground storage facility should be equal to 1-2 air changes.

It should be borne in mind that in adit cold stores in which the ceiling slopes towards the entrance, ventilation brings in too much warm air from outside and this must be allowed for when making thermal calculations of the amount of cold lost during operation.

In shaft cold stores sufficient fresh air comes in through the loading shaft when it is opened daily for hoisting and lowering produce. With longer intervals between these handling operations the ventilation and service shafts should both be opened for 15-20 minutes a day.

The amount of cold used to ventilate and compensate for operating losses in adit cold stores in which the roof slopes away from the entrance and in shaft cold stores can be determined from the formula

$$Q_4 = \sum bV\,[0{,}31(t_н - t_к) + r'(\psi\varphi - \psi'\varphi')],\ ккал/сутки, \qquad (11)$$

where b is the number of air changes per room each day, which for underground facilities is 1-2; V is the volume of the room being ventilated, in m^3; $t_H - t_K$ Is the difference in temperature between [the air outside and inside the room, in degrees; r′ is the heat of] condensation of the water vapour (at $t_K < 0$ degrees, allowing for the water-ice transformation, r′ equals 0.69 kcal/g); Ψ, Ψ' are the moisture contents of the air at t_H and t_K, in g/m^3; φ, φ' are the relative humidities (in decimal fractions) at t_H and t_K; 0.31 is the heat capacity of the air.

Formulas (8)-(11) determine the process heat requirements. Let us now estimate the reserve of cold accumulated in the frozen soil around the cold store when outside air is passed through the corridor and rooms during winter.

The thermal calculations for estimating the reserve of cold in the walls of the cold storage facility include determining the cooling radius and temperature distribution in the cooling zone.

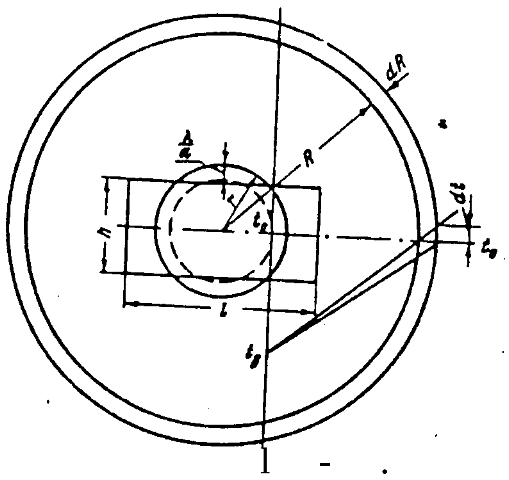

Fig. 11. Determination of cooling radius of the soil around the chamber of an underground cold store in an infinite rock mass

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Below we give an approximate estimate of the radius of the cylindrical cooling zone around a cold storage facility consisting of a single room and a number of rooms (Figs 11-13).

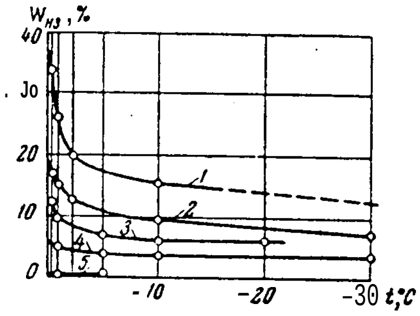

Fig. 12. Curves depicting the unfrozen water content in frozen soils
1 - clay; 2 - cover clay; 3 - loam; 4 - loam sand; 5 - sand

/44

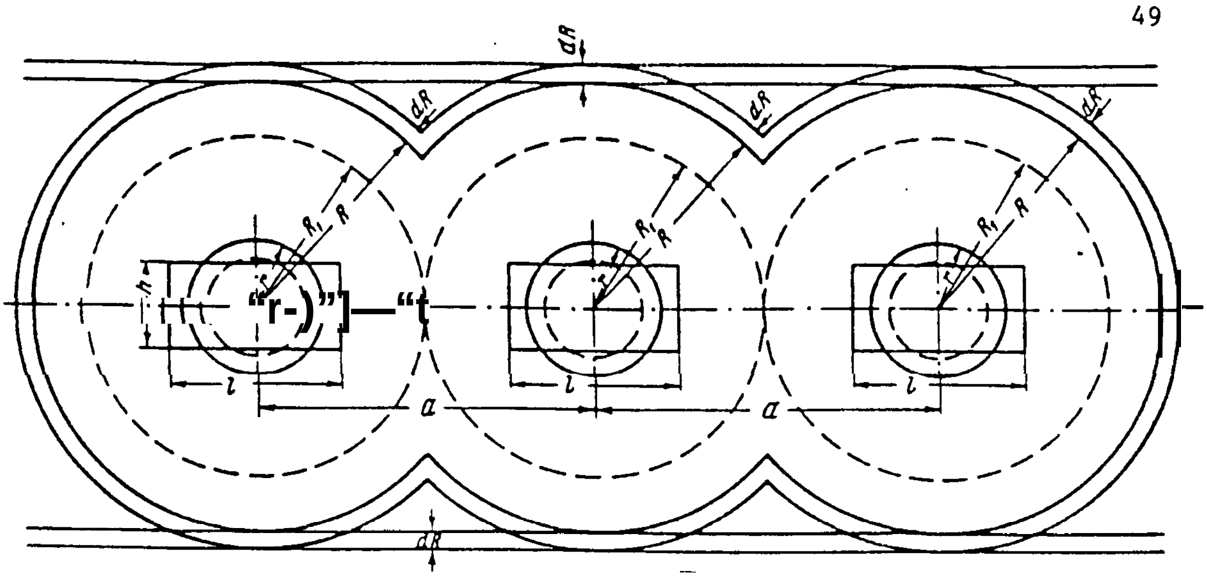

Fig. 13. Determination of the cooling radius of soil around several rooms of an underground cold store in an infinite rock mass

Calculation of the cooling radius for a single room

/45 As already noted, computation of the reserve of cold accumulated by an underground cold store in winter involves determining the radius of the cylindrical zone of cooling of the soil around the store.

Approximate solutions to the more complex problem concerning the freezing rate of moist soils were obtained by N.I. Saltykov (1944), Kh.R. Khakimov (1949), N.G. Trupak (1954) and others. They all consider the phase changes of the water, and take as their boundary conditions constancy of the temperature on the inner surface of the freezing cylinder. Ice formation on the outer surface of the cylinder causes the crystallization temperature on this surface to stabilize virtually at 0°C. The temperature distribution throughout the soil mass therefore has the character of the field typical of a 2-layer body around which the temperature remains invariable. This kind of solution is not valid for the cooling of a homogeneous (in our case frozen) body .

As the soil temperature drops, the amount of unfrozen water 'H3 in frozen soil diminishes in accordance with the law graphically depicted in Fig. 12.

The heat loss through 1 square metre of room surface

$$Q = \frac{2\pi(t_0 - t_п)}{\frac{1}{\lambda_м}\ln\frac{R}{r}}, \tag{12}$$

where t_{Π} is the temperature of the surface of the chamber; λ_M is the thermal conductivity of the frozen soil; to is the constant temperature of the frozen soil in the annual zero temperature fluctuation zone; R is the radius of the cooling zone; r is the radius of the room.

The heat exchange between the frozen soil and the refrigerating medium (air)

$$Q = \alpha(t_п - t_в). \tag{13}$$

Adjusting equations (12) and (13) for the temperature of the inner surface of the room, we obtain

$$t_п = \frac{\frac{2\pi\lambda_м}{a} t_0 - t_в \ln\frac{R}{r}}{\ln\frac{R}{r} + \frac{2\pi\lambda_м}{a}}. \tag{14}$$ /46

Substituting this value of $t_{п}$ in (12), we find the amount of heat lost by the soil through 1 square metre of inner surface of the room, expressed in terms of the temperature of the heat transfer medium,

$$Q = \frac{2\pi\lambda_м(t_0 - t_в)}{\ln\frac{R}{r} + \frac{2\pi\lambda_м}{\alpha}}. \tag{15}$$

Let us examine the problem of the cooling of an infinite mass of frozen soil with an initial temperature t_o and a moisture content W averaged over the entire volume (in kg/m^3), and enclosing a cylindrical room which represents the source of cold. The room 'temperature 'B is constant in time and throughout the length of the room, and this is achieved by appropriate selection of the rate of ventilation. We need to determine the radius of the cylinder of cooled soil after time τ .

Let us consider a thermal problem in which the heat flow is radial and the temperature distribution in the radial direction in the cooled zone of frozen soil is assumed to be linear.

Given this assumption, we can speak of an average value of the soil temperature in the cooled zone

$$t_{cp} = \frac{\text{'in''.} + t_0}{2}.$$

Let us note that the heat release of the soil Q_{rp} , which is equal to the heat loss per square metre, is made up of

$$Q = Q_{rp} = Q'_1 + Q'_2, \qquad (16)$$

where $Q'_1 = \rho\,(W_{H3_1} - W_{H3_2})$ is the amount of the heat liberated in the crystallization of the unfrozen-water contained in 1 cubic metre of frozen soil, in $kcal/m^3$ [here W_{H3i}, which is the amount of unfrozen water in the frozen soil prior to the onset of cooling (i = 1) and at the end thereof (i = 2), is determined from the graph (Fig. 12); ρ is the latent heat of ice formation, equal to 80 kcal/kg];

$Q'_2 = \frac{1}{2} C_M$ (to - tB) is the amount of heat liberated during the" drop in soil temperature from t_o to t_{cp}, /47

in $kcal/m^3$ (here CM is the heat capacity of the frozen soil, in kcal/m^3-degree).

Let the radius of the zone be equal to R at moment τ after the onset of cooling. The infinitely small interval dτ corresponds to an increase in the radius of the cooling zone equal to dR.

Then the volume of a cooled ring of soil of unit length during time dτ will be

$$dV = 2\pi R dR. \qquad (17)$$

During this time the heat liberated will be

$$dQ = Q_{\text{rp}} dV = 2\pi (Q_1' + Q_2') R dR. \qquad (18)$$

During the same time interval dτ the amount of heat released through 1 square metre of room surface will be

$$dQ = \frac{2\pi\lambda_{\text{м}} (t_0 - t_{\text{в}})}{\ln \frac{R}{r} + \frac{2\pi\lambda_{\text{м}}}{\alpha}} d\tau. \qquad (19)$$

Equalities (18) and (19) give the thermal balance equation in differential form

$$2\pi (Q_1' + Q_2') R dR = \frac{2\pi\lambda_{\text{м}} (t_0 - t_{\text{в}})}{\ln \frac{R}{r} + \frac{2\pi\lambda_{\text{м}}}{a\alpha}} d\tau \, . \qquad (20)$$

Replacing Q_1', Q_2' and t_Π and separating the variables, we get

$$d\tau = \frac{2\pi\rho (W_{\text{нз}_1} - W_{\text{нз}_2})}{a (f. - t_{\text{в}})} R dR + \frac{\rho (W_{\text{нз}_1} - W_{\text{нз}_2}) + \frac{1}{2} C_{\text{м}} (t_0 - t_{\text{в}})}{\lambda_{\text{м}} (t_0 - t_{\text{в}})} \times$$
$$\times R \ln \frac{R}{r} dR \, .$$

The integral in the range between O and τ and between r and R gives the solution for the radius of the cooling zone

$$\tau = \frac{\rho (W_{\text{нз}_1} - W_{\text{нз}_2}) + \frac{1}{2} C_{\text{м}} (t_0 - t_{\text{в}})}{4\lambda_{\text{м}} (t_0 - t_{\text{в}})} (2R^2 \ln \frac{R}{r} - R^2 + r^2) +$$
$$+ \frac{\pi\rho (W_{\text{нз}_1} - W_{\text{нз}_2})}{a (t_0 - t_{\text{в}})} (R^2 - r^2) \, . \qquad (21)$$

Calculation of the radius of the cooling zone in the case of several rooms /48

Equation (21) can be used to determine the radius of the cooling zone around either one room or several, but only until the contours of the cooling zones are closed. After closure of the contours, equation (21) is unsuitable since the heat loss of several rooms is different from that of a single_room. Thus it becomes necessary to obtain a new formula for determination of the volume of the zone of cooled ground after closure of the cylindrical zones of the individual rooms.

Let us determine the increase in the volume of the soil cooling zone per unit length of room during interval $d\tau$, assuming that after closure of the zones of the individual rooms it has the shape of a paralleliped with sides $a(n-1) + 2R$, $2R$ and 1, where a is the distance between the axes of two adjacent rooms; n is the number of rooms.

In this case dV will be equal to

$$dV = 2a(n-1)dR + 8RdR. \tag{22}$$

By analogy with formula (18) the heat liberated will be

$$dQ = dVQ_{rp} = (Q_1' + Q_2')[2a(n-1)dR + 8RdR]. , \tag{23}$$

During time interval $d\tau$ the amount of heat released through the inner surfaces of all the rooms (Kutateladze, 1958) will be

$$dQ = \frac{2\pi\lambda_{M}(t_0 - t_{п})}{\ln\left(\frac{a}{\pi r}\,\mathrm{sh}\,\frac{2\pi R}{a}\right)}d\tau. \tag{24}$$

In this complex case the heat loss through 1 square metre of room surface according to Vlasov will be

$$Q = \frac{2\pi\lambda_{м}(t_0 - t_п)}{\ln\left(\frac{a}{\pi r}\,\mathrm{sh}\,\frac{2\pi R}{a}\right)}.$$

The heat exchange between the frozen soil and the refrigerating medium will be expressed by

$$Q = \alpha(t_п - t_в). \tag{26}$$

Solving these two equations together we get

$$t_п = \frac{t_в \ln\left(\frac{a}{\pi r}\,\mathrm{sh}\,\frac{2\pi R}{a}\right) + t_0\frac{2\pi\lambda_{м}}{\alpha}}{\ln\left(\frac{a}{\pi r}\,\mathrm{sh}\,\frac{2\pi R}{a}\right) + \frac{2\pi\lambda_{м}}{\alpha}}. \tag{27}$$

Then equation (24) will take the form

$$dQ = \frac{2\pi\lambda_{м}(t_0 - t_в)}{\ln\left(\frac{a}{\pi r}\,\mathrm{sh}\,\frac{2\pi R}{a}\right) + \frac{2\pi\lambda_{м}}{\alpha}}\,d\tau. \tag{28}$$

Joint consideration of equation (23) and (28) gives

$$d\tau = \frac{\rho(W_{нз_1} - W_{нз_2})\left[\ln\left(\frac{a}{\pi r}\,\mathrm{sh}\,\frac{2\pi R}{a}\right) + \frac{2\pi\lambda_{м}}{\alpha}\right]}{\pi n\lambda_{м}(t_0 - t_в)}[a(n-1)\,dR +$$

$$+ 4R\,dR] + \frac{\frac{1}{2}\,\text{CM in}\left(\frac{a}{\pi r}\,\mathrm{sh}\,\frac{2\pi R}{a}\right)}{\pi\lambda_{м} n}[a\,(n-1)\,dR + 4R\,dR].,$$

$$\tag{29}$$

Since $\frac{2\pi R}{a} > \pi$ (= 3.14) is the error permitted in engineering calculations, we can set

$$\ln\left(\frac{a}{\pi r}\,\mathrm{sh}\,\frac{2\pi R}{a}\right) \approx \ln\frac{a}{\pi r} + \frac{2\pi R}{a} - \ln 2.$$

After substituting this value of in in equation (29) and integrating it over the range from τ_1 to τ and from R_1 to R, after simple operate.

With forced ventilation using cold air from outside, the speed of air movement through the rooms is much higher than 0.07m/see, so the heat transfer coefficient a should be determined by the formula for turbulent motion

$$Nu = \frac{\alpha d}{\lambda} = 0{,}023\ Re^{0{,}8}\ Pr^{0{,}4}. \qquad (31)$$

When determining the Nusselt number Nu for underground cold storage facilities with an L/d ratio of less than 40 the value of a from formula (31) is multiplied by the appropriate correction factor Δε (see table below) taken from M.A. Mikheev (1947):

L/d	1	5	10	15	20	25	30	35
Δε	1,76	1,54	1,34	1,22	1,14	1,09	1,05	1,01

The Prandtl number Pr in formula (31) can be taken as constant /51
and equal to 0.724 for underground cold storage facilities with a temperature of minus 8-20°C; $Pr^{0.4} = 0.88$. Then formula (31) assumes the form

$$\alpha = 0{,}02 \frac{\lambda}{d} Re^{0{,}8}, \qquad (32)$$

where d = 4F/P is the equivalent room diameter; F is the cross-sectional area; P is the perimeter of the cross-section; Re is the Reynolds number.

The amount of the liquid phase of water in frozen soils should be determined from the graph in Fig. 12 which is taken from N.A. Tsytovich (1958b).

When the cold store is in service the soil temperature should not be allowed to rise above the temperature needed for storage of the items in question.

transformations we obtain

$$\tau-\tau_1=\frac{\rho\left(W_{\text{нз}_1}-W_{\text{нз}_2}\right)+\frac{1}{2}C_{\text{м}}\left(t_0-t_{\text{в}}\right)}{an\lambda_{\text{м}}(t_0-t_{\text{в}})}[a(n-1)(R^2-R_1^2]+$$

$$+\frac{2}{3}\left(R^3-R_1^3\right)\Big]+\frac{\rho(W_{\text{нз}_1}-W_{\text{нз}_2})\left(\ln\frac{a}{\pi r}+\frac{2\pi R}{a}-\ln 2\right)+}{n\pi\lambda_{\text{м}}(t_0-t_{\text{в}})}$$

$$+\frac{\frac{1}{2}C_{\text{м}}\left(\ln\frac{a}{\pi r}-\ln 2\right)(t_0-t_{\text{в}})}{n\pi\lambda_{\text{м}}(t_0-t_{\text{в}})}\times[a(n-1)(R-R_1)+ \quad /50$$

$$+2(R^2-R_1^2)]. \qquad (30)$$

When we derived the design formulas the actual cooling process of the soil was simplified to some extent, and this naturally leads to some distortion of the true results. However, the assumptions are justified by the increased simplicity of the solutions. A much greater error in calculation normally results from incorrect choice of the values of the thermophysical characteristics of the soil. For this reason we shall look more closely at the determination of some of the initial data needed for the calculations.

The heat conductivity coefficient of frozen soils is weakly dependent on temperature fluctuation. This means that we can use an averaged value of the coefficient based on Table 2 of the "Specifications for Basement and Foundation Design in Permafrost (CH ?1-60)'" (1960) when calculating the cooling radius. The room temperature should be averaged over time.

The magnitude of the cooling radius is greatly affected by the heat exchange between the air and surrounding soil, which in turn depends on the heat transfer coefficient a and the speed of movement of the air through the rooms (when the speed is increased the coefficient of convective heat transfer becomes much higher). For normal room cross-sections (height 2.5 m., width 3-5 m.) the critical speed of laminar air flow does not exceed 0.07 m/see. Such speeds are observed only during the warm part of the year, when ventilation does not

The effective reserve of cold in the walls which is used for cooling, refrigeration and storage is determined by the quantity of heat by which the soil can be heated from its temperature to the storage temperature of the produce. Thus, a temperature of no more than minus 9 degrees is needed for the storage of meat and fish (Komarov, 1962); hence the soil around the room must have a temperature of minus 9 degrees or lower.

The effective reserve of cold needed to maintain a predetermined temperature in the chambers can be calculated by the formula

$$Q = \pi C_{\text{м}} (R_{x}^{2} - r^{2})(t_{x} - t_{\text{в}}) + \pi \rho (W_{\text{нз}_1} - W_{\text{нз}_2})(R_{x}^{2} - r^{2}), \tag{33}$$

where t_x is the minimum operating temperature in the rooms (storage temperature); Rx is the radius of the cylinder of frozen soil with a temperature on the outer surface of t_x --

$$R_{x} - r = \frac{t_{x} - t_{\text{в}}}{t_{0} - t_{\text{в}}} (R - r). \tag{34}$$

The simplicity of the computation is illustrated by a specimen calculation of the net reserve of cold for an underground cold store at Amguema.

Computational data: frozen soil temperature at the level of the facility to = -8°; average heat conductivity of the frozen soil λ_M = 1.8 kcal/m-hour-degree; heat capacity of the frozen soil /52 CM = 425 kcal/m^3; the frozen water content of the soil at $t_0 W_{H3_1}$ = 24kg and at t_{Cp} W_{H3_2} = 18 kg; the average air temperature during the cold season t_B = -22 degrees;

the length of the cold season T = 3600 hours; the heat transfer coefficient with forced air circulation a = 2 kcal/m-llr-degree; room width 5 m; room height 2.5 m; the distance between the axes of the room a = 10 m; we assume that the ventilation system operates for 20 hours a day.

Let us determine

1. The equivalent radius of the chamber

$$r = \frac{2\cdot 5\cdot 2,5}{2(5+2,5)} = 1,67\ м.$$

2. The time taken to cool the soil up to the moment of closure of the cooled zones around each room, *or* up to the formation of the cooled zones, with R = a:2 = 5 according to equation (21):

$$\tau_1 = \frac{(24-18)\,80 + \frac{1}{2}\,425\,(-8+22)}{4\cdot 1,8\,(-8+22)}\left(2\cdot 5^2 \ln\frac{5}{1,67} - 5^2 + 1,67^2\right) + \frac{3,14\cdot 80\,(24-1}{2\,(-8+22)^2}\left(\ldots - 1,67^2\right) = 1118 + 984 =$$

$$= 2102.$$

3.′ Using equation (30) we determine the cooling of the soil for τ = 3600;

$$3600-2102 = \frac{(24-18)\,80 + \frac{1}{2}\,425\,(-8+22)}{10\cdot 5\cdot 1,8\,(-8+22)}\,(10(5\ -I)X$$

$$\times\ (f?'-25) + \frac{2}{3}(R^3 - 125)] + \frac{(24-18)\,80\left(\ln\frac{10}{3,14\cdot 1,67} + \frac{2\ 3,14\ 1,8}{2} - 0,69\right) + \frac{1}{2}\,425\left(\ln\frac{10}{3,14\cdot 1,67} - 0,69\right)(-8+22)}{5\cdot 3,14\cdot 1,8\,(-8+22)}\ \times$$

$$\times\ [10\,(5-1)(R-5) + 2\,(R^2-25)];\qquad R = 5,7\ м,$$

/53

4. Using equation (33) we determine the net reserve of cold used for cooling, freezing and storage, and for technological purposes

$$R_x - r = \frac{-9+22}{-8+22}(5,7-1,67) = 3,74;\qquad R_x = 4,4\ м;$$

Q= 425X3.14 (19.36 - 2.79) X (-9 + 22) + 3.14 X 80 (22 - 18) X

$(19.36 - 2.79) = 287000 + 16\ 500 = 303\ 600$ kcal/linear metre of room.

Once we have estimated the cold reserve it is easy to find the quantity of fish that can be chilled and frozen. For this we also need to estimate the amount of heat required for ventilation and to make good operating losses.

5. Practical experience in operating underground cold storage facilities in Chukotka has shown that the heat requirement for these two purposes is equal to the losses incurred from 3-4 air changes every 24 hours. The number of air changes can_be reduced by frequent opening of the outside doors for operational purposes. In addition to external air exchange we recommend internal exchange, i.e. ventilating the rooms with the air in the corridors.

Given the following conditions: average summer air temperature $t_1 = 3°$; inside air temperature $t_B = -9°$; volume of one linear metre of room $V = 5 \times 2.5 \times 1 = 12.5$ m^3; outside humidity $\gamma = 5.98$ g/m^3, inside humidity $\psi_1 = 2.49$ g/m^3; relative humidity, in decimal fractions: inside air $\phi' = 0.95$, outside air $\phi = 0.8$; heat of condensation of water vapour allowing for the transformation of water into ice, $r = 0.69$ kcal/g; and the heat capacity of the air $C_B = 0.31$, the heat required for ventilation and to compensate for operating losses per day per linear metre of room will be:

$$Q_, = 4\cdot 12{,}5\, 10{,}31(3+9) + 0{,}69(5{,}98\cdot 0{,}8 - 2{,}49\cdot 0{,}95)] = \\ = 220\ \textit{ккал/сутки}.$$

For the entire warm season (six months) the figure will be

$Q_4 = 220 \times 6 \times 30 = 39\ 600$ kcal/linear m of room.

6. The amount of fish in the room that can be cooled to its freezing point $t_{кр}$ during the warm season (T = 180 days) /54

$$G_{\text{ох}} = \frac{Q_{\text{п}}}{C_{\text{р}}(t_1 - t_{\text{кр}})}.$$

Thus, with a net reserve of cold Q_{11} = 303,600 - 39,600 = 264,000 kcal, a heat capacity of the fish C_p = 0.68 kcal/kg-degree, temperature at delivery of t_1 = 10° and a temperature at the onset of freezing of the juices in the produce of $t_{кр}$ = -2°, we obtain

$$G_{ox} = \frac{264\,000}{0{,}68\,(10+2)} = 32\ m,$$

or related to the room area (S = 5 m^2) and to a unit of time equal to twenty-four hours (the length of the warm season τ is equal to 180 days),

$$\frac{c_{ox}}{S\tau} = 32\,000:180\times5 = 37\ кг/м^2\cdot сутки$$

7. During the warm season fish previously coiled to freezing temperature can subsequently be frozen in quantities of

$$G_{зам} = \frac{0{,}5Q_п}{C_{р.м}\,(t_{кр}-t_2)+W_р\,\varphi_р\cdot80}\cdot$$

per linear metre of freezer room.

Given a heat capacity of the frozen fish of $c_{p.m}$ = 0.43 kcal/kg-degree, a moisture content of W_p=0.8 kg/kg of fish, a juice separation ratio φ_p= 0.7, temperatures $t_{кр}$ = -2° and t_2 = -9°, and a heat of crystallization of the fish juice equal to 80 kcal/kg, we obtain

$$G_{зам} = \frac{264\,000\cdot0{,}5}{0{,}43\,(-2^\circ+9^\circ)+0{,}7\cdot0{,}8\cdot80} = 27'60\ кг,$$

or, in terms of room unit area and unit time per day, we obtain,

$$2760:180\text{X}5 = 3\ kg/m^2\text{-day.}$$

The examples given above convincingly demonstrate that it is possible in the climate of Central Chukotka to accumulate enough cold for the cooling, freezing and storage of food products.' In the eastern regions of Chukotka, where the temperature of the frozen soils at the /55 level of the zero annual temperature fluctuation zone is somewhat higher (minus 5°) and the mean air temperature during the cold season is also higher (minus 15-200), the reserve of cold accumulated may not be sufficient to compensate for the freezing load. This means that special mechanical refrigerators must be provided. A suitable appliance would be the rapid-freezing unit designed by Gimpelevich at VNIKhI*. It consists of several freezing-sections.

The outside measurements of the 2-section freezer are 4.20x2.40x1.64 m. The inside measurements of each section are 2.1X2.1 m. At a circulating air temperature of approximately minus 28° 3 tons of fish per day can be frozen in each section. At a temperature of minus 33° the refrigerating load per section is 15 000 kcal/hr. Each section is equipped with a fan with an output of 12 000 m^3/hr at a power consumption of 3 kWh.

From this calculation it is clear that in the central and northern areas of Chukotka the amount of cold accumulated during the winter is enough for chilling, freezing and storing produce and to compensate for operating losses.

In the climate of the east coast of Chukotka underground cold storage facilities can be used for the cooling and storage of frozen fish and meat without mechanical refrigeration equipment. These products can be frozen with the cold produced by eutectic solutions or freezers.

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* All-Union Refrigeration Industry Research Institute. - Translator.

Chapter IV

OPERATION OF UNDERGROUND COLD STORAGE FACILITIES AND THEIR ADVANTAGES OVER SURFACE FACILITIES IN NORTHERN CONDITIONS

The optimum operating conditions for an underground cold store relying on the cold reserve accumulated in the frozen soil during winter are achieved when the temperature and humidity are maintained all year long at levels ensuring preservation of the produce and structural stability of the installation, and when the icing on the walls of the rooms and corridor, which is an integral structural part of the installation, is periodically renewed.

A characteristic feature of underground cold stores is relative temperature stability during the warm season. In winter, on the other hand, when ventilation of the rooms is intensified by the introduction of cold air from outside, the room temperature becomes dependent on the temperature of the incoming cold air and therefore fluctuates.

During operation the humidity inside the cold store depends on the local climate and the temperature of the walls of the rooms. In winter, when the wall temperature is rather higher than the temperature of the circulating cold air, the relative humidity rises, which causes sublimation of the ice and promotes drying of the soil and stored produce. During summer, when the temperature of the outside air entering the facility is somewhat higher than the temperature of the walls, the relative humidity rises significantly and often reaches 100%. At this time of the year moisture is released and crystallizes on the cold walls of the rooms.

When the produce (meat, fish) is stored in separate rooms, the large temperature fluctuations and low relative humidity in winter are undesirable since they cause excessive weight loss. The temperature /57 fluctuations in the rooms containing the produce can be restricted by closing the individual inside doors. If the entire facility. is supplied with cold air via special ventilation ducts, the supply of cold air to the individual rooms can be shut off by a valve.

One of the storage rooms should be used for storing the usually small amount of produce in winter. This is justified by the fact that it is the storage rooms that have the coolest walls in summer.*

The temperature regime of an underground cold store in summer depends on the refrigerant charge in winter, the thermophysical characteristics of the surrounding frozen soil, the quantity and temperature of the food items being stored, and the heat gain resulting from handling operations and ventilation.

As already stated, freezing of produce by the cold accumulated in the surrounding soil during winter can be done in the continental areas of the temperate zone as well as in the Arctic and Subarctic, but with less success. In the southern parts of the permafrost zone, however, produce (meat, fish, meat products and fish products) must be frozen by freezers or with the help of eutectic mixtures.

Observations of underground cold stores in some parts of Chukotka situated in the temperate zone revealed that freezing and chilling of fish and other products (Table 4) to a temperature of minus 8-9 degrees with the accumulated cold can be done only in spring and

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* Translator's note: A puzzling statement, since it would seem logical to use storage rooms for storage no matter what the season.

early summer. During the rest of the warm season it is usually impossible to get the temperature below minus 5-7 degrees, which is a little too high. Nevertheless produce can be stored at this higher temperature for the 1-2 months of warm weather that remain, since the

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Table 4

/58

Optimum conditions for storage of meat, fish, meat products and fish products
(after N.S. Komarov, 1962)

Product	Storage temp., °C from	to	Humidity %	Storage time, months
Frozen meat:				
beef	-9	-18	95-100	8-12
pork	-9	-18	95-100	5-10
mutton	-9	-18	95-100	8-12
Corned beef	0	-5	80-85	4-6
Sausages:				
smoked	-7	-9	85-90	4-6
semi-smoked	-7	-9	85-90	2-3
Smoked meats	-7	-9	85-90	4-6
Rendered animal fats	-8	-12	80-90	4-6
Frozen fish:				
sturgeon and salmon	-9	-12	90-95	3-5
ordinary fish & cod	-9	-12	90-95	4-6
Salted fish:				
salmon	-5	0	90-95	3-8
ordinary fish	-5	0	85-90	4-10

bulk of the juices (up to 70-80%) in the produce freeze solid at temperatures above minus 5 degrees (Komarov, 1962).

In all cold stores the rooms should be used only for their intended purpose: for storage, freezing or cooling. No supplementary freezing or chilling whatsoever should be permitted in the rooms intended only for storage. Any failure to adhere to this rule will result in deterioration of the stored produce, since there is a temporary rise in temperature.

Chilling should be done in rooms specially set aside for this purpose. They should be located near the service shaft or entrance.

The ice lining on the walls of the chilling room and all the other rooms as well should be 25-30 cm thick. Where necessary the lining can be renewed by spraying on water or laying blocks of ice. This work should be done in winter. The quickest and simplest method is to use precut blocks of ice. They are installed like any other /59 lining, using water or wet snow (snow plus water) as the cement. The surface of the block is wetted with water and the block is laid straight away. The block can be dipped in a bucket of water or else can be moistened by a hand encased in a tarpaulin glove. Damage can be repaired with snow moistened in water. Gaps between the soil of the room walls and the lining can be filled with water or wet snow. The circular domes of the rooms are lined using a special falsework. The gaps between the lining and the soil of the roof can be packed with very wet snow. The ice blocks for lining the vaulted roofs must be made very carefully. Before the blocks are placed in position any dried out soil on the walls should be removed with a metal scraper or spade.

The procedure for chilling, freezing and storage is as follows.

Produce to be chilled is stacked on the Ice floor which has been cleaned of all traces of previous batches of produce and sprinkled with snow or fine ice.

Fish to be chilled is arranged in a single layer on the snow- or ice-covered floor and cooled and partly frozen solid so that it will not change shape when being transported into the freezing rooms. In underground cold stores located in Chukotka, fish spread on the floor in a layer 10-15 cm thick takes two days to cool and freeze solid at a temperature of the ice and underlying frozen soil of minus 8-10 degrees. It is then moved to the freezing room and frozen further until it reaches the storage temperature. The supplementary freezing is also done on an ice floor covered with snow or fine ice.

Meat is cooled and partially frozen in the same way, on an ice floor. In this case the time taken depends on the thickness of the carcasses. For example, it takes 3-4 days to chill and partially freeze deer carcasses at a temperature in the surrounding soil of minus 8-10 degrees. During this time 50–60% of the meat juice freezes. For final freezing the meat is taken into the freezing rooms where it is once again arranged in a single layer on an ice floor strewn with snow /60 or fine ice. After the temperature of the meat has been reduced to the storage temperature it is transferred to special storage rooms.

When placing produce in the chilling rooms care should be taken that the air temperature in those rooms does not rise above minus 2°. Any further increase in temperature will produce large amounts of unfrozen water in the soil of the arched roof and render the latter unstable. As a rule an increase in temperature above minus 2° is accompanied by partial collapse of the dome.

The maximum loading rate in the chilling rooms calculated for specific soil and temperature conditions must be adjusted In accordance with the air temperature at the vault, which should not exceed minus 2°.

Overstocking can be offset by supplementary ice-salt or mechanical refrigeration. If the room is large enough, an unduly high temperature can be countered by reducing the storage rate. This will lower the temperature and the relative humidity. Recourse to these measures will be particularly common in the temperate zone and in the region of stable cold winters (zone III).

Pockets for the ice-salt cooling mixture (Fig. 14) are placed in niches excavated in the walls. The barrels should be leak-proof. They and the cages on top of them should be vertical, clear of the walls, and out of the way.

The composition of the ice-salt mixture is determined by calculation according to its melting point, which must be equal to the required temperature inside the room. The mixture of given composition should be prepared as a homogeneous mass. The diameter of the ice cubes should not exceed 20-25 cm. To get the proportions right the mixture should be poured into measuring boxes strictly in accordance with the established norms.

The melting point t_{cm} of the mixture of ice and common salt can be determined using a formula from the work of N.S. Komarov /61 (1962)

$$t_{\text{см}} \approx -0{,}7x, \qquad (35)$$

where x is the salt content in % of the weight of the ice.

The refrigeration effect of the ice-salt mixture (latent heat of melting of the mixture) q_0 can be estimated approximately (to within 10%) from the equation

$$90 \approx 80 - |t_{\text{см}}|,\ \text{ккал/кг}, \qquad (36)$$

where $[t_{\text{cm}}]$ is the absolute value of the mixture's melting point.

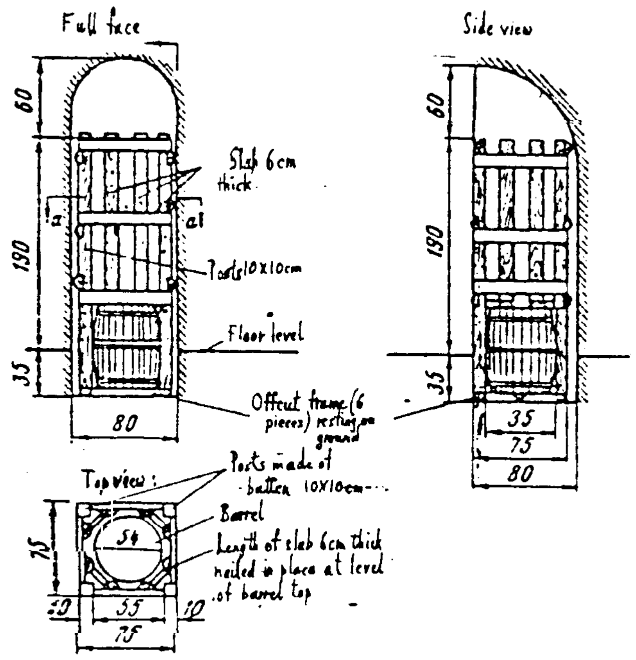

Рис. 14. Льдосоляной карман

Fig. 14. Pocket for the mixture of ice and salt

Instead of equations (35) and (36) the data in Table 5 can be used.

A stock of ice ready to prepare the ice-salt mixture and for other purposes should be kept in specially designated rooms, and also /62 on the floor of the corridor and the other rooms. Gradually, as needed, it can be spiked 'loose and taken away to be loaded into the wooden pockets depicted in Fig. 14.

Table 5

t_{cm} and q_0 as a function of x

Amount of salt (related to the weight of ice, x) , %	5	10	15	20	25	30
Temperature of the ice-salt mixture t_{cm}, °C	-3.1	-6.2	-9.9	-13.7	-17.8	-21.2
Refrigeration effect of mixture q_o, kcal/kg	75	68..	62	57	51	46

The required lateral surface of the pockets can be calculated for each room. The starting point for such a calculation is the quantity of cold needed Q.

The calculated surface

$$F_{cp} = \frac{1.2\,Q}{24\alpha\,(t_{к} - t_{см})}, \tag{37}$$

where Q is the quantity of cold needed; a is the heat transfer coefficient of the surface of the ice-salt mixture in the pockets; 1.2 is the safety margin; $t_{\kappa}-t_{cm}$ is the difference between the air temperature and the melting point of the ice-salt mixture.

The daily rate of consumption of the ice-salt mixture is estimated by the formula

$$G_{cm} \cdot \frac{1.2\ Q}{q_o}$$

where q_o is the refrigeration effect (latent heat of melting) of 1 kilogram of the mixture, taken from Table 5.

In the first few. hours after depositing the thawed produce in the cold store, when the refrigeration yield per square metre of the cagework pockets has to be greater, air circulation within the rooms should be increased. The current of air should be directed at the ice-salt mixture.

Underground cold storage facilities are airtight, so heavy stocking with produce and the prolonged presence of personnel results in an increase in the amount of carbon dioxide in the atmosphere. This makes itself felt particularly strongly in small shaft-type facilities in which ventilation by outside air admitted through the service shaft alone is extremely limited. /63

Experience in the operation of underground cold stores in Chukotka has shown that adit-type facilities can be adequately ventilated by opening the doors of the entrance. In shaft facilities the premises must be aired periodically by opening the service and ventilating shafts simultaneously. In general, ventilation is timed to coincide with loading and unloading operations. Where necessary forced ventilation should be used.

Observations have also shown that a layer of frost 2-4 cm thick forms on the walls of the rooms and corridor at the end of winter. During the warm part of the year the frost prevents the soil from getting too warm and keeps the humidity down.

The frost forms in winter throughout the entire period when the walls are being artificially cooled. At this time the functioning of the cold store is adversely affected by the frost, which restricts the normal cooling of the soil. The frost should be removed from the walls at the beginning of the accumulation of the cold reserve when the rooms are being ventilated with outside air. Only the frost forming towards the end of winter and towards the end of the artificial soil cooling operation should be kept for summer.

bring summer due attention should be paid to waterproofing measures. Surface and other water should be kept out of the facility since it will increase the humidity and raise the temperature. The latter rises and stays high until the water is frozen.

Normal functioning of an underground cold store and its safety also depend on loading and unloading operations. Produce should be brought into the facility quickly so that the doors of the entrance are /64 not left open too long.

In the case of a shaft-type cold store, the intake of produce through the loading shaft should be organized so that raising and lowering takes place as expeditiously as possible. Automatic devices should be available to make it possible to close the intermediate hatches in the loading shaft as soon as the goods cage has passed. In the adit type of facility the doors of the entrance should likewise be closed as soon as the loading platform has gone through.

The transport equipment inside the cold store should ensure rapid movement of the produce from the loading shaft to the rooms.

Vertical transport is best done with the aid of shaft winches, whereas a telpher system or narrow-gauge platform wagon is the most efficient way of moving produce horizontally. The narrow-gauge tracks should be laid at the same level as the ice floor of the rooms and corridor. The turntables permitting entry into the rooms should have a locking device lining up the railhead of the turntable with the track leading into the room.

The meat should be stored as carcasses vertically and at a slight angle, Or else suspended on special hangers. In this position the carcasses are kept quite well ventilated.

Fish the size of the chum salmon, inconnu, broad whitefish, Siberian taimen and the like should also be stored vertically, head down, and close together. Small fish can be kept in boxes or bags placed on a special grid so that the produce is thoroughly ventilated. Sometimes meat and fish to be stored for a long time is covered with snow or fine ice. Practical experience has shown that produce stored in this way keeps its taste longer even at a relatively high temperature.

When operated properly an underground cold store lasts for a long time. However, the stability can be endangered if the air temperature rises above minus 2°. At such a temperature the soil /65 becomes plastic and the vaults of the rooms virtually lose their load-bearing capacity, so that part of the roof caves in. The results may be not merely spoilage of the produce but even the destruction of the facility.

As already noted, watertightness is very important. Breaches in the waterproofing should be mended carefully. On top of the entrance there should be a layer of soil twice as thick as the summer thawing layer. To prevent thawing out of this soil ice should be stored in summer in cagework pockets along the inside walls of the entrance. The floor of the entrance should slope towards the exit.

The rigid moisture barrier lining the ventilation ducts should be overhauled from time to time to prevent water infiltrating. If perfect watertightness cannot be achieved, the duct can be blocked up and frozen for the summer. In winter the duct should be repaired and reopened.

Other tasks for the winter are renewal of the ice lining on the walls of the cold store, the preparation of an adequate stock of snow and ice for operational needs, filling the ice pockets in the entrance, and accumulating cold in the quantities indicated by thermal " calculations. At the same time the ventilation system should be fitted with an automatic device to switch it on when the temperature difference between the outside air and the room surface reaches a certain level (not less than 5°C).

The electric wiring inside the facility should be made of waterproof material. The wires should be laid separately in individual insulators 10-15 cm away from the surface of the wall. This is to prevent the wires being embedded in the frost on the walls. The voltage in the system must not exceed 36 V. In some underground cold stores the lighting has a voltage of 220 V, which is rather dangerous. If the facility is fairly remote from a population centre, electricity may be supplied by mobile power stations.

The air temperature in the cold store is recorded and /66 controlled by a distant-reading resistance thermometer of type MMT-4 (a thermistor), or by psychometric thermometers installed in each room 1.2 metres above floor level.

* * * * *

Until recently, surface cold stores have generally been built without taking into account the local climate. Now, in the Far North, we are beginning to construct underground cold storage facilities in frozen soils. As a rule they have been built by the direct labour method, using preliminary designs unsupported by special thermal calculations, though to some extent this approach was justified by the small size of the installations. Moreover, the type of cold store (surface or underground) selected did not always correspond to the technical and economic requirements. Recently there has been an ever-greater demand for larger cold stores. For this reason analysis of the thermophysical and economic parameters is absolutely essential for rational planning.

Below we give some of the technical and economic indices for the construction and operation of surface and underground cold storage facilities in northern conditions.

Underground cold stores were built at the villages of Shakhterskoe in 1959 and Ust'-Belaya in the Anadyr district of the Magadan region in 1963. In 1964 a surface distributing cold store with a capacity of 3400 metric tons was constructed in the city of Magadan.

The underground facility at Shakhterskoe and the distributing cold store in Magadan were both built by specialized construction organizations making maximum use of mechanization. The underground store on the First Chukotka Revolutionary Committee collective farm at Ust'-Belaya was built by manual labour without the use of explosives to loosen the frozen soil. The respective costs per cubic metre of capacity were 18.3 roubles for the underground facility at Shakhterskoe, 51 roubles for the facility at Ust'-Belaya, and 53 roubles for the store in Magadan.

To compare the efficiency of use of the cold stores, the operating costs can be expressed as the cost of processing one centner /67 of produce: the cost of processing (chilling, freezing and storage) of one centner of fish and meat in the underground cold store at Ust'-Belaya was 2.2 roubles per annum in 1963 and 2.48 roubles in 1964. By contrast the annual (planned) cost of storing one centner of produce in the distributing cold store at Magadan is roughly 8.8 roubles.

The data presented above are clearly an argument in favour of proceeding with the construction of underground cold stores in the Far North.

Conclusion

Theoretical calculations and long-term observations of the operation of underground cold stores have convinced us of their high efficiency. In spite of this they are being built far too slowly. One of the stumbling blocks is the absence of computational formulas enabling designers to perform the thermal calculations needed to provide the basis for specifying the operating conditions of the underground facilities.

When designing and constructing underground cold stores particular attention should be paid to the depth from the ground surface to the roof, which should be 10-15 metres. It is especially important to have the roofs of the rooms and corridors sloping away from the entrance (2-4%). The entrances and shafts must be carefully waterproofed. Builders and operators should remember that the integrity of the roof and constancy of the temperature regime in the cold store depend on the watertightness.

The computational formulas developed for underground cold stores built in frozen soil and the calculations presented make it possible to embark on the study and economic justification of their construction not only in the Far North but also in other parts of the country.

The experience that has been acquired in the construction and operation of the first underground cold stores, their comparatively low estimated cost given sufficient mechanization, and their low running costs point to the need to make extensive use of this type of facility in the different parts of the Far North.

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COMMUNITY	FREEZER SIZE	ADMINISTRATION	MAINTENANCE	COMMENTS
Frobisher Bay	(1) 14'x60' (2) 14'x36' (3) 30'x20' (4) 10' X10' (1) & (2) approx. size	I. T.A.	D. P.W.	.) H. T.A. use 3) Fish Plant- commercial use 4) New holding fr at meat cuttin plant
				ll freezers ovine y G.N.W.T. , Dept enewable Resourc .T.A. may soon t ver maintenance ontract out to D ther freezers:Th
Pangnirtung	size of sma matchbox	Hamlet	D.P.W.	air condition o-op and communi se.
Broughton Island	367 Sq. ft.	Hamlet	minor - Haml major - D.P.W	Good conditi Enough space Bay & 1 othe store have o freezers.
Arctic Bay	12'x20' (approx.)	H.T.A.	Hamlet	eeds shelving & ervicing. ay has own free o-op closed, sm utdoor freezer(ot being used.
Pond Inlet	30'x20'	H.T.A.	D.P.W.	ood condition, 20 yrs. old. Overloaded in su No co-op freezer
Igloolik	12'x20'	Hamlet	Hamlet & G.N.W.T.	Full in summer. Bay has small fr
Resolute Bay	No freezer. Unheated warehouse.			

COMMUNITY	FREEZER SIZE	ADMINISTRATIO	MAINTENANCE	COMMENTS
Lake Harbour		Settlement Council		ised by Bay & 'ildlife Committe :ommittee orders :rom Pangnirtung. freezer only.
Clyde River	Outside measurement: 19'x19'x7½'	Hamlet, but will soon be turned over H.T.A.	iamlet-minor).P.W.-major	3ood condition, enough space in summer. ! freezer only.
..Hall Beach	size of matchbox store size	Settlement Council Co-op	).P.W. Co-op	Jsed by H.T.A., C 3ay & community. Not big enough. Old freezer, mote not very good.
Rankin Inlet	(1) 410 sq f	Hamlet	D.P.W.	Good condition. Enough space.
	(2) 3 freeze 10'X12'	Dept. of Economic (future uncertai	D.P.W.	?ish plant- comme use only.
	(3) 30'x12'			Roof needs repair otherwise good condition.
Eskimo Point	504 Sq ft.	Hamlet	Hamlet	Old freezer. Too full in summe Used by co-op & community. Bay has own freez
Cambridge Bay	Fish plant- blast freezes 20,000 lb. in 2 hours (-21°) 25,000 lb. holding room	Co-op	Co-op	Commercial use on
	336 sq. ft". (28'x12')	H. T.A.	GNWT Fish & Wildlife	

COMMUNITY	FREEZER SIZE	ADMINISTRATION	MAINTENANCE	COMMENTS
Coppermine	16′ x30′	D. P.W. Hamlet status gained Apr.1, Admin. may gc to Hamlet	D. P.W.	00 small, overlc n summer.
Holman Island	ice house	Settlement Council	Settlement Council	Small & inefficie ouncil has appl or Special ARDA unds for 900 sq. alk-in freezer. pproved construe egins in summer.
Pelly Bay	(1)15'x25' (2)20'x60'	Co-op ..._ Co-op	Co-op D-op	Mainly co-op use. ish plant - ommercial use or ish shipped in freezer remain: dormant in winte
Spence Bay	(1)10′X12′	Hamlet	Hamlet	Community use. Overloaded in su
	(2)121X15′ Under construction	Hamlet	Hamlet (GNW paying cons	Old freezer may losed.
Chesterfield Inlet	592 sq. ft	Hamlet	Hamlet	Full in summer, but large enough for community.
Grise Fiord	12'x20' (approx.)	Settlement	D.P.W.	Good condition, large enough
Baker Lake	666 Sq. ft	Hamlet	Hamlet	
Coral Harbour	445 Sq. fl	Hamlet	Hamlet	

COMMUNITY	FREEZER SIZE	ADMINISTRATION	MAINTENANCE	COMMENTS
Repulse Bay	495 sq. ft	Hamlet	Hamlet	
Whale Cove	620 sq. ft	Hamlet	Hamlet	