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LITERATURE SURVEY OF COLD WEATHER CONSTRUCTION PRACTICES

John A. Havers
and
Robert M. Morgan

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13. ABSTRACT

The objective of this study was to survey existing literature on cold-weather construction practices. The seasonality problem was defined and its economic and operational implications were identified. The effects of cold weather on men, material, and equipment were reviewed. Cold weather construction tasks were examined for technological constraints and comparisons were made with existing military and civilian codes. Research and observations pertaining to the construction tasks being examined were listed to provide a base for current and future development of cold-weather construction techniques. An attempt was made to analyze the natural and technological constraints imposed by the weather on men, material, and equipment. The economic feasibility of cold-weather construction was examined by reviewing the recorded experience of many segments of the international construction industry, and the economic advantages of cold-weather construction were listed. It was concluded that 1) construction seasonality in the United States is a major economic problem; 2) reducing it and overcoming its effects are major tasks to be accomplished; and 3) cold-weather construction is not a panacea for seasonal unemployment, but would help to alleviate it.

14. KEY WORDS

Cold-weather construction
Cold-weather effects on men, materials and equipment
Concrete construction
Earthwork
Waterproofing, dampproofing, calking
Timber construction
Economic feasibility
Masonry
Painting
Plastering
Roofing
Steel construction

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PREFACE

Authority for the study reported herein is contained in FY 1968, Instructions and Outline, Military Construction Investigations, Engineering Criteria and Investigations and Studies, Investigation of Arctic Construction; Subproject 65, Cold Weather Construction.

The Military Construction Investigations program is conducted for the Directorate of Military Construction, Office of the Chief of Engineers. This investigation was under the technical direction of the Engineering Division of this directorate, Civil Engineering Branch (Mr. F.B. Hennion, Acting Chief).

This study was made by Purdue Research Foundation, Purdue University, under Phase 1 of Contract DAAG 23-68-C-0020, with the U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL). Mr. R.M. Morgan, Graduate Assistant in Research, made the investigation and prepared the report under the technical direction of the Principal Investigator, Dr. J.A. Havers, Associate Professor of Civil Engineering.

The study was conducted under the immediate direction of Mr. C.W. Fulwider, Project Officer for the contract, USA CRREL, and under the general direction of Mr. E.F. Lobacz, Chief, Construction Engineering Research Branch, Experimental Engineering Division (Mr. K.A. Linell, Chief).

The report was technically reviewed by Mr. C.W. Fulwider. Mr. C.W. Kaplar assisted in the technical review of the report.

The authors wish to express their sincere thanks to Mr. C.W. Fulwider, USA CRREL, Project Officer for the contract, whose invaluable aid contributed significantly to the literature search.

Lieutenant Colonel Joseph F. Castro was Commanding Officer/Director of USA CRREL during the publication of this report.

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LITERATURE SURVEY OF COLD-WEATHER CONSTRUCTION PRACTICES

by

John A. Havers and Robert M. Morgan

INTRODUCTION

Objective

The purpose of this study was to survey existing literature on cold-weather construction practices to accomplish the following objectives:

1) To identify facilities and construction tasks where cold weather is a constraint.

2) To identify and analyze technological constraints on the construction of facilities in cold weather for the future development of improved construction techniques.

3) To examine constraints on the productivity of men and equipment in adverse weather and on the economic feasibility of cold-weather construction.

Plan of Study

First, the construction seasonality problem was defined and its economic and operational implications were identified. Actions by this country and other countries in combatting construction seasonality were probed to identify existing sources of the problem.

Relevant terms and definitions were listed and appropriate maps were gathered. An analysis was then made of the effects of cold weather on each of the three resources in most construction methods: men, material, and equipment.

Next, available methods of performing cold-weather construction tasks were examined for technological constraints and comparisons were made with existing military and civilian codes.

Finally, the economic feasibility of cold-weather construction was examined by reviewing the recorded experience of many segments of the international construction industry. This was done to provide a consensus of the economic advantages of winter construction to the facility owner and his contractor.

BACKGROUND

The weather has shaped the destinies of man from his beginnings. His customs and habits, his movements, and his economic and social progress are all affected by the weather. Indeed, the story of man could be told in terms of his relative success or failure in overcoming the weather's adverse effects.

Man has advanced in many technological areas; yet, the effects of bad weather upon certain key facets of society are still profound. Man the builder can construct comfortable homes that provide warmth and protection in all but the most catastrophic conditions. He can build fine all-weather highways and airports that carry tremendous volumes of traffic with only minimal hindrances by the weather. He can build dams to control the disastrous aftereffects of weather, and huge factories and industrial complexes where manufacturing and production may be carried on year-round. Yet, ironically, it is in the critical interface of construction that man's campaign against the weather has met with decidedly limited success.

Before attempting to discuss construction seasonality and its inherent ramifications, we shall define the terms *adverse weather* and *construction season.*

"Adverse weather involves abnormal conditions created by natural forces that may be detrimental to the design and construction of a project."[4] These may be extreme conditions of wind, cold or heat, rain or snow, dryness, dust, floods or a water shortage, any of which may delay the development of a project. From the standpoint of the contractor and engineer, the adverse weather areas of the world are characterized by extreme temperature or precipitation, or by combinations of these two factors. "Thus four main types of areas can be distinguished: wet hot, wet cold, dry hot and dry cold."[4] This study is limited to the types of weather that blanket the Arctic, Scandinavian countries, Canada, northern United States, Europe, and Antarctica: wet and dry cold. Consequently, in this report adverse weather is used synonymously with winter or cold weather.

The construction season normally refers to the period of high building activity during the year; this excludes the winter. In Sweden this season lasts from four months in the north to six months in the south. In southern Canada it lasts from seven months on the prairies to more than nine months on the lower British Columbia mainland. In the upper fringe of the United States the duration is comparable to that of southern Canada. Thus the construction season, as defined, is relatively short.

Economic Implications

The economic implications of adverse weather on the construction industry are apparent when we consider that:

> "... about forty-five percent of construction operations, which amounts to nearly *40 billion dollars* annually, can be classed as weather sensitive. Further, it is estimated that about *one billion dollars* in lost wages each year can be attributed to seasonal weather fluctuations. Equipment valued at some *700 million dollars* is idle during the winter months due to adverse weather conditions."[1]

A report by R.J. Meyers, Deputy Commissioner of Labor Statistics, and S. Swerdloff, Chief of the Division of Program Planning and Evaluation, criticized the construction industry for its failure to cope with seasonal employment. This failure is:

> "... costing the nation (private owners and taxpayers) at least $3 to $4 billion a year in economic waste, is creating unnecessary hardship for some 4.6 million workers who make at least a partial living in construction, and is an obstacle in the present campaign against inflation. ... Except for agriculture, construction has the greatest seasonal variations of any major industry division. Its employment is characterized by summer peaks and winter valleys. Its unemployment rate (regularly 10 to 12%) is normally higher than

that of any other major industry, and the industry takes more money out of the unemployment insurance system than it puts in. Its workers have annual earnings that are lower than those of workers in several other heavy industries despite the comparatively high hourly rates that prevail in construction.

"Not only are construction workers more likely to be unemployed at some time during the year than workers in any other major industry group outside agriculture, but they are also more likely to have several periods of unemployment and be jobless for a total of 15 weeks or more."[3]*

A 1964 report by the Travelers Research Center (TRC), Inc., for the U.S. National Weather Service attempted to calculate the cost of bad weather to the construction industry. Table I * shows the relative volume of construction by category for 1964 and the amount of work considered susceptible to seasonal and intermittent weather losses. As one might suspect, there are considerable differences in the impacts of the various categories.

Table I. Estimated annual business in potentially weather sensitive construction, 1964 (after ref 9).

Category	Total $Billions	Sensitive $Billions	Sensitive % of Total
Residential	17.2	4.8	28
General building	29.7	8.9	30
Highway	6.6	4.8	73
Heavy and specialized	12.5	10.0	80
Repair and maintenance	22.0	11.2	51
Total	88.0	39.7	45

This study tried to determine the potential economic benefits of improved weather information. Advance information about the weather has its value; however, if such information is used *only* to stop work, most of the problems caused by the weather are not really solved. As will be shown, the only positive solution seems to be the protection of construction materials and equipment and the provision of a suitable working environment for the workmen.

Operational Implications

In its study, TRC published a composite list of important construction operations considered at least partially weather sensitive (see Table II*). An analysis of individual construction operations indicates that adverse weather affects most operations to some degree, but has a major impact only on exterior operations and perishable materials. Only a few weather conditions are responsible for these adverse effects. The most detrimental weather conditions are low temperature, precipitation, winds, and combinations of temperature and winds (chill factor).

Table II. Operations influenced by weather.*

Operation	Sleet	Snow and Freezing rain	Low temp (F)	Ground-freeze
Surveying	L	L	0 to −10	
Demolition and clearing	M	L	0 to −10	x
Temporary site work	M	L	0 to −10	x
Delivery of materials	M	L	0 to −10	
Material stockpiling	L	L	0 to −10	
Site grading	M	L	20 to 32	x
Excavation	M	L	20 to 32	x
Pile driving	M	L	0 to −10	x
Dredging	M	L	0 to −10	x
Erection of coffer dams	L	L	32	x
Forming	M	L	0 to −10	x
Emplacing reinforcing steel	M	L	0 to −10	x
Quarrying	M	L	32	x
Delivery of premixed concrete	L	L	32	x
Pouring concrete	L	L	32	x
Stripping and curing concrete	M	L	32	x
Installing underground plumbing	M	L	32	x
Waterproofing	M	L	32	x
Backfilling	M	L	20 to 32	x
Erecting structural steel	L	L	10	
Exterior carpentry	L	L	0 to −10	
Exterior masonry	L	L	32	x
External cladding	L	L	0 to −10	
Installing metal siding	L	L	0 to −10	
Fireproofing	L	L	0 to −10	
Roofing	L	L	45	
Cutting concrete pavement	M	L	0 to −10	x
Trenching, installing pipe	M	L	20 to 32	x
Bituminous concrete pouring	L	L	45	x
Installing windows and doors, glazing	L	L	0 to −10	
Exterior painting	L	L	45 to 50	
Installation of culverts and incidental drainage	L	L	32	x
Landscaping	L	L	20 to 32	x
Traffic protections	M	L	0 to −10	x
Paving	L	L	32 to 45	x
Fencing, installing lights, signs, etc.	M	L	0 to −10	x

L – light [effect] M – moderate [effect] x – a factor

[Author's note: Indicates initial level of weather activity that makes the operation difficult.]

* Copyright, the Travelers Research Center, Inc., The Center for the Environment and Man, Inc.; reprinted by permission.

Concurrently the British Ministry of Public Buildings and Works generated its own list of the effects of weather on certain construction operations. This is given in Table III*, which also includes low temperature, precipitation, winds, and their combinations as detrimental weather conditions.

Table III. Effects of weather.[4]*

Phenomenon	*In conjunction with*	*Effect*
Low and subzero temperatures		1. Damages mortar, concrete, brickwork, etc.
		2. Slows or stops development of concrete strength.
		3. Freezes ground and prevents subsequent work in contact with it, e.g. concreting.
		4. Slows down excavation.
		5. Delays painting, plastering, etc.
		6. Causes delay or failure in starting of mechanical plant.
		7. Freezes unlagged water pipes and may affect other services.
		8. Freezes material stockpiles.
		9. Disrupts supplies of materials.
		10. Increases transportation hazards.
		11. Creates discomfort and danger for site personnel.
		12. Deposits frost film on formwork, steel reinforcement and partially completed structures.
	High wind	Increases probability of freezing and aggravates effects of 1-12 above.
Snow		1. Impedes movement of labour, plant and material.
		2. Blankets externally stored materials.
		3. Increases hazards and discomfort for personnel.
		4. Impedes all external operations.
		5. Creates additional weight on horizontal surfaces.
	High wind	Causes drifting which may disrupt external communications.

* Copyright, National Builder, Journal of the National Federation of Building Trades Employers; reprinted by permission.

Government Action

Seasonality in construction is one of the greatest problems relating to the use of manpower and industry resources. In 1967, the President of the United States directed the Secretary of Labor, in cooperation with the Secretary of Agriculture and the Acting Secretary of Commerce, to make a detailed survey of seasonal unemployment and underemployment in this country and to find ways to deal with these problems. Later he directed the heads of various departments to reduce seasonal unemployment by implementing various suggestions (see Fig. 1[4]).

Office of the White House Press Secretary

THE WHITE HOUSE

MEMORANDUM FROM THE PRESIDENT
TO THE HEADS OF DEPARTMENTS AND AGENCIES

Subject: Reducing Seasonal Variation in Construction Activity and Employment

The construction industry has long been plagues (sic) by unemployment of labor and other critical resources during off-season periods. This "construction seasonality" hurts the contractor through idle equipment, the worker through greater unemployment, and the consumer through higher prices. These costs are substantial and persistent -- seasonal unemployment represents a substantial proportion of all construction unemployment.

More stable employment and the resulting higher annual incomes would attract and hold skilled labor in construction. The reduction of seasonal variation in construction serves the Nation's goals of high employment and price stability.

The Federal Government is a major purchaser of the work of the construction industry. Through many of its programs, the Government has an indirect effect on fluctuations in construction activity. We in the Federal Government have a unique opportunity to help reduce seasonality in construction.

Therefore, I am requesting each department and agency with responsibility for the direct or indirect expenditure of construction funds to take the following steps:

1. Ensure that, in the planning and programming of construction activity, due consideration is given to reducing seasonal variation.

2. Make contracts and schedule projects with regard to local conditions.

3. Encourage completion dates and penalty clauses that facilitate the strtch-out (sic) of work into the off-season.

4. Determine whether current authorization and appropriations procedures introduce a seasonal pattern into the letting of contracts and the scheduling of construction.

5. Encourage recipients of Federal grants and loans for construction to engage in activities to reduce construction seasonality.

6. Identify and disseminate to appropriate recipients information on techniques and procedures for facilitating year-round construction.

7. Take such additional steps, as may be permitted by law, to promote the scheduling of their construction activities during off-season periods, as will not entail undue impairment of program goals of excessive additional costs.

I am also asking each department or agency with construction responsibilities to transmit to the Director of the Bureau of the Budget, not later than July 1, 1969, a report on the steps it has taken to comply with the provisions of this memorandum, together with recommendations for additional measures to reduce the adverse effects on seasonality of its construction programs.

Under Title IV of the amended Manpower Training and Development Act, which I recently signed, the Secretaries of Labor and Commerce are directed to study and report to the Congress by December 31, 1969, the opportunities for lessening construction seasonality. I therefore ask that the head of each addressee to assist the Secretaries of Commerce and Labor in their inquiry into additional measures required to lessen seasonal variation in construction.

Figure 1. Presidential memorandum.[4]

Testifying before the Select Subcommittee on Labor, Committee on Education and Labor, House of Representatives, in 1968, Under Secretary of Labor James Reynolds listed several symptoms of construction seasonality in this country:[7]

1. August employment in contract construction for the Nation as a whole is typically about one-third higher than February employment.

2. Unemployment rates in 1967 for this industry ranged from 13% in February to 4.3% in August.

3. The pattern of seasonal employment has not improved significantly since World War II.

4. The construction unemployment rate is about double that of all other industries combined.

5. The impact of unemployment on the individual employed in the construction industry is severe.

6. Plumbers, electrical workers, and sheet metal workers generally have longer average annual employment than do laborers.

7. Even in the peak season the unemployment rates affect all craftsmen, but affect the laborers the most.

Scientists, architects, and engineers have developed scores of materials and techniques to permit cold-weather operation:

> "Rust-resistant steels that do not require painting; and additives and heating procedures that permit pouring concrete in subfreezing temperatures.
>
> "Polyethylene films that allow large work areas to be enclosed from cold and rain; improved low-temperature lubricants; space heaters to warm work areas; and power equipment that works in frozen soil.
>
> "Drywall construction techniques unaffected by cold; and offsite preparation of curtain walls, which can be quickly installed to protect workers.
>
> "Precast and prestressed concrete structural elements; a mud-hardening process using lime to alleviate boggy conditions; and systematic scheduling, including the use of computers, to avoid unsheltered work in the coldest, wettest weather.
>
> "Although these methods are widely known, they are not as widely used as they should be. It would certainly appear that the Federal Government could do much more to promote these techniques and inventions."[7]

Experience in Other Countries

Seasonality is expensive, and it is inconceivable that the construction industry will continue to do so little to improve conditions affecting it. Many ideas to counteract it have been tried abroad, and foreign nations have accumulated considerable operating experience in these efforts.

The Organization for Economic Cooperation and Development (OECD) has published an analysis of these methods and results that may benefit the United States.[10] Substantial attacks on construction seasonality have been made by governments of Canada, Austria, Belgium, Denmark, Finland, West Germany, The Netherlands, Norway, Sweden, and the United Kingdom. "Administrative action has been taken to plan Government construction to yield year-round employment, to require that maximum possible winter work be done by all departments, and to influence private projects by withholding permits."[10]

Subsidies have also been paid to municipalities, contractors, or private owners. In some cases these subsidies are paid out of unemployment insurance savings.

Canada has been especially active in public education programs that are designed to create a demand for winter construction through radio and television announcements, pamphlets, stickers, and letter inserts.

Mr. A.T. Bone, a director of J.I.E. Price & Company, Ltd. of Montreal and a past-president of the Canadian Construction Association, emphasizes that the Canadian grants and bonuses (subsidies)

> ". . . are directed at the owner rather than offered to the contractor. This reflects the philosophy that the construction industry is not looking for subsidies itself and, indeed, should not require any special inducements—but is willing to provide construction services at any time of the year. The Canadian Government, for its part, feels that the funds spent internally and externally on wintertime construction and promotion have paid off handsomely in terms of business activity and reduced outlays from the unemployment insurance fund and in unemployment assistance."[1]*

A sample of additional methods attempted abroad includes:

> "Grants or loans to contractors, sometimes conditioned on measures to winterize the project; loans to purchase winter equipment; and grants to workers for winter clothing and to owners who build in winter;
>
> "Free travel for visits to his family for a workman who follows a job to another area; and
>
> "Revision of building codes to permit use of modern advances, such as pouring cement in far colder weather by the use of additives; education of the many small contractors on modern techniques; and subsidized training for workers."[7]

It is concluded (as OECD likewise concludes) that the problems of construction seasonality have been largely neglected in the United States and there is no indication that seasonality has diminished since World War II.

Breeders of Seasonality

Construction in the United States is seasonal for several reasons. According to OECD, militating against remedial action in this country are the construction industry's "inertia and resistance to change," the mixed reactions of workers who often like high wages with overtime and winter vacations financed by unemployment insurance, the tendency to exaggerate the costs of winterizing construction sites, and a lack of knowledge about what can be done to ease the seasonality problem.

At its 1968 seminar on *Seasonality in construction*, the Associated General Contractors of America produced many questions, but few answers. However, Dr. D.Q. Mills, Massachusetts Institute of Technology, listed what he considered to be the breeders of construction seasonality:[8]

1. Winter weather, requiring additional planning and perhaps increased costs, for operations to proceed.

2. Traditional practices of the industry.

3. Seasonal patterns in consumer demand

4. Certain project specifications which inhibit winter work

5. Patterns of distrust and prejudice against winter work among architects, engineers, owners and the public generally.

The most obvious cause contributing to seasonality is bad weather during winter months. Cold, precipitation, and high winds hinder many construction operations.

This study does not purport to present a panacea for the seasonality problem. Instead, it examines only one, but the most obvious breeder of construction seasonality in international circles: cold weather.

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TERMS, DEFINITIONS AND BOUNDARIES

At this stage, the reader may agree that there is a seasonality problem, perhaps does not agree completely with the list of causes, and probably does not know how the climatic atmosphere in his locale of interest measures up to the classification of *cold weather.* In addition, he may have heard terms (e.g., permafrost, Arctic, Subarctic) for which he has only a casual "feeling," but whose understanding is crucial to a meaningful discussion of cold weather construction.

Consequently, to establish a common basis of understanding for the reader, basic definitions of the terms used throughout this report and maps illustrating the climatic conditions of interest are given in the following sections.

Terms and Definitions

Adverse weather.[4] Abnormal conditions that are created by natural forces and that may be detrimental to the design and construction of a project.

Arctic.[2] The northern region in which the mean temperature for the warmest month is less than 50°F and the mean annual temperature is below 32°F.

Dry-cold weather area.[4] Area with conditions typical of the Arctic Ocean, Greenland, and the Antarctic. Here, dry powdery snow and compacted ice prevail for most of the year. Extreme winter winds are occasionally experienced in Greenland and in the Antarctic; speeds may exceed 85 mph. Visibility may be as low as 8 to 10 ft and temperature may fall below -100°F.

Antarctic. The region lying south of the Antarctic convergence, an unbroken, sharply defined circumpolar boundary roughly parallel to the 50°F isotherm for the warmest month.

Frost heave.[2] The raising of a surface by the formation of ice in the underlying soil.

Ice segregation.[2] The growth of ice as distinct lenses, layers, veins, and masses in soils commonly, but not always, oriented normal to the direction of heat loss.

Mean annual temperature.[2] The average of the average annual temperatures for several years.

Muskeg.[2] Poorly drained organic terrain consisting of a mat of vegetation overlying peat, varying in thickness from a few inches to many feet, characteristic of topographically low situations in subarctic regions.

Permafrost.[2] Perennially frozen ground.

Subarctic.[2] The region adjacent to the Arctic in which the mean temperature for the coldest month is below 32°F, the mean temperature for the warmest month is above 50°F, and there are fewer than 4 months having a mean temperature above 50°F.

Wet-cold weather area.[7,8] The Antarctic coastline and the subarctic regions, particularly those areas adjacent to the oceans. Average temperature of warmest month below 50°F but above 32°F, winters long and cold but absolute minimum temperatures rarely fall below -50°F. Total annual precipitation, much of which is "wet" snow, ranges from 10 to 20 inches, except in the foothills and coastal mountain regions where it is heavier. On the average, winds along the coastal regions are stronger than in the colder and drier interior and on occasion may exceed 100 mph. Fog and poor visibility are common in this region, especially during the warmer months.

Boundaries

Figures 2-4[3,5,6] illustrate climatic boundaries in the Northern Hemisphere pertaining to this study.

Table IV[1] is a Fahrenheit-centigrade conversion table. The conversion formula is °F = (°C × 1.8) + 32.

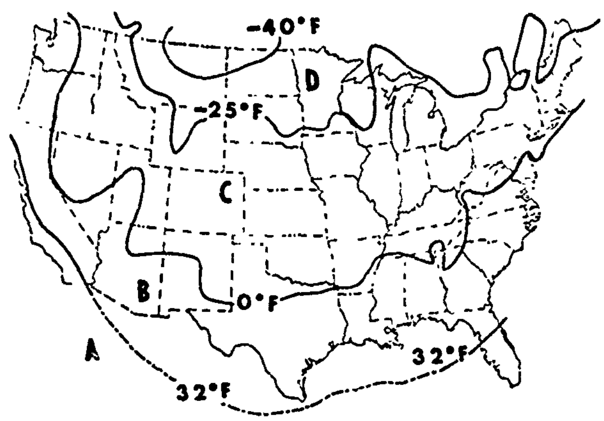

Figure 2. Lowest 1-day mean temperature isothermal lines (after ref 5).

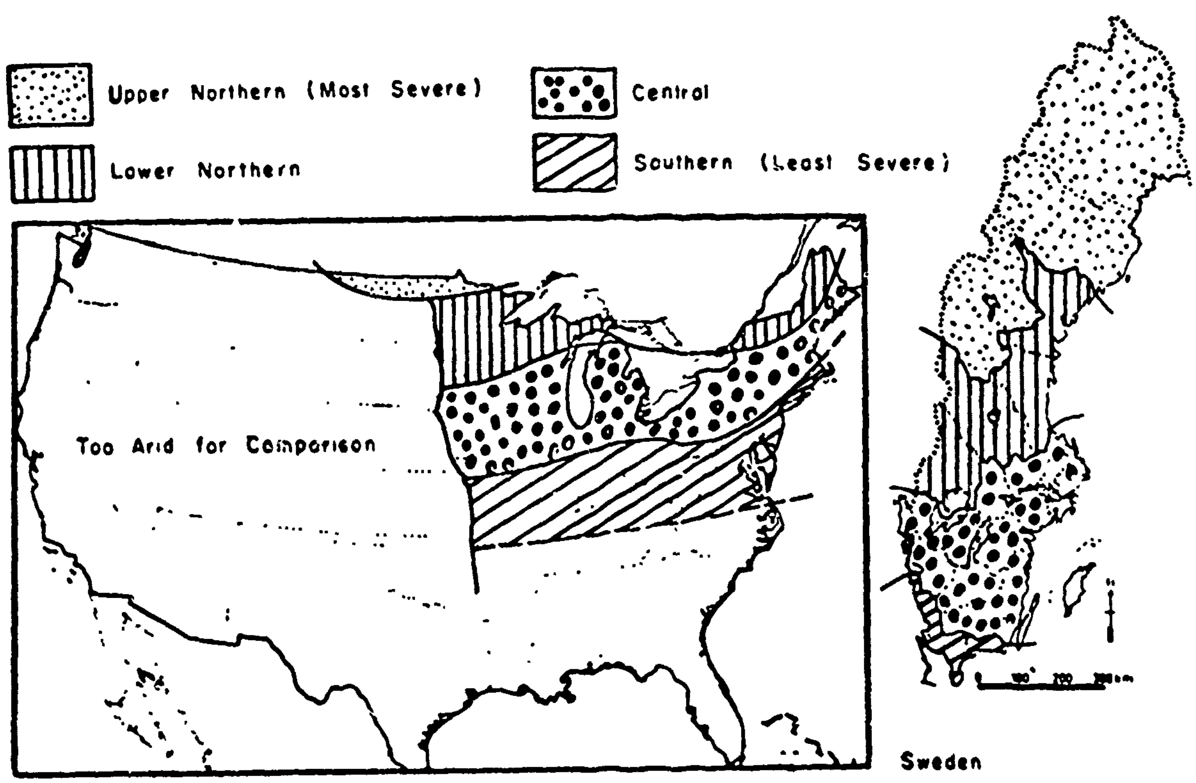

Figure 3. Comparison of climatic conditions of Sweden and the United States.[3]

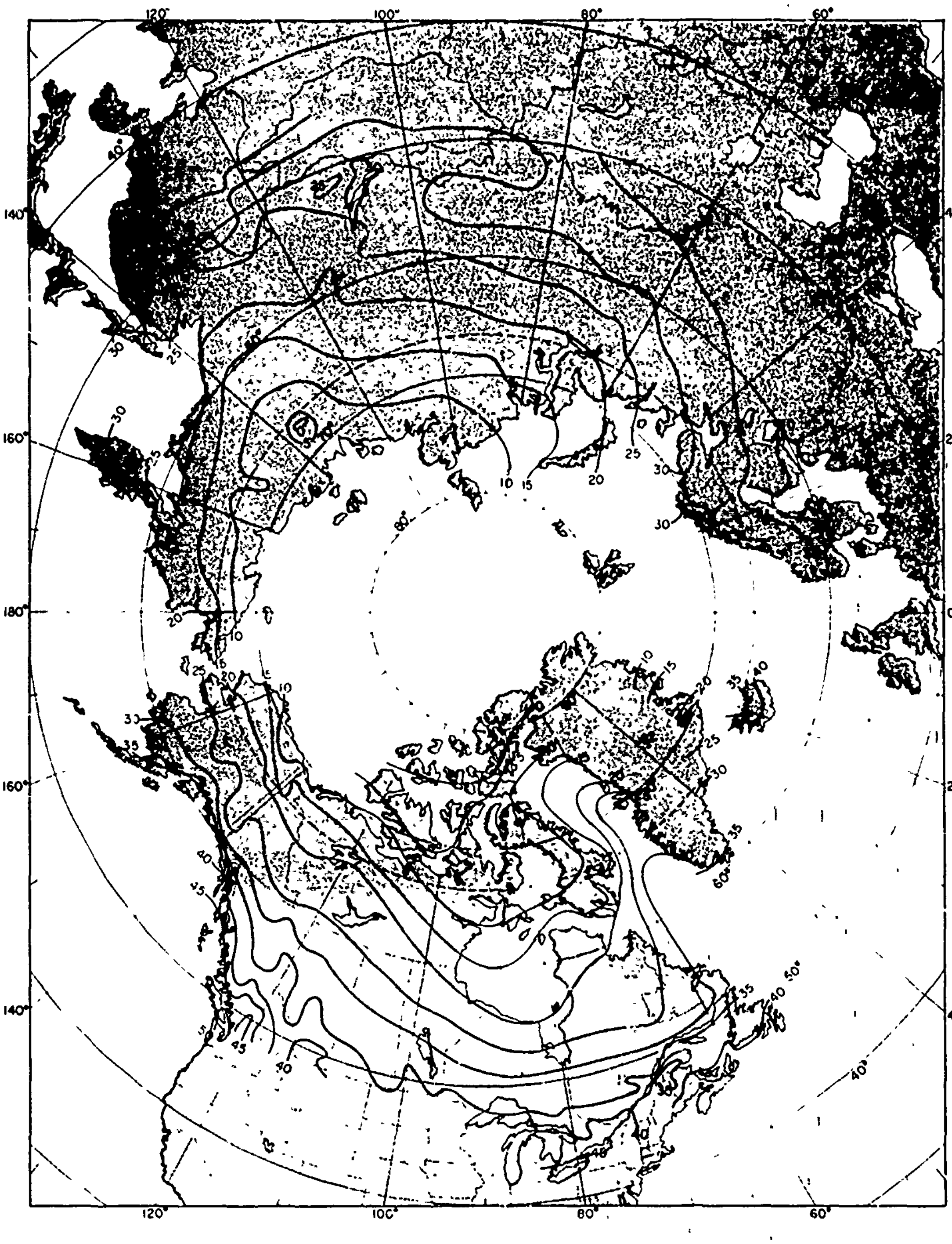

Figure 4. Mean annual temperatures of the Northern Hemisphere.[6]

Table IV. Fahrenheit – centigrade (Celsius) conversion table.

°C	°F	°C	°F	°C	°F	°C	°F
–40	–40	–15	5	10	50	35	95
–39	–38.2	–14	6.8	11	51.8	36	96.8
–38	–36.4	–13	8.6	12	53.6	37	98.6
–37	–34.6	–12	10.4	13	55.4	38	100.4
–36	–32.8	–11	12.2	14	57.2	39	102.2
–35	–31	–10	14	15	59	40	104
–34	–29.2	–9	15.8	16	60.8	41	105.8
–33	–27.4	–8	17.6	17	62.6	42	107.6
–32	–25.6	–7	19.4	18	64.4	43	109.4
–31	–23.8	–6	21.2	19	66.2	44	111.2
–30	–22	–5	23	20	68	45	113
–29	–20.2	–4	24.8	21	69.8	46	114.8
–28	–18.4	–3	26.6	22	71.6	47	116.6
–27	–16.6	–2	28.4	23	73.4	48	118.4
–26	–14.8	–1	30.2	24	75.2	49	120.2
–25	–13	0	32	25	77	50	122
–24	–11.2	1	33.8	26	78.8	55	131
–23	–9.4	2	35.6	27	80.6	60	140
–22	–7.6	3	37.4	28	82.4	65	149
–21	–5.8	4	39.2	29	84.2	70	158
–20	–4	5	41	30	86	75	167
–19	–2.2	6	42.8	31	87.8	80	176
–18	–0.4	7	44.6	32	89.6	85	185
–17	+1.4	8	46.4	33	91.4	90	194
–16	3.2	9	48.2	34	93.2	95	203
						100	212

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MEN

This section deals with the most important segment of the construction industry – man. To adequately evaluate feasible construction plans we must consider the effects of cold weather on human performance and capabilities. How does man react to the cold? Winterton et al., in a Welding Research Council bulletin,[24] suggest two forms of reaction: psychological and physiological. This review adheres to these classifications, and, in addition, subclassifies the physiological

The element of time is then discussed as it relates to the cold acclimatization of the human body. This suggests the possible application of acclimatization as a means of physiological protection from cold injury. Next, winter productivity and efficiency are studied to note losses in these areas, if any, and degree. The section ends with a chronological review of developments in the protective clothing industry.

Psychological Reactions

The major psychological problem associated with working in the cold is the same as that encountered with employment in any other extreme condition: no one likes unpleasant working conditions.

The Defence Research Northern Laboratory of the Defence Research Board, Department of National Defence, Canada, has had considerable experience with men working in a cold climate. It has published a booklet on the subject for the guidance of men working on Distant Early Warning (DEW) line construction.[24] This publication emphasizes that men should be convinced that, provided with warm clothing, they should find working in the cold no more unpleasant than working under other extreme conditions.

Engineering News-Record reported on a road construction project in the Himalayas, where the men had to endure a 3-mile-above-sea-level altitude with 50-mph winds and temperatures that dropped far below zero. The high altitudes and low temperatures caused the men to become "extremely irritable, tending to quarrel and become undisciplined. Their energy, willpower and morale also declined from oxygen starvation."[7] Concurrently, there was a loss of judgment and sleep.

To further illustrate the point, W.P. Fox of George Washington University found that non-physiological factors contribute significantly to the performance decrement. "Such factors as wind noise, severe cooling of the extremities, and perceived threat of physiological injury from cold exposure seem to serve as competing stimuli and produce distraction or inattention to the task at hand."[6*]

Physiological Reactions

Tissue damage

Even though there may be no absolute lower temperature limit to performing a given construction task, there is still a restraint on the exposed body of a human. The Department of the Army, in its *Basic Cold Weather Manual*, describes the cause, symptoms, effects, preventive measures, and treatment of many cold injuries.[3]

* Copyright, Human Factors; reprinted by permission.

Frostbite is the freezing of some part of the body by exposure to temperatures of freezing or below. Depending on the damage caused to the tissue, frostbite signifies dead skin and flesh with a possible loss of the body part.

High altitude frostbite results in gangrene of the extremities, particularly of the hands, owing to exposure to the cold at high altitudes "following 30-second exposures."[20]

Trench foot is a cold injury resulting from prolonged exposure to temperatures near freezing. The temperature does not need to be below 32°F to cause this injury. Walking becomes difficult and painful. In extreme cases the flesh dies and amputation of the foot or of the leg may be necessary.

Immersion foot is caused by "exposure to dampness and cold, while trench foot results from exposure to cold and dampness as well as fear of death."[20] In both instances, mobility of the limb is reduced.

Keratitis and chilling of the lungs is referred to but not explained by Tikhomirov.[22] He found that these serious diseases were common in the interior of Antarctica under conditions of high altitudes, low partial oxygen pressure, and extremely low air temperatures.

Snow blindness occurs when the sun is shining brightly on an expanse of snow. It is caused by the reflection of ultraviolet rays, and is particularly likely to occur after a fall of new snow.

Blisters of the skin, around the lips, nostrils, and eyelids, easily develop in below freezing temperatures, caused by sunlight reflected from the bright surfaces of snow and ice.

Chilblain or pernio is "another clinical entity resulting from cold injury, characterized by blotchy changes in the skin and marble skin."[20] The main factor in the production of acute chilblains is exposure of a limb to cold and dampness, followed by sudden warmth, producing a sequence of events characterized by severe spasm with pain, then injury to the vessels.

A Boston physician, J. Peter Kulka,[10] has used rabbits and mice to study the injurious effects of cold on the skin. The problem he has attacked might be formulated as shown in Figure 5.

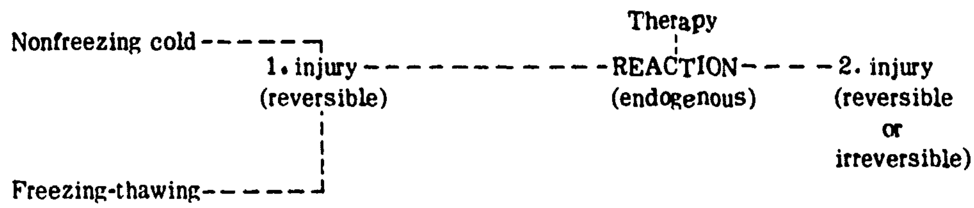

Figure 5. Cold injury: A tentative schema.[10]

In vol. 11 of *Archives of Environmental Health*, in October 1965, Dr. Kulka wrote:

> "Both the freeze-thaw type of exposure and nonfreezing cold produce an initial injury which seems to be largely reversible. This primary injury can lead to an exaggerated reaction, producing further injury which may culminate in irreversible gangrene. The primary injury we can influence only by preventing or modifying the cold exposure; but the endogenously mediated reaction we hope to influence by therapy. If we fully understood this secondary endogenous reaction to cold, we could plan a rational regimen of combating it. Therein lies our challenge."[10]*

If the direct effects of cold account for most of the irreversible injuries, Dr. Kulka considers that the battle is already lost after cold exposure has ended and the tissue is rewarmed. But he concludes that evidence is overwhelmingly in favor of the theory that most of the irreversible injuries are the results of secondary reactive changes. "There are well documented instances in man as well as animals in which an extremity that has been frozen solid recovered with little or no permanent tissue loss."[10]

His studies indicate that both freezing and nonfreezing cold injuries of the skin are direct consequences of the progressively impaired functioning of the microcirculatory system, which is initiated by blood vessel contraction or spasm. The development of tissue damage parallels neither the distribution of blood vessel constriction nor a cooling gradient, but corresponds closely to the extent of secondary stoppage of the normal flow of fluids in the organs and vessels of the body. Irreversible tissue damage (gangrene) is associated with the occurrence of widespread "necrotizing angiitis and thrombosis which gradually extend from the microvasculature into the major veins and arteries."[10]

New York physicians H.E. Tebrock and M.M. Fisher[20] have written an article on the trauma and vascular diseases arising from cold injury. They surmise that "In all vasospastic conditions following exposure to cold the intensity [of injury] depends upon the exposure and the individual's susceptibility."[20] Prolonged exposure to cold by itself with normal blood vessels produces arterial spasm. This is followed by diminished circulation through the area supplied by these blood vessels. The blood vessels that previously have been diseased with arteriosclerosis are more sensitive to cold injury.

Nontissue damage

This section contains only studies concerned with some behavioral measure of human subjects, where the effects of cold fall short of tissue damage.

Dehydration is caused by failure to correct the body's imbalance of liquids by replacing liquid and salt that have been lost by excessive perspiration. The effect of dehydration on the individual is to incapacitate him for a period of a few hours to several days. A 1969 *Time* magazine article described an Army maneuver in Alaska at −60°F in which ski troopers in the desertlike dry cold required "between three and five quarts of water daily."[2]

Shock is a condition characterized by a reduction in the effective circulating blood volume. Shock usually develops more rapidly and progresses more deeply in extreme cold than in normal temperatures.

Severe chilling results from total immersion in cold water for even a few minutes. This is often accompanied by shock.

Constipation often results when individuals delay in relieving themselves because of the cold weather conditions. Constipation is also caused by changes in eating habits and failure to drink a sufficient amount of liquids. An individual so affected may be incapacitated for some time by severe stomach cramps, headaches, dizziness, and weakness.

Heart-vessel (cardiovascular) activity has been studied in Antarctica by Tikhomirov.[21] His data are derived from his observations of personnel at Vostok Station during 1959. Investigation of this group revealed certain characteristic features of cardiovascular activity. Changes in the cardiovascular system took place gradually. "After 1-2 weeks at the station, several subjects developed murmurs in the region of the apex of the heart and a month later were found to have enlarged hearts. After two months at the station, almost all personnel developed murmurs and enlarged hearts."[21]

Arterial pressure showed particularly marked changes in the same group, falling from the beginning of the wintering periods. "The variation in the pulse rate was different from blood pressure. Upon the arrival of the personnel at the station, the pulse rate was sharply accelerated, and then gradually slowed to the original level (after 3 months). However, the pulse rate then continued to decrease until the end of the wintering period."[21]

Respiration underwent characteristic changes in the personnel at Vostok Station. "The respiratory rate increased greatly during the first days of wintering. Then, over the remainder of the year it gradually declined, until after a year's stay at the station it was not only below the original level, but was lower than the accepted normal value, averaging 13 respirations per minute."[23]

Nitrogen balancing within men under the effects of severe cold stress was studied by the research division of a Philadelphia hospital. The basis of this study lay in the fact that in the adult organism a nitrogen equilibrium can be achieved and maintained at any level of protein intake (above the protein minimum), provided there is no striking discrepancy between the daily caloric intake and the energy output. "A restricted calorie supply as well as muscular work or exposure to cold can increase the urinary excretion of nitrogen."[8]

The purpose of this investigation was to expose healthy young men to cold stress, which induces an almost continuous shivering with a concomitant increase of the metabolic rate to at least twice the basal metabolic rate (BMR). It was hoped that under such circumstances, a study of the nitrogen balance would yield information about the protein metabolism of men in the cold and its relationship to the overall increase in metabolic rate.

The Philadelphia experiments showed an important difference between the depletion of body protein, induced by dietary restriction, by exposure to severe cold, and by the combination of the two stresses. "Whereas the recovery period following a diet insufficient either in protein or in both protein and total calories at normal room temperature was characterized by a rapid repletion of the protein stores of the body as indicated by the return to a positive N balance, no such repletion could be observed after a severe cold stress had been superimposed on the dietary stress."[8] In the latter case, increased destructive metabolism of body protein appeared to persist for four to five days after the cold exposure.

Caloric requirements of man in the Antarctic were studied by the Arctic Aeromedical Laboratory of Fairbanks, Alaska. This study was conducted because of the tremendous logistical problems involved in supporting human operations in the Antarctic. It was found "unsound to provide more food than required to maintain normal body weight; overfeeding leads to overweight and the concomitant decrease in physical fitness is undesirable."[12]*

Typical energy expenditure of the test subjects (scientists and U.S. Navy sailors who lived in the Antarctic during 1957) was estimated on the basis of time-activity data, as illustrated graphically in Figure 6.[12]

"For the IGY personnel (scientists) the average daily expenditure was about 3775 calories and the consumption 3400 calories per man in March (antarctic summer), 3370 and 4396, respectively, in June (antarctic winter), and 4175 and 4285, respectively, in September."[12] On this regimen all of the subjects gained weight during the antarctic stay.

The U.S. Army Alaskan maneuver (referred to earlier) proved the following: "Each infantryman must tuck in a formidable 5,000 calories of food a day to replace heat lost by his body."[2]

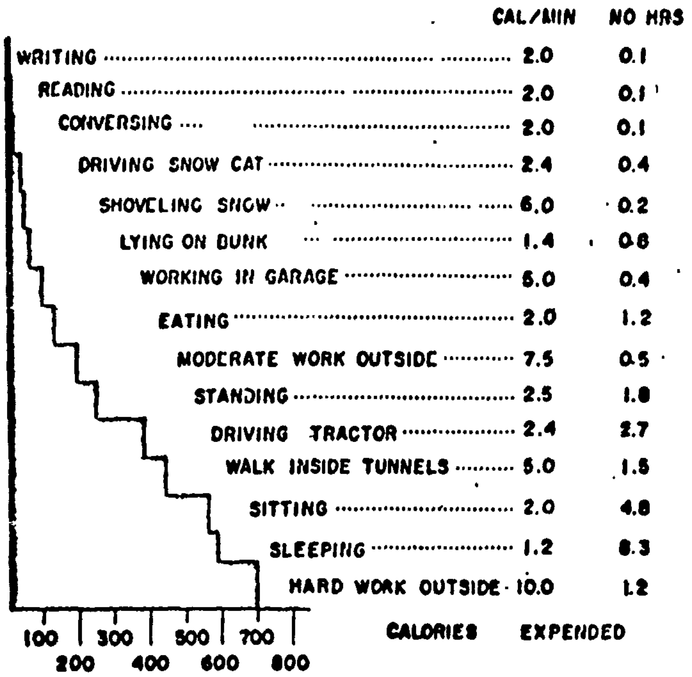

Figure 6. Antarctic average 24-hour energy expenditures.[12]

"How much energy is expended by an individual in his attempts to survive in hostile surroundings? A recent arctic hike, conducted by NASA and the Air Force, is expected to provide the answer, leading to improved rescue techniques of flyers and astronauts forced down in unfriendly environments."[10] The hike consisted of 10 days spent in trudging 100 miles on snowshoes through temperatures of 20° to 40°F below zero. There were 26 physiological parameters measured regularly during this experiment. However, no results were published.

Cold Acclimatization

"Cold acclimatization in humans has been investigated with a view toward eventual application as a means of physiological protection from cold injury."[9]* One study reported the results of cold acclimatization in soldiers exposed to cold climates in Alaska and Greenland, while carrying out normal tasks of troops in these areas. The only significant change found was a decrease in shivering activity.

Shivering when one is cold is a moderately efficient method of heat production and consequent maintenance of body temperature. "The finding that shivering decreases to insignificant amounts without a corresponding change in oxygen consumption implies very strongly that cold acclimatization initiates another source of heat production to replace that due to the muscular work of shivering."[9] Specific biochemical changes at the cellular level, undefined but suggested, must occur to allow the cold-acclimatized individual to produce heat and maintain body temperature, even through he is not actively working.

This study further demonstrated that mere presence in a cold climate is not sufficient to fully acclimatize an individual if he remains clothed. "Acclimatization of large numbers of individuals will probably best be done by partial removal of clothing during cold weather."[9]

The Russian personnel at Vostok Station in 1959 underwent significant cardiovascular changes during their acclimatization process. As previously mentioned, cardiovascular activity was greatly accelerated, but later, as other compensatory changes developed, it gradually returned to the original level.

On the basis of the data obtained by the Russians, it could be concluded that men would attain stable acclimatization after 5-6 months at the station. Without exception, however, the subjective sensations of all the wintering personnel indicate otherwise: while at rest, the individual feels perfectly normal, but during physical work annoying symptoms continue to occur until the end of the year's residence at the station. "Thus, in the internal regions of Antarctica acclimatization is not complete within one year."[21]

Why be interested in cold acclimatization? According to Captain P.W. Roberts, "The degree of acclimatization and adaptability of workmen to cold is extremely important in productivity and directly affects the worker's output."[17]

With that in mind, we will now turn to the subject of winter productivity and efficiency.

Winter Productivity and Efficiency

Variables

Operator efficiency is reduced as compared with performance under normal conditions. This is the general opinion of Fox, George Washington University. In his review, he determined that "Performance decrements upon exposure to low ambient temperature appear to stem from the physical lowering of the surface temperature of the hand (HST) and the competing stimuli in a unique and sometimes stressful environment."[6]

Lowering HST has two effects: numbing of cutaneous sensitivity and attenuating manual dexterity. Fox[6] has found that for both effects there appears to be a critical HST above which performance is relatively unaffected and below which performance precipitously declines. "For tactile sensitivity the critical HST is near 8°C (46°F). For manual dexterity the critical HST is somewhat higher, between 12°C (54°F) and 16°C (61°F)."[6]

The Welding Research Council is particularly interested in the dexterity of fingers and strength of hands exposed to low temperatures. It finds a "remarkable reduction" in dexterity within half an hour at 15 to 20°F. "There is an accompanying decrease in touch sensitivity attributed to a reduction in the number of touch receptors which function when the skin temperature is lowered from 88 to 34°F."[24]

An article on arctic construction estimates that "100% of stateside production is possible in all trades at +50°F and 0% production is possible at -50°F; in between, the production is subject to several variables."[18] These are windchill, darkness, phase conditions (whiteouts, foehn winds, blowing snow), frost, snow and the usual loss of efficiency normal to a seven-day work week.

The windchill effect is illustrated in Figure 7.[4] The ingredients, as devised by the U.S. Army, are those weather elements which govern the feeling of comfort: "air temperature, surface-wind velocity, and relative humidity."[4]

A windchill value of 800 is considered "cold" when discussing worker efficiency and a value of 1000 is termed "very cold." Remembering these values while examining Figure 8,[5] the reader can easily visualize that a significant portion of the United States experiences "cold" labor-efficiency weather, with the northern fringe battling "very cold" efficiency conditions.

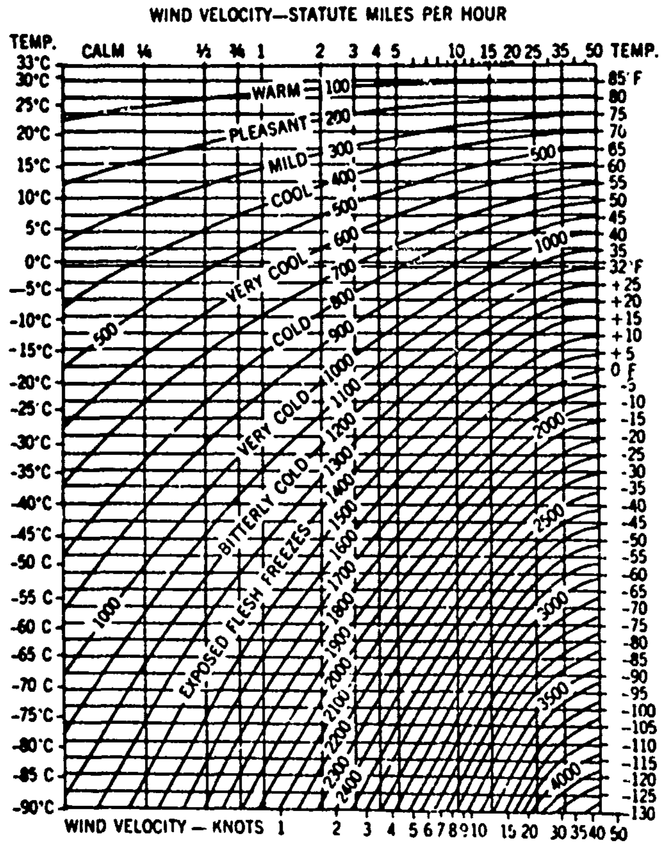

Figure 7. Graph of windchill related to temperatures and surface-wind velocity.[4]

A survey of the experience of Swedish contractors and engineers relates the efficiency of construction workers to the factors of air temperature, light, and precipitation. Table V[13] is a consensus of that survey. The combined working efficiency is found by multiplying the appropriate efficiencies shown for each of the three variables. For example, at a temperature of 25°F at dusk with heavy snow falling, the working efficiency for manual laborers is (0.95) (0.92) (0.41) = 36%.

The Russians have a similar term: "the weather severity index."

> "The 'weather severity' is defined as the sum of the negative (centigrade) temperature of the air and double the velocity of the wind measured in meters per second. No construction work is performed in open air when the weather severity exceeds 45, which corresponds to an air temperature of -25 (-13°F) and a wind velocity of 10 meters per second. However, the weather severity index frequently reaches the 80 and even the 100 level."[11]

Extent of reduction

Though the Swedish do have a formula for estimating the percentage reduction of efficiency, little factual information is available on the subject.

Observations provide many educated guesses as to the reductions. The following serve as examples:

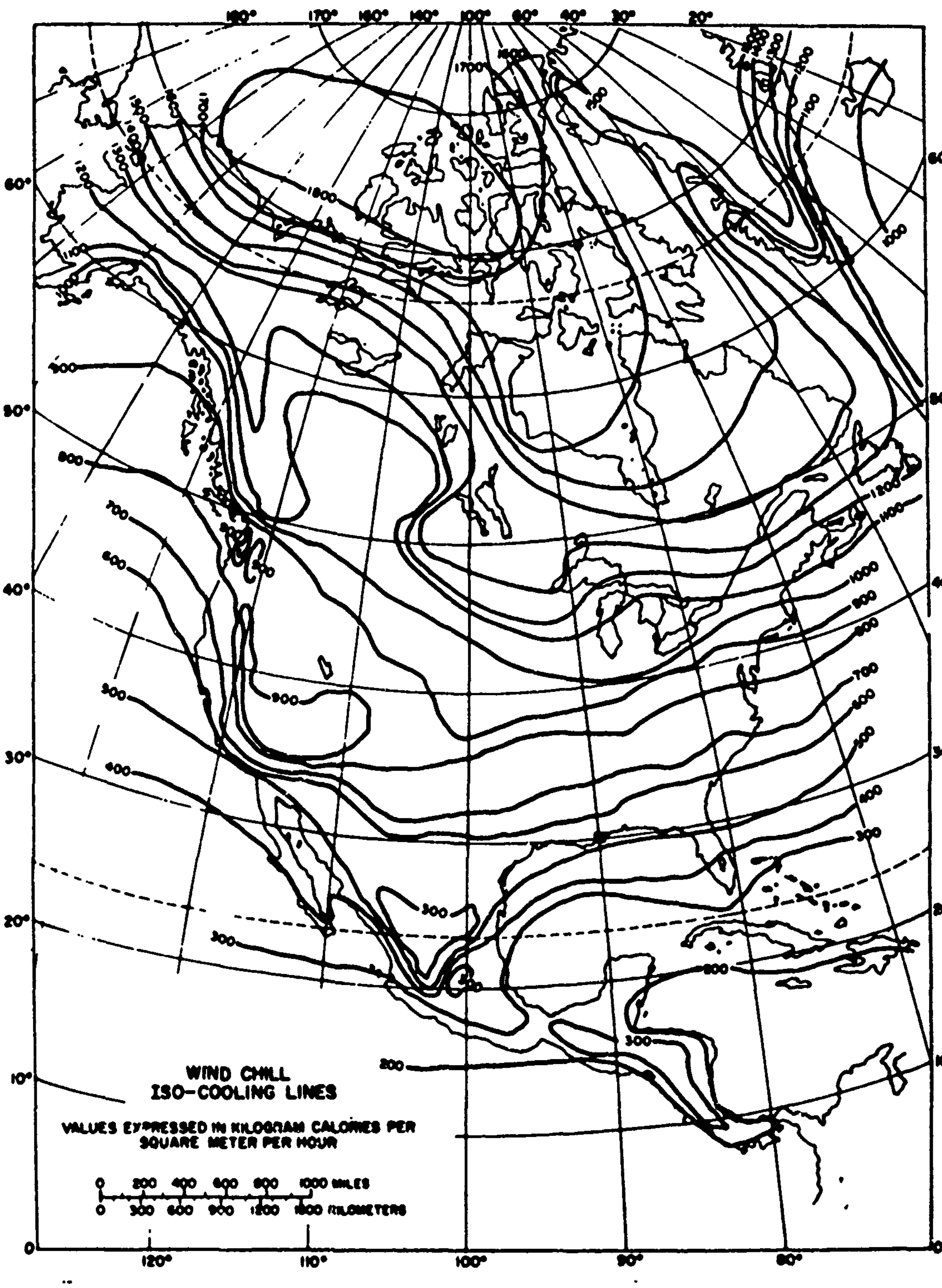

Figure 8. January windchill values for North America.[5]

Table V. Relative working efficiency of manual laborers.[13]

Weather factor	Working efficiency (%)
Air temperature (°F):	
85	72
70	95
50	100
40	98
32	97
25	95
15	88
−5	73
−25	33
Light condition:	
Bright sunshine	97
Indirect sunshine	100
Dusk	92
Subarctic winter twilight	56
Precipitation:	
Heavy rain	36
Light rain	89
Dry, temperature 50°F	100
Light snow	90
Heavy snow	41

1. At the road construction site in the Himalayas, it was found that "Efficiency drops almost 50% after prolonged exposure to the heights."[7]

2. Navy Captain H. Stevens, Jr. wrote that the high elevation and extremely low temperatures in the Antarctic helped reduce normal efficiency of construction personnel by approximately 50%.[14]

3. In the Anchorage area of Alaska, "Statistics indicate that the efficiency of men working outside handling tools during winter drops to one-third below normal."[16]

4. The levels of production in the Arctic may be stated as follows for outside or partially outside work: "Mid-June to mid-September 100%, mid-September to mid-November 60%, mid-November to mid-March 20%, mid-March to mid-April 40%, and mid-April to mid-June 60%."[18]

Since little factual information is available on the effects of adverse weather conditions on productivity, the British Building Research Station conducted a detailed study of five housing sites to determine these effects.[1] It studied five categories of man-hours lost because of bad weather. One of these categories was "reduced productivity." The "reduced productivity" as a percentage of the "total bad weather losses" of bricklayers, plasterers, and tilers on the five sites is indicated in Table VI.[1] These figures are only approximations, but they indicate the possible extent of productivity loss in relation to the total loss for each trade.

Other similar studies include those of the Organization for Economic Cooperation and Development (OECD); data from these studies are given in Tables VII and VIII.[25] It can be observed from these tables that bricklaying, formwork, and reinforcing are influenced by the weather much more than are concreting and earthwork.

OECD considers that other factors that may adversely affect productivity during winter as much as the weather include insufficient lighting, inadequate site organization, and delayed deliveries. It contends that, in countries and at sites where productivity tends to be low, an investigation into the causes may often reveal deficiencies that could easily be remedied.

Table VI. Reduced productivity.[1]

Trade	*Reduced productivity as % of total bad weather losses*
Bricklayers	14%
Plasterers	71%
Tilers	42%

Table VII. Percentage reduction in performance in different climatic zones at different temperatures.[28]

	32 to 27°F			*27 to 21°F*			*21 to 16°F*			*Below 16°F*		
Type of work	*I*	*II*	*III**	*I*	*II*	*III**	*I*	*II*	*III*	*I*	*II*	*III*
Preparation of site					3	4	3	5	7	6	8	10
Loading and unloading					3	4	3	5	7	6	8	10
Earthwork (not mechanized)							3	5	7	6	8	10
Transport on site					3	4	3	5	7	6	8	10
Formwork	4	6	8	12	17	22	17	22	37	22	30	38
Reinforcing	8	12	16	12	20	28	20	30	40	35	50	65
Concreting		2	3	2	3	4	3	5	7	6	10	14

* = Germany (F.R.) Zone I – dry climate, generally little wind; zones II and III – more humid.

Table VIII. Decrease in productivity at low temperatures.[28]

In percentages

			Germany (zone III)†*			
	*Sweden***	*Poland†*	*49 to 27°F*	*27 to 21°F*	*21 to 16°F*	*Below 16°F*
Concreting	–3.8	–14	– 3	– 4	– 7	–14
Formwork	–3.4	– 8	– 8	–22	–37	–38
Reinforcing	–7.3	–20	–16	–28	–40	–65
Bricklaying	–8.8	–25				

* For definition, see Table VII.
† Institute for Building Research, Warsaw, Bohn-Dreschel.
** Bertil Näslund: Building construction in winter – A cost study, Stockholm, 1965. See also Folke Eriksson and Jan-Ake Jonsson: Vinterbygge merkostnader i landets olika zoner (winter construction – Additional costs in different climatic zones of the country), Stockholm, 1962.

Generally speaking, there is a loss of productivity on all outdoor work in the winter. The extent of this loss depends on the climatic conditions and the types of operations.

Protective Clothing

Basic principles

If the body is to operate efficiently, it must maintain a normal temperature by adjusting to the variable external conditions it encounters. This adjustment is evidenced by the need for more food to produce additional heat during colder weather, by perspiration to increase removal of heat during hot weather, and by the gradual darkening of the skin as protection against extended exposure to the rays of the sun.

Proper clothing, correctly worn, assists the body in its adjustment to extreme climatic conditions. The clothing does this by holding the body heat in, thereby insulating the body against the cold outside air. Clothing not only protects the body against cold but gives protection in various other ways: it repels snow or rain, reduces the effects of the winds, and lessens the force of flying blocks and splinters of ice or frozen ground caused by projectiles.

Any material resisting the flow of heat is known as an *insulating material*. Since dry air is an excellent insulator, those materials which hold quantities of motionless air are effective insulators. "The principle of trapping air within the fibers of clothing provides the most efficient method of insulating the body against heat loss."[3]

"*Several layers of medium-weight clothing provide more warmth than one heavy garment*, even if the single heavy garment is as thick as the combined layers."[3] Again, the insulating effect of the layers of air (trapped between the layers of clothing) is the secret. The layer principle also allows maximum freedom of action and permits rapid adjustment of clothing through a wide range of temperatures and activities. The addition or removal of layers of clothing allows the body to maintain proper heat balance.

Perspiration fills the air spaces of clothing with moisture, reducing insulating qualities; and, as it evaporates, it cools the body. To combat these effects, cold weather clothing is designed so that the neck, waist, hip, sleeve, and ankle fastenings can be opened or closed to provide the *desired degree of ventilation.*

Chronological review of industry developments

More attention should be devoted to the question of adequate winter clothing for building workers. OECD considers the ideal winter outfit as being warm and providing protection against wind and rain without being uncomfortable or hampering movement. Although a considerable amount of research has been devoted to the development of suitable winter clothes for building workers, with excellent results in the United Kingdom, practical accomplishments have, on the whole, been fairly modest.

1961. The Russians were concerned that the eyes, respiratory organs, and face had received practically no protection from the effects of external environment. They considered the existing protective devices unsatisfactory since they were narrowly specialized, inconvenient, difficult to use, and quick to fog up and freeze over.

In their study they divided the many types of protective devices into two groups: those that formed a heat-insulating air cushion without using additional heat sources, and those that used artificial heat sources or the heat of exhaled air.[22] Within the second group, they designed a mask that electrically preheated the air with storage batteries. They also experimented with a mask utilizing the concept that exhaled air may be used to preheat inhaled air.

The Russians concluded that existing masks facilitate work in severe cold, but that their cumbersomeness and tendency to fog up make them somewhat inconvenient.

1965. Construction crews building roads over the Himalayas, India, must fight high altitudes, strong winds and sub-zero temperatures. "For protection from the cold, the men wear surgical gloves over their normal woolen gloves, or they use electrically heated gloves. Whenever they have to work without gloves, they warm their hands in tin cans of hot diesel oil."[7]

1969. The Directorate of Building Development in the British Ministry of Public Buildings and Works has carried out a program of on-site testing and development work on protective clothing. Initial site testing was carried out on commercially available protective clothing from different parts of the world. From this testing the directorate was able to produce what is considered to approach the optimum design.

Following a competition within the British clothing industry for the design of protective clothing, it was evident "that 4 oz. nylon, although far from perfect, was the best all round material commercially available. Certain fabrics comprising polyurethane on a fabric backing showed great promise, and an indication of materials which will be used in the future."[13]

Some of the desirable characteristics that evolved from this competition included:[13]

1. Clothing must be light with a maximum weight of 3 lb.

2. Fastenings must be robust and simple.

3. Condensation must be avoided by allowing large ventilation areas in the design of the garment.

4. Design should eliminate loose flapping cuffs and hems.

5. A minimum of two pockets should be provided.

6. Materials should be durable to the extent of having torque tear strengths of at least 12 lb-ft and abrasion resistance equal to that of 205-denier 3.7-oz nylon.

The British directorate found that the transient nature of the labor force provided little encouragement for many contractors to provide modern efficient clothing to maintain production. They summarized by stating that "Sometime, somehow, somebody must resolve the problem of who provides what to whom and who is responsible for its maintenance."[13]

Summary

Cold weather affects man psychologically and physiologically. His major psychological problem is that he does not enjoy the thought of being exposed to unpleasant working conditions. Physiologically, man may experience tissue or nontissue damage, depending upon his exposure, with the ultimate damage (other than death) being loss of an extremity.

Cold acclimatization in humans has been investigated with a view toward eventual application as a means of physiological protection from cold injury.

Man's winter productivity and efficiency are influenced by air temperature, surface-wind velocity, precipitation, and light. Although many observers have offered their educated guesses concerning the amount of this reduction, little factual information is available on the subject. However, there is a loss of productivity on all outdoor work in the winter; the extent depends upon the climatic conditions, the type of operation, and the degree of protection.

The basic principles of protective clothing – insulation, layers, and ventilation aid the body in its continual battle to maintain normal body temperatures under variable external conditions. The state of the art has developed a nylon or polyurethane material for a winter outfit that is warm, provides protection and comfort, and does not hamper movement.

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MATERIALS

One of the main problems of winter construction seems to be obtaining "adequate knowledge of what happens to different materials at low temperatures and to provide that information as basic material for specifications which guarantee a good result in the construction with the greatest economy."[7] This chapter deals with this subject and in addition describes the effects of frost on some of the basic building materials.

Low-temperature Effects

Metals become brittle when cold. How cold is *cold*? An Army group on a midwinter maneuver in the wastes of the Arctic found that at -60°F steel would break more easily than at normal temperatures. U.S. Navy Seabees in Antarctica found that their pneumatic tools (used as impact drivers) broke frequently because of the brittleness of the steel at the subzero temperatures.

In an article on subzero weather operations in Canadian mines, the Iron Ore Company of Canada reported that normal carbon plate steel becomes quite brittle under shock at low temperatures. During the cold-weather operations (when operating and maintenance problems are magnified), it was found necessary to resort to alloy grades of steel, such as quenched and tempered low-alloy steels. These "can be used, assuring good performance at temperatures as low as -50°F."[9]

Metals for subzero service may be classified by service temperature as shown in Table IX.[10]

Table IX. Materials for subzero temperatures (after ref 10).

Service temperature	*Material*
0°F to -20°F	Carbon steel
-20°F to -50°F	Carbon steel, aluminum killed
-50°F to -150°F	Alloy steel
-150°F to -320°F	Alloy steel or nonferrous

The minimum service temperature at which a material should be used depends upon whether it will be subjected to shock loading or to a steady static load. If the load is a steady static load, brittleness is of little significance and plain-carbon steel could withstand extremely low temperatures. Since this loading condition rarely exists in construction, it is important to select materials for subzero services which will withstand the shock expected at the service temperature.

According to data furnished by a Russian handbook (*Metal working and heat treatment, standards and specifications*, 1957), the impact ductility of one basic type of steel was "reduced from 10.5 at +20° (C) to 0.8 at -40° (C)."[8] The brittleness of ordinary metal at low temperatures was so pronounced that even small dynamic loads caused the formation of cracks and destruction.

Rubber becomes stiff during extreme cold, and bending causes it to break. When a vehicle is parked for several hours during subzero weather, flattened-out areas develop in tires; these flattened-out areas have little resiliency until the tires have warmed up.

In the antarctic winter, construction crews found rubber inelasticity at -56°F. The U.S. Army found rubber as brittle as glass at -60°F in the Arctic.

The welding industry employs a synthetic type of rubber "which is flexible down to -45°F."[13]

Timber **often drys out at near-zero humidity and subzero temperatures,** "causing splitting and warping up to 90 degrees (bending)."[3] While performing well at normal temperatures in large structural sizes, "Wood is generally much stronger at lower temperatures – from 1¼ to 3½ times stronger – dependent upon the strength property involved."[11] This property is being used in designing laminated beams for use in special tankers which will haul liquified natural gas at supercold temperatures, around -260°F.

Canvas becomes stiff (much the same as does rubber) and difficult to fold or unfold without being damaged. *Glass*, being a poor conductor of heat, cracks if it is exposed to any sudden increase in temperature. *Leather* cracks unless properly treated with neat's-foot oil.

Paint tends to crack very easily when exposed any great length of time. In Antarctica, paints and adhesive have to be warmed for use, and some of them separate when they freeze. The Russians have found that "At low temperatures it is very difficult for paint to resist reliably corrosion."[8]

Oils tend to become thick, and consequently retard the flow through the oil pump to places where it is needed for lubrication. Thickened oils also increase the drag on the entire engine, thus making it more difficult to turn over. At -60°F "standard lubricating oils solidify into a buttery mess."[4]

The Welding Research Council observes that "Wax present in ordinary lubricating oils precipitates at low temperature to form semisolid wax sponges which prevent oil from reaching the pump."[13] However, "Gear lubricants that are too viscous at low temperatures tend to 'channel' rather than to 'flow' around the gears to provide a lubricating film."[13]

Grease, which is a semisolid to begin with, becomes hard and loses a great number of its lubricating properties. Greases for low-temperature service must have low enough viscosity to be delivered to the lubrication site, and they must be fluid enough so that the starting torque is not excessive.

Fuel does not freeze but becomes more difficult to vaporize. "Since only vapor will burn, combustion of gasoline inside an engine is more difficult and unburned gasoline dilutes the oil in the crank-case."[9]

> "It is estimated that the Antarctic Forces consume approximately 5 million gallons of fuel annually, of which 40% is for heating purposes and 60% is for power generation and aircraft. As a result of the low temperatures prevailing in Antarctica, the primary requirement in these fuels is a very low pour point, with flow at -70°F being considered most desirable."[12]

"*Concrete* that is allowed to freeze soon after placing gains very little strength and some permanent damage is certain to occur."[3] The Portland Cement Association (PCA) has observed that concrete that has been frozen just once at an early age may be restored to nearly normal strength by providing favorable curing conditions. However, PCA contends that such concrete is not as resistant to weathering nor is it as watertight as concrete that has not been frozen.

Temperature affects the rate at which hydration of cement occurs. Low temperatures retard concrete hardening and strength gain: the latter practically stops when moisture required for curing is no longer available.

The U.S. Army has determined the effects of frost on concrete at two time periods: after initial set and after final set (partial curing). If the concrete freezes after its initial set (but while still green), the strength after thawing and subsequent curing remains low, "because of the disruptive effect of ice crystals upon the bond between the component materials of the concrete. The expansion of water while freezing exerts a force sufficient to destroy the cohesion between the particles of the green concrete."[4]

The report continues by stating that "If the freezing occurs after the concrete has attained reasonable strength and hardness and is not saturated with water, there is no appreciable damage to the concrete."*

While discussing concrete, we have touched upon the area of frost. We will now study this in more detail.

Frost Effects

Changes in temperature play an extremely important part in frost action, but the deleterious results of freezing would not take place if water were not present.

"Unlike most other liquids, water ceases to contract just above the freezing point (39°F) and begins to expand again. On conversion to ice at the freezing point there is a further sudden expansion of 9 percent by volume."[1]*

However, water (and thus frost action) is associated with only porous materials. The pores in porous building materials are containers that may be filled, in varying degrees, with water. "Whether or not expansion of the water within the pores during freezing is likely to cause damage to the walls of the pores depends on a number of different factors – chief of which include moisture content, moisture gradient, rate of freezing, temperature gradient, freezing/thawing cycles and pore structures."[1]

Thus, we may conclude that "Damage due to frost action is generally confined to the shattering of the surface of materials."[1] The degree of shattering and the manner in which it takes place depend largely on the pore structure and strength of the material and the conditions during freezing as outlined earlier.

Natural stone is variably susceptible to deterioration as the result of frost action. The best stones are unaffected while "Some stones with pronounced cleavage along the bedding planes are unsuitable for copings or cornices."[1]

Clay products are likewise variable. The best bricks and tiles are unaffected. "Some products, insufficiently fired, or with flaws of structure originating in the machine, may deteriorate, especially bricks in copings, and tiles on flat-pitched roofs."[1]

Clay stone, concrete, and asbestos cement of good quality are rarely affected.

As a note to the above discussion, "A laminar structure usually makes a material more liable to deterioration."[1]

Plaster applied at low temperatures has two basic problems. "Firstly, the rate of drying out is considerably reduced thus delaying the following trades and, secondly, the risk of the plaster freezing, etc. is significant."[1]

Paint applied during winter may be seriously restricted because of the presence of moisture on or under the surfaces to be painted and the delayed drying out of the porous paint itself caused by low temperatures.

In summary, the frost resistance of materials depends on the interrelationship of the properties of the material, the position in which the material is used, and the climatic conditions.

Summary

Admittedly, one of the main problems of winter construction is obtaining an adequate knowledge of the effects of low temperature and frost action on basic building components and construction aids.

Metals may be quenched and tempered for designed performance at temperatures as low as -50°F. Rubber tends to lose its flexibility as temperatures approach -45°F. In an atmosphere of sufficient humidity timber is generally stronger as a structural member at low temperatures. Concrete that has attained reasonable strength and hardness (and thus is not saturated with water) is relatively unaffected by low temperatures. However, water-saturated concrete is retarded from hardening and gaining strength by freezing temperatures. Oils and grease become thick, restricting proper lubrication; and fuel becomes more difficult to vaporize, restricting combustion.

Frost affects only porous building materials; the pores provide containers for water. Upon freezing, the water expands, shattering the pores and thus the surface of the materials. Frost resistance depends upon a material's properties, its position of use, and the existing climatic conditions.

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EQUIPMENT

For the purposes of this discussion, definitions of the general terms *cold* and *arctic* differ from those of the introduction.

"A cold climate extends from approximately +32°F down to the lowest temperature at which the most temperature-critical component or material employed is capable of performing its function reliably and unaided."[21]* This assumes circumstances of reasonable maintenance and average mechanical condition; absence or unavailability of external aids and special accessories, such as heaters; and proper use of commonly available servicing, fuels, lubricants, etc. "An arctic climate is therefore any temperature condition below this limit, or one in which auxiliary heat, power, or other special assistance is mandatory for starting and operation."[21]

The winterizing of equipment for arctic use is to a considerable extent a matter of accessory and application engineering – a search for means of artificially providing a warm (summer) climate for the locality of the engine and vehicle.

Paradoxically, the matter of starting and operating equipment in cold climates is more complex, and generally less well understood, than the arctic winterization concept. Perhaps for this reason, "We are apt not to recognize the practical limit of cold climates, or worse, fail to appreciate and take advantage of the inherent capability of our nonarctic equipped machinery."[21]

The military used to demand by specification that "gasoline engines start at a cold soaked –40°F, and diesels at –25°F without external aid."[21] This performance could be accomplished with a new piece of equipment, in carefully controlled test chambers. Unofficially, the military recognized the fallacy of such specifications as a matter of everyday practicality. "Zero to –20°F are now more generally accepted limits of unaided starting."[21]

Low-Temperature Effects

The normal question asked by the operator is how to start the engine after leaving it outside overnight at –20°F. However, after we examine the problem, we may conclude that it is much better if the engine does not start, unless proper precautions have been taken to protect all components of the units against the cold.

"The most common failures caused by cold-starts causing extensive damage and accidents are: seized main bearings, scored cylinder liners, burst oil coolers, broken flexible oil, fuel, and air lines, seized transmissions and differentials."[17]

Let us examine, systematically, the components of most equipment and determine the problems associated with each.

Engine

"Wear and tear" are higher, and reliability lower under severe winter conditions. "Difficulties of starting engines are greatly increased because of the reduced output of cold batteries, the increased cranking stiffness of cold engines, and the reduced atomization and vaporization of cold fuels."[7]*

Cooling-system leaks cause loss of expensive antifreeze and are more difficult to eliminate; errors in antifreeze mixtures cause freeze-ups with occasional severe damage to engine blocks and radiators. The glycol-water antifreeze solutions particularly must be mixed and used properly.

"While a 60-40 solution of glycol with water will not freeze at -50 to -60°F, an 80-20 glycol-water mixture will freeze at -10°F, and pure ethylene glycol will freeze at something above zero."[21] The Army learned long ago to premix antifreeze before packaging and shipping it; they had too many eager service mechanics figure that if 60% was good, 100% would be that much better.

Gasoline fuel systems generally suffer from the effects of water condensation and freezing with subsequent plugging of filters and fittings. Formed ice particles are frequently so minute as to remain in suspension, impinging and adhering to metal walls at fittings and valves.

The characteristics of gasoline most influential on engine startability are its distillation and Reid vapor pressure. These characteristics are recognized by the oil companies, who attempt to blend and provide higher vapor pressure fuel as local weather gets colder. "Warm weather fuel will begin to give starting difficulties at +20°F."[21]

The fuel supply system, not the fuel itself, is the most common cause of cold-weather fuel trouble. Paradoxically, it is comparatively less troublesome in the Arctic than in nonarctic areas.

Fuel pump diaphragms of compounds that remain flexible to temperatures in the range of -40°F have been manufactured. However, a diaphragm is likely to fail by age-cracking with changes in season, so it should be checked in the event of power loss in older equipment.

Practically all of the larger equipment power plants are diesels, and practically every design feature peculiar to diesel engines accentuates the cold-weather problem.

Compared with gasoline engines the diesels have higher compression ratios, more piston rings, and larger bearings, necessitating greatly increased cranking torque. "The power required to crank a diesel at 0°F will run from 3 to 8 times that necessary for equivalent speed at +70°F, and the battery's ability to deliver cranking power at 0°F is approximately one-half of its potential at 70°F."[21]

The diesels must utilize heavier fuels with their aggravated low-temperature problems of atomization and ignition (plus tendency to precipitate waxes which clog filters). Once started, the higher efficiency of diesels makes it more difficult to maintain adequate temperatures in their combustion chambers, fuel systems, and lubricating systems.

At what temperature should we resort to external aids and accept the fact that the environment has become arctic? "Everything else being adequate, proper fuel will normally enable cold starts as low as 0°F with average compression ratios and cranking speeds of 150 rpm."[21] Engines that crank more slowly have a somewhat higher minimum starting temperature, and engines with higher compression ratios start at somewhat lower limits.

Chassis

Reported effects of severe-cold or arctic conditions on chassis continue to include brittle failures of metal; freezing of brakes; freezing of tires or tracks to the ground; brittle-failures of tires, belts, and hoses; seal shrinkage and leakage; high friction torque in bearings; high friction loss in transmissions, transfer cases, differentials, final drives, etc.; and sluggish hydraulics.

Investigations have shown "that certain unalloyed low-carbon steels are subject to embrittlement within the 0° to -65°F range, but that most ferrous alloys developed for high strength under normal conditions retain their strength and impact resistance down to temperatures considerably lower than -65°F."[7]

Commercial wheeled vehicles continue to be equipped with brakes at the wheels; and until brakes are hermetically sealed or moved inboard, there will continue to be brake freeze-ups. Tire and track adhesions apparently also are a problem.

"Elastomeric materials covered by Society of Automotive Engineers standards, codes and recommended practices are generally usable, for the intended applications, to temperatures of -40°F or below."[7]

Hydraulic fluids and hydraulic-system components, including critical items such as O-rings and hoses, now seem to have no inherent low-temperature limitations.

Lubricants

Much work has been directed by the oil industry and the military services to the development of oils and greases adequate for the peculiar problems associated with cold-climate lubrication. Results of these efforts have varied with different types of lubricants and are discussed in the following paragraphs.

The proper engine lubricating oil for low temperature operation is a compromise between the need for low viscosity at time of engine cranking and warmup and an operating temperature viscosity sufficient to inhibit metal-to-metal contact.

Preoccupation with engine lubrication without consideration for the transmission and axle oils can lead to "channeling" and excessive gear wear. Gear lubricants are available for subzero use.

Grease, like antifreezes, should present no particular problem at low temperature since a considerable number of compounds work very well to temperatures of -25°F. However, a problem arises when a machine is shipped from a temperate zone to an arctic area. The problem is identifying the grease installed in the equipment, particularly in "sealed-for life" components.

Manufacturers are increasingly taking advantage of the solid lubrication-type plastic materials for small bushings and bearing surfaces and even for application as thin films on metal surfaces where both low friction and surface protection against corrosion are required.

Miscellaneous mechanical and electrical components

So far we have touched on the problems associated with the engine, chassis, and lubricant components of equipment. However, there are accessory elements which are common to most engine systems as original equipment, and which have, to some degree, a potential for causing low-temperature trouble. Most of these give little difficulty in a *cold* environment, but nearly all require special treatment in an *arctic* climate.

Conventional fuel pumps are generally serviceable without special precaution to temperatures of -40°F (see p. 32).

Coolant pumps also seldom cause low temperature starting or operating problems. However, seals and packings are displaced frequently enough so that leaks are quite common. Glycol antifreezes also tend to leak or seep much more readily than water.

Thermostats fail more frequently than is generally recognized, but such failures go unnoticed during summer operation.

With air brakes, condensate freezing seems to be the most common problem, but the loss of hose line and fitting strength at temperatures below zero should also be checked. Cracks due to the strain of contraction may form in the hose line.

"Depending on the age and original material employed, coil and spark plug lead wiring in most cars begins to get brittle at temperatures of +10° to -40°F."[21] The first couple of cylinders fired may flex the wiring enough to cause open cracks to form in it, resulting in weak or poor ignition.

"The plastic and hard rubber parts of the coil case and distributor will also show a tendency to brittle failure at temperatures in the 0° to -20°F range."[21] Since the operating parts of most switches and relays are plastic, similar difficulties with these parts can be expected at temperatures below zero.

In some larger engines for trucks, construction equipment, and other heavy duty machinery, winterization of the starter engaging drive is needed for use at about 0°F.

Tires are not ordinarily considered as temperature sensitive in the -5° to -15°F range. However, below this range, cold rubber flexing makes permanent cracks and unexpected flats.

Another source of potential trouble is the air cleaner. The usual difficulty is the sludging of oil in the oil bath cleaner, resulting in an increase in level to the point of partial air stoppage.

Finally, the most widely recognized villain in automotive cold weather is the battery. As temperature drops, the rate at which a charged battery can discharge drops steadily and proportionately. "The average well-charged battery should handle a properly maintained and winterized engine system continuously as needed without difficulty in temperatures to -25°F for periods of up to 12 hr., -10°F for periods to 36 hr., 0°F for periods to 4 days, and +20°F continuously for periods to 2 weeks."[21]

Conclusions

Operationally, cold weather may be considered as beginning at the freezing point of water and extending to a lower limit varying from +10°F to -20°F. Arctic climates, defined as beginning at the temperature below which external aids are required, therefore extend from as high as +10°F to -20°F. For diesels, these temperatures are approximately 20°F higher.

The critical temperature of most automotive components and material if they are provided with ordinary winterization and preventive maintenance is below -20°F. The question of the starting and operation is reduced to essentially a matter of cranking speed and fuel for diesels, and cranking ability for gasoline engines.

Construction equipment advances

Advances in construction machinery design are often incompatible with cold climate operation. The following examples are typical.

> "*Engine turbochargers.* External oil lines, preheating difficulties, and critical oil viscosity complicate immediate bearing lubrication.
>
> "Required external location of air cleaners results in clogging with snow and ice.
>
> "Higher engine bmep plus higher bearings and valve train loads create demand for immediate lubrication. Engines are more susceptible to damage if loaded without proper warmup. Some turbocharged engines are hard to start at low temperatures.
>
> "*Hydraulic power.* Engine-driven pumps for power train components, steering assist, and accessories create a parasitic load on the engine during cranking.
>
> "Emulsion-type fluids are susceptible to freezing; glycol types are limited by mixture ratio; petroleum oils are limited by pour point and increased viscosity at low temperatures.

"Elastomers that suit extreme-low-temperature durometer requirements can abrade and clog orifices of small systems.

"Dispersed location of reservoirs, filters, pumps, and controls and poor access to them makes preheating of the fluid very difficult.

"Pumps with higher speeds, pressures, and flow rates will introduce material and leakage problems.

"With hydraulic servo replacing manual controls, more heat will be needed in cab, or else a higher level of protective clothing.

"Alternator-battery charging performance is excellent. However, insufficient protection against reverse current diode failure due to improper battery connections is a cause of grave concern.

"The problem of diodes in alternator circuitry also applies to solid-state regulators. Some electronic components are unreliable at temperatures below -30°F."*

In addition to having their own cold-weather problems, the newer construction equipment seems to have inherited the susceptibility of the old equipment to winter troubles, particularly with regard to engines.

Efficiency

Having developed an appreciation for the physical impact low temperatures have on equipment and in keeping with the theme that construction may need to be maintained under almost any severe winter condition, we now examine conclusions of a recent Swedish survey relative to the operational efficiency of construction equipment (Table X).[18] The variables of concern are temperature T, light L, and precipitation P. Efficiency values $E_t\%$, $E_\ell\%$, and $E_p\%$ may be combined in a model of the form:

Table X. Relative efficiency of operation of construction machinery (after ref 18).

Weather factor	*Excavation machinery*	*Hauling machinery*
Air temp (°F):	$E_t(\%)$	$E_t(\%)$
85	87	89
70	99	100
50	100	100
40	99	100
32	99	97
25	98	100
15	92	96
-5	78	88
-25	43	66
Light condition:	$E_\ell(\%)$	$E_\ell(\%)$
Bright sunshine	96	96
Indirect sunshine	100	100
Dusk	88	96
Subarctic winter twilight	65	82
Precipitation:	$E_p(\%)$	$E_p(\%)$
Heavy rain	81	85
Light rain	97	98
Dry, temp 50°F	100	100
Light snow	97	95
Heavy snow	73	76

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$$\text{Net relative efficiency } E\% = \frac{(E_t\%)\,(E_l\%)\,(E_p\%)}{10{,}000}$$

When operating machines manufactured without consideration of the specific conditions of the North, the Russians found that they had to contend with an average monthly number of winter breakdowns that was "triple the number of summer breakdowns."[22] Their data were compiled on about 2000 machines of 50 different lines operating in low ambient temperatures, high humidity, and strong winds. Inefficiency of gantry cranes in Russia reaches 100% when "the velocity of the wind exceeds 12-15 meters per second."[11]

Winterization

Design and modification of military and commercial construction equipment for successful operation in cold regions have been less than an unqualified success. Despite 20 years of intermittent development and testing, there remain unsolved many key problems which inhibit an extension of operations into the vast resources of the polar regions.

However, environmental scientists have accumulated essential data to aid in the winterization of construction equipment. These data facilitate accomplishment of the four basic objectives of winterization [as viewed by the Society of Automotive Engineers (SAE)][7]:

1. Provide reasonable protection, comfort, and visibility for the operator.

2. Provide the capability of reasonably prompt and reliable starting and warmup of equipment.

3. Provide emergency starting help from any type of ancillary source.

4. Provide additions or modifications to the machine needed to obtain proper internal operating temperatures.

Cab

Several cab-equipped heavy machines have good external appearance, neat window installations and provide operator protection at ambient temperatures as low as -65°F. To conserve heat and protect the operator from cold metal surfaces, cab interiors and floor plates are usually insulated. Improved cab design results in greater visibility and better space accommodations for operators clothed in arctic garb. Safety is stressed to a greater degree, resulting in provision of escape hatches, knock-out windows, nonskid steps and floor plates, and fire-resistant materials. The improvement in weather stripping and the addition of boots around levers and pedals keep out cold drafts and blowing snow. However, more consideration must now be given to ventilation and the elimination of toxic or obnoxious fumes.

The main cab problem, which is seldom fully recognized or adequately solved, is visibility. When we surround the equipment operator with steel and glass and provide heat, we protect him from the weather but immediately set up a visibility problem. This is partially a matter of reflections and of transparency loss from dust and dirt; but more acutely, it is a problem of defrosting, defogging and deicing. The heating-defrosting system, which provides a relatively high heat input with 100% fresh air delivery from fuel burning heaters, furnishes the most acceptable method according to SAE. Several types of heavy-duty windshield wipers suitable for low temperature operations are also available.

Engine

Although many theories and techniques have been published relative to cold-starting, the only positive solution is to heat the critical components to a temperature at which they perform reliably.

Two techniques for heating engines and related components to a condition for starting in extremely cold temperatures have been developed for ordnance: *standby* and *quick heat*. "Standby heat is the technique based on the concept of not permitting the pertinent vehicle components to fall below a certain minimum temperature, regardless of the ambient."[25] To accomplish this, the heater is continuously operated.

"Quick heat is the technique that allows the vehicle temperature to drop as low as the existing ambient temperature. When vehicle operation is desired, sufficient heat is then applied to the engine and batteries to raise their temperature to a value that will insure reliable starting."[25] The time required to obtain the desired temperature may be as much as one hour. Thus the *quick heat* technique cannot be employed where vehicle use demands instant operation.

Although the application of heat is the key to successful low-temperature operation, it takes more than a heating system to start an engine in low temperatures. The heating system can only warm the critical components to a selected temperature. Engine, batteries, fuel system components, and other equipment must be in good condition and must be provided with the proper fuels, lubricants and antifreeze for successful low-temperature starting.

The Society of Automotive Engineers (SAE) considers engine winterization systems for two types of equipment, main-line and auxiliary. Main-line equipment justifies the use of a complete engine winterization kit as suggested in Table XI.[7] The use of such a kit is uneconomical for equipment used relatively infrequently or seldom for more than a fraction of a day. For these auxiliary operations, SAE has published Table XII.[7]

Various arrangements for winterization heating are shown in Table XIII.[7] These arrangements are set up primarily in the order of their effectiveness. The authors consider that hot fresh air is the best medium for delivering heat to the batteries and to the engine crankshaft bearings, but that hot antifreeze solution is the most effective for carrying heat into the pistons, cylinders, and combustion chambers. Very hot exhaust gas from a combustion heater, circulated through a *shroud* around an oil sump, can raise oil temperatures more rapidly than can other media. All of the arrangements indicated as "secondary-best" are practicable for preheating, and can meet the requirements of standby heating, which requires relatively low rates of heat transfer. With several areas to be heated and with multiple choice of heating arrangements for each, there can be many system combinations.

Another cold-starting combustion aid for gas and diesel engines is a starting fluid. The major ingredient is ether, which is injected manually or through starting fluid injectors. The ether vaporizes more readily than diesel fuel and ignites at a lower temperature. The immediate ignition of the starting fluid heats the combustion chamber; this makes firing easier and dries the combustion chamber and spark plugs. However, too much starting fluid can seriously damage the engine; even though the combustion is helped, the engine being started is a cold engine. Such an engine may be too cold to start and starting may only cause extensive damage.

Another combustion aid for cold-starting of diesel engines is glow plugs. "A glow plug is a low-voltage heating element inserted in the intake manifold, energized by the vehicle's battery and controlled by a switch on the instrument panel."[27] The glow plug heats the air in the intake manifold, providing an initial warm charge of air to help the fuel vaporize and burn. A glow plug does not help to preheat the block; therefore, with only this item, we are still starting a cold engine.

Table XI. Winterization materials, components and systems (after ref 7).

Tentative selections for different temperature ranges where operation is routine or frequent, long-duration (several hours), moderately heavy duty, and can seldom be postponed or suspended.

Temperature above +10°F 90% of time in January below 10°F 10% of time	*Temperature above −20°F 90% of time in January below −20°F 10% of time*	*Temperature above −40°F 90% of time in January below −40°F 10% of time*
Commercial antifreeze	Commercial antifreeze	Arctic antifreeze
Diesel fuel w/cloud point −20°F	Diesel fuel w/cloud point −45°F	Arctic diesel fuel w/cloud point −65°F
SAE 20W engine oil*	SAE 10W engine oil*	SAE 5W engine oil*
SAE 80 gear oil	SAE 75 gear oil	SAE 75 gear oil
Normal-grade hydraulic oil	Winter-grade hydraulic oil	Arctic-grade hydraulic oil
Ether-primer	Ether-primer	Ether-primer
Cab with wipers, mastic insulation, "hot-water" heating, ventilating, defrosting *system*, commercial weatherstripping	Cab with wipers, mastic or foam insulation and floor mat, heating, ventilating and defrosting *system*, hot-water and/or fuel-burning silicone weatherstripping	Cab with wipers, foam insulation and floor mat, heating, ventilating and defrosting *system*, hot-water and fuel-burning, silicone weatherstripping
High-temperature thermostat	High-temperature thermostat	High-temperature thermostat
Large radiator bypass line	Large radiator bypass line	Large radiator bypass line
Engine enclosure, "winterfront"	Engine enclosures, "winterfront"	Engine enclosure, insulated, with "winterfront"
Battery box, larger battery	Battery box, with provision for heating	Battery box, insulated, with provision for heating
Electric "standby" heater for engine	Heating system for engine coolant, oil-pan and battery; electric or fuel-burning "standby" type	Heating system for engine coolant, oil-pan and battery; electric or fuel-burning "standby" and "quickstart" type
Carry "jumper" cables	Install slave receptacles all equipment	Install slave receptacles all equipment
	High-capacity generator	High-capacity generator
		24-volt electric system

* Except for very high engine loading.

Table XII. Winterization materials and components (after ref 7).

Tentative selections for different temperature ranges where operation is occasional, short-duration, light-duty, and can usually be postponed or suspended for a limited time.

Temperature above +10°F. 90% of time in January below 10°F 10% of time	*Temperature above −20°F. 90% of time in January below −20°F 10% of time*	*Temperature above −40°F. 90% of time in January below −40°F 10% of time*
Commercial antifreeze	Commercial antifreeze	Arctic antifreeze
Diesel fuel w/cloud point 0°F	Diesel fuel w/cloud point −30°F	Diesel fuel w/cloud point −50°F
SAE 10W engine oil	SAE 5W engine oil	SAE 5W engine oil
SAE 80 gear oil	SAE 75 gear oil	SAE 75 gear oil
Winter-grade hydraulic oil	Arctic-grade hydraulic oil	Arctic-grade hydraulic oil
Spray-primer, gasoline engine	Spray-primer, gasoline engine	Ether-primer, gasoline engine
Ether-primer, diesel engine	Ether-primer, diesel engine	Ether-primer, diesel engine
	Cab with wipers, defrosters fuel-burning heater	Cab with wipers, defrosters, fuel-burning heater
Carry "jumper" cables	Carry "jumper" cables	Install slave receptacle, carry cables
	Use portable heater or "slave kit" as necessary	Install fuel-burning engine heater, or adaption to "slave" heater or adaption to "antifreeze-transfusion" from slave kit or vehicle.

Table XIII. Winterization-heating arrangements (after ref 7).

	Heated during:			*Heat delivered by:*						*Heat source:*		
Part to be heated	*Pre-heat*	*Stand-by heat*	*Operation*	*Hot fresh air*	*Anti-freeze solution*	*Hot exh gas*	*Con-vection*	*Con-duction*	*Rad-iation*	*Comb htr*	*Elec elem't*	*Engine*
	D		R-C									
Cab	X		X	X			X			X		
			X		X		X					X
Block	R	R-C	*									
Cyls	X	X-T	X		X			X		X		
Pistons	X	X-T			X			X			X	
Heads		X-T	X	X			X			X		
Crank-	R	R	*									
shaft	X	X		X			X			X		
bear-	X	X			X			X	X	X		
ings		X			X			X	X		X	
	R	R-C	D									
Oil	X	X				X	X			X		
sump	X	X-I			X					X or	X	
		X-T						X			X	
			X-I		X							X
	R-C	R-C	R-C									
	X-T	X-T	X-T	X			X	X		X		
Batteries	X-T	X-T	X-T			X			X	X		
		X-T	X-T				X				X	
			X-T		X		X		X			X
			X-I	X			X	Use heated air discharged from cab				

* With adequate engine enclosure, large radiator-bypass and high-set thermostat, heating during operation should never be necessary; however, some engines will overcool when idling; then operation of heater may be advisable as an expedient.

Code: R = required; D = desirable; C = control of temp required; T = thermostatic control provided; I = inherently safe against overheat.

Conclusions

Heat must be provided by some source to raise the temperature to the point at which the fuel is ignited. This heat can be generated by using any or all of the following methods[19]:

1. Longer cranking period to increase temperature through repeated compression of air charges.
2. Auxiliary heating of the water jacket.
3. Auxiliary heating of the intake air.
4. Auxiliary heating of the lubricating oil.
5. Auxiliary heating of the batteries to aid in longer cranking.
6. Heating of entire engine and battery compartment.
7. Auxiliary heating of the combustion chamber with glow plugs.
8. Use of ether as a starting fluid (with still cold engine).

These practices, coupled with the use of insulation in other engine components (air cleaner and induction system, fuel lines, battery, radiator, etc.) and with the use of winterized lubricants and fuels, will establish a winterizing procedure adequate for equipment operation.

Operating practices

Operation of the engine in cold weather (following preparation, cranking, and starting) is probably the most important aspect of cold weather considerations. In both gasoline and diesel power plants, prolonged idling of the engine is commonly resorted to in avoiding cold starting. This is a bad habit with any engine at lower temperatures, but is particularly poor practice with the diesel. "The condensation and sludging of crankcase oil will make eventual starts more difficult, promotes crankcase corrosion, and interferes seriously with the lubrication of wearing parts."[21] Due to the large amount of air the engine is *breathing*, cooling can take place rapidly. During lunch hour, coffee breaks, etc. the engine stays warm longer if shut down. However, a good practice is to idle the engine for a few moments before shutdown to prevent after-boil and coolant loss. When the engine must be idled, operators should keep the speed up to the 800-1000 rpm range to maintain lubrication and battery charging.

In engines equipped with a compression release, it is a good practice to release compression to shut down the engine. This results in washing oil off cylinder walls and a moderate dilution of the crankcase lubricant, reducing drag on subsequent starts and resulting in faster initial cranking speed and quicker cylinder heat buildup.

Because of low humidity in arctic weather, there may be little condensation in the fuel tanks, but the usual good practice of leaving vehicles with well filled tanks should be followed. Various commercial water removal additives are successfully used in the Arctic.

It can be safely stated that regardless of how well equipment is winterized, improper operating techniques shorten its life.

Chronological Review of Winterization Aids and Procedures

1961. The special section in *Engineering and Contract Record*, entitled "Winter Methods Fieldbook 1961-62," described the winterizing of equipment by a Toronto consultant. A 50% mix of antifreeze, lighter weight transmission oil, and special winter grease were used as preventive maintenance.[29] The same section contained an article suggesting five general rules for starting diesels in cold weather. Another article in the same section offered a note on the winter care of fuel systems. By filling the fuel tank every night and draining the water off every 50 hours, frozen fuel lines can be avoided.

The Quinn Construction Company of Canada recorded its observations concerning equipment used in northern Manitoba. Equipment maintenance was extremely important with temperatures of about −65°F, causing even special low-temperature lubricants to fail. "Generally the crews found that equipment with electric controls performed best at extremely cold temperatures. Air controls performed next best and hydraulically controlled machinery gave the least satisfaction, according to Quinn officials."[15]

1963. The White Motor Company of Canada suggested several measures that could be taken to ensure the most efficient operation of automotive equipment in cold weather. Essentially this can be obtained if "equipment, lubricants and accessories are made to the correct specifications or are adapted to the operating conditions."[17]

1964. The test and evaluation of MP-1 (a multipurpose antarctic fuel) in diesel engines, space heaters, emergency camp stoves, and lanterns, were reported by the U.S. Naval Civil Engineering Laboratory.[30] Another NCEL report covered the development and testing of an engine-mounted kit to facilitate starting and operating liquid-cooled engines in low temperatures. "The kit was designed to preheat the engine, oil, and battery and to provide ignition assistance during cranking. The components included a gasoline-burning coolant heater, an electric coolant heater, an ether priming system, a battery heating system, and a crankcase shroud."[9] Results showed that the kit as a whole was adequate for subzero engine starting, when subzero oil was used for the engine lubricant.

The most common problem reported by British engineers operating diesel vehicles during the winter was blockage of the fuel feed at the primary filter between the fuel tank and feed pump. A nonchoking separator was needed. The solution offered was the Type SS sedimenter, which removes all the larger water droplets from the fuel and hence prevents blockage by ice.[5]

The January 1964 issue of *Pit and Quarry* suggested the observance of the following rules before and during cold weather:[24]

1. Obtain the fuels, lubricants, and other fluids which your supplier recommends for the lowest anticipated temperature.

2. Store such supplies for protection from water.

3. If heated buildings are not possible, be prepared with electric or fuel fired heaters to warm engine blocks and cooling circuits, crankcase oils, batteries, and hydraulic oils and greases.

4. Provide methyl alcohol for prevention of line freezing, gasoline and kerosene or diesel fuel for dilution purposes, and ethyl ether capsules for starting aids.

5. Anticipate cold weather and install low-temperature fuels and lubricants in the equipment before its onset.

6. Establish a regular routine for lubrication and battery maintenance, supply, and storage control.

1965. Indian engineers, building roads over the Himalayas, have not found a satisfactory method for starting diesel engines at high altitudes. "Sometimes the operators introduce ether directly into the carburetors of the engines while they are being cranked, and sometimes they tow the machines with others in order to start them."[10] The high Himalayas can freeze ordinary fuel, so chemists have developed special fuels with a working range down to -94°F. "Occasionally the operators boil the diesel oil and feed the tanks only enough to run the engine for 10 minutes."[10]

The British arm of Caterpillar Tractor Company published notes concerning some of the more simple but critical servicing operations which experience has shown them are too often overlooked. These include checking the cooling system, checking for water in the fuel and air system, choosing the correct oil for the engine and hydraulics, and obtaining optimum starting conditions. Such is possible by "keeping cranking load to a minimum, providing maximum cranking power, and conditioning the fuel air mixture so that it will ignite more easily."[12]

The use and application of ether compounds, engine heating devices, and glow plugs as starting aids were discussed in the November 1965 issue of *Diesel and Gas Engine Progress.* The intent of the article was to "focus attention on some of the latest developments in cold weather starting equipment and their design and operating philosophy."[14]

1966. Mays, in a 1966 article in *Transmission and Distribution,* wrote: "A home-made hot-water heater inserted into the oil reservoir of hydraulic equipment such as earth augers and bucket trucks is reducing winter-time hydraulic pump breakdowns, speeding machine operations, and cutting maintenance costs. Results are excellent."[18] While both electric and hot-water heat exchangers were considered, it was found that electric immersion heaters would be susceptible to corrosion. Also, if coupled with a sticking thermostat, an immersion heater could raise the oil above its flash point, causing a hazard.

Representatives of the British American Oil Company stated that the choice of suitable fuels and lubricants for winter conditions in western Canada is governed by the range of temperatures, conditions of snow and ice, and the "windchill" factor. "In western Canada the pour should be held to at least -35°F; for more northerly service -40°F. In both cases, the closer one can get the cloud point to the pour point, the better."[6] The most suitable greases for low temperatures are the lithium calcium complex soap greases. These are "capable of lubricating at -60° to 150°F."[6]

Delco-Remy Division of General Motors Corporation studied cranking motor requirements for satisfactory cold starting. "Improved cold cranking performance can be obtained by either increasing the power available or decreasing the load, or both."[20] The increased cranking power may be obtained by using batteries with greater power output. According to this study, the major way to decrease engine load is to reduce the oil viscosity.

The Spray Products Corporation embarked in 1955 on a program for the development of pressurized starting fluid in aerosol cans. In 1966, it claimed the development of an injection control priming system (utilizing ether), that has "materially reduced battery requirements, and at the same time satisfied customer requirements for quick-starting engines."[19]

The Cummins Engine Company has studied cold starting and available equipment to aid in such. It reported at SAE, in January 1966: "One of the most effective means to add heat to the intake air of an operating diesel is the arctic preheater. This preheater uses a small radiator core mounted in the air intake stream to transfer heat from the coolant of the engine to the air intake."[24] This article mentioned the development of new and improved systems such as the positive engagement starter, the thermostat controlled glow-plug air heater, and the sustained-operation heater for the air intake system.

Engineers of the GMC Truck and Coach Division of General Motors described a simple method of making every truck a cold-weather truck. "A simple 25 amp wiring arrangement, plugged into a 110 v outlet at the terminal before the truck's daily run, activates a series of immersion heating elements which will raise the engine, radiator, battery, and the fuel in the tanks to summer starting temperatures."[28]

Staff engineers of Delco Remy wrote an article on the role of electrical equipment in improved cold weather starting of diesel equipment. Their solution was to install a charging system that would support the vehicle electrical load at engine-idle speed. Such a system "prevents the battery from discharging and insures that it will be maintained in a high state of charge regardless of the temperature."

The 1966 December issue of the Canadian Mining and Metallurgical Bulletin contained four articles on subzero weather operations in Canadian mines. The first of these articles reported that the "use of special-purpose lubricants, fuels, antifreeze, rubber compounds, and alloy steels has reduced the cold-weather hazards."[1] Tables XIV and XV depict winterization heating arrangements for shovels, drills, and trucks."[1]

The second article dealt with measures taken to maintain effective operations of heavy-duty equipment in open-pit mining during periods of extreme cold. "The points covered include equipment modifications designed to improve cold-weather performance, effective lubrication of machinery that is vulnerable to extreme cold and operating procedures designed to prevent equipment damage."[21]

Table XIV. Heating arrangements for shovels, drills, and trucks (after ref 1).

	Heated during:			*Heat delivered by:*					*Heat source:*			
Part to be heated	*Pre-heat*	*Stand-by heat*	*Opera-tion*	*Hot fresh air*	*Anti-freeze solution*	*Hot exh gas*	*Con-vec-tion*	*Con-duc-tion*	*Ra-dia-tion*	*Comb htr*	*Elec elem't*	*En-gine*
Shovels:												
Cab			U-M	U-M			U-M				U-M	
Gear cases		X	X					X			X	
Centra-lized lube reser-voirs*		U-M	U-M				U-M	U-M			U-M	
Boom		U-M	U-M				U-M	U-M			U-M	
Stick		U-M	U-M				U-M	U-M			U-M	
Drills:												
Cab			U-M	U-M			U-M				U-M	
Comp block		X	†		X			X			X	
Oil sump gear cases		X	X					X			X	
Water inj. tank**		U-M	U-M					U-M			U-M	
Hydrau-lic tank**		U-M	U-M					U-M			U-M	
Motor genera-tors and ex-citers		U-M	†					U-M			U-M	
Trucks:												
Cab			U-M	U-M			U-M				U-M	
Engine block cyl heads	X	X	†		X			X			X	
Oil sump	X	X						X			X	
Trans-mission	X	X						X			X	
Differen-tial	X	X						X			X	
B[illegible]††			U-M			U-M	U-M					U-M

* Heated enclosure on lowers.

† With adequate compressor or engine temperature controls, thermostats, radiator shutters, enclosures, etc. heating during operation should never be necessary.

Symbols: U-M = used and maintained; X = use discontinued

Aux equipment: Rubber tired tractors, loader and mobile cranes that are single or two shift service equipment have block heaters. Equipment with cabs have heaters-defrosters.

** Where tanks are exposed.

†† Some units.

Table XV. Insulation applications.

	Shovels	Drills	Trucks	Insulation
Insulation applications				
Operator's cab	X	X	X	Urethane spray
Machinery house	X			Urethane spray
Engine oil pan			X	Urethane spray
Fuel tank			X	Wool fiber
Water injection lines		X		Wool fiber
Other				
All hose Mil-H-13531 AII Exposed hydraulic lines recirculating.	X	X	X	
Air systems incl alcohol vaporizer.	X	X	X	

The third article described the methods of open-pit mining for iron ore in the subarctic regions of Canada. The fourth dealt with three major problems associated with mining operations during the winter. Included was a description of the maintenance of the cooling systems of diesel engines by the efficient use of thermostats, radiator shutters, etc.

1967. One of the accessory manufacturers working with the military in developing equipment to start engines in polar conditions was Benmar Heater Division of Test Institute Corporation. "Benmar engineers have approached the cold weather starting problem with the viewpoint that the quickest, most complete heating is accomplished by heating the entire engine block by forcing the antifreeze through a small high capacity heater at a rapid rate."[14] They recently developed a 30,000 Btu/hr forced circulation, multifuel coolant heater. This lightweight compact burning unit was built to military standards for operation at temperatures as low as -65°F.

The Germans developed "a novel laboratory test for predicting low temperature operability of diesel fuels."[3] This new test method was developed to give a direct, much more precise correlation with the field data, and is suggested for adoption as a petroleum industry standard (German) to replace existing specification and control tests.

1969. While conducting war games in -60°F weather in the midwinter wastes of the Arctic, the U.S. Army found that, "Unless engines are kept turning over, they risk a 'cold soaking' that seizes every moving part in icy immobility."[4]

Summary

The lowest temperature at which an equipment component or material can still function reliably and unaided defines the boundary between "cold" and "arctic" operating environments.

Nonarctic equipped machinery can normally start and operate down to -20°F with ordinary winterization and preventive maintenance. Below this critical temperature, arctic winterization aids are required. Diesel equipment becomes temperature sensitive near 0°F.

At low temperatures, difficulties of starting engines are greatly increased because of the reduced output of cold batteries, the increased cranking stiffness of cold engines, and the reduced atomization and vaporization of cold fuels.

Chassis experience metal and rubber brittleness, lubrication leakage, and gear friction loss at low temperatures.

Lubricating oils and greases are available for temperatures of -25°F or lower. However, the proper engine lubricating oil for low-temperature operation is a compromise between the need for low viscosity at time of engine cranking and warmup and an operating temperature viscosity sufficient to inhibit metal-to-metal contact.

Auxiliary mechanical and electrical components (thermostats, ignition systems, tires, batteries, etc.) become temperature sensitive around 0°F.

Several cab-equipped heavy machines provide operator comfort at ambient temperatures approaching -65°F. However, more consideration must now be given to the persistent problems of visibility and ventilation.

Although many theories and techniques have been published relative to cold-starting, it has been found that the only positive solution is to heat the critical components to a temperature at which they will perform reliably.

Standby and quick heating arrangements service main-line and auxiliary equipment. With several equipment areas to be heated and with multiple choice of heating arrangements for each, there can be many winterization combinations. Practical limit of operation with such ancillary aids would be near -40°F.

Regardless of how well equipment is winterized, improper operating techniques by its operators shorten equipment life. The most common fault is prolonged idling, which causes extremely rapid cooling of the engine.

A chronological review of winterization aids and procedures indicates that many companies are actively investigating possible "solutions" to equipment winterization to lower the critical temperature limits, and thereby expand equipment productivity.

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PLANNING AND PREPARATION

It is common to talk about the uncertainties of weather. Everybody talks about it, but no one does anything about it. Fortunately, building contractors are beginning to do something about it. They are finding that, with advance planning and preparation, winter building techniques need be neither difficult nor expensive.

The Canadians apply two main principles to their wintertime construction: planning and protection. The authors go one step further by defining protection as a part of preparation. Accordingly, this section will examine planning and preparation as two possible tools for the contractor to use against the adverse effects of winter.

Planning

Routine planning

Planning winter construction operations requires a knowledge of basic site data. Such data might include local weather conditions; hydrology and drainage; potential water supply and sanitation; topography; accurate surface and subsurface information; location of suitable sources of construction materials; existing or potential transportation facilities; and availability of labor, construction equipment, and supplies. These data may be collected partly from reports, records, and maps. However, further reconnaissance of a site (by personal visits, supplemented where necessary by surveying and subsurface explorations) is essential.

Although meager information is available for many northern regions, data on adjacent or similar areas may provide useful information on general conditions that may be encountered. Of particular interest is a knowledge of the geology and climate; both are intimately connected with the formation and existence of permafrost.

Field investigations usually consist of an exploratory survey and a detailed examination of the site. Following these, the site should be prepared for occupancy. The aim of efficient management must be to provide in advance the basic facilities that enable the work to continue in adverse conditions.

The principal operations affected concern earthworks and foundations or concrete. It is normally possible to phase the starting date of earthwork projects to avoid the two to five critical months. The technical problems of cold-weather concreting are largely solved and it is possible to work continually at whatever preselected temperature level is required.

In the far north, the time element interposed by permafrost (as well as the "normal" winter difficulties of nonarctic areas) must be considered in scheduling operations. The factors of weather can be carefully analyzed and combined in graphic form with the work to be accomplished. This provides a seasonal work-feasibility reference chart. Figure 9[15] is an example. This figure indicates (among other things) when surveying is not possible because of poor visibility and cold; when earth-moving is not possible, although foundations may still be excavated by explosives or by thawing; and when outside work requires floodlighting.

The construction timetable should be worked out early to allow sufficient time for preparing the different winter measures.

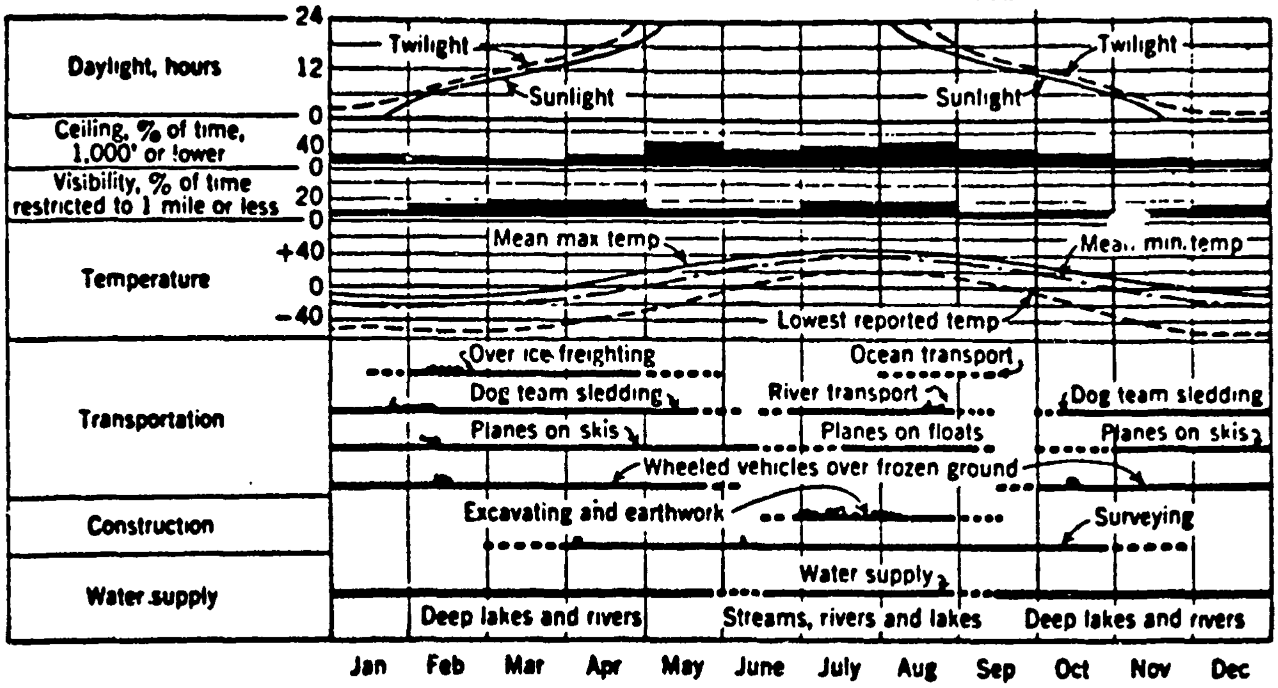

Figure 9. Work feasibility chart for a U.S. Navy Bureau of Yards and Docks Project.[15]*

Scheduling not only involves operations or activities but materiel requirements as well. Equipment must be ordered, winterized and lubricated for operation at subzero temperatures. Requirements for spare parts should be carefully studied, and items that are likely to fail in cold weather should be adequately stocked or replaced. Hand tools should be provided in ample quantities. Provision of an abundance of protective measures (shelters, clothing) should be given priority.

When materiel requirements are being calculated, great importance should be attached to construction work which is to be carried out during the winter. Orders for the delivery of materials can be prepared in detail, and delays can thus be avoided. Materials requiring costly weather protection should not be stored longer than necessary. If supply and transportation facilities permit it may be more advantageous to arrange with the suppliers for continual delivery of small quantities of material to the building site in agreement with the timetable.

While scheduling activities and material availability, the contractor should prepare the construction site, particularly if weather timing is critical. Transportation facilities, shelters, utilities, and fire protection should be among the salient factors considered.

Expedient planning

An ingenious construction contractor can derive much larger profits than the contractor who merely plods his way through the normal planning and preparation process.

During the winters of 1959 through 1961, a Canadian government pier, well within the Arctic Circle, was successfully defended against destructive ice pressures by a relatively modern development: a bubbler system using compressed air and submerged polythene pipe. This technique is now being used for a variety of jobs throughout Canada.

Essentially, with this technique compressed air is released at the bottom of a lake or river to push warmer water up to the surface and thus prevent ice from forming. Such a bubbler system was used to keep the water open while crews built piers for a four-lane bridge carrying an Ontario highway over Vernon Lake Narrows.[13] A compressor on shore supplied the air for the underwater pipes.

* Copyright, Civil Engineering; reprinted by permission.

Ice, which normally is a winter hazard, occasionally can turn into a positive asset. When it forms across a river or lake in a sheet strong enough to support vehicles, it converts that body of water from a summer *obstacle* into a winter *bridge*. Construction men are just beginning to realize the potential of ice, either as bridges or as work platforms on which to build permanent bridges.

A Canadian contractor built a winter tote road and is leap-frogging along its 126-mile course, taking advantage of the freeze-up to clear out areas of muskeg and leaving the clearance of ridge areas for summer work. "Rivers are crossed with ice bridges, created by pumping water on the ice until it builds up to the 5-ft thickness that can support construction equipment and the sled-mounted trailers in which the mobile camp is housed."[13]

Another Canadian company actually "froze the Saskatchewan River artificially to create an ice bridge over which they planned to haul 200,000 tons of gravel. The ice bridge cut their haul distance by 3½ miles."[14]

It can be gathered from these experiences that the contractor is not limited to routine planning methodology. In fact, he will probably profit by trying a little expedient planning.

Preparation

Site access

Before winter operations begin, and particularly before the first period of heavy frost or heavy snowfall, access roads, drainage, land clearing, lot layouts and excavations should be prepared. Some of these jobs can be difficult or impossible once winter has set in.

Roads and ditches should be readied early so that equipment and materials may be easily moved to and from the site. Side clearances should be provided for snow removal. Roads are much easier to build before the ground freezes and before fall rains or early snowfalls. Good drainage is necessary to keep a road usable and trouble free for several months.

Ideally, a site's road system is developed for construction use, usually by performing the necessary earthwork and by laying the base course at the outset. Alternatively, temporary roads may be laid with timber sleepers, clinker, or proprietary metal tracks. Stabilized earth is a further possibility.

Because suppliers have little demand from contractors for building materials and equipment during the winter, the availability of these supplies on short notice is one of the advantages of building in cold weather. It is important, therefore, not only to provide roads but to keep them open and in good condition.

One of the most appreciated machines for keeping access roads and construction sites free of snow during and after heavy snowfalls is the snowplow. Blowing snow away from roads and sites may also be an efficient way to clear snow rapidly. This is accomplished by equipping the basic machine with a rotary attachment. A rotary snow brush may be used for removing compact dirt or mud as well as snow.

Ice can be controlled by distributing calcium chloride over the roads with a number of small spreaders. A generous application of crushed aggregate helps to maintain a hard, nonslippery road surface.

Construction of site roads in the Arctic involves more precautions. Essentially, it requires that the existing overburden not be disturbed; cuts should not be made unless necessary. A rough rule of thumb indicates that the use of 4 ft of fill as the roadbed is a good starting point, if detailed road location and site investigations have not been made.

After acquiring site access, the contractor should try to maintain the building site during the winter. The site must be left at the end of the day in such a state that work can begin the next morning without delays, even if the weather is unfavorable.

Protection of housing

Construction priority should make possible the early use of such permanent facilities as barracks, mess halls, shops and storage buildings by the construction party. The size and permanence of the facility, the time construction must be carried out, the availability of materials, and the construction methods adopted must be evaluated before building plans are prepared.

In the Arctic, permafrost adds one more dimension to the variables. As long as the permafrost remains undisturbed, it has ample bearing strength; problems appear only if the permafrost is allowed to thaw. Thus, a solution is to keep the soil underneath a building as nearly as possible in its natural state; this requires inserting an insulating layer between the building and the ground.

Two ways of doing this are in common use. The first is to support the building on piles: the free airspace underneath greatly reduces the amount of heat transferred to the ground. The other, and usually cheaper, method is to put an insulating layer, typically a gravel pad, on the ground and to use this as a foundation.

Other solutions sometimes available to a contractor include: avoiding (if possible) permafrost conditions; eliminating frozen material; and thawing the frozen ground with the expectation of subsequent ground settlement.

Special procedures for workmanship and for handling of materials are required. Tight construction and good workmanship are essential in the Arctic. Even tiny cracks admit quantities of snow during high winds. All buildings must be properly insulated.

> "In heated buildings, vapor barriers are required as inadequately insulated walls will tend to sweat. Double windows are a necessity, both to conserve heat and to eliminate ice formation on the pane. Double doors with storm entrances are needed both to maintain an air lock and to provide a space in which excess snow can be removed from the clothing."[14]

These harsh logistics of building in the north have stimulated both the development and use of advanced prefabricated systems over the past two decades.

One successful approach to low-cost northern prefabrication has been developed by the Canadian Department of Northern Affairs and National Resources.

> "It uses basic stressed skin panels with full thick insulation and cedar plywood exterior to achieve a highly prefabricated, thermally efficient, low-maintenance enclosure.
>
> "The closed stressed skin panels do not suffer from internal condensation and require neither vapour barriers nor vents.
>
> "The joints and all details were easy to manufacture and over-all costs were very low."[11]

A few years ago a panelized structure was developed by the U.S. Army Engineer Research and Development Laboratories. It has given good service both in Greenland and Antarctica, with some drawbacks.

> "It is strong, and able to resist the 100-knot winds of Arctic storms. It is far too heavy for remote camps, however, because of the plywood skins and timber framing of the panels. The fiberglass batt insulation is not adequate for extremely low temperatures, and too much time, labor and construction skill are required to erect the underpinning and superstructure."[16]

A 1960 investigation by the Snow, Ice and Permafrost Research Establishment (SIPRE)*, U.S. Army Corps of Engineers, produced the first strong, lightweight, portable, easily assembled, and thermally efficient shelter for use by small parties in remote areas. This plastic arched shelter was tested with an outside ambient temperature of -60°F, and an inside temperature of +70°F with excellent thermal performance. In addition, no problems were encountered with frost or condensate buildup, or from the 100-knot winds.

The point to be made here is that prefabrication, to the extent that it transfers labor requirements from the construction site to the factory, eliminates or reduces the time required for the accomplishment of certain weather-sensitive steps in the construction process. Of significance are those steps essential to getting the site *closed in* so that work may continue inside.

Protection of construction operations

If the construction of a site can be scheduled so that it is *closed in* before the extreme weather is experienced, most of the weather problems are solved. Failing that, it is necessary to provide protection from the elements in some form of shelter.

Shelters may provide for total enclosure of the working areas, or for the roof or sidewalls only. They are generally divided into three groups: scaffolding, air-supported structures, and drapes and windbreaks.[17] Tents are considered a possible fourth group.

Scaffolding enclosures may be sheet materials fixed to a framework, usually the scaffolding of the building. The nature of the building operation and the degree of protection required determine the extent of the cladding on the framework. The cladding is either of rigid material such as corrugated iron, asbestos or plywood, or flexible material such as tarpaulin or plastic. Translucent materials are best fixed to either timber or galvanized steel mesh frames. Polyethylene is widely used for this purpose, but there is a wide range of other plastic materials such as nylon and terylene, which may be bought in sheet form.

Air-supported structures are the subject of one of the most recent and comprehensive studies; this study was made by Hodges.[9] Simple in concept, the air-supported structure compares with a tent held erect by a low pressure cushion of air. Its three principal systems include the structural envelope that is the fabric walls and roof of the "tent," the inflation system that provides the air pressure for holding it up, and the anchorage system that holds it down. Hodges recommends that the inflation blowers provide pressure of about 5 lb/sq ft and sufficient air volume to maintain that pressure in the face of normal air loss. "Of the number of fabrics used for the structural envelope, vinyl-coated nylon offers a number of advantages and is the most commonly used at this time."[9]

According to Hodges, the present state of the art enables units up to about 200 ft in width, of unlimited length, and capable of operation in design winds of 80 mph to be produced.

Drapes and windbreaks may be of tarpaulin, polyethylene sheeting or any other suitable flexible material. They are used to protect new construction or exposed working areas from high winds and driving rain. The advantage of polyethylene in this application is its translucence, thereby admitting natural heat and light.

* SIPRE was merged with the former Arctic Construction and Frost Effects Laboratory, U.S. Army Corps of Engineers, in 1961, to form USA CRREL.

Tents are another form of protection. Among various measures used, a tent-like enclosure gives the most extensive protection by turning a building site into an interior. Although it has been intensively studied and frequently advocated for 15 years, it has been the least used protective measure.

In 1968, however, four- to six-story dwellings on a 40-acre site in London were built in a giant workshop-tent (36,000 sq m) which was heated in winter and illuminated at night. This procedure was not entirely new. It relied on conventional tent building and on 12 years of experience.

> "Manufacturing costs of tent structures have remained almost constant during this period, indeed rationalization and refinement have reduced them slightly, whereas the expense of bad weather has grown considerably, and today people are ready to spend significantly more money on protective measures."[20]

Apart from a few minor exceptions, no large-scale project of this nature had previously been worked out. It would have been pointless to develop a structure tailor-made for one project; the designers therefore sought an all-purpose structure, which could be straightforwardly made and erected but which could be suited to a great variety of tasks. The roof needed to be raised or mounted differently for exhibitions and sporting events, so that the structure could be used profitably – rented when no building was in progress.

Protection of construction materials

Materials that may be damaged by rain, frost or snow, and cannot economically be stored in permanent shelters, may be partially protected by flexible tarpaulin or polythene sheeting. Fuller protection may be provided by using these sheets in conjunction with insulation and heat.

Certain materials, such as reinforced steel and cast-iron pipes, are not directly damaged by limited periods of exposure, but work is delayed if they are encrusted with snow and ice. Inadequate and unsatisfactory storage can lead to loss of materials dispersed about the site, particularly if the site is muddy. Where possible, the building itself should be used as storage space. The necessary precautions are outlined in the following paragraphs.[17]

Sand and aggregate should be protected from frost. The stockpile may be kept warm by local heaters such as salamanders or electric blankets, or covered with tarpaulins insulated by a suitable material such as straw matting. Alternatively, a simple network of perforated pipes with blanked-off ends may be laid near the bottom of stockpiles so that if there is a danger of freezing, a steam plant may be brought to the site and connected to the network.

Bricks, blocks, and tiles should be kept dry by proper stacking off the ground on a simple platform and should be protected from rain by well anchored tarpaulins or plastic film covering.

Bagged cement, lime and plaster should be stored in a weathertight building with a floor.

Insulation and plaster boards readily absorb moisture and must be kept dry, preferably in heated, covered storage.

Timber that is to be incorporated in any part of a building should never be left lying fully exposed. It should be protected from the effects of weather in transit, on the site, and until it is incorporated in the building. If this protection is difficult to provide, and the timber may be left in the open for a considerable time, it should be treated with moisture retardants.

Water supply and waste disposal

Municipal services (such as electric power, water, and sewers) should be arranged well in advance of the construction starting time so that there will be no holdups due to bad weather or trenching in frozen ground. In the Arctic, such standard services present several problems, mainly because of the low ground temperature, which makes it impossible to bury pipelines below the depth of frost.

Where storm sewers are to be provided, the site should be drained before cold weather sets in. It is best to install septic tanks at the time of excavating for the foundation. A septic tank can be put in place in winter, provided the ground is first covered by snow, brush or straw to prevent frost penetration and to make cold-weather excavation possible.

In nonarctic areas, disposal beds should be backfilled and covered with straw or snow to prevent freezing and heaving of the tile. Workmen and vehicles should be kept away from the disposal bed area because compacted snow cover will increase frost penetration. If cold weather is expected before there is snow on the ground, the disposal area should be covered with a foot or two of straw until after the septic tank system has been in operation for several weeks.

In winter, precautions must be taken against freezing of water pipes to ensure an adequate water supply for on-site concrete, masonry, and plaster work. Additionally, water should be available for fire-fighting purposes. Water pipes can be protected against freezing by insulating or heating.

Protection for temporary service pipes can be provided by placing the pipes in a trench and backfilling before freeze-up. If trenching is not practicable, pipes can be laid in boxes filled with shavings or sawdust. "Four to six inches of dry insulation will prevent freezing of still water in pipes for 24 hours on most construction sites."[4]

Electrical heating of pipes is effected by passing a low-voltage current, supplied from the power lines by a transformer, through the pipe. *Wrap-around* heating cables that operate on normal supply voltages are available and these, together with some insulation, provide enough protection for most winter jobs.

To allow uninterrupted flow in all service piping in the Arctic, the practice of using utilidors (Fig. 10)[7] has been developed both here and in Russia.

> "These utilidors are heated and insulated boxes through which the pipelines run. The boxes are usually installed on piles abovegound to prevent heat transfer from pipe to ground and subsequent thawing of permafrost. These utilidors work, but at a price, both in dollars and inconvenience. The inconvenience is created because these boxes running aboveground act as a barrier, either restricting traffic from one side to the other, or acting as a snow trap for roads running parallel with it. Crossings have to be made by means of costly overpasses or pipe bridges."[8]*

Even the smallest settlement in the Arctic must depend on surface water, with its problems of contamination and transport. This is due to the impracticality of drilling wells through the thick permafrost layer for water.

Permafrost also makes the disposal of waste difficult. Septic tanks with tile fields are impractical, and in winter even dirty water is difficult to eliminate.

> "Kitchen wastes are commonly poured outside to freeze into grey masses, which in the spring turn into grey puddles and only slowly disappear.
>
> "Human waste is often put on the ice to be lost during break-up; in summer it is dumped into the river or the sea...

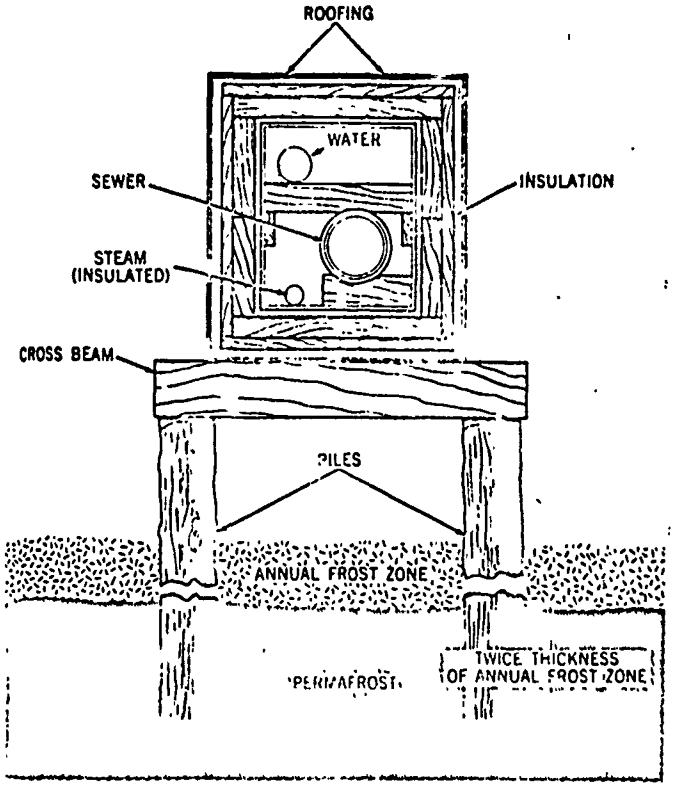

Figure 10. Utilidor.[7]

"Other sewage is dumped in a natural coastal lagoon, which is cleaned out periodically during heavy storms."[3]

Recently, some attempts have been made to treat a portion of the sewage. "Incineration has been tried. . . and attempts have been made to use a biologic system for mineralization of the organic sewage."[1] Both types of systems treat only human waste and still leave the problem of disposal of wash water and related material.

Since the end of World War II, activities have increased in northern regions at a significant rate, bringing with them all of the environmental problems encountered in temperate regions. Some progress has been made on methods of water procurement, but more needs to be done. Perhaps the future will see the conversion of salt water to supply arctic coastal areas with adequate supplies of fresh water. Atomic power plants may one day become cheap enough to make this method practical.

Sewage treatment has consisted principally of the disposal of human waste. A large-scale treatment process that will be functional at conditions near or below zero must still be developed.

Heating and ventilation

One of the obvious measures to counteract the influence of low outdoor temperatures on building operations is the use of heating equipment. Generally speaking, "The most economical and certain method of providing temporary heat is to rely on independent transportable heating units rather than on the 'built-in' system."[5] However in Sweden "built-in" systems are apparently used to a considerable extent and are designed accordingly. Whichever system is employed, the medium for transporting the heat will probably be steam, hot air, or electricity.

Steam boilers are recognized as an economical source of heat for winter projects. They usually are fired by solid fuel, fuel oil, or propane gas. Steam from the boilers may be used for a variety of tasks: to heat various buildings and enclosures; to heat concrete aggregates and mix water; to thaw out forms; and/or to protect concrete after placement. Control of the enclosure temperature is easiest with live steam. Steam is also advantageous because of the ever-present hazard of fire in heated enclosures.

Another widely applied heating medium is hot air. Portable warm air units fired with oil, coke, coal, or gas are available in various designs and capacities. They are equipped with blowers which direct the air where it is required. These heaters are easily handled and inexpensive to operate. They are convenient for small jobs but have two important drawbacks: they produce a dry heat, and they emit carbon dioxide. Hence, ventilation is essential when using them.

In the United States and Canada, infrared heat for winter concreting is used with success. It is a clean and efficient medium for heating structures or for keeping concrete from freezing. Banks of infrared lamps or sheathed heater elements in portable designs, connected by cable to a reliable supply of electric power, are used in concrete curing. "It is claimed that infrared heaters have protected concrete placed at -15°F."[21]

Temporary electric heat maintained a comfortable 60°F temperature within a two-story office building during a New Jersey winter. "Twelve portable 24-KW electric heaters maintained comfortable temperatures in the building under construction."[19] According to the contractor, it was not only practical but economical, speeding construction to meet building schedules.

"Heating systems in most arctic construction consist of conventional radiation or fan-coil units fed by multiple hot-water boilers, or waste heat exchangers from diesel electric generating units."[10] Multiple pumps, boilers and piping circuits are designed for reliability and continuity of operation should one part of the system fail or require maintenance.

Miscellaneous additional heating equipment is also available. Electric heating tapes for wrapping around oil or water pipes to prevent freezing of temporary supply lines are available. Electric overlay pads for placement over newly poured concrete are also on the market. In places of excess moisture, dehumidifiers are excellent for use in removing moisture from walls and wet finishes.

All heaters burning coal, coke, oil or gas (which discharge combustion products into the heated space) must be operated with care to prevent buildup of harmful gases. Ventilation must always be provided when men work within an enclosure. It must also be provided during the first 24 hours after placing concrete. During this period, floor slabs and other exposed surfaces will be damaged if the carbon dioxide content reaches a high level. If carbonation does take place, concrete surfaces must be ground down to correct the damage – a very expensive and time-consuming operation.

In the Arctic, ventilation is required to remove odors and maintain a livable environment. The low absolute humidity common in arctic areas during the winter months produces extreme dryness indoors. Humidification equipment and ventilation systems are required to raise the relative humidity to a comfortable level.

Power and communications

These are generally problems only in an arctic environment. Electric power is the lifeblood of most developments. Power has to be generated locally in the Arctic, because transmission lines from the southern power grid are not, as a rule, an economical solution. The power supply has to be reliable and dependable, because without power there is no production, no economic life. Besides being reliable, the power system must be economical.

"Because of the high cost of imported fossil fuel (which in some areas will cost as much as 50¢ per Imperial gallon laid down at the site) it becomes essential that maximum use be made of waste heat."[8]

In general, power costs for any northern development are high, because of high fuel costs. And the major part of the fuel cost is transportation. Two alternatives may be available to the contractor. The first is to use locally available fuel. The second is to use nuclear power. The latter seems to be an ideal power source because of minimal fuel requirements for the reactor. However, small reactors have not yet been developed.

Thus, for the present, and for the immediate future, conventional methods of power generation must be used. Where an adequate supply of low-cost cooling water is available, steam turbines should be considered. Where high year-round waste heat usage is possible, gas turbines with high overall heat and power economy will usually be the choice.

As has been mentioned, site lighting has a measurable effect on the efficiency of workmen. One British survey resulted in Figure 11.[12] This shows how limited the working day can be when a contractor relies solely on daylight. His investment in other winter protection devices is lost money if he can use this extra equipment only with a restricted working day. Therefore, it can be concluded that the use of artificial light increases productivity by increasing the efficiency of the workmen and the length of the working day.

The best source is the main supply, if connected, with portable generators as an alternative. The normal layout of equipment for lighting a site, on the exterior or interior, is to use two separate systems. First, the whole area should be adequately covered by fixed floodlights. These should then be supplemented by portable lighting at all important working points.

A relatively small number of *exterior floodlights*, provided that they are powerful enough and mounted to a "height of not less than 25 ft from the ground, will enable the average outside job to be carried on after dusk."[6]* Sufficient height of mounting is essential to avoid shadows and glare. "As a guide to the amount of light required, 0.5 lumens/sq ft is needed for general purposes but 1.5 lumens/sq ft is needed for detailed work such as placing reinforced concrete."[6]

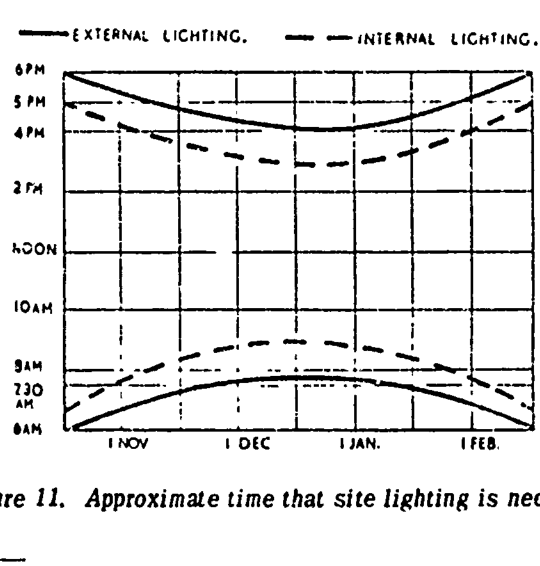

Figure 11. Approximate time that site lighting is needed.[12] †

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† Copyright, Civil Engineering and Public Works Review; reprinted by permission.

Interior lighting is preferably taken from the permanent electrical installation. Such lighting is required to facilitate the movement of men and materials for general work and for special finishing operations such as plastering and decorating. As with external floodlamps, avoidance of glare and shadows is desirable. "A useful rule of thumb for even-illumination is that lamps should not be spaced farther apart than 2½ times their height from the floor."[4]

Fire protection

In cold weather, the fire problem becomes more acute than in summer. Water may not be suitable to fight a fire, even if available in adequate quantities, because it may freeze. Often dry chemical tanks are more reliable.

"Nitrogen is the best gas for pushing the chemical through hoses as it retains its pressure at low temperatures."[18] The use of rubber hose that does not harden or get brittle in cold weather is essential.

Most winter fires are started by heaters getting too close to tarpaulins. Others are caused by welding and cutting operations. It is helpful to flameproof the tarpaulins and to make sure that all heaters are kept well clear of wood supports and the tarpaulins themselves.

Climatic conditions make fire an extreme hazard in arctic locations, and an adequate fire protection system must be provided for each installation.

Summary

Contractors are finally beginning to do something about the weather. They are finding that, with advance planning and preparation, winter building techniques need to be neither difficult nor expensive.

An ingenious contractor can derive much larger profits from a project than the contractor who merely plods his way through the normal planning and preparation process. Expedient planning should complement, not compete with, the routine planning methodology.

Following preliminary planning and field investigations, the actor should focus his attention on preparing the site for occupancy. His efforts should be directed to site access, housing and construction protection, utilities, and fire protection.

One of the first tasks in preparing a site for occupancy is to provide access roads, drainage, land clearing, and excavations. Arctic construction sites must cope with permafrost as well. After acquiring site access, the contractor should make a concerted effort to maintain the site during the winter.

Essentially, protection is provided for housing, construction operations, and construction materials. The criticality of the need for supplying housing protection rapidly in arctic environments is speeding up the development of prefabricated shelters.

Protective shelters for construction operations and materials are of four types: scaffolding enclosures, air-supported structures, drapes and windbreaks, and tents. The cladding is either of rigid material such as corrugated iron, asbestos or plywood, or of flexible material such as tarpaulin or plastic (polyethylene). Fuller protection is provided by combining these shelters with the use of insulation and heat.

Municipal services (such as electric power, water, and sewers) should be arranged well in advance of the construction starting time. Heating by steam, hot air, or electricity must be provided in conjunction with ventilation. Further, humidification is required at arctic sites. Power and communications are generally problems only in an arctic environment. Gas or steam turbines are conventional methods of power generation at present. However, nuclear power is a future possibility. The provision of artificial light will increase productivity by increasing the efficiency of the workmen and lengthening the working day.

In cold weather, the fire problem becomes more acute than in summer. Water may not be suitable to fight a fire, even if available in adequate quantities, because of the danger of its freezing. Often dry chemical tanks are more reliable. In arctic locations, climatic conditions make fire an extreme hazard and an adequate fire protection system must be provided for each installation.

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EARTHWORK

Earthwork within the construction industry is extremely weather sensitive. The weather affects both excavating and filling. Each operation has its critical limit, beyond which man must either submit to the elements or fight them with the aid of winterizing methods. The objective of this section is to delineate these natural or man-made limits and to describe available winterizing procedures for relaxing them.

Military Requirements

The dozen military guides may be grouped into five categories according to the restrictions they place on the various operations.

Essentially, all regulations have some stipulation about the *prohibition of frozen materials*, and three military guides' restrictions are limited to only that clause. Typical boundaries for fills include:

> "8.1. *Satisfactory materials* shall be used in bringing fills to the lines and grades indicated and for replacing unsatisfactory material. Satisfactory material shall be free from roots and other organic matter, trash, debris, frozen materials, and stones larger than 3 inches in any dimension. . . .
>
> "8.3. *Placing*: No material shall be placed on surfaces that are muddy, frozen, or contain frost."[19]

The guides concerned cover excavation, and filling and backfilling for buildings and subgrades.

Specifications for limerock and drybound-macadam base course construction contain loosely worded limitations concerning weather, with no definite temperature limitation. A typical restriction is:

> "6. *Weather limitations*: . . . base course shall be constructed only when weather conditions do not detrimentally affect the quality of the finished course. . . ."[20]

No placement at 40°F or less and protection at 35°F or less are restrictions contained in the guide specification for portland-cement-stabilized base course, subbase, or subgrade for roads and streets.[21] *No placement at 35°F or less and protection at 35°F or less* apply to four guides describing construction of stabilized-aggregate base and subbase courses.[22] *No placement at 32°F or less and protection at 40°F or less* apply to the construction of a waterbound-macadam base course.[17]

It can be concluded from these observations that there are no existing military restrictions for any earthwork operation except filling. Depending upon the type of fill, the restrictions can be classified into five general groups, ranging from loosely defined temperature limitations to 40°F for placement and protection. However, all restrict the use of frozen material as a fill or the use of unfrozen material on frozen bases.

Civilian Requirements

Europe

The general civilian requirement, according to the Organization for Economic Co-operation and Development (OECD), is: "When excavations cannot be made before the beginning of the winter, the ground usually needs to be covered to reduce frost penetration."[50] Denmark has a more definitive requirement: "As soon as there is a risk of frost, surfaces which are to be excavated during the period December to March are to be covered in order to prevent the ground from freezing."[50] In all cases studied by OECD, straw, preferably covered with tarpaulins, is the recommended method of protection.

Canada

The Canadian Research Council points out that, although most excavating and trenching should be done before cold weather sets in, excavating is sometimes easier in the winter. "Rock excavations present no particularly difficult problems at temperatures above 0°F."[14]

The Canadians also recommend the use of straw covered with tarpaulins for protection. Heavy snows preceding periods of very low temperatures provide a blanket of insulation over the area as well.

As did the Europeans, they also recommend excavating foundations just before placing concrete to limit the amount of protection required. Thawing operations may be necessary when excavations must be made at the height of the cold weather.

The Canadians state that no backfilling should be done until spring unless unfrozen material is used. "This should be placed in layers of 6 inches to one foot and compacted to prevent future settlement and subsequent ponding of water. . . ."[14]

United States

Most states require that frozen material containing frost shall not be used in construction of embankments or in backfilling around structures and that embankments shall not be constructed on frozen ground.[51]

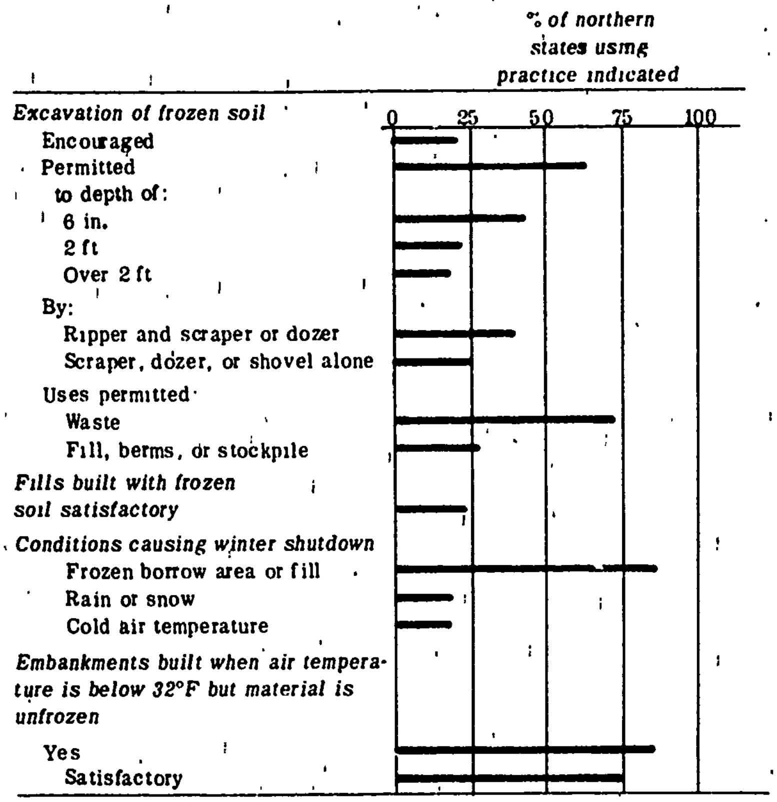
In a comprehensive survey of state highway departments, Yoakum[51] found that Maine, Pennsylvania and Wisconsin specifications state that material which may be frozen may be placed in the embankments. Maine's specification requirements are that "Embankments may be formed when the depth of the fill plus the depth of the frozen ground does not exceed 5 ft."[51] Maine's specifications also state that "Base courses may be formed on frozen subgrade when the subgrade has been properly compacted prior to freezing."[51]

Pennsylvania allows the forming of embankments on ground frozen to a thickness no greater than 3 in. Wisconsin prohibits the formation of embankments in the fall or early winter except when the material is primarily granular.

According to Yoakum,[51] five of the state highway departments do not specify that frozen material shall not be used in embankments but they do specify that embankments shall be constructed of material acceptable to the engineer and of soil containing no unsuitable, perishable, or deleterious material.

In a comprehensive study at Purdue University, Lovell and Osborne[35] canvassed various state and provincial engineers and contractors. They compared practices of 21 states in the area of significant frost and summarized cold weather practices (see Table XVI).[35] The percentage of states (75%) that successfully built satisfactory fills when air temperature was below 32°F was surprising.

Table XVI. State of winter earthwork in the northern United States (after ref 35).



In its report for the U.S. Weather Bureau, the Travelers Research Center (TRC), Inc. found that "Precipitation and low temperature are the elements most likely to interfere with earthwork."[44] The low temperatures chill personnel as well as increase the ground freeze, making equipment operation more difficult.

Excavating

Winter construction involving excavation is handicapped by the hard ground conditions, difficulties of equipment operation at low temperatures, reduction of daylight hours, and lowered worker efficiency. According to Department of the Army Technical Manual 5-852-1,[14a] frozen soils may have strength properties equivalent to those of lean concrete at only moderately low temperatures.

> "At very low temperatures the compressive strength may exceed 3,000 pounds per square inch and frozen rock may be even stronger. Thus, excavation of frozen materials at low temperatures is comparable to excavating concrete of various degrees of strength."[14a]

These statements apply to the arctic environment but they also inform the contractor who is contemplating either mass or foundation excavation in the wintertime in a less harsh climate.

Nevertheless, the excavation of frozen soil is becoming more common, as more construction is being carried on throughout the year. Most excavation of frozen soil is performed on a small scale (foundations) through the ingenuity of the contractors; however, large-scale excavation of frozen soil is usually preplanned, using the most practical and economical methods available.

Mass

Mass excavation of soil is analyzed as a two-part operation: preliminary treatment and stripping.

Preliminary treatment. Before starting excavation, a contractor may be justified in performing certain preliminary tasks: 1) protecting the ground before freeze sets in; 2) disintegrating the ground with explosives; or 3) thawing the ground after the occurrence of frost. His choice is influenced by several factors: the toughness of the soil, the availability of equipment and explosives, the timing of the project's required completion, and his financial position.

Protecting: Earth that is to be excavated after winter sets in can be covered with brush or straw to reduce frost penetration, especially if covered early enough in the season. Black polyethylene sheeting placed over limited areas has been found effective in limiting freezing or promoting thawing by high absorption of solar radiation. The main disadvantage of this method is that it is costly in labor and transport, particularly when straw is not available locally.

If a contractor is "lucky," there will be a heavy snowfall just before a period of very low temperatures. This snow cover should be left undisturbed to provide a blanket of insulation over the area of concern. One Canadian authority states that "A deep layer of snow reduces frost depth by more than 30%."[27]

Just before stripping, the contractor should remove the protective snow or straw mat, leaving an area just large enough for equipment spread for use that day. As soon as an excavation is made steps must be taken to prevent frost from getting into the ground. Again, straw can often be used and re-used to protect frost-susceptible soil.

Disintegrating: In the United States "Large scale excavation of soil frozen deeper than about 2 ft is normally carried on by blasting with explosives or by breaking up the frozen ground with tractor-mounted rippers."[51]

In the past, explosives have been the most commonly used agent for breaking up thick layers of frozen soil. Cold weather does not present any great problems for drilling and blasting, but a few suggestions may prevent the contractor engaged in wintertime blasting from having many problems.

The main concern should be to keep the boreholes as dry as possible. "The most common trouble is the 'ice collar' in permafrost areas. This collar forms when water, melted from ice and forced up by the heat of the drill, freezes again at the top of the hole."[26]*

Likewise, powdermen, loading the drilled and cleaned holes, must work fast to place explosives in them before the water in the holes freezes up again and obstructs the loading operation.

Although frozen dynamite is abnormally sensitive to shock and friction, modern high explosives do not freeze, and they detonate and retain their sensitivity at even the lowest temperatures. The Canadians recommend that warming modern explosives makes them easier to handle.

Winter operations also present added problems in the use of blasting accessories.

> "Knots are more difficult to tie when making connections between Primacord downlines and trunklines. In electrical blasting, similar difficulties will be experienced in connecting up legwires and leadwires to complete the blasting circuit."[26]

In addition, blasting machines, galvanometers and any equipment running on stored electrical energy must be given special attention during winter work, because of the inefficiency of batteries at low temperatures.

Chelnokov, in a somewhat dated Russian translation, stated that "Loosening the ground with small blasts is the most inexpensive and simple method. Small blastholes and the method of horizontal holes are the methods used."[10]

In a later Russian work, Bakakin and Zelenin estimated that "Well over 500 million cu m of frozen ground is excavated in the Soviet Union annually."[3] But in what seems to be a direct contradiction of Chelnokov, they found that the most expensive form of excavation was the preliminary disintegration (blasting).

The Swedish found that rock blasting is one of the most suitable winter jobs. "Even with the more extreme Swedish temperatures, it is rated a year-round job without any notable increase in cost, except, perhaps, in the northern part of the country with its sub-arctic climate."[29]

According to Yoakum, equipment manufacturers have recently produced tractor-mounted rippers which have proved to be more economical and more efficient in loosening frozen soil than blasting.

> "A system of cross ripping has been found to be most satisfactory. Several passes are sometimes required, but all frozen soils and subsoils can be loosened. The spacing of the passes by the tractor-ripper should vary with the condition of the frozen soil and the desired breakage size."[51]

Corroborating Yoakum's findings, Technical Manual 5-852-1 states that "Frozen ground can be broken more economically and faster with a heavy bulldozer equipped with a sturdy ripper than with the use of explosives if a large area has to be excavated and the ground temperature is marginal (30 to 32°F)."[16a]

The Swedish found winter excavation of 2½-m-deep gravel only 10% costlier than similar summer operations; they used a mechanical excavator. The Canadians believe that modern excavating machinery can readily operate in ground frozen to a depth of 1 ft.

Because perennial or seasonal frozen ground covers more than 90% of the USSR, extra energy is needed to disintegrate it. Bakakin and Zelenin found that effective excavating machines are scarce because of the unavailability of basic data for calculation and design. However, they concluded that "Processing untreated frozen ground with machinery appears to be least expensive."[3]

An interesting suggestion from the Russians is that of cutting the ground into sections that are easily excavated. Experiments made by the All-Union Scientific Research Institute for the Organization and Mechanization of Construction (VNIOMS) and the Ministry of Construction show that "Frozen ground can be removed without being loosened by first cutting it into squares to its entire depth or only to a depth of 0.8 meters. This method of preparing the ground requires only the power needed to make the cuts."[28] Disk saws operating at high speed (revolving at 40 m/sec) or low speeds (2 m/sec) have been used for cutting frozen ground. High-speed disk saws warm up while cutting, thus facilitating the cutting process. However, the cutting devices wear away rapidly; this makes the method impractical at present.

Mechanical crushing is an effective means of disintegrating the ground under certain conditions. "When the depth of freezing does not exceed 0.7-0.8 meters and the height of the holes is 1 meter greater than the thickness of the frozen layer, frozen ground can be excavated by mechanical means with wedge-shaped strikers."[10] This method is successfully used by the Moscow Administration of Underground Construction.

The striker is a cast-iron wedge, weighing 1.5 to 3 tons, suspended from the boom of the derrick of an excavator or crane. It is dropped from a height of 10 m or less and breaks the frozen ground into fragments that are easily excavated. Bakakin and Zelenin found that "When the wedge is forced into frozen ground, from 80 to 85% of the power is spent in crushing the frozen ground and only 15 to 20% is consumed in separating the frozen ground from the forefield."[3]

From this observation, it is concluded that this method of working frozen ground seems to be more economical for foundation pits and trenches than for mass application.

Thawing: Thawing of the ground before large-scale excavations is another preliminary treatment used in this country. Soil is flooded or sprayed with water to facilitate thawing. However, besides its slowness, "Unless the soil is sluiced away, thawing by either of the water application methods will penetrate only about 2¼ ft."[51] Other methods tried include the use of steam jets, hot sand, a mixture of salt and hay covered by tarpaulins 3 or 4 days before excavation, and fires. These methods are slow but may thaw up to 2¼ ft of frozen ground.

Beistline has seen thawing methods begin with wood fires, and then develop through hot rocks, steam, and water at natural temperatures, finally arriving at solar thawing.[4] According to him, solar thawing has been effectively used by both dredge and small-scale operators in Alaska. Essentially, this method requires the removal of all muck overburden to expose frozen gravel to the atmosphere for one or several seasons. "Gravels to depths of 20 ft have been thawed successfully for dredging, but layers of clay on the surface of the gravel may inhibit thawing."[4]

The Canadians use steam for thawing by one of the following methods:[14]

1. thin coils laid on the frozen surface
2. steam jets keeping water warm in a pit
3. steam points melting their way into the frozen crust.

They consider the last method to be the most effective means of thawing with steam.

In northern USSR, frozen ground is thawed by steam, electricity, and, occasionally, by thermochemical (artificial heat) sources.

The thawing of frozen ground by electrical heating, in spite of its higher cost, is widely used because it is a simple method and accomplishes rapid thawing. Heaters made of tubular brass pipe filled with spiral heating elements of Nichrome wire are inserted into drilled holes. The number and interval are determined by the volume of ground to be excavated. The time required for heating varies from 12-14 hours. Heating is done during the night shift, when electricity consumption is low. During the day, the thawed ground is removed, and the adjoining area is prepared for heating.

Besides heating, Soviet practices often include thawing with water needles and, less frequently, with chemicals. Thawing of a seasonally frozen layer by using short needles (well points), vertical electrodes, and other devices with all the inherent limitations are described by Chelnokov.[10]

This system consists of a water boiler, a tool for drilling frozen ground, and a system of water needles connected with rubber hose. The needles are inserted into the holes; rubber hoses are then connected to the suction and heating pipes of the boiler in a closed circuit. Hot water is fed through the system from needle to needle. One boiler serves 50 to 60 needles simultaneously. This thawing process lasts several days.

To resist seasonal freezing, Soviet specialists use NaCl and other chemicals that protect only to about 5°F with considerable specific consumption. Aqueous solutions of silicones have also been tried lately to prevent seasonal freezing.

Whatever method is chosen, Bakakin and Zelenin deduced that "The cost of well-organized thawing of frozen ground in mass, including required preliminary development and amortization of installation, is not generally less than 100% of the remaining operation expenses."[8]

A gas-operated ground-thawing device that may revolutionize wintertime construction methods and result in substantial savings is now being tested by the Minneapolis Gas Co. Named the Hot Rod, it allegedly "thaws frozen ground in as little as one-sixth of the time required under present methods and at one-sixtieth the fuel cost."[37]

The "Hot Rod" is a pipe with a gas burner on one end and a portable propane tank on the other. This is housed in a larger pipe, and the whole assembly is set in an augered hole to radiate its heat into the soil.

> "Two such probes 30 in. apart will thaw ground as compact as clay in 12 hours and permit an excavation 5 to 6 ft deep, 5 ft long and 3 ft wide. Under the present thawing method, up to 72 hours and a ton of coke are required."[37]

An obvious advantage of this defrosting device is that the heat source is below ground, where practically all the heat output is being used. Present methods thaw from the top down and most of the heat is dissipated into the air.

Stripping. Following any combination of the preliminary treatments previously described, the contractor can use his equipment spread to strip the overburden. The golden rule is "Don't chew off more than you can handle." Excavation during the winter should be planned so that no surface is exposed to freezing for more than a day or two before re-excavation. This requires confining the area of the work.

Yoakum feels that excavation at the face of a pit with a dipper shovel is less affected by winter weather than excavation with scrapers. "Once an area is opened up and the floor of the pit established, excavation can be readily accomplished, if it is continuous from day to day."[51] However, as in the case of all excavation in the winter period, the coarser, more free-draining, and lower water-content materials are more readily excavated than other types of materials when a frozen crust develops on the surface.

Excavating is sometimes easier in winter, especially when muskeg and peat are involved. "In the construction of the 500-mile road in Manitoba, the excavation of more than 1,000,000 cu yds of muck and the provision of more than 1,500,000 cu yds of borrow were carried out successfully in winter."[40] Freezing of muskeg during the winter improves the construction of access roads and provides an improved surface for equipment movement.

When the excavation of permafrost is required, the surface should be stripped early in the summer to expose the frozen material. The thawed soil may be removed as thaw progresses to the required elevation. "In subarctic regions, fine-textured soil which has existed as permafrost may thaw as much as 6 inches per day following surface exposure."[16a]

Foundations

Design criteria and construction methods are well established for preventing damage to building foundations after the structure has been completed. The protection of foundations during the construction period may still be difficult and expensive for the contractor, if the foundation work has to be accomplished during the winter period.

Yoakum[51] believes that consideration should be given in the design to the possible construction problems created by freezing temperatures. He points out that shallow interior footings or shallow strip footings for support of interior partitions may be subject to heaving if not properly protected.

In school construction particularly, work may commence in the late summer or fall with the completion date the middle of the following summer and much of the foundation work accomplished during the winter. "Interior partitions supported on shallow strip footings have been damaged due to frost heaving during the construction period."[51]

This section is divided into operations: protecting, thawing, and stripping; and permafrost: foundation design and piling.

Operations.

Protecting: As has been previously emphasized, laying foundations against frozen ground is poor practice. In Yoakum's search of various specification requirements and practices throughout this country, he found that none of the organizations contacted allowed the placing of foundations on frozen soil. In addition, he found no instance in the literature of a foundation placed on frozen soil. Excavations, therefore, must be protected from freezing both *before* and *after* foundation placement to prevent frost heaving.

A covering of saltwater hay is frequently used in the coastal areas to protect a bearing surface between the time of excavation and the time of placement of concrete footings. Another effective means of protecting a bearing surface is a covering of calcium chloride topped by polyethylene sheeting. "This method has protected a frost-susceptible silt bearing surface over a weekend period when the night temperatures were about 15°F."[52] Other methods used in this country include covering the foundation areas with earth, or enclosing and heating the areas.

The Canadians protect the inside of their excavations by using straw mats covered with tarpaulins. The straw is removed immediately before the foundation is placed and replaced soon after placement to ensure frost heave protection.

Thawing: When thawing operations are necessary, the Canadians use fires fueled by a foot of hay or straw covered with 3 in. of slack coal. They claim that the ground will be thawed to a depth of as much as 3 ft by one *burn*. In addition, flame throwers are beginning to be used for thawing small sections of ground at a time. And, as has been previously mentioned, steam is used frequently, usually by steam points melting their way into the frost crust.

Several of the thawing methods listed under mass excavations are probably more economically suited to the laying of foundations. These might include electrical heating, thermochemical sources, and the Minneapolis Hot Rod.

Permanent steam coils under foundation slabs have been found effective in preventing the ground from becoming frostbound during a winter building project in Swedish Lappland. No frost occurred adjacent to the footings and the arrangements presented no difficulties in subsequent works.

The Swedish found straw insulation to be unsatisfactory, both because it was not effective and because it interfered with other work.

> "Excavations were started in mid-December. As work proceeded, the bottom of the excavation was covered with some 30 cm of straw. By the time the steam coil was ready for use, only a few days after the completion of handwork, the ground had become frostbound to a depth of 10-15 cm, despite the straw. This frostbound soil was thawed out by the steam heat. Straw was removed from the ground as the placing of the foundations proceeded."[2]*

During the first week, steam heating was applied daily, partly to thaw out existing frost. Later, when the ground had absorbed a certain amount of heat, heating needed to be turned on only at sporadic intervals when the temperatures at the measurement points in the foundations were found to have dropped below a certain level.

Stripping: For large and medium-size buildings the basement is generally excavated by an excavator. A strong machine works right through a frozen crust 1.5 to 2.0 ft thick.

Soil, excavated by hand and used for refilling, is not covered, as a rule, and usually freezes. The following Swedish methods may be applied to such frozen soils:

> "1. The frozen crust is broken up with the aid of wedges. In case of moderate frost a pick axe or an iron bar may be used.
>
> "2. The frozen crust is broken up with a pneumatic spade, a very effective device for frozen soil. However, only in the case of a large building would the purchase or rent of a compressor be justified.
>
> "3. The frozen crust is blasted; however, for the sake of safety this can only be recommended when the building is at sufficient distance from other buildings, or else only small quantities of explosives should be used.
>
> "4. The frozen crust is defrosted. In Denmark tests were made in this respect with a hot-water steam under a layer of straw, chemical agents, etc."[38]

Permafrost. A study of foundations in permafrost areas clearly reveals that permafrost can only be regarded as a variable. It is deceptive, baffling and powerful, and must be approached with the greatest respect.

Its extent is uncertain, but the USSR claims that such perennial or seasonally frozen ground covers more than 90% of its land. The approximate distribution of continuous and discontinuous permafrost in North America is shown in Figure 12.[16a]

Although permafrost is defined as "perennially frozen ground,"[46] it could be more aptly referred to as "not so much a material as a condition in which materials exist."[42] Figure 13[16a] illustrates the various conditions in which permafrost may be found.

Foundation design: In foundation design permafrost can present problems to every engineering project in the Arctic or Subarctic. "To assess and solve these problems the engineer should first investigate, then consider the following possibilities: vacate, separate, eliminate, insulate, cooperate, and create."[39]

Where permafrost is encountered, usually the best advice is to vacate the site, except in rare instances where permafrost can be used to advantage. To vacate may mean moving the site some distance or only a few feet.

Where it is impossible or unfeasible to avoid frost completely or to vacate the site, separation can be achieved in other ways. The construction of a building above grade on piling achieves separation. Insulation of the construction from frost may also be considered as separation. However, complete separation cannot be achieved.

Permafrost can be eliminated economically when it occurs in relatively small quantities. Frost lenses, frequently excavated or thawed, are removed completely from the site. Elimination can sometimes be combined with separation and insulation.

Frozen earth makes an excellent structural foundation material, but the problem is to preserve it in a frozen state. Insulation or the prevention of heat transfer into frozen material maintains the frost in its original and useful state. Separation is also a form of insulation as it prevents heat flow into the frozen ground.

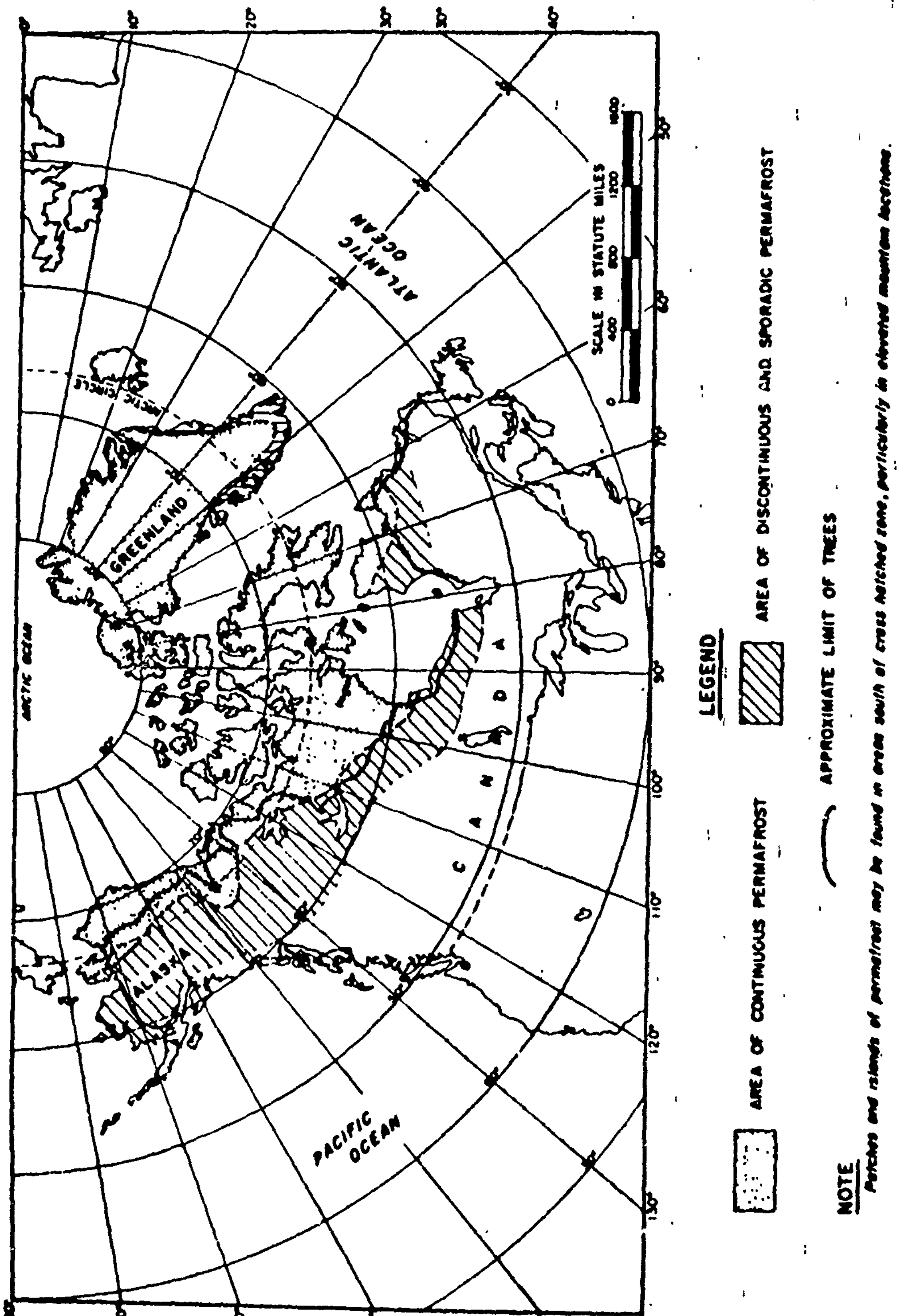


Figure 12. Approximate distribution of permafrost in North America.[16a]

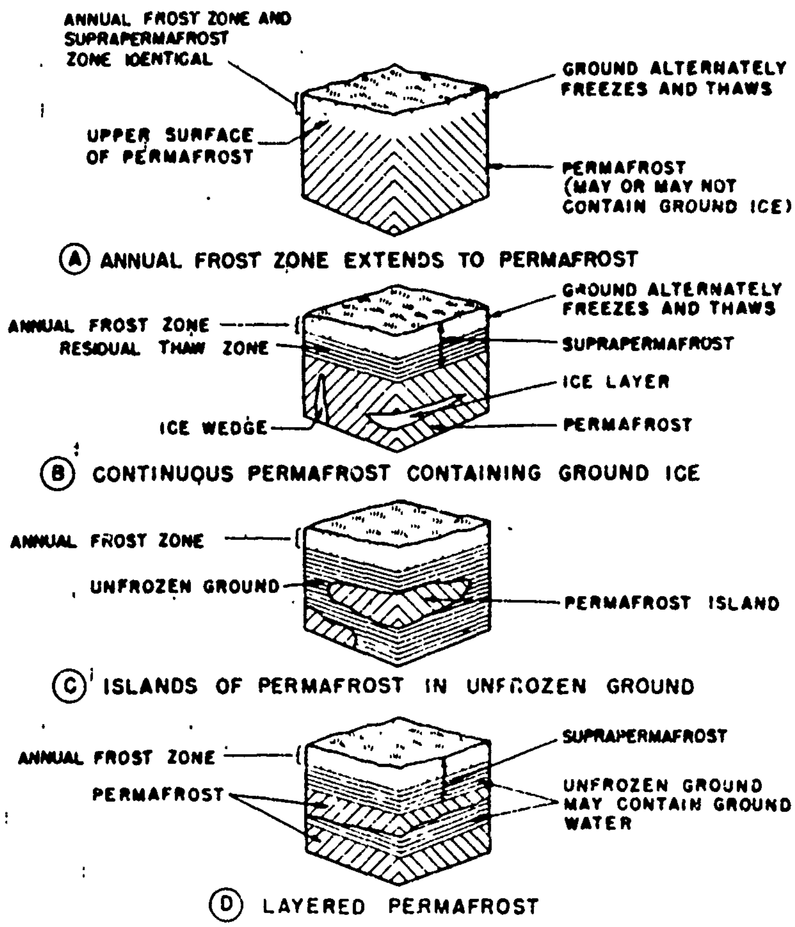


Figure 13. Typical sections through ground containing permafrost.[1a]

Perhaps the best, easiest, and often cheapest way to deal with permafrost is to live with it, cooperate with it, and even use it to advantage. Many successful structures have been built on piles driven and frozen into permafrost. The piling has two functions: to preserve the permafrost and to eliminate seasonal frost action. The thermopile invented and developed in Alaska is an excellent example of cooperation with frost. Refrigerated footings have been used on permafrost employing conventional refrigeration systems; but these have usually been expensive to operate and maintain.

For many years, men have been so busy fighting frozen ground and trying to eliminate it that very little throught has been given to creating frozen ground and using it to advantage. Engineers are still pioneering in finding ways to create frost and to use it as a foundation material, a construction material, or a construction aid.

Piling: Many structures in arctic regions, both in North America and in Russia, have been put on piles, allowing an air space between building and ground. The air space prevents heat transmission from the structure to the underlying permafrost, thus preserving the frozen, stable state.

Much experience has been gained with this type of construction. Five major factors have to be considered with regard to the use of piles in permafrost: "site preparation, type of pile, pile placement methods, depth of embedment, and refreezing characteristics."[11]

It is imperative that individual construction sites (as well as the area as a whole) be disturbed as little as possible to maintain the frozen ground condition. Under no circumstances is the insulating moss cover to be disturbed. Therefore, movement of construction equipment and clearing of brush must be under strict control.

Piles differ as to material and form. They may be made of wood, reinforced concrete, and metal; they may be shaped as "cylindrical (pipe and solid), prismatic (square and rectangular) and composite profile (H-piles, cross-shaped, etc.)."[7] With steel piles, heat transfer must be watched. Therefore, "Wood piles are generally considered more desirable since there is less tendency for heat to be conducted down the pile into the permafrost to cause melting."[24]

Satisfactory performance of pile foundations depends upon adequate anchorage of the pile in permafrost. "The method by which piles are placed in the ground can have an appreciable effect on refreezing conditions and ultimately on their performance."[31]

Driving of wood, concrete or steel piles is difficult in undisturbed permafrost. Therefore, piles normally are set in prethawed, predrilled or excavated holes.

Generally, steaming is used for low permafrost temperatures. This method employs a simple pipe through which steam is injected into the permafrost. Since most of the silty soils in the Arctic also contain ice, the steam melts the ground into a slurry of mud. The pipe is allowed to penetrate into the ground to the distance required for the length of pile being used, and at such a rate of travel that only a hole large enough for the pile will be thawed. Due to the natural cold temperature of the ground, only the ground in direct contact with the steam will thaw so that the surrounding permafrost is not materially affected. The pile must be placed immediately after steaming. "The prominent disadvantages of the steaming method are that a water source must be available to generate the steam, and due to the inadvertent spillage of steam and overflow of water, the ground surface becomes wet and muddy and impedes operations. The advantage lies in the simple type of equipment and the fact that generally unskilled labor can be used."[24] (An additional disadvantage of steaming is possible excessive thawing of permafrost.)

A 1968 Canadian translation of a Russian building code, *Guide for design and construction of pile foundations in permafrost*, lists the equipment and materials needed for thawing the ground with steam: "a steam boiler, network of steamlines, steam points, distributing manifold with flexible hoses for carrying steam to the points, and crane carriages for placing points and supporting them in a vertical position during embedment."[7]

In a 1967 USA CRREL report concerning pile foundations in permafrost, Crory wrote:

> "Normally steam is used only in cold permafrost which can safely absorb the heat introduced. In warm permafrost, freezeback may take months or even several years. Even in cold permafrost, steaming of holes for piles should be done only by experienced operators who know the effects of using such equipment in various soil and ice conditions."[15]

Consequently, steaming is seldom used in Alaska today.

Holes are drilled with percussion or rotary drills adapted for boring frozen soils. According to Crory,[15] most pile foundations constructed for military facilities in Alaska have been installed in dry augered holes and backfilled with soil-water slurry. Holes less than 24 in. in diameter can be augered at the rate of about 1 ft/min, approximately the same as in steaming.

Constant blowing of the hole is necessary to keep water and cuttings from sticking to the drill. However, drilling is a relatively dry operation compared with steaming and generally affords better accuracy in pile alignment. Its main disadvantage is the initial cost of the boring rig; further, the rig, normally mounted on wheels to permit ease of mobility, requires specialized maintenance of auger heads and ancillary equipment.

The previously mentioned Russian code recommends the installation of a pile into a drilled hole within 3 hours (summer) or 3 days (winter) after completion of drilling. Prior to pile embedment the hole is protected with a removable cover.

Following either of these methods of pile placement, the pile is simply dropped into a hole and a silt- and sand-slurry backfill is placed around the pile and allowed to freeze back. Under some circumstances, it may be possible to drive the pile into a predrilled or prethawed hole that is smaller in diameter than the pile. However, problems of realignment, caused by easy deflection of the pile as it is driven, make this method unattractive.

An unusual pile-driving technique has been proposed for rapid pile driving into permafrost. "A fast-burning rocket could be fixed to the end of a pile, a steel tube for example, and launched vertically in the direction of the ground, letting the pile penetrate under the influence of its kinetic energy alone."[9] Experimental studies including both laboratory and field tests are being conducted for the U.S. Army to determine the economic and technical practicality of this method.

To drive piles directly into the permafrost, the Russians have found "It is most effective to use the percussive method, and, in particular, the diesel hammer. For this purpose it is necessary to develop a special design of a hammer adapted for northern conditions."[49] However, they found it much more effective to first penetrate the strata with a lead hole, having a diameter smaller than the pile's cross section. This aided the accuracy of placing the pile considerably.

In nonpermafrost areas, steel *H*-piles are commonly driven with a conventional-type hammer through about 3 to 4 ft of frozen soil. When the frost has reached a depth greater than 3 ft the contractor will, many times, prebore a hole through the frozen portion of the ground by chopping with an open-end pipe, dropping a deadweight hammer or drill, or driving a mandrel.

All of the pile-driving contractors in the New England area recommended to Yoakum[51, 52] that wood or precast piles not be driven through frozen soil more than about 2 in. thick.

Only limited information is available with regard to the required depth of embedment of a pile in permafrost. "Although some of the load on the pile may be taken by end bearing, it is believed that when the pile is completely frozen into the surrounding soil much of the load is transferred to the permafrost by the tangential adfreezing strength developed between the soil and the surface of the pile."[31]

Because of the lack of information, this general rule of thumb for embedment of piles in permafrost has generally been followed: "Piles should be embedded in permafrost to a depth equal to at least twice the depth of seasonal freezing and thawing during the life of the building."[31]

The refreezing period required for piles placed in permafrost is of the utmost importance to a construction schedule. Superstructures cannot be erected until the foundations are adequately anchored in permafrost. Refreezing of piles is dependent on many variables, including the time of year piles are placed, steaming interval, ground temperatures, soil type, and soil moisture content. Of these, "perhaps the most important factor is the steaming interval."[31] Excessive steaming prolongs the refreezing period considerably, by as much as several weeks. Piles placed in late winter in properly steamed holes normally will be refrozen at the 10-ft depth within a month and at the 20-ft depth within a few days in low-temperature permafrost.

The observed natural freezeback of over 100 piles of different types has been correlated with theoretical heat transfer equations and has produced a method of calculating the time required for natural freezeback. Detailed discussions of the freezeback of piles in permafrost have been reported by Crory. Figure 14 gives the approximate heat paths during summer and winter.[15]

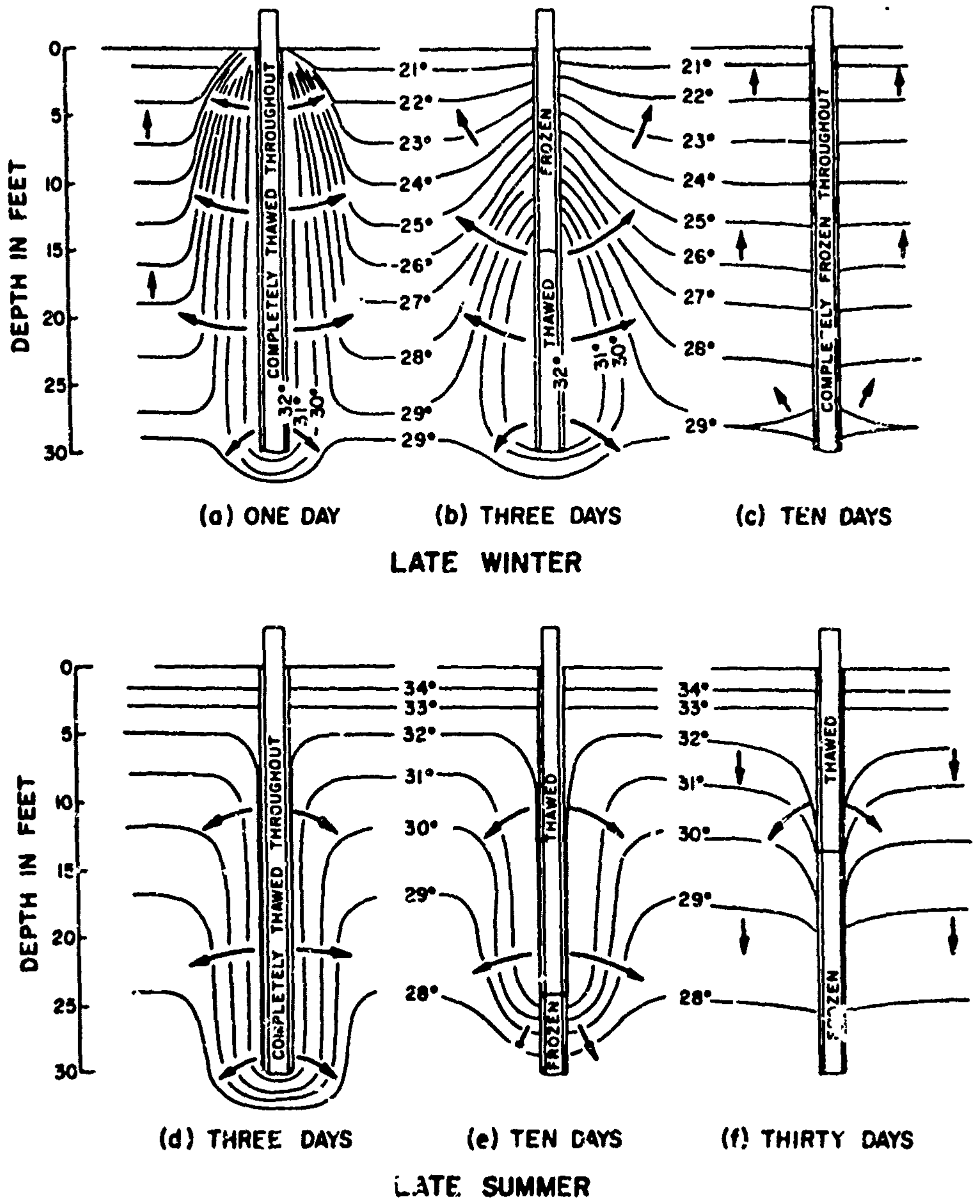


Figure 14. Natural freezeback of piles in permafrost during winter and summer.[15]

Because pile foundations are finding increasing application in building on permafrost ground, and because of the long period of natural freezeback of piles into their boreholes, methods of artificial refrigeration are being developed.

Pipes or tubing can be attached to the piles prior to installation and connected to a portable refrigeration system. According to Crory, artificial freezeback can be achieved in less than 2 days by careful control of the slurry temperature and water refrigeration. The refrigeration pipes, purposely designed to remain in place, are available for use throughout the life of the structure if further refrigeration is required.

The Long Thermopile is a seasonal self-refrigerating foundation support or anchor with a high conductivity of heat out of the ground and a high resistance to heat flow into the ground. "When properly used, the Long Thermopile will maintain a permanently frozen soil condition near the pile."[34]

The Russians use a chilling operation in which the boreholes or hollow sunken piles are used as vertical elements for carrying away heat. Their latest research concludes that "Cooling of the soils in bases during the laying of foundations ensures increased bearing power on the base soil, including strong freezing-in of the piles."[36] This method employs the use of hollow piles that are ventilated during the winter by external air whose temperature is below freezing. Further research revealed that the chilling process does not have to be repeated every year; once is enough.

Trenches

In many respects, the examination of this subject is repetitive of that already discussed. However, a brief outline of available methods of trenching may be helpful for clarification.

Essentially, the contractor must follow the two steps mentioned for mass excavation: preparing the soil and then removing it.

When the size of the job warrants the use of a large machine (a large backhoe with a capacity of 2 or 2½ cu yd), the machine often can excavate the frozen ground without prior soil preparation. Breakdowns are frequent, however, and operating costs are high. To increase production and decrease machine maintenance costs, various methods of soil preparation should be employed.

The Russians have tested a rotary multishovel trench excavator with chain conveyor for driving.[45] Scrapers with blades replace the conventional scoops. The experimental trench excavator cuts swaths 1.8 m deep and 0.85 m wide (in ground frozen at 7°F to a depth of 1.3 m) at speeds of 5 to 6 m/hr.

As previously discussed, soil preparation involves either disintegrating or thawing the soil.

Blasting is a possibility, but the literature cites only one example of its use and that was by the Russians in a field test.[33] Instead, ripping or mechanical crushing seems to be more prevalent. Equipment needed for this purpose might include a commercial one- or two-tooth frost or rock ripper mounted on the rear of a big crawler tractor, or a shop-made frost breaker consisting of pointed drop hammers on pile-driving leads. Pneumatic and hydraulic hammers may be used as well, but they rarely are used because of their relatively high cost of operation.

Cutting with equipment is becoming popular. A giant circular saw mounted on the rear of an industrial tractor was tested recently in Saskatchewan.[12] The frost cutter, as it is called, consists of a 60-hp industrial tractor with a 72-in.-diam steel cutting wheel with removable cutting teeth. The set of teeth cuts from 800 to 1200 ft in frozen ground before requiring resharpening.

Levitin tested a trench excavator for cutting frozen ground into workable components for removal.[33] He then compared this method with others (see Table XVII) to illustrate its practicality.

Thawing methods described for mass excavation are similar to those required for trenching, with burning of coal and straw the most widely used methods. However, the method of thawing with gas burners has possibilities. "With this setup a 3 by 5 ft trench 4 ft deep can be thawed overnight."[23] Minneapolis used it for 5000 excavations one winter.

Following soil preparation, the trench is dug with available equipment, usually a backhoe. But lately multiscoop rotary excavators have been proving their economy and speed.

Table XVII. Russian excavation methods.[33]

Methods of Loosening	Total of working 1 m³ of frozen ground: Time, Machine-shift	Time, Man-hr	Cost in rubles and kopeks*: Total	Cost in rubles and kopeks*: Labor
Cutting a trench 1 m wide manually; depth of frost is more than 1 m.		13.8	34.67	34.67
Loosening with a pneumatic drill and removing the earth manually.	0.002	9.84	24.78	24.74
Loosening the ground with a wedge drill; removing earth with an excavator (straight shovel, capacity of bucket 0.5 m³).	0.03	0.53	11.40	2.19
Loosening with an earth cutter; removing the earth with an excavator with a bucket having a volume of 0.5 m³.	0.025	0.45	9.76	1.83
Loosening with an earth-cutter in the trenches; removing the earth by means of a multi-shovel excavator.	0.022	0.4	8.22	1.69
Loosening by explosives; removing the earth with an excavator having a bucket volume of 0.5 m³.	0.003	0.36	7.42	1.23

* 1 ruble = 100 kopeks; 1 ruble = about $0.50.

One of the main advantages of winter trenching in muskeg areas is the capability of the normally wet, unstable soil to support heavy excavating equipment. Consequently, cleanup costs along the trench routes are lower in winter because the frozen ground is relatively unaffected by the equipment loads.

Excavating trenches in alluvial deposits by hand, mechanical equipment, or hydraulic mining allows vertical sections to be exposed. When surface overburden on the trench area is removed, the gravel thaws because of heat of the atmosphere. Thawed material is excavated and a fresh face is exposed for thawing. "Economic trenching depends upon exposing sufficient frozen material to the atmosphere to provide enough thawed material to keep equipment working at maximum capacity."[4]

The cut-and-cover method of snow-trenching has been used on the Greenland Ice Cap. A number of trenches have been made using this method. As outlined in USA CRREL Technical Report 126,[1] the method entails cutting a trench with the Peter plow, then arching and covering it.[1] A total of 105 hours of Peter-plow time was required for the cutting of a 1600-ft-long trench at Camp Century, Greenland. "The trench-cut average was 359 yd³/hr or 134 tons/hr."[1] with diesel fuel consumption at 14.9 tons of excavated snow per gallon.

A later report[38] on the same camp further substantiated the feasibility of creating subsurface facilities by cutting wide trenches in the snow with the Peter plow and covering them with corrugated steel arches.

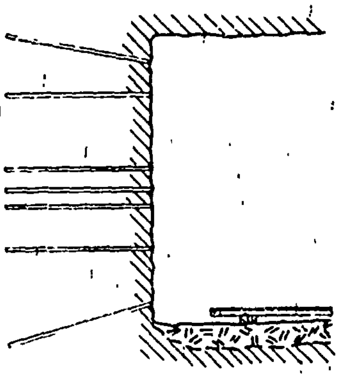
Tunnels

The desirability of subsurface camps in arctic environment has led to new tunneling methods by the U.S. Army. USA CRREL Technical Report 174[13] outlines the advantages of subsurface over above-surface camps as follows:

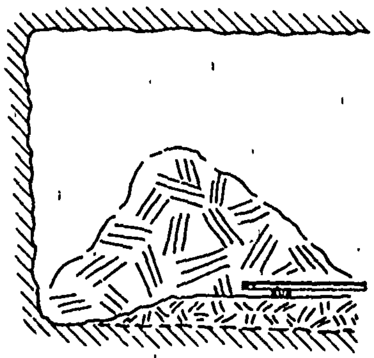
"a. The initial construction cost is lower.
b. The severe above-surface environment is avoided.
c. Less fuel is required for heating purposes.
d. Less imported construction materials are required.
e. The problem created by drifting snow is minimized.
f. Effective camouflage is made easier.
g. Vulnerability to enemy attack is greatly reduced."[13]

At Camp Tuto, a "1,100-ft tunnel was excavated into the Greenland Ice Cap using a Joy Continuous Miner which removed 31,000 cu yd of ice."[43]

Operations. The mining cycle normally consists of four routine operations: drilling, blasting, ventilating, and mucking.



LONGITUDINAL SECTION OF DRILL PATTERN.



ACTION OF ONE ROUND.

Figure 15. Tunnel blasting.[47]

Drilling: Swinzow[47] reported that the best drill pattern for advancing in permafrost was a burn (central holes) pattern, drilled to two-thirds of the width of the tunnel. One drill and two men in a 10-hr shift could advance the drilling 220 ft, but average productivity was around 150 ft. Figures 15a and b illustrate the shot pattern before the blast and the resulting muck.

Blasting: Medium-strength, medium-velocity explosives are recommended, with a delayed blast and a 0.5-sec interval. However, Swinzow[47] noted that charging the burn (central holes) with higher-velocity explosives provides advantages, since the material in the face is shattered by the sharp impact of the burn, placing a compact pile with good fragmentation.

The best stemming is a wet clay-silt (permacrete) that fills the drill holes fully and is allowed to freeze back completely, sealing the entire hole.

Material breaks like a conglomerate. The similarity is complete except that the cementing agent in this case is ice. This has its benefits: a cobble loosened in conglomerate stays loosened; but a cobble loosened in permafrost may regelate and become a spare part of the roof or wall.

Ventilating: The natural airflow in a tunnel during the summer is fairly simple to demonstrate (Fig. 16)[47]: warmer outside air enters the tunnel through the portal and moves slowly inward, depositing hoarfrost on the walls; dry, cold, dense air moves out along the floor of the tunnel forming a layer only 1.5 ft high.

An explosion at the end of the tunnel instantly liberates a large amount of hot fumes and offsets the natural circulation, forming dangerous stagnant fume pockets. Swinzow found that forced ventilation applied at two points to act parallel with natural convection currents was most effective in eliminating the gases.[47]

Mucking: "Conveying systems can be generally classified in three major categories: 1) pneumatic, 2) hydraulic, 3) mechanical."[25] The standard excavation rate is assumed to be 2000 cu ft/hr of ice, frozen snow or permafrost (100 tons/hr of permafrost and 50 tons/hr of ice) by Foster-Miller Associates, Inc.[25] Tables XVIII and XIX[25] summarize their findings concerning the various systems. They recommend the pressure system (*P*-1) for pneumatic and the modular screw conveyor system (*M*-3) for mechanical transporting.

Figure 17[25] is a schematic illustration of the pneumatic pressure concept. Compressed air is cooled and fed to a rotary feeder device which also receives cuttings from the mining machine. A mixture of air and cuttings passes through the pipeline and discharges near the tunnel portal. The feeder is permitted to advance with the mining machine by means of telescopic pipes.

Figure 18[25] depicts the modular screw conveyor concept. This system uses a 30-ft feed screw section which moves with the miner and overlaps the main conveyor line. The screw conveyor line is composed of 20-ft modules, each having separate drives and arranged in series as shown in Figure 18.

Regardless of which method is used, mucking should start right after the blast to prevent the chunks from freezing together.

Research and observations. Swinzow[47] feels that since tunneling has proved to be feasible for military installations in *cold* permafrost, it should be investigated for *warm* permafrost (only a few degrees below freezing) in a region such as Alaska or northern Canada. Additionally, he recommends that investigation of permacrete be continued in the laboratory and field.

In other tunneling developments, the contractor at the Churchill Falls hydro project is using the completed pilot bore of his ventilating shaft to heat the cavern for winter work.

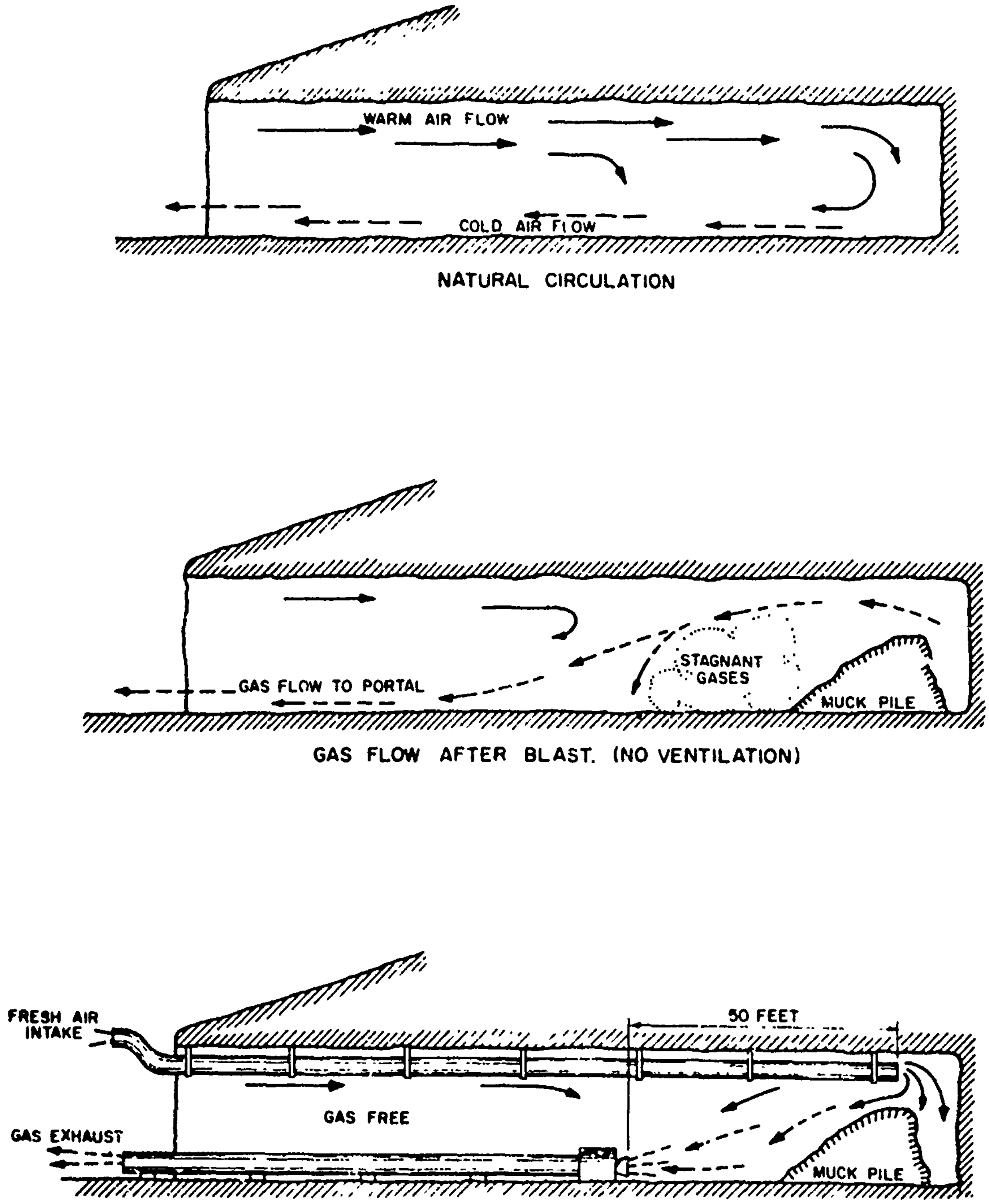


Figure 16. Ventilation.[47]

"At the surface, a heating plant and blowers put 17.5 million btu hourly down the shaft into the cavern for the comfort of workers and prevention of frost accumulation, like freeze-ups and fogging. Cavern temperatures run around 45°F, as contrasted with outside temperatures that drop to −56°F."[11]

This project involves the excavation of 2.3 million cu yd of rock by jumbos teamed with shovels for mucking and scaling.

Table XVIII. Advantages and disadvantages of promising pneumatic and hydraulic transport systems.[25]

System	Advantages	Disadvantages
Pressure system P-1	Most conventional pneumatic system. Most of equipment in tunnel fairly light pipe sections. Adaptable to operate with slopes and bends. Lowest power requirements of pneumatic systems. Main drive (compressible) outside tunnel.	Sensitivity to particle size. Limited test data available on performance with large particles. Cooling required to limit material temperature rise. High-pressure telescopic pipes required for extending. Rotary feeder in tunnel a possible jam area. Nonpositive transport.
Vacuum blowers and separators P-2	Low weight moving with miner. Low weight in tunnel. Easy to extend. Self-ventilating. Easily adaptable to operate with slopes. Requires no moving parts in tunnel. Main drive outside tunnel. No refrigeration required.	No test data available for large particles. Limited length capability. Very high power requirements. Complexity of equipment outside tunnel. Material separation difficulties. Performance of blowers passing fine particles unknown.
Jetstream conveyor P-3	Modular system that permits nearly continuous operation. Should perform on slopes. Bends feasible. Transport channel open for clearing jams. No moving parts contact material.	High cost of equipment, high weight of sectio s. Performance untried with mixed size particles. May blow dust all over tunnel. Large power requirements. Small slots that may clog.
Melting and pumping	High confidence in performance. Self-propelled on horizontal. Self-winching on slopes. Low first cost. Low system weight. Excellent on slopes and bends. High rate efficiency. Self-purging that provides easy extension.	Usable for ice and snow transport only. Requires exhaust for combustion products. Heat generation in tunnel. Large melting and pumping unit in tunnel. High oil consumption.

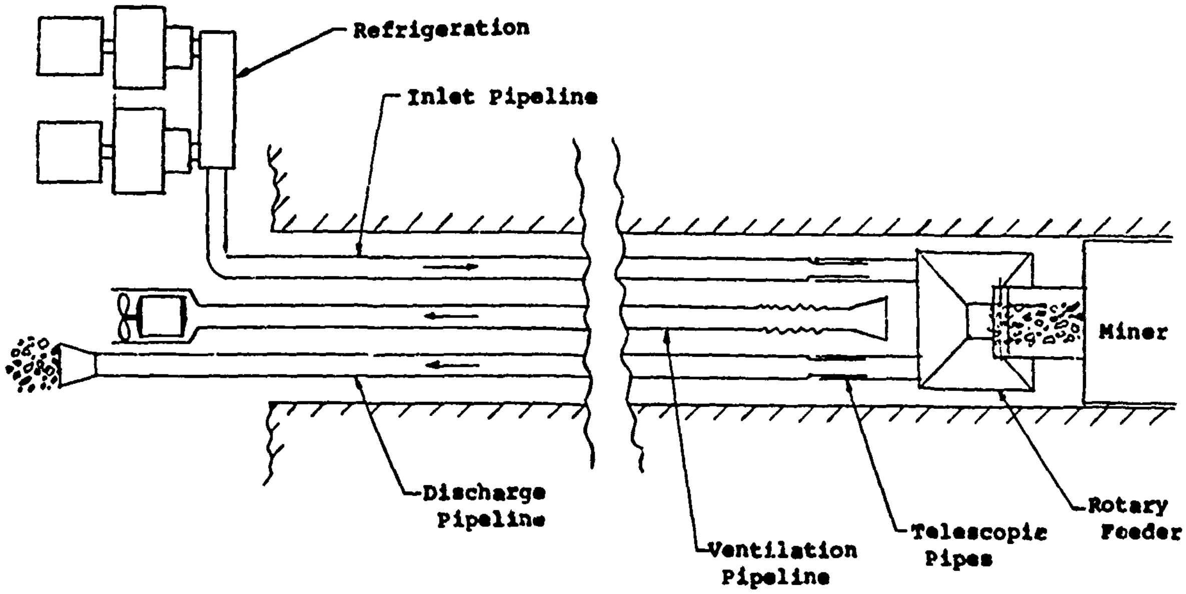


Figure 17. Pneumatic pressure concept.[25]

Table XIX. Advantages and disadvantages of promising mechanical transport systems.[25]

System	Advantages	Disadvantages
Modular belt conveyor *M*-1	Virtually continuous transport. Low power requirements. Transport insensitive to particle size and material. Modules that increase flexibility. Operates on bends and limited slopes.	Multiplicity of drives and drive rolls which can slip. Requires special rolls to prevent buildups. Long sections (50') to handle. Many transfer points.
Extensible belt conveyor	One drive located outside tunnel. Low power requirements. Insensitive to material and particle size. Relatively low total weight.	Long mission time due to down time required for extending. Large heavy tail section required in tunnel. Cannot operate on bends. Skill required in assembling components.
Modular screw conveyor *M*-3	Virtually continuous transport. Insensitive to particle size below 6 in. Materials that do not pass hanger bearings. Positive transport. Transports on slopes and bends. No accurate alignment of sections required. Modules that increase flexibility. High confidence in performance.	Multiplicity of drives and motors. Moderately heavy system. Relatively high power consumption.
Relay shuttle cars *M*-4	Basic components reliable in coal mining operations. Insensitive to particle size and material. Mobility of components gives high flexibility.	Traction required on horizontal runs. Operator skill required in transferring load. Few, but very large, heavy components.

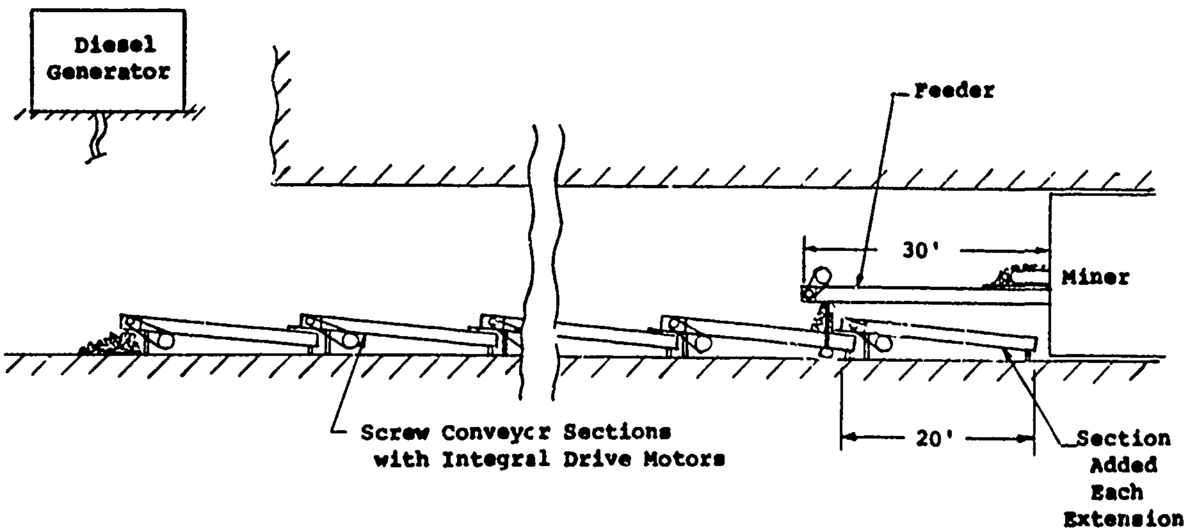


Figure 18. Modular screw conveyor concept.[25]

Filling and Backfilling

In Yoakum's[52] extensive survey, all specifications of all organizations contacted stated that foundations should not be placed on frozen soil; and most of the organizations did not allow the use of frozen soil in their embankments.

On frozen soil

The impetus behind the consensus is that structural damage invariably develops when foundations are placed on frozen soil. However, in a paper submitted to the Association of Asphalt Paving Technologists, Beagle[41] contended that "Hot plant-mixed asphalt base can be placed on frozen subgrade, in subfreezing weather – if it can be kept hot enough during rolling."[41]

In January 1964, he placed hot plant-mixed base on frozen subgrade (frost penetration was 10 in.) in an air temperature of 23°F. Cores were taken in July 1968 (4½ years after placement) and were tested at 99 to 100% of laboratory density. The minimum required temperature for the mix is 200°F. Beagle concluded: "It has been found that hot plant-mixed asphalt base may be laid on frozen subgrade in subfreezing temperature, with the same probability of success as that for warm weather paving, as long as it is practical and economical to properly prepare the subgrade."[41]

Maine permits placing base courses on frozen subgrade when the subgrade has been properly constructed of unfrozen material and adequately compacted before freezing. Pennsylvania allows forming of embankments on ground frozen to a thickness no greater than 3 in.

The North Atlantic Division of the Corps of Engineers reported to Yoakum[52] that it allowed a foundation for pavement to be placed on frozen soil. The material consisted of gravel frozen to a thickness of about 6 in. "The project was considered to have performed satisfactorily."[52]

Where roads and runways are constructed over permafrost, they may be expected to settle somewhat until such time as subgrade conditions become stable. Technical Manual 5-349,[16] therefore, advises the construction of temporary surfaces, providing for their extensive and continuous maintenance, until settlement and stabilization are complete. Then, a better type of pavement may be justified.

In freezing weather

The consensus is that placement of permanent backfill should be deferred until favorable weather conditions prevail. However,

> ". . . if placement is an absolute necessity during freezing temperatures, either dry, cohesionless, non-frost-susceptible materials or material containing additives, such as calcium chloride, to lower the freezing temperature of the soil water should be used."[18]

Each lift should be checked for frozen material after compaction and before construction of the next lift is begun. If frozen material is found it should be removed, rather than disked in place.

Yoakum[51, 52] found case histories indicating that embankments and foundation projects can be successfully constructed using both cohesive and cohesionless soils; however, the ease with which soils can be placed decreases considerably as soil temperatures dip below freezing.

The Highway Research Board discovered through its research that "When soil temperatures reached 20 to 25°F it was extremely uneconomical and impractical, if not impossible, to achieve specified densities."[52]

The Michigan Highway Department has satisfactorily compacted both cohesive and granular nonfrozen soil at about optimum moisture content at temperatures as low as 20°F. It is felt that "Granular materials could be satisfactorily placed at temperatures as low as 15°F provided the material was compacted to proper density immediately after placing."[15] However, the Department stresses that material already frozen is not acceptable and that it is very difficult to place properly soils at temperatures as low as 20°F.

New York highway engineers tested calcium chloride in the soil to prevent freezing, but abandoned the practice because of the cost of the chemical. The conclusion was reached that it is extremely uneconomical to construct embankments using even relatively clean, cohesionless, granular soils during winter months. They also discovered that as the soil temperature dropped below 30°F the compactive effort required increased tremendously; and, at 20°F, it was almost impossible to achieve specified densities, regardless of the compactive effort or the type of equipment.

Yoakum concluded[52] that it is doubtful that soils can be placed and adequately compacted in embankments when temperatures are below 15°F; however, dry coarse rock can be placed at any temperature.

The Canadians allow "placement under reasonably acceptable conditions to a temperature of 16° when no excessive wind prevails."[27] Robert F. Legget, Canadian Research Council, contends that "When the temperature falls below 28°F, it has been impossible to obtain relative densities in excess of 50% with the normal sands and gravels encountered at the site."[32] Consequently, the placing of compacted embankment materials usually has been confined to frost-free periods from 1 April to 31 October.

Canadian National Railways placed embankments from 80 to 90 ft in height while constructing one of its north-south lines along the east face of the Rocky Mountains during the winter of 1966-67. Mr. A.V. Johnston, its Chief Engineer, reported that, "The results to date of this work have been quite gratifying and there have been no major fill failures because of inadequate compaction."[30] Mr. Johnston found that the fills being constructed were of reasonably good quality. However, engineers had to relax somewhat on density requirements (90 to 95% compaction) and they had to endeavor to avoid any frozen uncompacted soil in the higher fills.

Normally, the handling of the materials in placing fills for the new railway embankment must be carried out in the summer months because of the -50°F temperatures experienced in winter, which cause the earth materials to become solidly frozen.

The application of ballast material to new line track structures is continued throughout the winter months whenever ballast pits have been located in which the material is very dry and can be handled without difficulty in the coldest weather.

With frozen soil

As has been mentioned, three state highway departments permit frozen material to be placed in embankments: Maine, Pennsylvania, and Wisconsin. However, the limitations are stringent.

Based on the premise that frozen ground (having high bearing capacity and impermeability) can be used successfully as a dam foundation and impervious core, the USSR began constructing such dams in 1792.[6]

As long as the foundation and body of a dam (when built of local earth, rockfills, etc.) or the foundation alone (when the dam consists of concrete, reinforced concrete, etc.) is kept frozen for the duration of its life, the dam will successfully function. Therefore, measures should be taken to prevent ice melting or possible water seepage through storage reservoir banks. Refrigeration is usually accomplished with brine or cold air. Artificial freezing of the dam body is economically done with cold air, injected down holes. In some areas, artificial refrigeration is necessary for only a couple of "summer" months.

The northernmost dam on the North American Continent was constructed with an impervious frozen core made from a saturated pervious soil lined on both sides with a riprap of oil drums. Because of the cold climate, water seeping from the fresh water lagoon froze in the dam to form an impervious barrier. The dam has been in place since 1964 with no evidence of settlement, shifting, cracking, or other movement. "The temperature of the dam core has been measured as +27°F and, although the underlying brine has reliquefied, the water has held at the spillway level with no evidence of seepage."[4] An even more northerly dam, at Thule, Greenland, was constructed of frozen granular material.

In connection with the construction of a number of large dams in northern Sweden, the State Power Board began investigation of the properties of frozen coarse-grained soils, particularly gravel and sand.[5] The first dam, where placement of frozen gravel was permitted to a certain extent in noncritical areas, was the Messaure Dam, which was 100 m high (1964). The experience thus obtained is being applied on two other dams of comparable size with provisions made for using frozen soils for some noncritical portions of the fill.

Summary

At present, military specifications delineate limits on filling operations only; none exist for excavating. Depending on the type of fill, these restrictions range from "loosely defined temperature limitations" to "40°F for placing and protection." All restrict the use of frozen material as a fill or restrict the use of unfrozen material on frozen bases.

Most states require that "Frozen material containing frost shall not be used in construction of embankments," and that "Embankments shall not be constructed on frozen ground." Maine's specifications are the most liberal: "Embankments may be formed when the depth of the fill plus the depth of the frozen ground does not exceed 5 feet." However, approximately 15 states have constructed satisfactory fills when air temperature was below 32°F.

Canada and European countries have guidelines requiring frost protection before, during, and after excavation. The predominant method of protection is "straw covered with tarpaulins." Rock excavations present no particularly difficult problems at temperatures below 0°F.

Under construction methods (p. 61) excavation was treated under mass, foundations, trenches, and tunnels. Mass excavating was delineated as either preliminary treatment or stripping. Preliminary treatment was subdivided into three sections: protecting, disintegrating, and thawing. Then filling "on frozen soil," "in freezing weather," and "with frozen soil" was examined. The chapter ended with a discussion of "permanently frozen dams."

Mass excavation is handicapped by the hard ground conditions, difficulties of equipment operation at low temperatures, reduction of daylight hours, and lowered worker efficiency. Before starting excavation, a contractor may be justified in performing certain preliminary tasks: protecting the ground before freeze sets in, disintegrating the ground with explosives, or thawing the ground after the occurrence of frost.

A blanket of snow just before periods of low temperatures often provides adequate insulation of the area of concern. Without this "luck" a contractor may use brush or straw, covered with black polyethylene sheeting. Immediately before stripping, the protective layer is removed, leaving an area just large enough for equipment spread for use that day. Following excavation, the protective blanket is replaced.

In the United States, large-scale excavation of soil frozen deeper than about 2 ft is normally conducted by blasting with explosives or by breaking up the frozen ground with tractor-mounted rippers. The latest available Russian publications consider blasting an expensive form of excavation. The Swedish find it most desirable, particularly the blasting of rock.

A system of cross ripping with a tractor-mounted ripper loosens most frozen soils and subsoils. This practice is common in the United States. The Canadians feel that modern excavating machinery can readily operate in ground frozen to a depth of 1 ft.

An interesting suggestion from the Russians is that of cutting the ground into sections that are easily excavated. Frozen soil is cut into squares to a depth of 0.8 m by high-speed disk saws. However, the cutting devices wear away rapidly; this makes the method impractical at present. The Russians also employ wedge-shaped cast-iron strikers to batter the frozen soil. This method is more economical for foundation pits and trenches than for mass application.

Large-scale excavation in this country has been accomplished by thawing the area before operations. The most economical method of excavating in permafrost areas has been found to be cold-water thawing by points inserted into the ground. Soil may also be either flooded or sprayed with water and the thawed soil periodically scraped away. Other methods include the use of steam jets, hot sand, mixture of salt and hay covered with tarpaulins, fire, and electrical heating. The Canadians consider the use of steam points, which melt their way into the frost crust, the most effective method. In northern USSR frozen ground is thawed with steam, electricity, and thermochemical sources.

The latest method of thawing originated in Minneapolis. A pipe with a gas burner on one end, connected to a portable propane tank, is set in an augered hole to radiate its heat into the soil. It allegedly thaws frozen ground in as little as one-sixth the time required under present methods and at one-sixtieth the fuel cost.

Following any combination of the previous preliminary treatments, the contractor can use his equipment spread to strip the overburden. Excavation during the winter should be planned so that no surface is exposed to freezing for more than a day or two before re-excavation. The golden rule is "Don't chew off more than you can handle."

Protecting, thawing, and stripping operations are essentially the same for foundations as for mass excavation. However, impact breaking with wedges, cutting, and electrical heating may be more economical for foundations.

The definition, extent, and design considerations for permafrost were treated. Permafrost can only be regarded as a variable – it is deceptive and powerful, and must be approached with the greatest respect.

Because most structures in arctic regions (in both North America and Russia) have been built on piles, piling was discussed as a separate section. Five major factors have to be considered with regard to the use of piles in permafrost: site preparation, type of pile, pile placement methods, depth of embedment, and refreezing characteristics.

When trenching, a contractor may remove the soil, or prepare it and then remove it. A large (2 or 2½ cu yd) backhoe can often handle frozen ground without prior soil preparation. The use of rotary multishovel trench excavators is becoming prominent on larger jobs. Blasting is seldom used; but cutting, mechanical crushing, and ripping are common practices. The cut-and-cover method of trenching seems to be prevalent in arctic regions in snow.

The desirability of subsurface camps in arctic environments has led to new tunneling methods. The mining cycle normally consists of four routine operations: drilling, blasting, ventilating, and mucking.

All highway organizations state that foundations should not be placed on frozen soil, and most of them do not allow the use of frozen soil in their embankments. The subject of filling and backfilling was treated as "on frozen soil," "in freezing weather," and "with frozen soil."

Asphalt has been laid on frozen subgrade in subfreezing temperatures with satisfactory results. Maine and Pennsylvania permit base courses to be laid on frozen subgrade.

The consensus of organizations contacted in this study is that placement of permanent backfill should be deferred until favorable weather conditions prevail. However, if placement is an absolute necessity during freezing temperatures either "dry, cohesionless, non-frost-susceptible materials or material containing additives ($CaCl_2$), to lower the freezing temperature of the soil water, should be used." The minimum practical and economical temperature limit for placing backfill is about 20°F; for placing granular materials, 15°F.

The use of impervious barriers of frozen soil in earth dams and dam foundations is common practice in permafrost areas in the USSR. Similar methods of dam construction are being tried in Sweden and North America. However, the Russians have found that measures (normally artificial refrigeration) may have to be taken to prevent the melting of ice or the possible seepage of water during critical periods of summer weather.*

Analysis

Considering the three resources (men, material, and equipment), it is concluded that material (soil) is the initial limiting factor. The minimum practical limit for placing fill is about 20°F; for placing granular materials, 15°F. At these temperatures, men should be relatively unaffected. This implies that available equipment is unable to compact frozen soils, although machine starting and mobility are not problems at 20°F.

Military guides restrict placing of fills at temperatures above freezing. However, the successful placing of embankments at temperatures below this limit is becoming common. Hence, the military guides seem conservative on this point.

Excavating, coupled with available winterizing procedures, may be executed down to about 10°F. At this point, the comfort and efficiency of the workmen become limiting factors. Concurrently, nonarctic equipment may begin to balk at this temperature as well.

The panacea for allowing earthwork to be done at lower temperature limits than now attained must attack the *placing* of embankments, not the *excavating*. Furthermore, it must deal with obtaining optimum compaction to eradicate the resulting effects of frost thawing.

* [*Comment of CPREL reviewers*: In borderline permafrost areas it is impractical to attempt to keep a dam and its foundation permanently frozen. Even in arctic and subarctic areas the temperature of the water at the *surface* of lakes and reservoirs reaches 70°F or more in the summer. This is a powerful agent for subsurface thawing. By designing embankments of materials that adjust to settlements resulting from the thawing of permafrost it is possible to accept the consequences of thawing. *Case histories*: Hess Creek Dam, Alaska, and Kettle Rapids and Kelsey Projects on the Nelson River in Manitoba, Canada. These were built on permafrost, except that Kettle Rapids had permafrost only in the abutments.]

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CONCRETING

As temperatures fall, progressive precautions are essential for satisfactory concreting. The degree of cold that can be accepted when concreting depends on the circumstances, how urgent or difficult the work is, and how long the cold conditions are likely to continue. For major concreting in the warmer part of the year, preplanning is normal practice in some parts of the world. But, if quantities of concrete have to be placed in cold conditions, some or all of the steps described in this chapter will be helpful.

These steps will help to conquer the problem described in the following:

> "Structural cements function by hydrating with water in the liquid phase, forming compounds which adhere strongly to stone, steel, brick, etc. When temperatures fall below normal, the chemical reaction producing the new compounds develops more slowly and the build-up of strength is reduced. If the water provided for the reaction freezes it is no longer able to react. As water cools below 4°C (39.2°F) the volume increases and this expansion can cause permanent damage to the weak, newly-formed structure of cement particles."[1]

Temperature affects the rate at which hydration of cement occurs: low temperatures retard concrete hardening and strength gain. Figure 19[8] shows the age-compressive strength relationship for concrete that has been mixed, placed and cured at temperatures from 40 to 73°F.

At temperatures below 73°F, strengths are lower at early ages and higher at later ages. Concrete made with type I or normal cement and cured at 55°F has relatively low strengths for the first few days; but after 28 days it has slightly higher strengths than concrete made and cured at 73°F.

The higher early strengths that may be achieved through the use of type III or high-early-strength cement are shown in Figure 20.[8] Principal advantages occur before 7 days. At 40°F curing temperatures, the early advantages of this type of mixture are more pronounced and persist longer than at higher temperatures.

Strength gain practically stops when moisture required for curing is no longer available. Concrete placed at low temperatures (but above freezing) may develop higher strengths than concrete placed at high temperatures, but curing must be continued for a longer period. It is not safe to expose concrete to freezing temperatures in the early periods. If freezing is permitted within 24 hours, much lower strength results.

Military Requirements

The Department of the Army's myriad of guide specifications can be roughly separated by function: building, piling, and paving. Additional specifications relate to special purpose construction and maintenance repair, for example, patching.

Perhaps the latest guide (CE-204)[13] will be the pattern for future ones. Although it is written for building construction, its specific requirements are frequently less conservative and restrictive than those appearing in related guides. The requirements are:

> "16. PLACING CONCRETE:
>
> 16.2 *Cold-weather requirements*: Concrete shall not be placed when without special protection the concrete is likely to be subjected to freezing temperatures before the expiration of the specified curing period. If necessary to place concrete

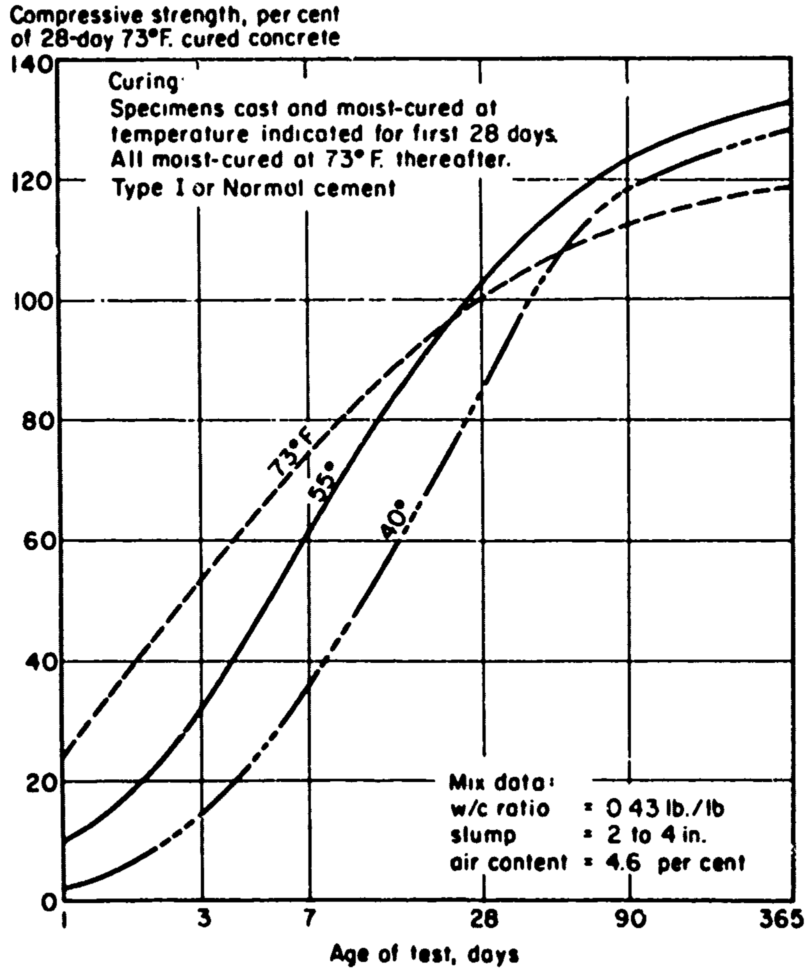

*Figure 19. Effect of low temperatures on concrete compressive strength at various ages.**

under conditions of low temperature, placement shall be approved by the Contracting Officer. The temperature of the concrete when placed shall be not less than 50°F nor more than 70°F. Heating of the mixing water and/or aggregates will be required as necessary to maintain the minimum concrete temperature of 50°F., and all methods and equipment for heating shall be subject to approval. Materials shall be free from ice, snow, frost, and frozen lumps before entering the mixer. Surfaces that will be in contact with concrete shall be free of frost, ice, or snow. Suitable covering and other means that will not stain concrete, as approved, shall be provided for maintaining the concrete at the temperatures and periods specified in paragraph: CURING. Salt, chemicals, or other materials shall not be mixed with the concrete to prevent freezing, except that calcium chloride may be used as an accelerating agent after written approval.

. . . .

"26. CURING: Concrete shall be protected against moisture loss, rapid temperature change, mechanical injury, and injury from rain or flowing water, for a period of time given below corresponding to the cementing materials used in the concrete.

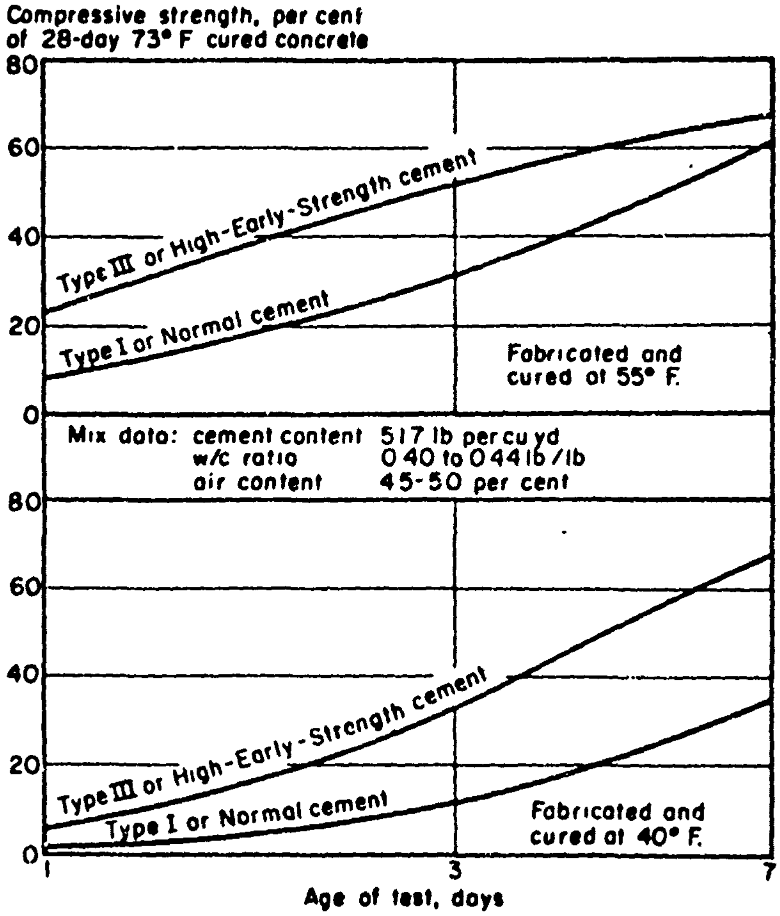

*Figure 20. Early compressive strength relationships involving portland cement types and low curing temperatures.**

Types III, IIIA cement .... 3 days
Types I, IA, II, IIA cement .... 7 days
Types IS, IS-A, S, SA, N or blends containing pozzolans, natural cement, or slag cement .... 10 days

Concrete shall be maintained in a moist condition at temperatures above 50°F throughout the specified curing period and until remedial work is started under paragraph: FINISHES OF CONCRETE OTHER THAN FLOOR AND ROOF SLABS. Fuel-burning heaters shall be vented to the exterior. Concrete shall be protected from local applications of heat. Concrete shall be protected from rapid temperature change and rapid drying for the first 24 hours following the removal of temperature protection. Curing activities shall be started as soon as free water has disappeared from the surface of the concrete after placing and finishing. . . ."[15]

These excerpts are necessary for clarity and comparison with civilian specifications, but their essence is the following: "Mixing water and/or aggregates shall be heated as necessary to result in an in-place concrete temperature of *between 50°F and 70°F*. Covering and other means shall be provided for maintaining the concrete at a temperature of *at least 50°F for not less than 72 hours* after placing."

Department of the Army (DA) Technical Manual 5-349,[14] in a chapter on *Concreting in cold weather*, notes that even in the Arctic the placing of concrete at temperatures below 0°F is not practical except for small projects or for extremely large-scale operations with sizable plants. Snows and blizzards, in addition to the cold, hinder the placing. The manual outlines several precautions. A summary of them follows:

1. Between 40° and 32°F, the addition of 1% of $CaCl_2$ by weight of cement, or the shielding of the concrete during curing by covering it with straw, or tarpaulins, protects it against frost damage.

2. Below 32°F, additional precautions are required, such as warming the water and aggregate before mixing, warming the forms before placing, and keeping the concrete warm during curing.

3. Mixing water should not be heated beyond 140° to 175°F to prevent "quick or flash" setting.

4. At atmospheric temperatures below 20°F, it is necessary to heat the aggregates as well as the water.

5. During cold weather, mixture or concrete should have a water/cement ratio of between 4 and 5 gal of water per sack of cemer

6. It is important, whenever a ncrete components are heated, to mix the water with the aggregate before adding the cement. T cement should never be heated, and should always be added last.

7. Portland cement concrete unmixed with $CaCl_2$ should be maintained at 70°F for at least 3 days or at 50°F for 5 days.

8. Concrete using high-early-strength cement requires a minimum temperature of 70°F for 2 days, or 50°F for 3 days.

9. Moisture must be provided during these periods, since the Arctic is, in many respects, a dry climate. During periods of slow setting and dry atmosphere conditions, much of the water may evaporate before the final set takes place, leaving insufficient water to combine chemically with the cement.

Civilian Requirements

Although it is generally agreed that "concrete winter" begins when the air temperature falls below about 40°F, and that mixing water will then have to be heated, opinions vary considerably concerning the temperature to which water should be heated, the minimum temperature of concrete after being placed, and the time during which it should be protected from freezing. Some of these differences can be explained by the variation in climatic conditions and in the types of cement and mixes generally used in different countries.

Two recognized authorities in the field of concrete are the American Concrete Institute (ACI) and RILEM, an international organization of some 20 countries. ACI in 1966 issued ACI 306-66,[2a] *Recommended practice for cold weather concreting*, that is customarily used in the United States. RILEM established a Winter Construction Committee in 1958, which met regularly every year until it published its work in December 1963.[11] The recommendations of this committee are generally followed by European countries. Winter concreting practice in Canada is governed by the Division of Building Research, National Research Council, which published its latest work concerning the subject in 1963.

The material in this section is presented under the recognized authorities: ACI, RILEM, and the National Research Council of Canada. In addition, each division is subdivided into the countries affected.

ACI 306-66

If the temperatures of concrete after being placed are not less than the temperatures shown in line 4 of Table XX[1a] freezing will be prevented until protection can be provided.

Table XX. Recommended concrete temperatures for cold weather construction (after ACI[1a]).

Air-entrained concrete

Line	*Min temp of fresh concrete mixed for weather as indicated*	*Thin sections (°F)*	*Moderate sections (°F)*	*Mass sections (°F)*
1	Above 30°F	60	55	50
2	0 to 30°F	65	60	55
3	Below 0°F	70	65	60
4	Min temp of fresh concrete as placed	55	50	45
5	Max allowable gradual drop in temp throughout first 24 hours after end of protection	50	40	30

In addition to maintaining the recommended minimum temperatures for concrete after mixing (as shown in lines 1, 2, and 3), the contractor may be required to provide thermal protection. This ancillary protection is to ensure that subsequent concrete temperatures do not fall below the minimums shown in line 4 of Table XX, for the periods shown in Table XXI,[1a] thus ensuring durability and development of strength.

Table XXI. Recommended duration of protection for concrete placed in cold weather (after ACI[1a]).*

Air-entrained concrete

Degree of exposure to freeze-thaw	*Normal concrete† (day)*	*High early-strength concrete** (day)*
No exposure	2	1
Any exposure	3	2

* Protection for durability at temperatures indicated in line 4, Table XX.

† Made with type I, II, or normal cement.

** Made with type III or high-early-strength cement, or an accelerator, or an extra 100 lb of cement.

Of the ingredients used for making concrete, mixing water is the easiest and the most practical to heat. The weight of aggregates and cement in the average mix is much greater than the weight of water. However, water can store five times as much heat as can solid materials of the same weight, because of its high specific heat (1.0) as compared with 0.22 Btu/lb per degree F for the cement and aggregate.

At temperatures above freezing it is seldom necessary to heat aggregates. At temperatures below freezing, often only the fine aggregate is heated to produce concrete of the required temperature. Care should be taken to prevent overheating of the aggregates: an average temperature should not exceed 150°F. This should prevent the occurrence of a "quick" or "flash" setting of the concrete.

Figure 21* depicts graphically the effect of the temperature of materials on the temperature of fresh concrete. This figure is based on the mix shown; however, it is reasonably accurate for other typical mixes.

If the weighted average temperature of the aggregates and cement is above 32°F, the proper mixing water temperature for the required concrete temperature can be selected from Figure 21. The range of concrete corresponds with recommended values given in lines 1, 2, and 3 of Table XX. Note that the maximum water temperature shown in Figure 21 is 180°F. Water hotter than this causes "quick" or "flash" setting of the concrete.

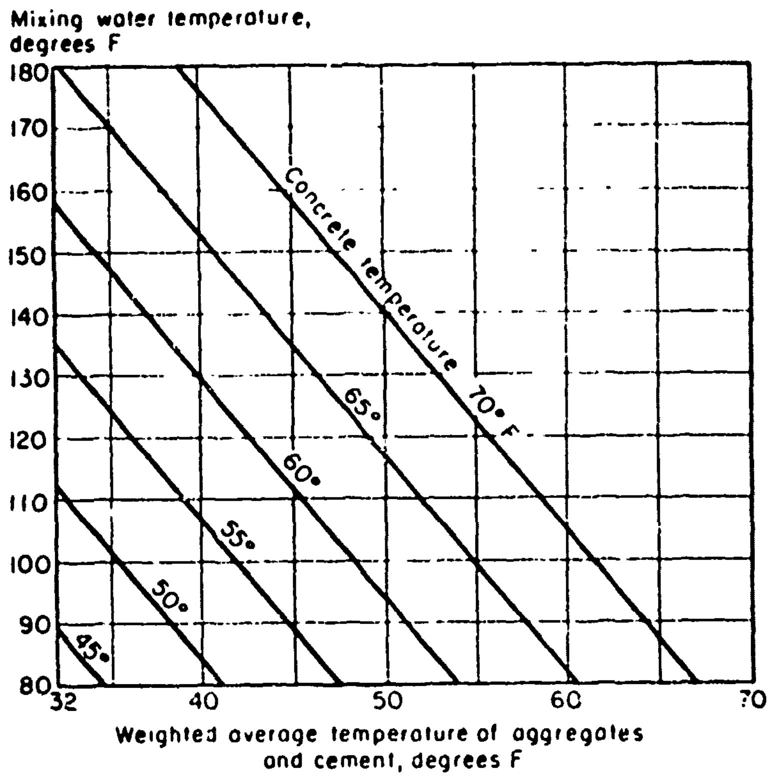

Chart based on following mix proportions:

aggregate	3,000 lb
moisture in aggregate	60 lb
added mixing water	240 lb
cement	564 lb

*Figure 21. Temperature of mixing water needed to produce heated concrete of required temperature.**

* Copyright, Portland Cement Association; reprinted by permission.

In some cases both the aggregates and water must be heated, as indicated in Figure 21. For example, if the weighted average temperature of aggregates and cement is below about [illegible]°F and the desired concrete temperature is 70°F, the aggregates must be heated to limit the water temperature to 180°F.

A comprehensive survey of winter construction practices, including concreting, was conducted for USA CRREL in 1966.[54] The objective was to review and summarize the current cold-weather-construction specification requirements and practices relating to concrete, earthwork, and asphalt of the Corps of Engineers, state and provincial highway departments, and other Federal and private agencies engaged in winter construction.

The standard specifications for [illegible] of the U.S. state highway departments and 4 Canadian provincial highway departments were examined and cold-weather-construction specifications were summarized.

The requirements of most of the highway departments for placing concrete in cold weather are similar to those of the Portland Cement Association,[8] which are based on the ACI code.[2a]

For placing concrete in cold weather, 29 of the highway departments surveyed require heating the water and/or aggregates before mixing all the constituents together. In most cases, the placing mix is at a temperature of 50°F.

Enclosing and heating the area, or covering the concrete after it is in place, is required by 38 of the highway departments during cold weather. For most departments the temperature of the concrete must be maintained above a minimum of 40 or 50°F.

Most of the highway departments allow the use of calcium chloride in quantities of 1 to 2% by weight of cement as an accelerator. Most hold to curing periods of 5 days at 32 to 50°F. Thus, all states and provinces require at least the minimum protection specified by ACI.

Surprisingly, only four highway department specifications change requirements when high-early-strength cement is used. In general, the allowable placement temperatures are reduced by 5°F and the required protection periods for curing are shortened by 1 or 2 days. Three state highway departments and three Canadian provincial highway departments require different minimum air temperatures for placing concrete in structures than those for placing concrete in pavements. Alaska, Missouri, Alberta, British Columbia, and Ontario require that concrete shall not be poured when the air temperature is below 35 to 40°F. Michigan requires that concrete shall not be placed when the atmospheric temperature is below 30°F for superstructures and below 15°F for substructures. In all cases the curing protection required for structures is greater than that required for pavements. Most states require 7 days at 50 or 60°F for concrete placed in structures.

RILEM

From the text, tables and diagrams in "Recommendations for Winter Concreting," RILEM Bulletin no. 21,[11] the following is extracted:

> "The temperature of water should not be above 60°C (140°F) on contact with the cement. The temperature of concrete should normally not exceed 25°C (77°F) for standard and 20°C (68°F) for rapid-hardening cement. The water/cement ratio should be kept as low as possible, preferably by increasing the cement content rather than reducing the water content. In cases where concrete is expected to be exposed to repeated freezing and thawing cycles in a condition of high saturation, air-entraining agents should be used. The controlled air content should be from 4 to 6%. The greater value should be used for

concrete where the maximum aggregate size is small. Accelerators containing chloride increase the risk of corrosion of the reinforcing steel, depending upon type of cement and steel, and exposure. Such admixtures are consequently not recommended for normal reinforced concrete.

"The necessary pre-hardening time for standard cement is calculated at ½ to 2 days at a concrete temperature of +20°C (68°F), ¾ to 3 days at +12°C (54°F) and 1 to 4 days at +5°C (41°F), the lower figures referring to a water/cement ratio of 0.4 and the higher figures to a water/cement ratio of 0.8."[33]*

A comparison with the recommendations of countries examined shows that most of the RILEM recommendations are even more cautious than the practices recommended or prescribed in most of these countries.

Belgium.[53] For concreting in cold weather (minimum temperature not below 0°C) rapid-hardening cement is recommended. The water/cement ratio should be as low as possible (0.5 recommended) and the cement content between 325 and 400 kg/cu m. Additional measures to be taken at temperatures below +5°C (41°F) are given in Table XXII.

Table XXII. Belgium concreting.

Temperature Average	Minimum	
+5 to 0°C (41° to 32°F)	-3°C (27°F)	It is recommended to add calcium chloride (max. 2% by weight of cement) or a plasticizer (1% by weight of cement) and an air-entraining agent (0.5% by weight of cement) to the mix. The inside of forms should be oiled. After placing, concrete should be covered with cement bags, plastic sheets or straw placed directly on the concrete.
0 to -5°C (32° to 23°F)	-7°C (19°F)	Water should preferably be heated. The temperature of the concrete at placing should be at least +10°C (max +30°C). If good protection is provided, the temperature may be reduced to +5°C. Protection: plastic sheets or tarpaulins with air space, or straw mats with or without air space. At the end of protection the temperature of the concrete must not be allowed to fall by more than 1°C per hour.
-5 to -10°C (23° to 14°F)	-12°C (10°F)	Water must be heated and the concrete protected at least as above.

At average temperatures below -10°C (+14°F) concrete should not be placed unless all precautions can be taken.

Water may be heated to a maximum temperature of +80°C (176°F). The mix of water and aggregates may not have a temperature exceeding +40°C (104°F) when cement is added. After being placed, the concrete should be maintained at a temperature of at least +5°C (41°F) for 3 days.

Denmark. From 1 November to 31 March, an air-entraining cement or agent should be used. The air content of the concrete should be 4 to 5%; the water/cement ratio, not higher than 0.6. The temperature of the water should be +60°C (140°F) with a maximum of +80°C (176°F). The concrete will then have an initial curing temperature of +12 to +14°C (57°F) and will not freeze after having been covered for three days. Concrete should generally not be placed at temperatures below -5°C (23°F).

$CaCl_2$ may be used only in unreinforced concrete up to a maximum of 2% by weight of cement. Where a certain reduction of strength is of no great importance, alcohol (15% by weight of water) has often been used to lower the freezing point of concrete for jointing between concrete components; this made it possible to continue work to -10°C (14°F) without damage.

Germany.[53] At air temperatures below +4°C (39°F) water should be heated and the concrete, after being placed, maintained at a temperature of +10°C (50°F) for at least 3 days. The temperature of the concrete, at placement, must be at least +5°C (41°F) with a maximum of +30°C (86°F). For cold weather concreting the cement content should be increased or higher cement qualities used. The water/cement ratio should be as low as possible. Water should be heated to about +80°C (176°F). Concrete should generally not be placed at temperatures below -10°C (14°F).

An air-entraining cement may be used to improve the workability of concrete with a low water/cement ratio. Antifreeze agents should not be used with reinforced concrete but can be used with caution in unreinforced concrete.

Sweden.[53] At temperatures between +5 (41°F) and 0°C (32°F), it is enough to heat the mixing water. At lower temperatures, it may be necessary also to heat aggregates: sand at temperatures below 0°C (32°F) and coarse aggregate at temperatures below -5°C (23°F). The temperature of the water (plus aggregates) should not exceed +60°C (140°F) for ordinary portland cement and +35°C (95°F) for rapid-hardening cement.

The temperature of concrete, when leaving the mixer, must not exceed +40°C (104°F) for portland cement and +25°C (77°F) for rapid-hardening cement. The minimum temperature of concrete, after placement, should be +10°C (50°F) for thin sections and +5°C (41°F) for mass concrete. After the concrete has been placed, its temperature must not be allowed to fall below +5°C (41°F) until it is frost resistant, within 2 to 4 days, depending on the cement content. (If rapid-hardening cement is used, this time is reduced by 50% and if $CaCl_2$ is used, by 25%.) The concrete must thereafter be protected from freezing for 6 days (3 days for rapid-hardening cement). Concrete should, as a rule, not be placed at temperatures below -20°C (-4°F).

$CaCl_2$ may be added as follows: concrete temperature maximum +20°C (68°F), 2% by weight of cement; concrete temperature maximum +30°C (86°F), 1% by weight of cement. If the temperature is +40°C (104°F), $CaCl_2$ should not be used.

Air-entraining agents are recommended for exposed positions (air content 4 to 5%; in special cases, air content 5 to 6%).

United Kingdom.[53] When frost occurs only at night, it is enough to insulate the newly placed concrete and to adjust the time of stripping formwork. To avoid freezing, the temperature of the concrete, after placement, must not be less than +4°C (39°F) and must not be allowed to fall below +2°C (36°F) for 7 days.

Water should be heated to 50 to 65°C (150°F) with a maximum of 71°C (160°F). For air temperatures below 0°C (32°F), it is usually necessary to heat the aggregates also (maximum temperature 120°F).

$CaCl_2$ may be used (maximum 2% by weight of cement) with ordinary or rapid-hardening portland cement.

Canada, Division of Building Research, National Research Council[53]

For concreting in cold weather the Canadians use Table XXIII for heating requirements.

Table XXIII. Canadian heating requirements.

Air temperatures (°F)	Water	Aggregates Sand	Coarse	Concrete temp at mixer (°F)
Above 30	Heated			60 to 80
30 to 0	Heated	Heated		65 to 90
Below 0	Heated	Heated	Heated	70 to 90

If water is heated to a maximum temperature of +60°C (140°F), it should suffice to heat aggregates to +15°C (59°F). The temperature of the concrete after placement must not be allowed to fall below +10°C (50°F) for a period of 5 days, or below +21°C (70°F) for 3 days. In either case, the concrete (after the initial curing period) should be protected from freezing until it has reached an age of 7 days. When high-early-strength cement is added to the mix, the protection period may be reduced to 3 days at +10°C (50°F), or 2 days at +21°C (70°F). At the end of the curing period, the temperature of the concrete should be gradually reduced at the rate of about 28°C (50°F)/day until the outside air temperature has been reached.

Salts and other chemicals must not be used as antifreeze agents. Calcium chloride may not be used in excess of 2% by weight of cement for reinforced concrete; however, only 1% is recommended.

Union of Soviet Socialist Republics

Quantities of calcium chloride and sodium chloride (up to 20% by weight of water) are used entirely as an antifreeze. Mass concrete has been placed in Russia using this method but it has mostly been used in large heavy works, such as foundations and canal structures, and in secondary roads. However, there are precautions involved which warrant treatment of the subject of "cold concrete" as a separate section of this chapter (see *Alternate Construction Methods and Procedures, Cold concrete*, p. 118).

Summary

Table XXIV compares the various concreting specifications previously discussed.

Concreting specifications of the various countries vary in most respects except for the temperature at which special precautions must be introduced (40°F) and the amount of $CaCl_2$ (2%) which may be used as an additive. The minimum practicable limit for concreting as viewed by each country varies from 23°F in Denmark to −4°F in Sweden. Curing of normal portland cement concrete ranges from 70°F for 3 days in Canada to only 41°F for 2 days in Sweden.

All countries recommend heating the water. Maximum temperatures range from 140°F to 180°F. The temperature limit for heating aggregates varies greatly, from only 60°F in Canada to 212°F as recommended by RILEM. Air-entraining agents are normally desired, particularly if the green concrete will be exposed to freezing and thawing cycles.

Construction Methods

Concreting in winter calls for extra precautions and involves closer control than concreting at normal temperature. However, if the necessary steps are taken, the quality of the concrete placed in winter will not be lower. The protection of concrete against freezing and the maintenance of proper curing conditions (to reach sufficient strength for removal of forms) can be obtained in three different ways: change of mix, thermos, and postheating.

Table XXIV. Compilation of specifications.

Authority Country	Min. Practical Limit for Concreting (Air Temp.)	Commencement of Special Measures @ (Air Temp.)	Min. Temp. Req'd for In-Place Concrete	Maximum Temperature Allowed								Req'd Curing (Min.)		Additives		w/c Ratio Desired		Air-Entraining Agents (Per Cent)
				H_2O		Agg.		Mix		Mixer				Type	Max. Amt.			
				P	H	P	H	P	H	P	H	P	H			P	H	
U. S. Army	0°	40°	50°	175°	140°							70° @ 3 days 50° @ 5 days	70° @ 2 days 50° @ 3 days	$CaCl_2$	2%			
ACI (United States)		40°	45° (mass) 55° (thin)	180°		150°		70°		70°		50° @ 3 days	70° @ 2 days	$CaCl_2$	2%			
RILEM		40°	68°-75° (Max.)	140°		212°		75°				54° @ 3 days 41° @ 4 days				0.7		4-6%
Belgium	14°	40°	50°	176°				104°				41° @ 3 days		$CaCl_2$ Plasticizer	2% 1%	0.5		0.5%
Denmark	23°	40°	57°	176°								57° @ 3 days		$CaCl_2$ Alcohol	2% 15%	0.6		4-5%
Germany	14°	39°	41°	176°								50° @ 3 days						
Sweden	-4°	40°	41° (mass) 50° (thin)	140°	95°					104°	77°	41° @ 2 days	41° @ 1 day	$CaCl_2$	2%			4-6%
United Kingdom		38°	39°	160°		120°				100°		36° @ 7 days		$CaCl_2$	2%			
Canada	0°	40°	60°	140°		60°				90°		50° @ 5 days 70° @ 3 days	50° @ 3 days 70° @ 2 days	$CaCl_2$	2%			

Temperature in degrees Fahrenheit (°F.)
P - Normal Portland Cement
H - High-Early-Strength Cement

A more rapid development of strength and heat of hydration may be obtained by an increase in cement content or by use of a cement of higher activity. (This method can be used in cold weather at temperatures above the freezing point.)

The thermos method is based upon prevention of heat losses; i.e., the concrete is placed at an initial temperature such that the heat of hydration in combination with insulation can maintain the concrete at a high enough temperature to obtain resistance to freezing. In some cases even sufficient strength for form removal is obtained. (This method can be used during moderate and short periods of frost.)

In the postheating method, the surrounding air is artificially heated to keep the temperature of the concrete at a certain level above the freezing point, thus maintaining the development of strength. The same effect can be obtained by heating the concrete proper, for example, by electricity. (This method can be applied under severe conditions.)

Which of the three methods to choose in an actual case depends upon local conditions: climate, cost of different cement types, massiveness of structure, cost of insulation against cost of heating and enclosure material, cost of labor, etc. Therefore, no general rules can be established. In some cases a combination of the methods might be advantageous.

Regardless of method, a general sequence of operations or "steps" is outlined. The procedure is divided into seven steps for clarity. Within each step, further divisions are made. As each division is presented, all pertinent data are examined and compared.

Planning

To place concrete in cold weather and protect it adequately from freezing requires careful planning, well in advance of freezing weather. Appropriate equipment should be available for heating the concrete materials, for constructing enclosures, and for maintaining favorable temperatures after the concrete is placed. To avoid excessive heat loss and ensure a mix at a satisfactory temperature after compaction in the forms, the processes of mixing, transporting and placing should be planned as well.

The cost of construction may be increased somewhat by these essential precautions and varies with the amount of protection required. However, increased construction costs can be largely offset by the advantages which are obtained.

Selection and preparation

Site. Concrete should never be placed on a frozen subgrade, since uneven settlement may occur when the subgrade thaws; this can cause cracking. Also, heat flows from the concrete, retarding its rate of hardening and making it possible for the lower part of the slab to freeze.

> "When the subgrade is frozen for a depth of only a few inches, the surface may be thawed by burning straw, by steaming or, where the grade permits, by spreading a layer of hot sand, gravel or other granular material. Concrete thaws and warms up sufficiently to ensure that it will not freeze again."[*]

The inside of forms, reinforcing steel, and embedded fixtures should be free of snow and ice when concrete is placed.

Equipment. Equipment should be thoroughly checked and put in working order. In some cases it may be necessary to defrost it with steam jets or hot water heating before it is used. If warranted, winterizing may be necessary.

Concrete constituents.

Cement: When cement hydrates, heat is given out by an exothermic reaction; the rate at which this heat is released is dependent on the nature of the cement and is usually related to the rate at which the concrete gains strength, the more rapid-hardening cements producing heat more quickly. Figure 22[7] compares this property, the heat of hydration, for four different cements.

Ordinary portland cement, rapid-hardening portland cement, and a proprietary type of extra-rapid hardening and quick-setting portland cement, in that order, have increasingly rapid release of heat of hydration. Since sulphate-resistant portland cement gives up its heat more slowly than the other cements considered, it is most affected by cold conditions.

Under normal conditions, the speed with which a concrete hardens and develops strength may be significantly dependent upon the degree of fineness to which the cement is ground. Fine grinding increases the speed with which the various constituents react with water, but does not change their inherent properties. Recent practice utilizes more finely ground cements, specifically manufactured to produce concrete of higher strength at earlier ages. Such concretes have a distinct advantage during cold-weather concreting operations.

Figure 23[14] shows the value of these high-early-strength cements under such conditions. For cold-weather work, high-early-strength cement (rapid-hardening) usually produces better early-strength concrete than does an admixture of portland cement with calcium chloride. The increase in strength is almost 100% for the first 3 days, tapering off to about 30% after a week.

Alumina cements derived from bauxite ore have a high alumina content. They are much more commonly used in Europe than in North America, but their high early strengths offer an advantage for cold-weather operations. "Concrete made with it becomes as hard in 24 hours as Portland-cement concrete becomes in 28 days."[14]

The quality of concrete resulting from the high-early-strength cement depends somewhat on the freshness of the cement. Unless carefully stored, cement tends to lose its effective properties with age. "Storage piles should be limited to a height of 12 sacks to prevent caking in the bottom sacks. Under arctic conditions the sacks should be moved and turned over every 2 months. Lumps that can be broken up to a powder easily between the fingers are not detrimental."[14]

Aggregate: Proper aggregate is one of the important factors in the production of good concrete. According to RILEM, aggregate should not contain minerals vulnerable to freezing, and should be free from ingredients retarding the hydration, for example, organic impurities, as the presence of retarding substances is particularly dangerous during low temperature curing.

To obtain satisfactory concrete the aggregate should be clean, well graded, and sound. Aggregate is clean when it is free from noticeable amounts of dirt and organic matter. The gradation should be such that there is no predominance of coarse or fine material. Soundness is the property of the aggregate to resist weathering and chemical action.

Adequate stocks should be arranged and aggregate storage areas provided so that water (draining out) can get away. When frost is likely, aggregates should be covered with a waterproof sheet.

Water. Water should comply with normal requirements for good quality concreting; impurities retarding hydration are dangerous.

The supply of fresh water in the Arctic is limited. "Sea water may be used for both mixing and curing. There is approximately a 10% reduction in compressive strength when sea water is used for mixing. This can be corrected by reproportioning the mix, using less water and 10 to 15% more cement."[14] Other than the slight reduction in strength, there are no harmful effects from the use of sea water.

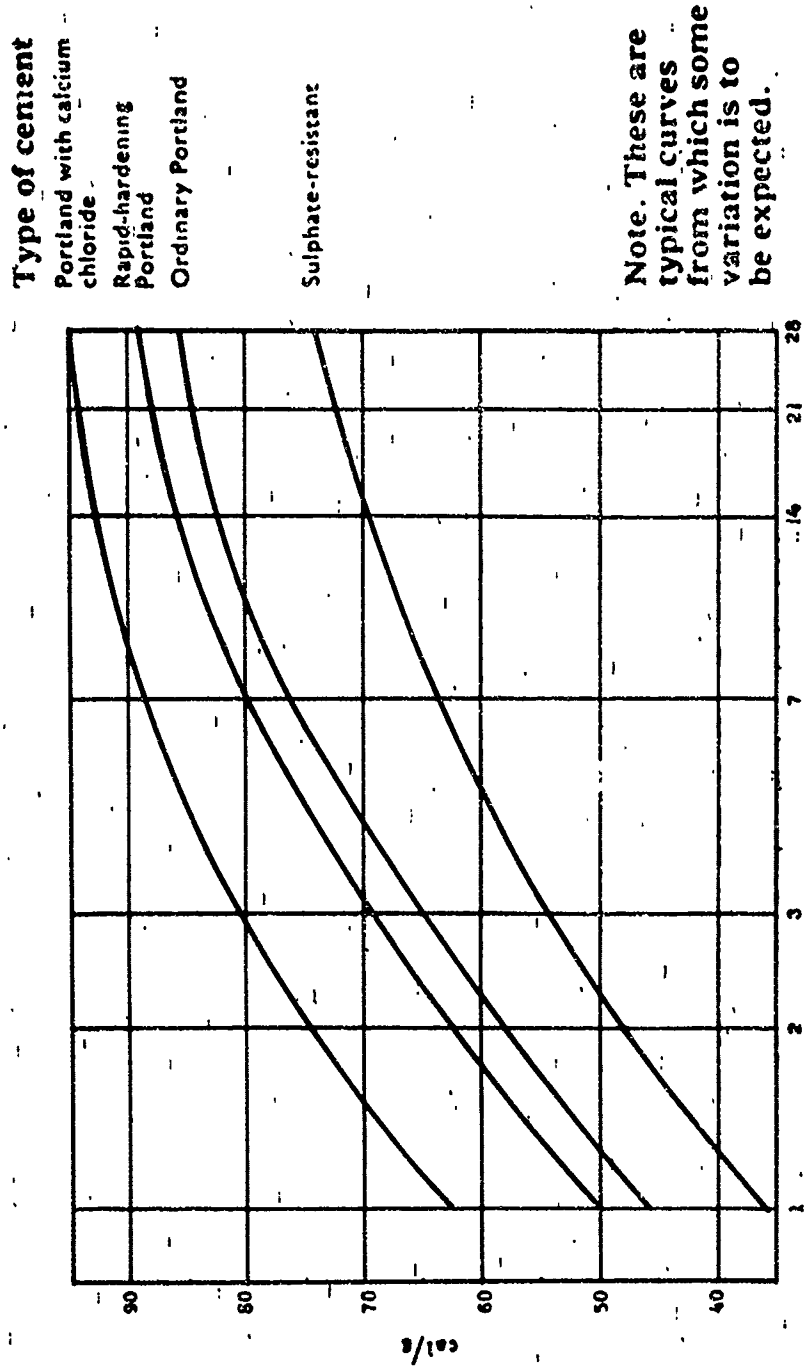

Figure 22. Heat of hydration for four different cements.[7] *(Copyright, Concrete Publications Ltd, Cement and Concrete Association; reprinted by permission.)*

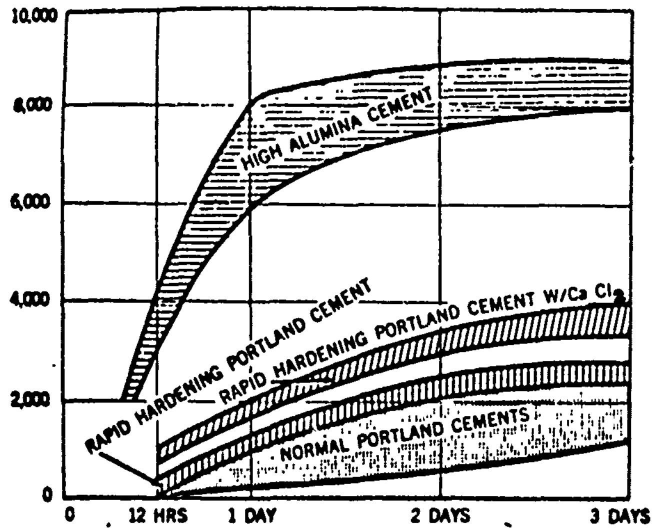

Figure 23. Comparison of compressive strengths.[14]

Admixtures. Admixtures may only be applied if their effects on the concrete properties are fully known. "They should not delay the process of hydration at low temperature, nor increase the permeability of concrete to gases and water, and should not promote the corrosion of the reinforcing steel."[33]

During winter concreting, accelerators and air entraining agents are applied. Accelerators, used in the proper amount, decrease the time of set and increase the early strength and development of heat of hydration at the beginning of the hardening period. Figure 24[14] illustrates the effect of acceleration ($CaCl_2$) on the development of heat of hydration. Figure 25[14] demonstrates the increase of early strength accompanying the use of accelerators.

The compressive strength increases using $CaCl_2$; this is shown quite clearly in Figure 26.[5]

However, accelerators entail liabilities as well as assets. The addition of an accelerator may decrease the final strength and increase shrinkage and electrical conductivity. The risk of efflorescence on the concrete surfaces may also be increased.

Accelerators (containing chlorides) increase the risk of corrosion of the reinforcing steel, depending upon the type of cement, steel and exposure. Consequently, such admixtures are not recommended for normal reinforced concrete or prestressed concrete.

Air-entraining agents increase the resistance of the hardened concrete to freezing and thawing, and at the same time improve the workability of the fresh concrete.

"Air-entrainment may be obtained either by use of air-entraining portland cement which contains an interground air-entraining agent or by use of air-entraining admixtures added at the mixer."[14]

"Air-entraining agents can be used with $CaCl_2$ in both normal portland cement and high-early-strength cement, but they should be added to the concrete mixture separately since $CaCl_2$ may cause a precipitation of some air-entraining admixtures which may clog water valves. Air-entraining agents are added at the mixer in solution if the cement does not have the agent milled into it. However, for prestressed concrete, air-entraining agents should be permitted only if they do not contain chlorides.

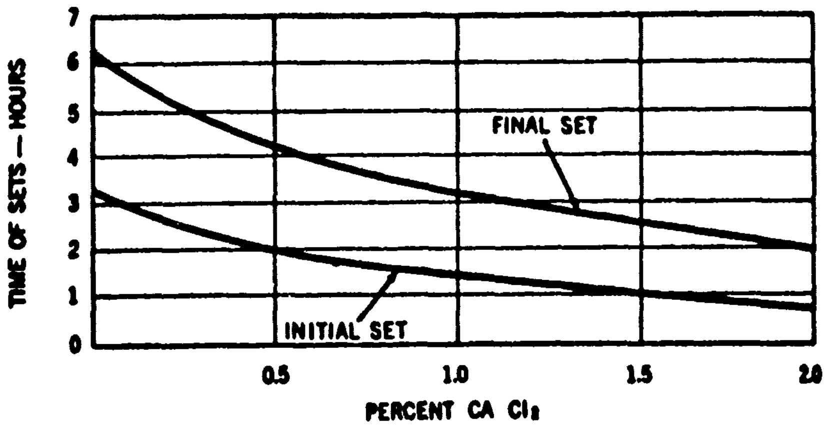

Figure 24. Effect of calcium chloride on initial and final set of portland-cement concrete.[14]

INITIAL AND FINAL SET

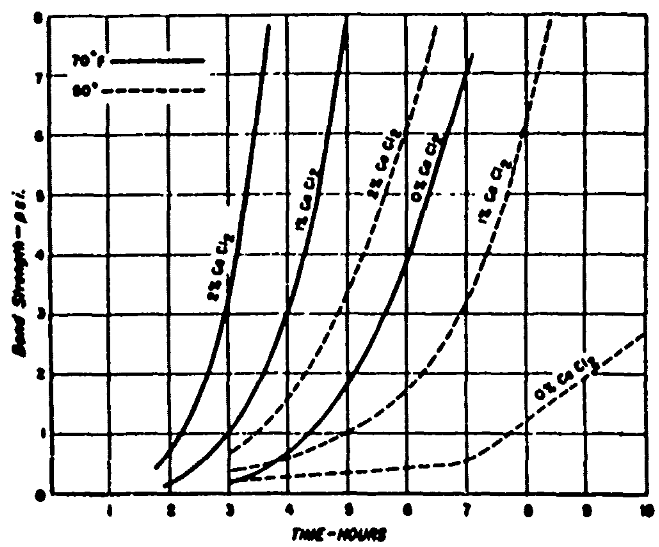

Figure 25. Increase of early strength accompanying the use of calcium chloride.[14]

Forms. Plastic coatings, proper oiling, or effective wetting can protect forms from deterioration, weather, and shrinkage before concreting. Form surfaces should be clean and free of frost. They should be treated with a suitable form oil or other coating that will prevent the concrete from sticking to them.

> "A straight, refined, pale, paraffin-base mineral oil usually is acceptable for wood forms; synthetic castor oil and some marine-engine oils are examples of compounded oils that give good results on steel forms. The oil or coating should be brushed or sprayed evenly over the forms. It should not be permitted to get on construction joint surfaces or reinforcing bars, because it will interfere with bond."[26]*

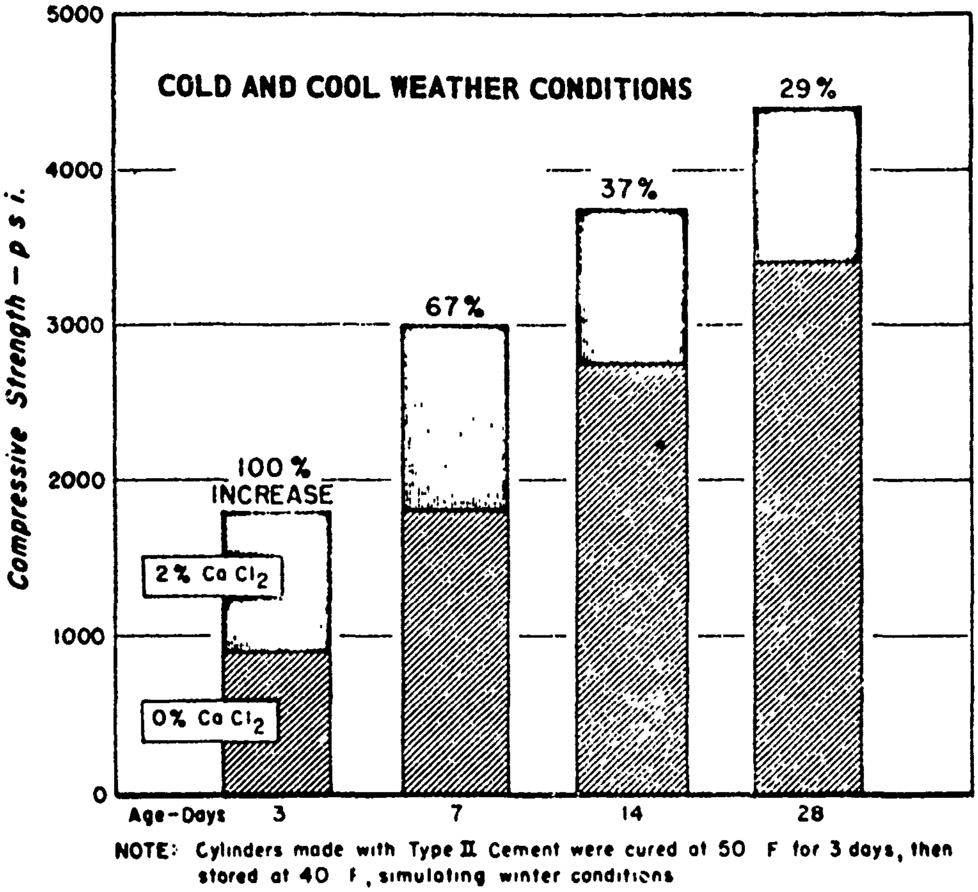

Figure 26. Compressive strength increase (using $CaCl_2$).[5]

To determine the effect of various surface treatments on different types of shuttering, especially plywood forms, the Swedish Building Research Institute carried out investigations on building sites in northern Sweden. The results have been tabulated in a working report. The following is a summary of that report:

"1. A form treated with high-temperature hardened plastic becomes worn mostly at the edges and corners due to physical ill-treatment, primarily when formwork is disassembled. The plastic finish is durable.

"2. Forms treated with plastic cured at room temperature may need oiling after being used a few times, as the plastic facing wears away relatively quickly.

"3. Non-plastic faced plywood forms must be oiled, especially in winter. If not, the facing veneers of the plywood spall and parts adhere to the concrete after the forms have been removed.

"4. Metal forms must be treated with oil before each time of use. The oil eases removal and protects the formwork against rust.

"5. The most widely used shutter oil is emulsifiable and is mixed with water.

"6. A relatively fatty oil with good adhesive properties without any water added is suitable for metal forms. Several such shutter oils are available."[3]*

The most suitable time for oiling in winter is immediately after the removal and cleaning of formwork, especially if the formwork is struck simultaneously with the ending of artificial heating of the concrete. The forms still retain a certain heat and the building is not entirely cold.

One other point should be mentioned. Forms should provide ready access for placement and vibration of concrete and for inspection.

Mix proportions

During winter concreting, greater care is generally required in proportioning the mix than at other times of the year. The water/cement ratio should be kept as low as possible, preferably by increasing the cement content rather than by reducing the water content. Low ratios increase the strength of concrete. However, if they are too low, workability of the cement is reduced, promoting potentially excessive volume changes on wetting and drying.

As previously mentioned, when concrete may be exposed to repeated freezing and thawing cycles in a highly saturated condition, air-entraining agents should be used. "The controlled air content should be from 4% to 6%. The greater air values should be used for concretes where the maximum aggregate size is small."[33]

Heating of materials

Water. Of the ingredients used for making concrete, mixing water is the easiest and most practical to heat. On small jobs, domestic types of water heaters are feasible. Larger projects may require heated water from a storage tank. "Storage tanks should be lagged and painted black. Supplying pipe lines should be buried below the level to which frost penetrates, or be well lagged."[9] A steam coil or steam jet heats the water in the supply tank. A medium size job might only require water passing through a coil in a large coke stove.

Aggregate. For short-term contracts or jobs where a small amount of concrete is to be placed during the winter months, it is considered "sufficient for straw antifreeze quilts to be placed over the aggregate stock-piles, but these should be overlaid with weatherproof tarpaulins, or similar material, in order to keep the quilts dry and maintain their insulation qualities."[47]

When aggregates also need to be heated, the "most practical and economical supplementary plant to adopt is a system of pipes located underneath the aggregates and heated by propane burners."[47]

Portland Cement Association notes that "Live steam, preferably at high pressure (75 to 125 psi), can be injected directly into the aggregate pile to heat it, but variable moisture content in aggregates might result in erratic mixing water control."[8] The steam can be injected via perforated pipes.

British methods recommended include:

"1. Stock piles tented over and braziers or other heaters placed in the enclosure.
2. Passing aggregate over heated plates.
3. Banking aggregate over large metal pipe in which fire is built.
4. Electric heating pads.
5. Heating on corrugated iron sheets over coke fires (small jobs)."[10]

On small jobs in the United States, aggregates are sometimes heated by being stockpiled over metal pipes in which fires are built. However, care must be taken to prevent the overheating of aggregates.

Mix. When the air temperature is just below freezing, the required temperature for the concrete mix can be obtained by heating the water only. Later, as the weather becomes colder and stockpiles freeze, heat is also applied to the sand. Figure 21 is a possible guide for determining when or how much to heat the various constituents.

Concrete in a mixer can be heated by steam jet or hot water just before use. The same heating procedures apply to wheelbarrows, skips, chutes, etc. However, these methods are not entirely reliable, and it is hard to control the final temperature of the mix. Also, the moisture content of the mix varies considerably.

Cement should never be heated and should always be added to the mix last.

Placing

Under normal circumstances, hot water and frost-free aggregates are used to produce the heated concrete. The following method of combining the aggregates, water, and cement should be used to avoid occurrence of a "flash-set":

> "The hot water should be discharged into the mixing drum before the aggregates are added, and it is better to mix the aggregates and the water before adding the cement. . . .
>
> "Using the Silover types of mixer, the foregoing method is practical, and there is little danger of a 'flash-set', which might occur if the cement and water came into contact at a temperature of above 140°F (60°C)."[47]

Before the concrete is placed, all ice, snow, and frost must be removed from forms, reinforcements, and other contact surfaces. The concrete is placed above the minimum temperature prescribed by the appropriate specification but also below the maximum temperature. There is nothing to be gained and damage can result if concrete is placed at too high a temperature.

Curing

Curing is another very important construction step for obtaining good concrete; yet it is often one of the most neglected, particularly in winter work. "Concrete that has been properly mixed, placed, and finished may still give poor service if improper curing is tolerated."[48]

The first few hours after concrete placement, when potential durability and strength of the concrete may be seriously damaged by one or two cycles of freezing, are critical.

It is essential to the contractor to know when any particular concrete can safely be exposed to freezing temperatures. Damage caused to concrete which is still plastic when frozen, making it quite useless, is obvious when the forms are removed. However, damage caused to concrete which has stiffened but has not matured sufficiently before freezing is not so apparent and might not be detected.

A number of researchers have attacked the problem from the standpoint of maturity and strength. Their research indicates that if the concrete is kept from freezing for a specified time, generally named the "prehardening period," it can then safely resist the damaging effects of subsequent freezing temperatures. "Maturity depends on both age and temperature and is defined as the product of the curing temperature (°C) and age (hours). The base of the temperature scale is -10°C; thus:

$$\text{Maturity (°C hours)} = (t + 10)\ \text{°C} \times \text{age (hours)}."^{50}$$

This formula can be used to calculate the "prehardening periods" required for concretes with different specified minimum strengths at 28 days (available in concreting tables).

Protective measures must be continued "at least until the prehardening period is complete." This completion should be confirmed by a strength test on cubes cured under the same conditions as the member.

It must be emphasized that the *prehardening period of concrete* is *not* necessarily the same as the *minimum length of time* that must elapse before striking formwork. The governing specifications for the contract work must be referred to for this time. Some specifications require longer form protection than the prehardening period. Prehardening time starts when the concrete first stiffens and not when placement has been completed.

Concrete in forms or covered with insulation seldom loses enough moisture at 40 to 55°F to impair curing. However, moist curing is needed during winter to offset drying within heated enclosures.

Moisture retention. Concrete may be kept moist either by applying moisture externally to the concrete surface or by preventing loss of moisture from the concrete by sealing the surface. The latter includes the use of mechanical barriers and chemical membranes.

"Mechanical barriers of waterproof paper or plastic film seal in the water and prevent evaporation."[48] These materials should be applied as soon as the concrete has hardened sufficiently to prevent surface damage. The widest practical width of material should be used; edges of adjacent sheets should be overlapped several inches, then tightly sealed with sand, wood strips, pressure-sensitive tape, mastic, or glue.

Liquid membranes can be sprayed on to retard or prevent the evaporation of moisture. They are effective curing materials when used correctly. They should be applied immediately after the surface has been finished. However, a membrane curing compound should not be applied when there is free water on the surface because the water will be absorbed by the concrete and the membrane will be broken. Further, it should not be applied after the concrete has dried out since it will be absorbed into the surface of the concrete and a continuous membrane will not be formed.

"Adequate and uniform coverage by curing compounds is essential. In most cases two applications are required. Sprayed-on membranes are suitable not only for curing fresh concrete but also for further curing of concrete after initial moist curing."[48]

The Army's TM 5-349 recommends coating the concrete surfaces in the Arctic with a sealing compound immediately after the concrete has been finished. They consider the most satisfactory material that containing finely ground white pigment dispersed in a vehicle of oil, wax, or resin. The compound is applied at the rate of approximately 1 gal/200 sq ft of exposed surface and is best applied in one coat by spraying. Spraying equipment should be of the pressure tank type with provisions for continual agitation of the contents during application. If pressure equipment is not available, a hand sprayer can be used. Brush application is not satisfactory for green concrete.

Heat retention. During the hardening of the concrete and especially in the first few days considerable heat is developed. If this heat is conserved, no heat from outside sources will be necessary to ensure good curing conditions.

Insulation: Recommendations on the amount of insulation necessary to protect concrete at various temperatures may be obtained from manufacturers of these materials or from ACI's Recommended Practice for Cold Weather Concreting ACI 306-66.[2a]

Heat may be retained in the concrete by using commercial insulating blankets or bat insulation. The effectiveness of the insulation can be determined by placing a thermometer under the insulation in contact with the concrete. If the temperature falls below the minimum required, additional insulating material should be applied. Corners and edges of concrete are most vulnerable to freezing and should be checked to determine the effectiveness of the protection.

"Ordinary timber formwork is a reasonably adequate insulator and may suffice for moderately cold spells. Combined with additional insulation, it will protect concrete during very cold periods."[30]

The British have found success with the types of insulation found in Table XXV.[1]

Table XXV. Insulation (after ref 1).

Type	*Materials*	*Remarks*
Shuttering	Timber board as normally used. Forms backed with straw, etc. Forms backed with closed air space formed by building paper, etc., tacked over battens.	Where timber formwork is used, this may provide sufficient insulation in itself to the surfaces it contains. Steel shuttering has very low insulating value and readily conducts heat away to other parts of structure as well as losing it to the air. Back with straw, etc.
Top cover	Several layers of building paper, sacking, cement bags, etc. 6 in. or more of straw or similar materials. Boards with canvas over. 6-in. to 24-in. air space over slabs and pavings formed by stretching canvas over wood frames.	Adequate lapping and tacking down at edges is important. Sacks, etc. kept dry by sheeting over with tarpaulin or building paper provide better insulation. Considerably improved by tarpaulin over. Heat is sometimes applied under the enclosure.
Enclosures	Complete covering of the job by thick canvas sheeting, etc., allowing 18 in. air space all around the work. Enclosure heated.	For severe conditions care must be taken to avoid all unnecessary openings.

A dead-air space can often provide a cheap, efficient insulation if the size and duration of the job permits the construction and use of double-wall forms.

"Concrete walks, floors, pavements, and other horizontal surfaces can be protected with blanket insulation or heavy curing paper covered with a 12-in. thickness of hay or straw."[48] The latter should also be covered with tarpaulins, waterproof paper or polyethylene sheets held in place at the edges with wood strips or other means.

Forms built for repeated use often can be economically insulated. "Commercial blanket or bat insulation used for this purpose should have a tough moistureproof covering to withstand handling abuse and exposure to the weather."[8]

In Britain, hessian is one of the most usual forms of protection. However, it loses its effectiveness when it gets wet. "If hessian is draped over slabs about 2 to 4 in. above the concrete surface and then overlaid with tarpaulins, good protection is provided."[47]

Heated enclosures: The alternative to the use of insulation is to enclose the member completely and provide heating inside the enclosure, thus maintaining a temperature above freezing until the end of the prehardening period. The enclosures can be made of wood, canvas, building board, plastic sheets, waterproof paper, or other suitable material.

"Wood framework covered with tarpaulins or plastic sheets is commonly used. Enclosures should be sturdy and reasonably airtight, with ample space provided between concrete and enclosure to permit free circulation of the warmed air."[8]

Enclosures may be heated by live steam, steam in pipes, oil-fired blowers, salamanders, and other heaters. Control of the enclosure temperature is easiest with live steam. In addition, it provides both heat and moisture.

Salamanders and other fuel-burning heaters produce carbon dioxide, which combines with calcium hydroxide in fresh concrete to form a weak layer of calcium carbonate on the surface. When this occurs, the final floor surface dusts under traffic. "For this reason, carbon dioxide-producing heaters should not be used while placing concrete and for the first 24 to 36 hours of the curing period, unless properly vented."[8]

For slabs, electrically heated insulating quilts are available. However, "These are expensive and tend to deteriorate quickly."[47]

Since considerable variation in temperature within a heated enclosure can occur in very cold weather, temperature differences must be minimized by venting and circulation.

Removal of forms

The time of form removal should be determined by the governing specification, but in no case should it be less than the prehardening period as determined by maturity tests. In addition, the record of temperatures should be kept until such time as the strength, computed from the maturity, is that approved for striking formwork.

It is generally best to leave the forms in place as long as possible to facilitate curing. But it is sometimes desirable to remove the forms promptly. Consequently, some criterion must be developed to use as a guide rather than utilizing guesswork.

RILEM suggests three criteria for removing formwork: strength of concrete at stripping, deformations, and risk of cracking.

Strength of concrete at stripping. For most conditions, it is better to rely on the strength of the concrete as determined by test rather than on guesswork. Many designers specify the minimum compressive strengths that must be obtained before the forms are removed. Table XXVI[48] may be used as a guide for usual concrete.

For determining these strengths, specimens cured at the same temperature and moisture should be tested. However, such test results may not always be available. In these cases, for average conditions, the information in Table XXVII[48] may be helpful.

The time required before removal of forms varies. It is good practice to leave forms in place as long as practical.

Table XXVI. Strength of concrete for safe removal of forms (after ref 48).

Structural classification	Min concrete strength (psi)
1. Concrete not subject to appreciable bending or direct stress, nor relying on forms for vertical support, nor liable to injury from form removal or other construction activity.	500
EXAMPLES:	
Vertical or approx vertical surfaces of thick sections.	
Outside of barrels, etc.	
Side walls of tunnel lining against rock.	
Tops of sloping surfaces.	
2. Concrete subject to appreciable bending and/or direct stress and partially relying on forms for vertical support.	
SUBJECT TO DEAD LOAD ONLY	750
EXAMPLES:	
Insides of barrels, etc.	
Arch of tunnel lining against solid rock.	
Under sides of sloping surfaces, 1:1 or steeper.	
Vertical or approx. vertical surfaces of thin sections.	
SUBJECT TO DEAD AND LIVE LOAD	1500
EXAMPLES	
Inside of galleries and other openings in dams.	
Side walls and arch of tunnel lining against unstable material.	
Columns	
3. Concrete subject to high bending stress and wholly or almost wholly relying on forms for vertical support.	2000
EXAMPLES:	
Roof or floor slabs and beams under sides of sloping surfaces flatter than 1:1.	
Walkways and platforms.	
Bridge decks and girders.	

Deformations. The creep of concrete is dependent on several factors, among which the relative strength and the moisture content of the concrete at the time of loading are included. "Excessive deformations may occur, if the delayed hardening due to low temperature has not been taken into account when fixing the stripping time. Excessive deflections may also develop if the concrete structure in state of loading is undergoing great temperature or moisture variations."[33]

Table XXVII. Probable strength gain for concrete cylinders (after ref 48).

Made with type I and III cements, 6 gal of water per bag of cement, and moist cured at 70°F for periods given.

Age of cylinders	Strength, psi Type I cement	Type III cement
6 hr		500
12 hr		750
24 hr	500	1500
36 hr	750	2000
2½ days	1500	
4 days	2000	

Risk of cracking. To avoid the formation of cracks, the rate of evaporation from the surface should be kept as low as possible.

"With increasing thickness of concrete members the risk of cracking is increased because the temperature differentials may become high in cold weather."[33] Whether temperature differentials cause cracking or not depends upon their magnitude and the induced stresses.

Generally, when the concrete is sufficiently strong, "so that corners and edges will not be damaged during stripping of forms, it will be strong enough to support its own weight without visible or measurable evidence of cracking, deflection, or other deformations."[41]

Summary

Winter concreting methods involve handling several variables, as shown in Table XXVIII.[33] The timing of their occurrences determines the extent to which it is possible to change them at the various stages of the concreting process. These variables are again listed in Table XXIX,[33] where they reflect their adaptability to the concreting methods.

Table XXVIII. Classification of variables (after ref 33).

Changes possible at the planning stage	Changes possible before concreting (at the job site)	Changes possible after casting
Temperature of ambient air (by the postheating method)	Form type	Insulation
Shape (of construction member)	Cement type	Duration of protection
	Cement content	
	Water content (w/c-ratio)	
	Concrete temperature (at placing)	

Table XXIX. The possibilities of influencing the variables by the different winter concreting methods (after ref 33).

x = Characteristic feature of the method.
* = Possible supplement to the method by combination with the other methods.

Variables	Change of mix design	Thermos method	Postheating method
Cement content	x	*	*
Water content (w/c-ratio)	x	*	*
Cement type	x	*	*
Time constant		x	*
Initial temperature of concrete		x	*
Duration of protection		x	*
Temperature of air			x

When the contractor understands the variables at his disposal, the methods of changing the variables at hand, and the seven basic construction steps outlined, he is sufficiently armed to undertake cold weather concreting.

Alternate Construction Methods and Processes

Ready-mixed concrete

The problems of temperature and moisture control that confront the contractor when mixing concrete on the site can be most simply bypassed by transferring the operation to a supplier of ready-mixed concrete.

In ready-mixed concrete depots, steam is normally employed to defrost bins, hoppers and their contents. When steam is applied directly to aggregates, the amount of water added in mixing has to be reduced to allow for the moisture content in the aggregate.

The measures to be taken in the preparation of ready-mixed concrete are the same in principle as those applying to site-mixed concrete. When concrete is transported by agitator, the water is added at the depot, and experience indicates that there is little drop in temperature during transportation. When water is added en route or at the site, the vehicle's water tank may need to be filled with hot water.

"Whether plant-mixed or truck-mixed in transit, the concrete must be supplied at a temperature of not less than 39°F."[13] This regulation is in effect for British contractors.

Another British authority states that builders in Canada and Sweden mostly use ready-mix concrete for concreting at all types of sites. "All the ready-mix concrete in Sweden during wintertime incorporates $CaCl_2$."[22]

Another contractor in Britain used ready-mixed concrete to cut his construction time in concreting a bridge by over 33%. The project involved a total of 4100 yd^3 and was carried out in January and February.

Precast concrete

Precast concrete offers advantages over conventional reinforced concrete because of the increased speed of construction possible, and its relative freedom from the influence of frost. Other factors, such as overall economy, the type of structure, the function of the building, the distance from the precast factory to the site, and the possible need for carrying out the precasting on site have to be taken into account.

The erection of floor units, stairs, etc., can proceed with the minimum of precautions; and roofs or floors of precast units offer an early cover for other work. Items such as these could well be considered at the planning stage to help maintain the program.

"Where precast frames are used, protection from frost will be required only at the joints, where it can often be reduced to simple box-type covers containing insulation or some means of heating. The heat of electric light bulbs is often sufficient."[10] In addition, column base joints require insulating and covering.

If overall temporary enclosures are contemplated, the erected framework can form the basis for the covering to enable work in other trades to proceed.

Multistory buildings in Canada are normally constructed by using prefabricated concrete elements or steel framing. Precast-prestressed components of a multistory structure in Canada were erected "despite weather as cold as 35° below zero. Erection began in mid January of 1966 and the first three stories were up inside of two weeks."[20]

One authority states that Moscow "has enlarged its precast factory capacity year by year until now it has doubled its rate of house building from these factory components in less than four years."[3]

Kushnev[23] confirms Russia's affinity toward the use of assembled reinforced concrete elements, especially for conditions of the extreme north. In 1940 the Russians were installing precast columns into foundation cups, fastening with wedges, and filling with concrete. However, because of the many difficulties involved, they soon realized that there must be a better way. Now columns are joined to foundations by welding, so that the entire load on the foundation is transmitted through the welded seams.

Untypical, heavy, and untransportable members in small number can be prepared at the construction site and directly at the place of use. "Curing of members can be done by steam or electric heating. When members are placed at a considerable distance from each other, electric heating is for the most part more convenient than steam heating."[42]

Lift-slab construction

A type of precasting used in building construction involves the casting of floor and roof slabs at or near ground level and lifting them to their final position, hence the name lift-slab construction. It offers many of the advantages of precasting and eliminates many of the storing, handling, and transporting disadvantages.

> "Typically, columns are erected first, but not necessarily for the full height of the building. Near the base of the columns, floor slabs are cast in succession, one atop another, with a parting compound between them to prevent bond. The roof slab is cast last, on top. . . .
>
> "To raise the slabs, jacks are set atop the columns. They turn threaded rods that pass through the collars and do the lifting. As each slab reaches its final position, it is wedged in place and the collars are welded to the columns."[26]*

A Salt Lake City contractor defied the weather by utilizing lift-slab construction. He built a wooden frame around and over the foundation and the first section of steel columns, and then covered this frame with polyvinyl sheeting reinforced with glass fiber. "The plastic housing proved a low-cost way to weatherproof the job and permit the men to place concrete in the lift slabs at an inside temperature of about 50°F."[39]

Use of the lift-slab method meant that the plastic enclosure had to be only about 30 ft tall to shelter the work area. If the slabs had been poured in place it would have been necessary to enclose the building to its full height to achieve the same schedule. The method used also reduced the amount of heat needed.

The use of the lift-slab method of construction seems to be well suited to Canadian winter work. In Ottawa, during the 1959 winter, all of the floor and roof slabs for a 12-story apartment building were cast inside a prefabricated metal building. When the concrete had cured, the slabs were jacked into position at temperatures as low as -20°F.

Electrical heating of concrete surfaces

In the USSR a system has been developed for heating the surfaces of the concrete by electricity.

> "Electrodes of ¼ inch to ⅜ inch round steel are placed at intervals of 8 to 12 inches on the inside of the forms and on adjacent concrete surfaces. The electrodes are heated by low voltage (50 to 90 volts) alternating current. The approximate time for electric heating is set as follows: for an air temperature of 15°F, 8 hours; for -5°F, 16 to 24 hours; for -20°F, 32 to 40 hours. Electricity is supplied by portable 50-kilowatt three-phase oil transformers and the consumption at -20°F is 6 kilowatts per square yard of exposed surface."[11]*

The advantages of this system are that it permits placing of concrete with a temperature of 40°F (without the danger of freezing at the edges) and it does not require a heated structure around the concrete during the curing period.

Slip-form concreting

Generally, forms are stationary. But, for some applications, such as highway pavements, precast concrete slabs, silos, and service cores of buildings, the use of continuous moving forms – sliding forms or slip forms – is advantageous.

> "A slip form for vertical structures consists principally of a form lining or sheathing about 4 ft high, wales or ribs, yokes, working platforms, suspended scaffolds, jacks, climbing rods, and control equipment (Fig. 27)."[26]
>
> "Spacing of the sheathing is slightly larger at the top to permit easy upward movement. The wales hold the sheathing in alignment, support the working platforms and scaffolds, and transmit lifting forces from yokes to sheathing. Each yoke has a horizontal cross member perpendicular to the wall and connected to a jack. From each end of the member, vertical legs extend downward on opposite sides of and outside the wall. The lower end of each leg is attached to a bottom wale. The jack pulls the slip form upward by climbing a vertical steel rod embedded in the concrete. Slip-form climbing rates range upward from about 2 to about 12 in. per hour."[26]†

In general, the procedure used in vertical sliding form construction is as follows:

"1. The foundation is built while the forms are being made.
2. Hoisting equipment is placed.
3. Sliding forms, reinforcement, and back rods are placed for the initial pour.
4. Continuous sliding form construction.
5. The topping-off, roof slab construction, and removal of forms.
6. Erection of interior beams, slabs, and features."[14]

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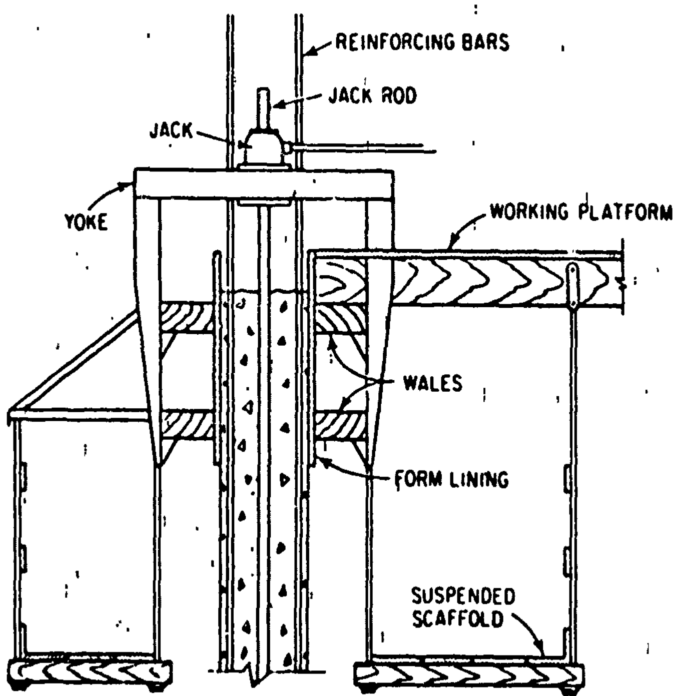

Figure 27. Slip form for concrete wall.[26]†

Camellerie[4] states that slip-form operations can be, and often are, conducted at temperatures below 40°F. To ensure a high-quality concrete, he recommends the following special provisions:

"1. Use of type III air-entraining cement.
2. Heating of concrete to 70°F in the forms.
3. Use of protective enclosure capable of maintaining air around green concrete at 70°F for 24 hours.
4. Use of reinforcing steel that is free of ice."[4]

Camellerie contends that these provisions are only one possibility among many. It is possible to use type I or type II cement or to keep the air at only 50°F, but this would require a minimum curing period of 3 to 5 days, thus making necessary enclosures up to 36 ft in length. With the use of type III cement, the enclosure need only be about 12 ft.

Camellerie found that the most common enclosure used on slip-form work consisted of tarpaulins hung from the deck hand rails down over the finishers' scaffolds. Although this method has been found satisfactory on many jobs, he favors an enclosure of rigid panels of plywood, masonite, or insulation board, hung from the forms by separate brackets as shown in Figure 28.[4]

Another form of winter protection was used while slip forming new storage silos in Utah in spite of snowfall and below-zero temperatures. Because of the slower set in cold weather and the need for keeping the concrete warm, the slip form was raised at a slower rate than usual. "The maximum movement was 16 feet in 24 hours."[27] Specifications required keeping the concrete warm for 24 hours after placement.

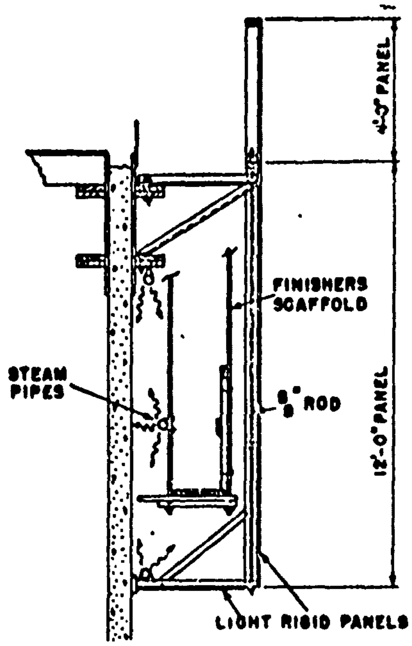

Figure 28. Rigid enclosure for winter slip-form work.[6]*

"To accomplish this, the contractor hung a 16-foot-wide shroud of Visqueen 6-mil polyethylene film from the slip form and placed 20 gas-burning heaters inside it. Nine additional salamanders were placed inside the bins at ground level.

"The temperature inside the silos seldom dropped below 70° during the 14 days of continuous concrete placement in the slip form. Under the shroud on the outside, the temperature did get down as low as 45° on a cold, windy night when the outdoor temperature hit 8 below zero. The average outdoor temperature during the 14-day period was 40°; the average low was 14 above zero."[27]†

The hydraulic jacks that raised the big form were controlled from a single station on the deck. This station was enclosed in a small wooden building to protect the operators and equipment and to keep the hydraulic oil warm.

The use of continuously moving forms is an economical and fast method of building a tall (over 30-ft high) reinforced concrete structure that has more or less the same shape throughout its height. Optimum speed of the lift is determined by weather conditions, experience of workmen, special forming, and day-to-day conditions. During the period of concreting, the lifting should not be stopped except for emergencies. In general, the method becomes optimum only after the contractor has gained experience with it.

According to a paper presented at Purdue University,[14] the development of the slip-form concrete highway paver along with its improvement and new techniques has kept the cost of concrete pavement from rising. In fact, slip-form pavers have cut the cost of highway paving in most cases. "They combine in one unit the operations of spreading, grading, and compaction of the concrete. The slab is then shaped to the desired cross section by an extrusion plate or extrusion meter."[14]

In general, slip-form paving is the same as other paving methods, except that no fixed side forms are required. Its main advantages are that it is much faster, it reduces the labor force needed, it requires less equipment, and it reduces the cost of the job.

However, nothing was found in the literature concerning pavement concreting by slip-forming under winter conditions.

Pneumatically applied concrete (PAC)

Pneumatically applied concrete derives its name from the process of conveying premixed dry cement and sand through a hose line. The materials are carried by compressed air at high velocities. Just before leaving the nozzle, the mixture is instantaneously hydrated in a water chamber or body. The sand and cement travel in suspension in the air stream much as dust in a dust storm.

"Pneumatically applied concrete is stronger and denser, has a higher specific gravity, has a lower water-absorption index, and generally is more resistant to weather and chemical exposure than conventionally poured concrete."[45]

PAC has been used with excellent results in restoration work and new construction. However, nothing is recorded on its ability to function in cold weather.

Concrete by intrusion grouting

Such concrete is made first by placing coarse aggregate in the forms. This is followed by filling the voids in the aggregate mass with intrusion mortar: a combination of portland cement, a high grade pozzolan, sand, water, and Intrusion Air. The latter is a patented chemical admixture which suspends the solid particles in the mortar, eliminates setting and settling shrinkage, and provides fluidity at low w/c ratios.

This method has proven particularly useful in a number of applications such as underwater concreting in bridge piers and cofferdam seals; mass concreting where low cement content and low heat of hydration are factors; very heavily reinforced concreting where placement by the usual procedures is very difficult; and repair concreting, particularly where the added concrete must be highly frost resistant and so well bonded to the existing concrete that it may be considered to be monolithic with it.

A 1966 article described the construction of a bridge by crews working 34 days during which the temperature never rose above -60°F. The contractor states: "We actually never tried to pour any concrete at that temperature except the *trémie pour.*"[16]

From this one article on the subject it may be inferred that concreting by intrusion grouting applied underwater with the aid of trémies is possible.

Permacrete

Since the use of large masses of artificially frozen soil in concreting is on record and the literature describes criteria for their treatment, it was decided to find criteria for small-scale applications of frozen soil mixes. "The main purpose was to find a substitute for concrete in an environment of permanently frozen ground."[46]

Curing portland cement mixtures is often difficult in very cold environments and transportation costs into remote polar areas are often almost prohibitive. This investigation concerned the utilization of natural local material with a minimum of pretreatment. "Permacrete" is a new building material, made of varying mixtures of fine-crushed rock, sand, clay, rock flour slurry, water and snow.

> "It has been demonstrated that permacrete may be successfully used as a substitute for concrete in many fields of construction . . . . There is not much difference between manufacturing pre-cast permacrete and pre-cast concrete. The difference is that permacrete does not require portland cement. Permacrete has a comparatively short "curing time," freezing time only, and can be remolded and reused at any time. Labor and machinery are utilized in the same way as in concrete work.
>
> "The use of permacrete in tunneling in permafrost is most advantageous when it is applied to roof and wall support by spraying and plastering with unfrozen material. . . . Permacrete may be used at the surface, as well as underground for foundations and fortifications in permafrost regions."[46]

Cold concrete

Russia has developed a "cold concrete" for use without protection even at temperatures below zero. This concrete contains a brine solution in place of water, the strength of the solution depending on the minimum temperature expected during the placing and curing period.

Most of the research concerning cold concrete has been reported in Russian literature and little has been translated. However, in 1966, Stormer[44] investigated the subject to verify some of the translated data and to determine whether the method was practicable and worth further investigation. His results, through experiments, design, and a cost analysis, revealed similarities with Russian results in the water/cement ratios, strengths, and curing temperatures observed. However, salt contents were 1½ to 2 times those reported in the Russian literature.

Stormer used his results for the hypothetical design of a side channel spillway in northern Alaska and the comparison of "cold concrete" with the insulated formwork method of winter concreting. The cold concrete technique seemed to cost less than the insulated formwork method. He concluded that when cold concrete is more thoroughly investigated, it may become a competitive winter concreting method.

Another source reports that the use of cold concrete has "been limited by its poor resistance to freeze-thaw cycling and rapid corrosion or reinforcement."[12]

Bituminous concreting

Referring again to CRREL Special Report 76,[34] the military specifications for asphalt placement are nearly the same with the exception of minimum allowable atmospheric temperatures. Almost all of the specifications permit the atmospheric temperature requirement to be waived by the Contracting Officer. Essentially the specifications state that the bituminous coat shall be applied only when the atmospheric temperature in the shade is 50°F and the ground temperature is above 40 to 45°F.

The bituminous sections of highway department specifications were the least standardized of any of the sections containing cold-weather restrictions.

Most of the highway departments in the United States and southern Canada do not allow asphalt pavement construction from approximately 1 October to 1 May. Minimum air temperatures for such construction are 40 to 60°F. However, many of the states require only that asphalt not be placed on frozen subgrade. Seven states specify a minimum ground temperature somewhat above freezing.

The Travelers Research Center (TRC)[36] states that bituminous concrete is sensitive to precipitation in any form or intensity. "Any precipitation can cause cracking and permanent damage to the pavement. The material usually sets faster than portland cement concrete but is still sensitive to precipitation for generally one to three hours after pouring."[36]

TRC contends that the quality of the pavement is greatly reduced by pouring at temperatures below about 45°F. Work is not usually carried out when the temperature is likely to approach this limit.

Except for emergency completion of limited areas, paving and grading are usually shut down during the winter in the Arctic.

> "Some minor extensions of the working season have been made by use of heated enclosures, application of heat to subgrades or binder courses by heater-planer (blade grader combined with heater) and in one case by use of aircraft jet blast to thaw and dry base course before asphalt laydown."[40]

Bituminous concrete is placed in colder weather than is usual in the United States. Higher mix and aggregate temperatures, higher asphalt content, shorter pulls of the laydown machine and more rapid application of the breakdown roller are the construction techniques used.

Cold weather paving may be the answer to the "hurry-up" needs of today's critical road construction, notes the National Bituminous Concrete Association (NBCA). To dispel the lingering bugaboo that hot-mix works must shut down in freezing weather, NBCA cited a bituminous concrete pavement laid in the winter of 1958 on the Chicago Skyway Toll Bridge. The two project contractors reported that the only limitation on laying down the mix was that there be no snow or ice on the surface on which asphalt was laid. "There were no ambient temperature limitations, though the presence of sunshine was helpful despite the near-zero air temperatures,"[24] one contractor said.

Both companies employed insulated trucks with tarpaulin covers left in place over the hot mix even during dumping. A rubber-tired roller was very useful in closing up the surface of the mixture during the extremely low air temperatures encountered. Equipment functioned day in and day out in the freezing weather.

As mentioned in section *Filling* (p. 80), hot plant-mix base was placed on frozen subgrade in an air temperature of 23°F. Four years later, sample cores were tested at 99 to 100% of laboratory density.

Research and Observations

1964. The British Ministry of Public Building and Works carried out an active program of investigation into the various parts of the total problem of construction in winter.

> "The work in resolving the winter construction problem is assisted by the great variety of winter building equipment and materials which are now coming on to the market. These make the protection and heating of construction works an increasingly simple operation. There are now available many different types of highly efficient space heaters of a sufficiently large output for the average construction contract, together with reinforced protective coverings, insulating quilts, etc."[41]

Seven cases covering a fairly representative range of structures and structural components in England were studied and then summarized as to winterizing techniques (Table XXX[50]). It can be seen that the measures taken to enable work to continue during very cold weather vary from none to the "full treatment."

Table XXX. Tabular summary of replies (after ref 50).

Case no.	Type of structure or component	Principal measures to enable work to continue	Remarks
1	Column bases and load-bearing walls	(a) Aggregates taken from supplier's stock piles. (b) Aggregates thawed with air heaters. (c) Additive used in mixing water. (d) Electric lamps used also as air heaters. (e) Work covered with hessian. (f) All shuttering in timber.	All cube tests up to specification. Work examined with test hammers and found satisfactory.
2	Precast concrete beams	None – beams were matured before sub-zero temperatures commenced.	Beams split due to freezing of water in cable ducts.
	Concrete slab	None – beams were matured before sub-zero temperatures commenced.	Surface of slab spalled after being subjected to sub-zero temperatures.
3	Precast concrete structure	(a) Joints between precast units enclosed in steel boxes which were then supplied with hot air; this was done before and after placing of joint concrete.	Joint concrete cube strength up to specification and achieved in a few days.
		(b) Rapid hardening cement used. (c) Accelerator added to mix. (d) Mixing water heated.	Damage at tops of precast columns due to freezing of water in dowel in holes.
		(e) Aggregates thawed with hot air. (f) In-situ work completely covered with hessian and tarpaulins and heated with braziers and hot air blowers.	No brittle fracture of mild or high tensile reinforcement during bending. Frost penetration in soil about 2 ft.
4	Twentieth floor of tower block-flat slab construction	(a) Mix richer than specification required. (b) Additive used in mix. (c) Work covered with polythene and plywood.	Temperature at floor level (about 200 ft above ground level) 3 to 4° lower than at ground level. Cube strengths above specifications minimum.
5	Parapet roof beam	None.	Severe frost damage; beam had to be reconstructed.
6	20-story flats in dense and no-fines concrete	(a) Aggregates steam-heated. (b) Calcium chloride added to mix. (c) Mixing water heated. (d) Braziers used in building during curing period.	Output appears to have been related roughly to mean daily (24 hourly) temperature.
7	Retaining walls	None, except covering of top of pour with hessian.	No concrete deposited after 2:30 pm. Ready-mixed concrete used throughout. All formwork of timber construction.

1965. The third edition of the technical brochure, "Concreting in cold conditions," published by the Cement Marketing Company Ltd, gives details of the various precautions that may be adopted to enable construction work to be continued when temperatures fall appreciably below normal. The topics discussed include the measurement of temperatures, the types of cement available, heating mixing water and aggregates, formwork, trial mixes, and concrete curing and protection.

Two surveys by the Joint Advisory Panel for the Building and Civil Engineering Industries in Scotland indicate "that whilst many builders in Scotland make efforts in one way or another to continue work in bad weather there is scope for more to be done, even by way of taking such simple precautions as covering stockpiles and completed work that is vulnerable to rain and frost."[49]

The panel found that sites within about four miles from a ready-mix concrete plant used this type of concrete rather than take the necessary precautions in site-mixing it.

1966. In a paper entitled "A research on the electrical heating methods for winter concreting," which appeared in the RILEM bulletin for December 1966, Nikkanen described research which is being carried out at the State Institute of Technical Research in Finland.

> "The principal research described is concerned with the method whereby the concrete is heated by passing electrical current through plastic-covered wires inserted in the concrete moulds. A characteristic of the method is that the temperature of the concrete in the immediate vicinity of the wire is considerably higher than elsewhere. Consequently, then the concrete in these areas is generally weaker than elsewhere."[51]

A contractor operating in the Yukon made these comments concerning cold weather concreting. "Most of our pours were carried out in temperatures around 40 to 45° below zero without any problems. It wasn't so much that we couldn't pour at those extremely low temperatures because of the material. . .it was mainly because of the crews."[16]

Welded-wire reinforcement and slab forms permanently marked with sleeve and insert locations helped a contractor maintain a two-floors-per-week pace on the construction of twin dormitory towers at Ohio State University. "Tarpaulins enclose the space under the slabs as they are cast, and space heaters maintain the required temperatures. On extremely cold days, live steam is used to heat wall forms before concreting starts."[52]

Cold weather curing of a bridge deck in Ontario is done with:

> ". . .a layer of polyethylene covered with 2 in. fiberglass and polyethylene blankets held in place by a layer of tied-down tarpaulins. The underside of the deck is completely enclosed to ground level with polyethylene sheeting and the air space between ground and deck is maintained at a temperature in excess of 55°."[37]

1967. A Canadian contractor found that pumped concrete made the difference between slow and fast pours.

> "Poole Construction Ltd felt that protecting fresh concrete, placed by conventional crane and bucket methods in twenty below temperatures, could be a problem, because the crane and bucket method would require openings in the roof of the enclosure which would permit heat to escape. Instead of employing a crane, they decided to pump as much concrete as was economically possible and so keep the structure enclosed at all times."[38]*

Since canvas tarpaulins cut out all light, Poole Construction Ltd decided to close the building in with standardized wooden frames covered by polyethylene. These enclosed the structure completely, allowing a non-weather-dependent pumped pour.

The English Electric Company, in conjunction with Concrete Formwork Ltd, is developing what is claimed to be one of the first systems of heated formwork for concrete.

> "The intention is to combine the heated panels with standard formwork frames to produce a system which is to be known as "Heatform." In addition to enabling contractors safely to carry out concreting at low temperatures, it is hoped to establish the use of the system for the effective rapid curing of concrete all year round."[51]*

The heated panels are ½ in. in thickness, and 8 ft by 2 ft in size. The panels are constructed to enable them to withstand building site conditions and they may be re-used indefinitely. Each panel comprises two layers of plywood with a heater element embedded between the layers. The electrical consumption is normally about 25 w/sq ft, and the heat produced prevents the temperature of the placed concrete from falling below 40°F, and yet does not raise it above 120°F.

In the construction of blocks of multistory flats in England, newly placed concrete was protected by the use of heavy-duty heaters obtaining fuel from a bulk-storage tank of propane. In the past, coke braziers had been used by the contractors, but it was felt that there were a number of disadvantages in the use of this form of heating.

> "With the newly-developed technique, the propane is conducted in pipes from the tank to the base of each building and then, by means of sectional vertical piping, to the heaters. Each section of pipe is fitted with a union so that another length of floor-to-floor height can be added as construction proceeds."[51]

1968. The Corps of Engineers specified strict controls on winter concreting at Dworshak Dam, the Corps' highest dam and the third highest dam in the United States. "The dam's surface and all vertical faces of freshly placed concrete must be covered with insulating blankets, covered with coatings of expanded urethane."[18] The placing temperature is one of the lowest ever set by the Corps – 45°F.

In speaking before the House of Representatives Select Subcommittee on Labor, A.T. Bone reviewed the concreting of Barnhardt Dam on the St. Lawrence River.

> "On the Canadian side the placing of concrete in high lifts made possible uninterrupted construction in spite of temperatures as low as 40° below zero. On the U.S. side concrete was placed in shorter lifts and the job was closed down during the winter. I should add that the American crews caught up during the summertime, but the point that is relevant here is that the requirements for manpower and materials were more stable year-round on the Canadian half due to the wintertime building."[4]

In November of 1968 the Associated General Contractors held its first conference on construction seasonality, which produced many questions but few answers for the 150 contractors who attended. It was noted that project specifications are sometimes such as to inhibit certain operations such as concreting. The feeling was that such requirements are justified as an assurance of quality work, but where protection is possible, and artificial provision of the required conditions can be made, winter concreting should be allowed.

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1969. Unlike conventional cements, a new type of cement developed by the Portland Cement Association at its Skokie, Illinois, laboratories, can be formulated to set as fast as desired. Called "Jetset," the new cement produces either "regular or lightweight concrete that can be walked on in 15 to 20 minutes instead of the several hours required by conventional concrete."[17] This cement reaches preliminary strength rapidly, but the hardening process then slows until it meets the normal curve of strength gain for regular cement.

Atlas Minerals and Chemicals Division is marketing a fast-setting concrete called "Mari-Crete." They claim that "It sets in six minutes after merely adding fresh or salt water, achieving high strengths rapidly. It can be applied both above and below water."[25]

A concrete-plastic combination with strength, durability and water-resistance characteristics said to exceed greatly those of ordinary concrete has been developed jointly by the Atomic Energy Commission and the Department of the Interior's Bureau of Reclamation. Known as "Concrete Polymer," this material is produced in much the same way as the radiation-processed wood-plastics that have been on the commercial market for several years.

> "The voids of the ordinary concrete are filled with the hardened polymer, giving it tensile and compressive strength four times greater than that of ordinary concrete. Its abrasion and cavitation resistance is four or five times greater than that of regular concrete. Because the voids are filled, the water permeability of concrete polymer is reduced to a negligible level, according to AEC. Also, the weight of a completely penetrated piece of concrete increases by less than 7%."[32]*

A concrete building material that substitutes small glass fiber rods for conventional steel reinforcing bars could substantially cut the costs of all types of concrete construction. The material, called "Fycrete," strengthens concrete much the way glass fibers reinforce plastics. Its developer is Sami A. Klink, Professor of Civil Engineering, in Beirut, Lebanon. According to Klink, the glass reinforcing is 55% cheaper than steel. He also points out that "when highways and roadways freeze, they expand [sic], and conventional concrete pavements crack. Fycrete will resist such cracking."[19]

In Richmond, California, chemical prestressing allowed construction of a six-story apartment building with walls only 2 in. thick. "Precast concrete modules making up the structure resulted from the use of concrete that expands as it cures, prestressing the reinforcing steel."[21]

A Russian project is producing interesting innovations in construction techniques. Through the bitter Russian winter, work goes on round the clock on an automobile factory, some 500 miles southeast of Moscow.

> "Though temperatures go as low as 20 degrees (F) below zero, the Russians have solved the problem of pouring cement by mounting aircraft jet engines on trucks, with their superheated jet streams trained on the cement and the ground prepared to receive it."[31]

Dutch engineers have developed a brick laying machine that they claim can pave roadways as fast as bricks are fed into it.

> "The machine grades the sand bed, places and compacts the brick courses, and then rolls the roadway to final compaction, all automatically. All the operator has to do is adjust the grading height, feed bricks and watch the machine go."[29]

While constructing a 471-ft tower in Toronto, involving 30,000 cu yd of concrete, the contractor "poured concrete at air temperatures ranging from −15°F to +48°F by heating the concrete to 70°F, placing it in insulated forms, and curing at 70°F for 3 days and then 50°F for 5 days."[15] He utilized tarpaulin enclosures with oil-fired heaters and insulated mats and formwork. A maximum of 1% $CaCl_2$ was allowed to yield higher early strength.

A Minnesota engineer stated that concrete is placed year-round at temperatures below 0°F. He noted that "The repeated use of forms (gang-forming) was quite popular in Minneapolis, as were pre-cast and pre-stressed structures."[20] However, he cautioned against the use of too much insulation, which would affect the strength development of the concrete. According to him the temperature of the concrete when delivered should be 60-65°F. At the site, concrete should be placed at 60-75°F except for footings and foundation walls, which should be placed at 50°F and heavy sections, which should be placed at greater than 32°F.

Summary

As temperatures fall, progressive precautions are essential for satisfactory concreting work. If the temperature falls below 40°F, water, provided for the hydration of the cement, begins to expand, causing possible permanent damage to the weak, newly formed structure of cement particles. Further, if the temperature plunges to freezing and below, the chemical reaction producing the new compounds is reduced, as the frozen water is no longer able to react. Consequently, all countries require commencement of special measures at ambient temperatures of 40°F.

The military guides, in essence, state the following: "Mixing water and/or aggregates shall be heated as necessary to result in an in-place-concrete temperature of between 50 and 70°F. Covering and other means shall be provided for maintaining the concrete at a temperature of at least 50°F for not less than 3 days after placing." Arctic concreting is not considered practicable below 0°F.

Concreting specifications of the various countries vary in most respects except for the temperature at which special precautions must be introduced (40°F) and the amount of $CaCl_2$ (2%) which may be used as an additive. The minimum practicable limit for concreting, as viewed by each country, varies from 23°F in Denmark to -4°F in Sweden. Curing of normal portland cement ranges from 70°F for 3 days in Canada to only 41°F for 2 days in Sweden.

A contractor can approach the problems of winter concreting in three different ways. In temperatures above freezing, a more rapid development of strength and heat of hydration may be obtained by increasing the cement content or using a cement of higher activity. During moderate and short periods of frost, the heat of hydration in conjunction with the initial concrete temperature and insulation is able to maintain the concrete at a sufficient level to resist freezing. Under severe conditions, the contractor must provide artificial heating.

Regardless of method, or combination of methods used, a general sequence of "steps" can be followed by the contractor in achieving satisfactory results – planning; selection and preparation of site, equipment, concrete constituents (cement, aggregate, water, and admixtures), and forms. maintenance of proper mix propertions; heating of the materials (water, aggregate, and mix). placing; curing by either moisture or heat retention; and finally, removing the forms. Each step is thoroughly examined and discussed with regard to hazards and accepted practices.

Winter concreting variables are then classified according to the extent to which it is possible to change them. Then, the possibilities of influencing these variables by the different winter concreting methods is tabulated.

Alternative construction methods and processes are discussed to identify winterization procedures in each.

The problems of temperature and moisture control that confront the contractor when mixing concrete on the site can be most simply bypassed by transferring the operation to a supplier of ready-mixed concrete. However, whether plant- or truck-mixed, the concrete must be supplied at a temperature of not less than 40°F.

Precast concrete offers advantages over conventional reinforced concrete because of the increased speed of construction possible and its relative freedom from the influence of frost. Most multistory buildings in Canada are constructed from prefabricated concrete components or steel framing. Moscow has doubled its precast factory capacity in less than four years to speed erection of structures in the extreme north.

A type of precasting used in building construction involves the casting of the floor and roof slabs at or near ground level and lifting them to their final position, hence the name lift-slab construction. It offers many of the advantages of precasting and eliminates many of the storing, handling, and protecting disadvantages.

Russia has developed a system of heating the surfaces of concrete by electricity. They consider it economical as well as practical. The main advantage is that the concrete does not require a heated structure around it during the curing period.

Generally, forms are stationary. But, for some applications, such as highway pavements, precast concrete slabs, silos, and service cores of buildings, use of continuous moving forms (sliding forms or slip forms) is advantageous. Slip-form operations can be, and often are, conducted at temperatures below 40°F. Enclosures of tarpaulin or plastic blanket the finishers' scaffold. Normally, artificial heat is provided as well.

"Permacrete" is a new building material, made of varying mixtures of fine-crushed rock, sand, clay, rock flour slurry, water and snow. It is successfully used as a substitute for concrete in some fields of permafrost construction.

"Cold concrete" requires no protection even at temperatures below zero. It contains a brine solution instead of water, the strength of the solution depending on the minimum temperature expected during the placing and curing period. Most of the research concerning "cold concrete" has been reported in Russian literature. However, one study in this country concluded that "cold concrete" should be more thoroughly investigated as it could become a competitive winter concreting method.

Bituminous concreting is normally restricted to ambient temperatures of 45 to 50°F and ground temperatures above freezing. However, hot plant-mix base has been placed on frozen subgrades in air temperatures of 23°F with satisfactory results.

The chapter concludes with a chronological review of recent developments in the field of concreting. Subjects covered include: fast-setting concretes; concrete reinforced with glass fiber rods instead of steel; the use of jet engines to warm concrete at -20°F; bricklaying machines; and electrically heated formwork.

Analysis

Concreting is among the most sensitive construction operations. Low temperature is the major factor of concern as pouring onto frozen ground or at temperatures below freezing cannot take place without protection and the application of heat.

Therefore, of the resource inputs (men, material, and equipment), material (water of hydration in concrete mix) seems to be the initial critical factor. This occurs at 40°F, a temperature which seldom phases men or machines.

With protection and the application of heat, concreting is considered practicable down to approximately 10°F. At this temperature, the efficiency and comfort of the workmen might be restrictive: further, economics may forbid additional winterizing measures. Equipment should be relatively unaffected.

Protective measures enable concreting to be done to temperatures of -45°F. However, at this temperature level, all three resource inputs require considerable winterization.

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MASONRY

Opinions concerning the precautions required for masonry are even more varied than those concerning winter concreting. Apart from requirements that bricks should be dry and sand free of frozen lumps, all the countries examined have different regulations for winter work.

Generally, masonry regulations have been based on the assumption that mortar is affected by low temperatures in much the same way as concrete. However, there is ample evidence that this is not necessarily the case. When mortar comes into contact with bricks, water is absorbed from the mortar rather quickly. "Experience of masonry construction without protection in Canada, Norway and Sweden has shown that *frost need not impair* the *strength* of *mortar* but will result in a certain loss of bond between mortar and bricks; . . . A *more serious problem* is the *increased expansion* and *contraction* of *brickwork* laid in cold weather."[15] The bricks are not damaged by frost unless saturated with water; consequently, it is considered more important to protect fresh brickwork against water penetration than against frost.

The *Architects' Journal* summarizes the problems of bricklaying as follows:

> "1. On freezing, expansion of water in wet bricks or in the mortar mix will disrupt the bond and crack the mortar, with a resulting loss of strength in the brickwork.
>
> 2. Rain saturated bricks are more likely to give rise to efflorescence and their slowness in drying will hold up following trades such as plastering.
>
> 3. Cold weather retards the rate of hardening of mortar cement and therefore the rate of strengthening."[9]*

Following is a discussion of current military and civilian requirements, current construction practices, and research and observations relating to cold weather masonry construction.

Military Requirements

Department of the Army Guide Specification CE-206.01, dated December 1968, reads as follows:

> "9.3. *Cold-weather installation:* No frozen work shall be built upon. Before erecting masonry during temperatures below 40°F, a written statement shall be submitted and approval received of the methods proposed to heat the masonry materials and protect the masonry from freezing as required below. Masonry units shall be kept completely covered and free from frost, ice, and snow at all times and shall have a minimum temperature of 30°F when laid. Temperature of mortar and, if used, grout shall be between 70°F and 110°F. Temperature of mixing water or of water and sand introduced to cement shall not exceed 160°F. The air temperature on both sides of the masonry shall be maintained above 40°F for at least 72 hours but may be reduced to 48 hours if high-early-strength cement is used instead of portland cement or masonry cement in the mortar. No masonry shall be laid at temperatures below -10°F unless authorized in writing."[10]

The specification contains a later paragraph in which it dictates the requirement for protection of exposed masonry and structural woodwork (over which brickwork is to be placed) when rain or snow is imminent. The protection recommended is a strong nonstaining waterproof membrane material. It also directs that adequate provision be made during construction to prevent damage by wind.

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Civilian Requirements

United States

In the United States, all major building codes have requirements relating to the construction of masonry during cold weather. A review of these requirements indicates considerable variation. However, all the recommendations and requirements are equivalent to or exceed the following requirements: "Masonry shall not be built when temperature of materials or surrounding air is below freezing and shall be protected from freezing for a minimum period of twenty-four hours."[4]

Canada

According to the Organization for Economic Co-operation and Development (OECD), the following regulation for bricklaying in cold weather applies to Canadian builders:

> "When the temperature falls below +4°C (39°F) the water should be heated to provide a mortar with the temperature between 15 (59°F) and 27°C (81°F). The water must not be heated to a temperature higher than 65°C (149°F). In very cold weather the sand also may require to be heated. All that is required is that the temperature of the sand shall be above freezing. In mild weather a suitable mix is one part Portland cement, two parts lime putty and eight or nine parts of sand (1:2:8 or 9) all by volume. In cold weather more cement is used (1:1:5 or 6). Mixes stronger than this are only recommended in engineering construction.
>
> "Bricks must be heated to a range of 4 (39°F) to 10°C (50°F) when the temperature falls below 0°C (32°F). The tops of unfinished walls must be covered at the end of the day's work. Bricks with initial rates of absorption above 20 grams per minute should be sprinkled with warm water just before laying. Walls should be kept at a temperature above freezing for at least 48 hours. Tarpaulins are usually sufficient for temperatures down to -4°C (25°F). At lower temperatures artificial heating inside temporary enclosures is required."[15]

Denmark

OECD relates that for bricklaying in cold weather (to -5°C) either warm mortar or mortar containing some admixture to lower the freezing point should be used. If alcohol is used, the proportion should be at least 1 liter to 100 liters of mortar. If mortar is used in thin layers or exposed to strong winds, 2 to 3 liters of alcohol to 100 liters of mortar should be used. The use of mortar that contains loamy sand is forbidden, and it is suggested that new brickwork be covered so that it is protected against rain and snow.

Germany

For winter work the use of mortar containing cement or hydraulic lime is recommended. "The temperature of the mortar should be at least +10°C (50°F) but less than 30°C (86°F)."[15] Antifreeze compounds are commonly used and have proven effective if correctly proportioned.

At temperatures to -6°C (21°F) bricks need not be heated. At temperatures below -6°C, bricks should be heated to a maximum of +15°C (59°F) when the air temperature falls to -15°C (5°F).

Newly completed brickwork must be protected against frost until the mortar has been sufficiently hardened.

Norway

According to OECD, bricklaying is generally not permitted at temperatures below 0°C (32°F) unless by permission of the owner. If the required precautions are taken, work may continue to -8°C (18°F) if lime mortar is used. At temperatures below freezing, the temperature of the mortar must be at least +15°C (59°F). Facing bricks shall always be laid at temperatures above +5°C (41°F).

Unfinished brickwork must always be protected against rain and snow. Fresh brickwork should also be protected against too rapid cooling from wind. OECD surmises that by providing protection, "there is practically no temperature limit to which work may proceed."[15]

Sweden

This country used winter work bricks with a sufficient rate of absorption. Mortar containing cement should be used and be heated to +20°C (68°F) [maximum 35°C (95°F) at leaving mixer]. Fresh brickwork should be protected against water penetration by covering the tops of unfinished walls with tarpaulins, building paper or other suitable material. "Bricklaying may in this way be continued to about -20°C (-4°F)."[15]

United Kingdom

In cold weather, the usual practice is to increase the cement content of the mortar. The Building Research Station recommends 1:1:6 cement/lime/sand or 1:6 cement/sand with plasticizer. Mortar plasticizers of the air-entraining type offer some help in improving the resistance of the freshly laid mortar to frost, but the use of antifreeze compounds is not advised.

When night temperatures fall to no lower than -4°C (25°F), only very simple precautions (such as using stronger mortar, and covering the completed work at night) need be used.

> "In extreme conditions, when the temperature falls to the region of -10°C (14°F), mortar should be heated, the most simple method being to heat the water to 49 (120°F) to 66°C (151°F). In extreme conditions, sand and perhaps bricks also should be heated, in which case the water content will need to be increased. The builder should aim to provide a mortar with a temperature of 16 (61°F) to 27°C (81°F)."[15]

On completion, new brickwork should be covered and protected for 3 to 7 days, according to the extent of frost. The temperature of the brickwork must not be allowed to fall below freezing point, and the provision of heat under the covers may be necessary.

USSR

"The USSR Building Standard, NITU 120-55, Chapter XII (*Design of masonry constructions built in wintertime*), has requirements which permit construction in outdoor temperatures below freezing and in some cases well below 0°F."[4] The USSR methods of construction in freezing weather will be examined shortly.

Summary

Table XXXI is a compilation of the specifications by country or authority with regard to the minimum practicable limit for cold weather masonry. However, the literature cites examples of where masonry has been laid at lower temperatures than those shown. The existing requirements for winter masonry work in the United States are considered by many to be too conservative.

Table XXXI. Masonry limits.

Country or authority	*Minimum practicable limit for masonry (air temp °F)*
U.S. Army	-10
United States	20
Canada	0
Denmark	23
Germany	5
Norway	32
Sweden	-4
United Kingdom	14
USSR	0

The Travelers Research Center considers the construction of masonry structures to be even more sensitive to low temperatures than the construction of concrete structures. They state that masonry is generally not attempted in areas of extremely low temperature because it does not stand up to conditions of instability which characterize permafrost; "32°F is considered the critical limit for outdoor masonry work. At lower temperatures the cost of production rises and at temperatures below 10°F the quality of the work declines."[13]

Construction Methods

Current code requirements, military and civilian, domestic and foreign, have been covered. The following recommendations are based upon research by the Structural Clay Products Institute (SCPI). Admittedly, the recommendations are conservative and undoubtedly will be revised as a greater understanding of cold weather masonry construction is gained.

In general, items to be considered for the protection of masonry construction in subfreezing weather are: storage of materials, preparation of mortar, preparation of masonry units, protection of masonry, and special precautions.

As each item is discussed, pertinent practices of other countries will be brought forth and examined for comparison and conflict, if any.

Storage of materials

The first step in preparing for winter masonry construction is to provide a storage space where masonry units and mortar materials can be kept on a platform raised to prevent wetting from ground moisture. They should be completely covered with tarpaulins, felt paper, polyethylene sheet or the like. Masonry units and mortar materials should never be allowed to become coated with ice or snow. The storage space need not be located in an area where the temperature is above freezing, although this is desirable.

Preparation of mortar

Ingredients. The chemical reaction of hydration slows down as temperatures drop and, when the temperature of the mortar mix is below 40°F, the hydration process virtually comes to a standstill. Consequently, to obtain hydration, hardening and full strength development of the mortar, the mix must have a temperature above 40°F.

Mortar, for use in masonry construction when the mean daily temperature is below 40°F, should be portland-cement-lime-sand mortar, conforming to ASTM Specifications for Mortar for Unit Masonry, C 270, types M, S or N.

The required protection period for recently constructed masonry may be reduced by using high-early-strength cement. "It is significant to note that the use of high-early-strength cement in mortars does not appreciably alter their rate of set but does increase their rate of gaining strength."[4]

To counteract the slower rate of hardening, the mix should be richer in cement than for other times of the year. "The British recommendation is for 1:1:6 cement/lime/sand or 1:6 cement/sand with an air-entrained plasticiser."[9]

Accelerators and antifreezes. "The use of admixtures or antifreezes to lower the freezing point of mortars should not be permitted."[3] The amounts of such materials required to significantly lower the freezing point of mortar would be so great as to have harmful effects. Excessive salts, added as antifreezes, can contribute to efflorescence and may cause spalling through recrystallization. The effectiveness of most commercial antifreeze compounds is caused by their actions as accelerators, which in most cases result from their calcium chloride content.

"In the past calcium chloride has been used extensively as a means of accelerating rate of set of mortar during the protected periods. However, recent investigations have indicated that the corrosion of metals embedded in mortar is intensified by addition of calcium chloride."[3]

When calcium chloride is used it should not be added in amounts greater than 2% of the portland cement, by weight. When used, it should be added to the mixing water. Care must be exercised to avoid combinations of high temperatures and high calcium chloride percentages which will result in excessively rapid setting of mortar (*flash set*).

The British likewise do not advise the use of antifreezes and offer one important note: "Mortars containing air-entraining plasticizers do not need calcium chloride as well."[1] They deduce that the addition of this salt cannot be relied upon to prevent frost damage and, further, that it introduces a risk of permanent dampness with eventual defects in plaster and decoration.

The use of calcium chloride does not take the place of other protective methods. Its value lies in the rapid set and strength gain which it imparts to the mortar.

Heating. When temperatures are likely to remain at or below freezing, preheating of the mixing water and possibly the sand will be needed.

Sand for use in mortar usually contains some moisture, which will turn to ice if the sand is stored in freezing temperatures. Therefore, before it can be used sand must be thawed by heating slowly and evenly (to prevent scorching) to remove the ice. "Scorched sand (with a reddish cast) must not be used in mortar."[3] Proper heating may be accomplished by piling the sand around a horizontal metal culvert or smoke stack section in which a slow fire is built. Oil drums may also be used. An alternate method is to pile sand over steam pipes.

An easy method of increasing the temperature of the mortar is to heat the mixing water. Water is the easiest constituent to heat; in addition, pound for pound it is a better carrier of heat than any of the materials that go into a mortar mix.

The mixing water should not be above 160°F, because of the danger of a flash set when portland cement is introduced.

"After combining all ingredients, the temperature of the mortar should be between 70°F and 120°F. If mortar temperatures are over 120°F, excessively fast hardening may occur, resulting in lowered compressive strength and reduced bond strength."[3]

In Britain, the techniques are similar to those discussed, but with slightly different temperature ranges. The mixing water may be heated no higher than 150°F. "The mortar used should be at a temperature of 60-80°F (16-27°C) and should still be above freezing point when the work is completed and covered."[1]

Mixing. Batch concrete mixers are recommended on all large jobs by the Structural Clay Products Institute. Some modern mixers are equipped with a skip hoist, water tank and water-measuring device, which control the mix and produce well-mixed mortar of the proper workability.

Steel mortar boxes may be used for hand mixing on smaller jobs. These should be raised above the ground on piers of masonry units laid dry. Fires of waste building wood or steam may be used to keep the mortar warm after mixing. Mortar should be delivered to masons at such rates that excessive cooling will not occur.

Preparation of masonry units

"To prevent sudden cooling of warm mortar in contact with cold units, it is recommended that all masonry units be heated when the temperature is below 20°F. Masonry units should be heated to about 40°F."[3]

It is further advised by SCPI that during cold weather construction, brick having excessively high rates of absorption should be sprinkled with warm or hot water just before laying; those with low rates of absorption should be laid dry.

The Canadians require bricks to be heated when the temperature falls below 32°F. This ensures that the temperature of the masonry is above freezing. Additionally, it permits the establishment of a good bond between the mortar and the brick. "The brick must not be over-heated, a temperature of 40 to 50°F being quite adequate."[8]

As previously cited (p. 130) the Canadians sprinkle bricks containing initial rates of absorption above 20 g/min. They contend that the suction of the brick can be controlled only when it is at a temperature above freezing.

Protection of masonry

Obviously, protection requirements will vary with weather conditions. "With warm mortar and mean daily temperatures above 25°F, tarpaulins covering the masonry may be sufficient. When mean daily temperatures are between 20°F and 25°F covers of insulating blankets may suffice for the completed wall."[3]

SCPI recommends the use of windbreaks at temperatures below 25°F and wind velocities above 15 mph. These not only protect the masons but also assist in preventing rapid loss of surface heat from the masonry being worked upon.

Britain requires that new brickwork, upon completion, be covered and protected for 3 to 7 days, according to the extent of frost. The temperature of the brickwork must not be allowed to fall below the freezing point during this time.

Canada desires that completed masonry walls be kept at a temperature above freezing for at least 48 hours. "Tarpaulins are usually sufficient for this purpose for temperatures down to 25°F. At lower temperatures artificial heat inside temporary enclosures is required."[8]

In the United States, consideration of the required protection of the masonry is based upon the mean daily outside temperature. The suggested SCPI protection requirements based on mean daily temperature follow:[3]

MDT is 40°F to 32°F: Protect masonry from rain or snow for 24 hours. *MDT is 32°F to 25°F*: Completely cover masonry for 24 hours. *MDT is 25°F to 20°F*: Completely cover masonry with insulating blankets for 24 hours. *MDT is 20°F and below*: Maintain masonry temperature above 32°F for 24 hours by enclosure and supplementary heat, by electric heating blankets, infrared heat lamps or other approved methods.

Various types of heating equipment are available. The type selected depends upon availability of equipment, fuel source and economics, size of project, and severity of expected weather.

Special precautions

Block and brick must never be laid on a snow- or ice-covered base. There are two reasons for this: There is danger of movement when the base thaws; and bond cannot be developed between the mortar bed and frozen supporting surfaces.

According to SCPI, walls properly covered when work is halted should require no ice or snow removal. However, if the covering is displaced, the bed may be thawed with live steam or a portable blowtorch. The heat should be sustained long enough to thoroughly dry out the masonry.

Although bricks with high absorption rates are to be sprinkled with warm water prior to laying, care must be exercised in not saturating the brick as it may disintegrate on freezing.

Summary

Construction projects vary greatly in size, height, design, location in relation to adjoining structures, and many other respects. Consequently, the most economical method of protecting and heating a particular project can be determined only after a detailed study of the job. For this reason, SCPI recommends that the contractor be given wide latitude in determining the protective methods to be used.

Alternate methods of construction

As previously mentioned, the USSR Building Standard (NITU 120-55) lists six different methods of construction in freezing weather, which are covered in the general conditions as follows:

> "General Constructions
>
> "240. Masonry constructions may be carried on in the wintertime by various methods in accordance with the type of masonry and the character of its performance in the construction, as follows:
>
> a. by method of freezing which permits early freezing of the mortar in the masonry and subsequent thawing under natural conditions which are taken into account in calculations of strengths and stability of the masonry;
>
> b. by method of freezing with a subsequent artificial complete or partial thawing of masonry and its aging under positive temperature (above freezing) for a definite length of time which assures initial hardening of the mortar up to development of a minimum required strength;
>
> c. by method of freezing using mortars with chemical additives (antifreezes) which assure improved monolithic nature and stability of masonry after thawing, of improved bond of the facing with the backup masonry and also partial hardening of the mortar during the exposure to frost and thawing of the masonry which leads to reduced shrinkage during thawing;

d. by application of electrical heating or steam heating to freshly laid unfrozen masonry during the time required to assure initial hardening of the mortar in the masonry up to the point of development of minimum required strength.

e. by application of rapidly hardening mortars having a blended cement which develops considerable strength prior to the time of thawing of masonry;

f. by using enclosures which insure hardening of the masonry in unfrozen condition in which the mortar develops the minimum required strength."[4]

Clarification of the Russian methods is provided by Crocker[6] in a technical paper of the Canadian Research Council. According to him, brick masonry is generally prepared in heated enclosures or protected by electrical heating. However, the Russians do practice the technique of "freezing" when laying masonry (as the first three outlined methods relate).

The masonry is allowed to freeze as quickly as possible, and the blocks develop sufficient strength by freezing to permit transporting them to the construction site and lifting them into position.

"Blocks prepared at freezing temperatures become fit for transportation within a few hours if the temperature is very low or within 10 to 15 hours at temperatures just below the freezing point.

"The blocks are placed on a thin layer of warm mortar which may have 'anti-freeze' agents incorporated in the mix. These chemical admixtures are always used when it is known that the temperature will fluctuate around the freezing point or when a sudden thaw can be expected."[6]*

Walls, erected with frozen masonry blocks, lose considerable strength when they thaw and some settlement occurs, often as much as 0.015 ft/ft in height, according to Crocker. As the mortar hardens at temperatures above freezing, the walls gradually acquire the necessary strength and stability.

Research and observations

The listed recommendations and requirements are equivalent to or exceed the following: "Masonry shall not be built when temperature of materials or surrounding air is below freezing and shall be protected from freezing for a minimum period of twenty-four hours."

"Nevertheless, many observers have publicly and privately reported the construction of masonry at temperatures below freezing with little or no auxiliary source of heat and with no apparent adverse effect upon the masonry."[4]

Winter visitors to Scandinavia and Russia report seeing masonry construction continuing at temperatures well below freezing without protection or the use of supplementary sources of heat.

In the 1967 March issue of *National Geographic*, Conger discussed construction in Siberia:

"Vladimir Dynin, construction director of the Yakutsk Autonomous Soviet Socialist Republic, took us in his jeep to an apartment house being erected, where bundled-up men and women were laying bricks in spite of the 50-below-zero temperature. The mortar is heated, he told us, but if the weather gets much colder, the crane that lifts the mortar won't operate properly. That stops us."[4]

"In the north of Sweden, bricklaying continues down to 5°F without enclosure."[5] Another source relates that "Even during weather as cold as -10°C (14°F), with strong winds, bricklaying proceeds as usual."[11]

The reasons are that the bricklayers use warm lime-cement mortar and are very careful to keep the bricks completely dry, putting mortar underneath just one brick at a time. Additionally, they are well equipped against the cold and the wind. "Investigations in Sweden have shown that this method of bricklaying is ideal so long as you do not use the tensile strength in the bricks and you do not use reinforced brickwork."[11] The explanation for this is that the single brick has a good capacity to absorb water from the mortar – sufficient to prevent frost damage. There have been few failures of brickwork in Sweden, during the ten years in which this method has been practiced.

The Canadians do not practice this method of bricklaying, first because of the very restricted specifications, but also because they very often use bricks with very little capacity for sucking up water.

In Technical Paper no. 87 of the Division of Building Research, National Research Council of Canada, Crocker states:

> "Most building codes in Canada require that all masonry materials be at a temperature not less than 40° when laid up, and that the temperature of the masonry be maintained at no less than 40° for at least 48 hours. In practice, however, it is quite common to see brick masonry being laid up in warm mortar, but without protection at temperatures below zero. In some areas, bricklaying proceeds until the weather becomes so cold that the mortar freezes before the brick can be placed in it.
>
> "Some builders working under rigid inspection asked the Division to look into this matter, since, in their experience, masonry laid up without protection in winter appeared in many cases to be superior to that laid up in summer."[7]

The absence of humidity and driving rain is one of Sweden's great advantages over Britain, despite low temperatures and a long winter. In the United Kingdom there have always been problems in bricklaying because of the wet climate.

Why doesn't Britain use the Swedish-type bricks having a high degree of absorption? "A higher degree of absorption makes for a poor bond between brick and mortar, but because of the absence of driving rain in Sweden this is regarded as unimportant."[14]

SCPI has documented a field study of winter masonry construction techniques in Boston.[2] Two projects were studied. The contractor, on the four-story steel-frame building with stone and brick facework, attacked winter construction by: 1. planning and preparing before winter came; 2. protecting the materials; 3. covering the job; and 4. heating when necessary.

Planning involved grading, excavating and roughing out an access road.

Masonry units and mortar materials were kept dry by storing them on pallets and by covering them with tarpaulins. Sand was delivered daily and was protected by a plywood and building-paper roof. It was heated before use by piling it on a metal culvert through which hot air was blown; water was not heated, but an accelerator was used to hasten mortar setting.

When the steel frame was finished, the contractor's men wired prefabricated polyethylene panels to the frame. The metal floor deck served as a roof. Heaters were installed, and when the area was warm enough, the concrete floors were poured. Outside scaffolding was set up to permit laying the outer withe. When the interior withe was finished, the panels were unwired from the frame and refastened to the scaffolding. To conserve panels, only the scaffolding where the masons were working was covered.

Oil heaters were used during workdays when the temperature was 40°F and falling. When the sun was out, it warmed the enclosure enough to permit the heaters to be turned off.

The masons had no complaints about the working environment and were happy to have winter work. "The winterization estimate was approximately 1% of the total job cost."[2]

The other project involved a six-story concrete-steel frame building. The scheme of winterization was similar to that of the other job with a few exceptions.

Masonry units and materials were similarly protected, but were delivered to the scaffolding a day ahead of time to defrost. Both sand and water were heated, but no accelerator was used for the mortar.

When the frame was finished, the entire structure was surrounded with scaffolding to its full height and was completely covered and roofed. Unreinforced polyethylene panels were wired to the scaffolding and 100 ft-long black canvas tarpaulins were nailed in vertical strips to alternate with the panels.

Blower-type propane space heaters were used only during masonry construction: at other times, solar heat sufficed.

The enclosure and paneling withstood up to 12 inches of new snow at a time and winds up to 80 miles an hour. "Total winterizing cost was about 1% of contract cost."[2]

From these observations, it becomes evident that research and construction requirements relating to cold-weather concreting do not necessarily apply to masonry construction. Generally, concrete is placed in forms so that there is little loss of water due to absorption by the forms or evaporation to the atmosphere. In masonry construction, thin layers of mortar are placed between thicker absorbent units which, with the exception of very low suction units, quickly absorb water from the mortar, stiffening it, lowering the degree of saturation, and reducing the water/cement ratio.

Although several organizations in the United States and other countries have conducted and are conducting research on the freezing effects on masonry properties, there are few published data at this time. The primary considerations (of the effect of freezing temperatures on masonry) are the influences on compressive strength, bond strength, durability and permeability. "In a recent effort by the Research Department of the Structural Clay Products Institute, a program was started to define the minimum protection conditions required to prevent cold weather damage to freshly laid brickwork."[4] Tentative conclusions drawn from the program include:

1. Neither the compressive strengths nor the bond strengths are significantly affected by the length of the protecting period imposed under the standard freezing conditions of 15°F held for a period of 3 days.

2. Ultimate bond stress is not affected statistically by the freezing action, indicating that the freezing action tends to delay full hydration but does not necessarily destroy it.

3. Statistically, there is less influence on bond strength than there is on compressive strength from the freezing conditions of the test program.

4. Concerning the use of admixtures, calcium chloride or alcohol, it appears that neither significantly reduces strength from a statistical viewpoint, although there is a trend towards the lowering of both compression and bonding strength with increasing percentages of the admixtures.

Whitlock of the SCPI testified before the previously mentioned House Subcommittee, studying seasonal unemployment, on 16 July 1968. In his testimony, he stated that the Mason Contractors Association of America, The Bricklayers International Union, The Laborers' International Union, The Concrete Masonry Association, The Portland Cement Association and The Structural Clay Products Institute, in joint cooperation, had formed the Masonry Industry All Weather Committee. "This committee is studying the 'State of the Art' and reviewing all of the available technology. . ."[4]

Within the past year, SCPI has sent engineers to Europe to investigate European methods of all-weather construction. Based on their findings, SCPI expects to release new recommendations for masonry construction in cold weather.

The existing requirements for winter masonry work may be quite reasonable but they do impose an added cost and are considered by many to be too conservative. The many cases illustrated where masonry was laid without protection in very cold weather and still appeared sound add to the need for these and more extensive laboratory investigations to determine the true factors that influence the quality of masonry erected in winter.

Summary

Opinions concerning the precautions required for masonry are even more varied than those concerning precautions required for winter concreting. The main difficulty stems from the fact that no one can agree on what is the main problem. Concrete's main problem is hydration. Masonry's main problem *may be hydration.*

The military requires winterization measures when the temperature falls below 40°F. Air temperature on both sides of the masonry is to be maintained above 40°F for at least 3 days (2 days with high-early-strength cement).

In the United States, all major building codes have requirements relating to the construction of masonry during cold weather. All the recommendations and requirements are equivalent to or exceed the following: "Masonry shall not be built when temperature of materials or surrounding air is below freezing and shall be protected from freezing for a minimum period of 24 hours."

In Canada and the European countries, winterization measures generally begin when the air temperature falls below 40°F. The measures include heating the water, adding accelerators, and enclosing the masonry construction with protective shelters. As in concreting, contractors must not allow excessive heating, thus preventing "flash set."

The minimum practicable limit for masonry, as viewed by each country, varies from 24°F in Denmark to -4°F in Sweden. The U.S. Army allows masonry construction to -10°F. One authority claims satisfactory construction at -50°F.

The Structural Clay Products Institute discusses winter masonry construction methods in relation to five items: storage of materials, preparation of mortar, preparation of masonry units, protection of masonry, and special precautions.

Storage requirements are not as stringent as with concreting: The main concern is keeping moisture out.

Preparation of the mortar is a four-step process: ingredients, accelerators and antifreezes, heating and mixing.

Masonry units are usually heated when the ambient temperature approaches 20°F and are normally heated to about 40°F. This precaution is to prevent sudden cooling of the warm mortar upon contact with the units.

Curing and protection requirements vary considerably. The literature cites many examples where no protection was provided and satisfactory results were accomplished. Most codes require curing at above freezing temperatures for at least 24 hours.

Special precautions treats the subject of block or brick laid on snow- or ice-covered bases, resulting in movement upon thawing and nondevelopment of bond between mortar bed and frozen base.

The Russians allow masonry to freeze as quickly as possible, providing no protection. Walls erected with frozen masonry blocks lose considerable strength when they thaw and some settlement occurs. As the mortar hardens at temperatures above freezing, the walls gradually acquire the necessary strength and stability.

From a field study of two Boston construction sites, SCPI relates that masonry winterization costs were approximately 1% of the total job cost. These winterization measures are discussed.

From these observations, it becomes apparent that research and construction requirements relating to cold weather concreting do not necessarily apply to masonry construction. Generally, concrete is placed in forms so that there is little loss of water due to absorption by the forms or evaporation to the atmosphere. In masonry construction, thin layers of mortar are placed between thicker absorbent units which, with the exception of very low suction units, quickly absorb water from the mortar, stiffening it, lowering the degree of saturation, and reducing the water/cement ratio.

The existing requirements for winter masonry work may be quite reasonable but they do impose an added cost and are considered by many to be too conservative.

Analysis

Opinions concerning the quality of masonry construction in cold weather and the sensitiveness of the construction to cold weather vary considerably. Hence, it is uncertain whether material (mortar hydration) or man is the initial limiting resource input. In either case, both are affected to a degree when the temperature approaches freezing. Below this point, protection and heat allow practicable masonry work to about 20°F in this country and 0°F in other countries.

Further winterization measures will allow masonry construction at temperatures lower than these, but quality of the work may begin to deteriorate.

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STRUCTURAL STEEL ERECTION

"Steel-frame buildings have advantage in that the structural steel may be erected in all but the most severe weather."[1] That statement was made about a decade ago but it still applies with equal validity today.

But, what about the brittleness of steel? True, normal carbon plate steel is quite brittle under shock at low temperatures. However, alloy grades of steel (such as quenched and tempered low-alloy steels) "assure good performance at temperatures as low as -50°F."[5]

Then, what about the joining process, i.e. welding? "Provided that proper precautions are taken, there does not seem to be any absolute lower limit to the temperature at which welding can be performed."[4]

It has been shown that winterized equipment operates relatively easily at subzero temperatures. Consequently, this brief analysis focuses on the only remaining stumbling block–man.

Worker safety and efficiency are the primary factors for consideration in the erection of steel work. The selection of temperature limits is somewhat arbitrary in that the low temperature boundary is related entirely to worker safety and efficiency.

Military Requirements

Department of the Army guide specification CE-214.01, dated 17 August 1959, with a change as late as September 1965, does not even mention cold weather.

Civilian Requirements

The 1964 study by the Travelers Research Center of Hartford, Connecticut, for the United States Weather Bureau found that within the United States "It is generally considered non-economically feasible to carry out steel erection below 10°F."[6] The study states that protection is usually difficult or effectively impossible to provide; hence, the decision on working rests with the erection crews.

OECD did not even mention the subject of structural steel erection as a cold weather problem within its exhaustive study of European, Canadian, and United States construction practices.

About the only codes on the subject are those controlling welding. However, "The idea of suspending welding operations when the ambient temperature falls to a certain level, as appears in one form or another in many national codes, is probably aimed at avoiding the various difficulties that arise when operators are distinctly uncomfortable."[4]

Construction Methods

No literature can be found that describes low-temperature erection of structural steel. However, much has been written on its welding aspect. Consequently, this discussion of construction methods is limited to welding problems and procedures.

Probably the leading authority on the matter of welding steel at low temperatures is the 1963 bulletin, "Welding of Steel at Low Ambient Temperatures," by Winterton et al, and published by the Welding Research Council.[8]

The authors presented their findings from all authoritative sources, including the results of correspondence with experts in many countries. They found that, provided proper precautions were taken, there is no absolute lower limit to the ambient temperature at which welding can be performed.

Unlike riveting or bolting, the act of welding involves melting the material of the joint, with its attendant metallurgical implications.

The metallurgical difficulties of welding at low temperatures stem from an increase in the rate of cooling; consequently, there is a greater danger of encountering cracking in the welded joint. Even if cracking does not appear, the higher cooling rate may result in hardening, generally associated with lower ductility and toughness in the welded joint.

The most obvious solution to the problem is to increase the overall heat input to the welded joint to slow up the cooling rate. This may be done "by preheating or by selecting a welding process which gives a high heat input, such as submerged-arc welding, thermit welding, electro-slag welding, etc."[8]

The use of preheating is more common, and may be easier to apply. A 1965 British publication offers the following thoughts:

> "Typical methods for preheating on site include electrical resistance or induction heating, or oxy-acetylene flame heating; the latter method, however, although regarded as the more convenient for the smaller welded sections does not afford the same accurate control in establishing and maintaining temperatures when compared with the electrical system."[3]

It may be sufficient to increase the heat input by increasing the electrode size or the welding current, or by decreasing the travel speed. "As a guide it has been recommended that the heat input should be increased by 5 to 8% for every 18°F drop in temperature below the normal ambient, in order to maintain normal cooling rates in the welded joint."[8]

Other means of securing the same benefits is to restrict the welding done in cold weather to certain types of joints or to set a limit on the thickness of the steel to be joined.

Weld joint preparation is necessary before the commencement of any welding operation. Extraneous matter, paint, oil or rust on ferrous materials can generally be removed by the comparatively simple operations of wire brushing, grinding or flame cleaning.

In certain instances where high-quality welds are required, surface imperfections on the joint faces have to be removed by scraping clean with a stainless steel blade.

"The correct storage of welding rods and wire is of particular importance with aluminum and its alloys since any surface contamination of these by moisture or foreign matter will result in porosity or oxide inclusions."[3]

Inspection is the final link in a chain of events initiated to establish welding procedures and techniques and to ensure weld integrity. "Apart from visual examination, radiography, magnetic particle crack detection, ultrasonics and fluorescent dye penetration are the methods of nondestructive testing employed."[3] Testing indicates only that the work has been done satisfactorily; it does not improve the quality of the welding carried out. In this regard, inspection should not be regarded as a panacea.

Research and Observations

In an article on arctic construction, Scheuren[7] intimated that there are really no unique problems in construction work on the ice cap. When the men, machines and material are all there the contractor can set steel, weld pipe, and perform other operations just as if he were doing cold weather work in Boston.

The Welding Research Council noted that "In some cases, crack-free welds have been produced when welding at ambient temperatures as low as -80°F."[8]

A contractor in Iowa laid and welded pipe through the heart of the Iowa winter. "Two welders were required working simultaneously on stringer and hot pass. Preheating was done during extreme cold."[4]

Crews in the harsh Yukon winter constructed a 485-ft steel and concrete bridge, 53 miles northwest of Dawson City. The bridge was completed in April after being constructed during winter temperatures that reached as low as 70° below zero.[2]

> "When you have to erect steel superstructure across a river it can lower your cost considerably on that phase. Elaborate steel placing methods do not have to be devised because you can go right out on the ice and erect your falsework."[2]

It can be safely concluded that, speaking in relative terms, erecting structural steel is no problem in cold weather.

Summary

The three main problems associated with erecting structural steel are the brittleness of steel, the welding operation and the safety and efficiency of the workmen.

Alloy grades of steel ensure good performance at temperatures as low as -50°F. Further, provided that proper precautions are taken, there does not seem to be any absolute lower limit to the temperature at which welding can be performed. Consequently, the only problem of importance is worker safety and efficiency.

Protection is usually difficult or effectively impossible to provide; hence, the decision on working rests with the erection crews. Although selection of a lower temperature limit is somewhat arbitrary, in that the boundary is related to man, it is generally considered noneconomically feasible to carry out steel erection below 10°F.

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TIMBER CONSTRUCTION

In the use of timber, either for lumber or piling, worker efficiency is the important factor and any conditions which affect this are significant.

Any precipitation can interfere, as well as lack of humidity. Adequate site storage and treatment with moisture retardants rectify the first problem rather easily; the second is harder to conquer. In extremely dry, cold conditions, i.e. 3% humidity, as is found at Thule Air Base in Greenland, the moisture is "pulled" from the lumber, causing splitting and warping.

Timber has many assets when used in cold weather, especially arctic weather: Structurally, wood is much stronger at lower temperatures; thermally, its insulating properties make timber desirable for piling; and economically, when locally available, timber is much cheaper than other building materials.

In this discussion, timber will be subdivided into lumber and piling. The lumber classification implies carpentry. Piling implies pile-driving, which is covered extensively in section *Earthwork* (p. 69).

Military Requirements

Lumber

The Army's construction guides on rough and finished carpentry, dated June 1968, do not mention cold weather.

Piling

Similarly, its guide on wood piling for building construction, with latest change dated May 1963, does not treat the subject of cold weather.

Civilian Requirements

Lumber

The Canadian Building Code for the north, dated 1968, specifies grades but does not mention cold weather.

A 1960 *Civil Engineering* article states that "Lower output from workmen must be expected when the temperature falls below -20°F."[7]

According to the report by the Travelers Research Center (TRC), "The temperature limitations which can interfere are those indicated by a chill factor of 1000-1200."[8]

Crocker stated in 1960 that "Wood-frame construction, widely used in residential buildings, is not affected by cold weather. In fact, the quality of such work is often better in winter since the frame is not subjected to wetting by rain as so often occurs in summer."[2]

Piling

Pile driving requires the use of heavy cranelike equipment, which is likely to be affected by high winds and freezing precipitation. TRC, therefore, states that any severe storm makes this operation hazardous.

Construction Methods

Lumber

Timber that is to be incorporated in any part of a building should never be left fully exposed. It should be protected from the effects of weather in transit, on the site, and until it is incorporated in the building.

The site storage period should be reduced to an absolute minimum. Where it is anticipated that a period of site storage under adverse conditions may arise, treatment of the lumber with moisture retardants, particularly on the exposed end grain, is advisable before delivery to site. Storage should be designed, where possible, for easy access and removal of any particular size and length required. "Air dried timber should be stored in the stick under cover. Kiln dried timber should be stored close piled."[1]

In arctic conditions at temperatures as low as -20°F "Carpentry work can be carried on if lumber is sawed at lower cutting rates and if nails are heated and driven by a carpenter wearing light cotton gloves."[7]

Conventional methods may be quite feasible for erecting wood-frame shells in winter. "Precut framing is usually assembled on the floor and tilted up into position. In reasonable weather the shell can be closed in five days."[6]

A 1968 article on arctic construction states that "Most of the wood beams with a thickness exceeding 2 in. are of glued-laminated construction, thereby avoiding the extensive checking and cracking which occurs in standard sawed beams because of the low humidity."[5] All main framing members can be precut prior to shipment to decrease time of erection at the site.

A British journal suggests that "Supply and fixing of internal wood finishings and joinery should be delayed until the heating system is in use, the building dry and at the same temperature at which it will ultimately be maintained."[3] Failure to observe these requirements increases the moisture content of the timber above the required limit.

Piling

It was illustrated at the 1963 Permafrost Conference at Purdue University that mainly wooden piles are used in Canada and the United States; reinforced concrete or metal piles usually are reserved for situations involving high vertical and lateral loads.

Generally, either of the two main types of foundations can be used in the Arctic: pile or spread footings. The soil conditions, materials available, or type of structure dictate the one to be employed.

Piling practices employed in the Arctic differ from those normally encountered in construction work.

> "The piles are expected to be permanently frozen into place and receive their support for adfreezing to the adjacent ground around the sides. Since the ground is frozen, the piles can usually not be driven in, but instead must be placed in previously prepared holes or pits."[4]

These holes are prepared by prethawing, predrilling or excavating. Adfreezing is provided by a slurry of water and sand, poured around the piles to freeze back.

Summary

Three main problems are associated with timber construction: interference of precipitation, lack of humidity, and worker efficiency. Adequate site storage and treatment with moisture retardants rectify the first problem rather easily; the second is harder to conquer, especially in the Arctic (3% humidity). Consequently, the initial limiting resource input is man.

Timber has many assets when used in cold weather, especially arctic weather: Structurally, wood is much stronger at lower temperatures; thermally, its insulating properties make timber desirable for piling; and economically, when locally available, timber is much cheaper than other building materials.

Again, the selection of a lower temperature limit is somewhat arbitrary in that the boundary is related to man. TRC considers pile driving and external carpentry practicable to –10°F.

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PLASTERING

Plastering is a wet and messy process. It brings more moisture into a building than any other operation. The natural rate of drying is at its lowest in winter, causing delays for the other finishing trades.

A recent article in a British publication cites the two basic problems associated with plastering at low temperatures. "Firstly, the rate of drying out is considerably reduced (high humidities during winter are important in this) thus delaying the following trades and, secondly, the risk of the plaster freezing, in which the coldness of the surfaces to be plastered is significant."[1]

Military Requirements

Department of the Army specification CE-240.01, dated October 1968, directs plastering as follows:

> "15.1. *Plastering in cold weather*: When the ambient temperature is below 55°F, heat shall be maintained in the building continuously and uniformly at not less than 55°F from 1 week prior to beginning of plastering operation, during plastering, and until plaster is sufficiently dry to receive surface finishing materials or for at least 1 week after the plaster has set when no finishing materials are required. Fans and baffles shall be provided when necessary for adequate ventilation and circulation to avoid overheating.
>
> "15.2 *Masonry and concrete surfaces* shall be thoroughly cleaned and free of frost, paint, efflorescence, oil, grease, acids, and loose or foreign matter prior to application of plaster. Smooth concrete surfaces shall be roughened or dash-coated with portland-cement grout as specified in USA Standard A42.1, prior to application of plaster finish. In lieu of the aforementioned treatment, bonding compound may be used on smooth clean concrete surfaces in the manner specified hereinafter.
>
> "16. *Mixing of plaster*: Plaster shall be mixed in mechanical mixers except where hand-mixing is approved for small quantities. Frozen caked, or lumped material shall not be used. . . ."[5]

Civilian Requirements

Canada

Section 23 of the 1968 Canadian Building Code for the North discusses plastering, with one paragraph particularly attuned to cold weather. "In cold weather, plaster shall be applied at 50°F to 70°F and maintained at this temperature range for at least 96 hours and above freezing thereafter. Ventilation shall be provided for the proper drying of the plaster during and subsequent to its application."[2]

Britain

The *Architects' Journal* published that country's current specification:

"When the air temperature is 40°F or less, the portion of the building to be plastered shall be completely enclosed. The air temperature shall be raised to ensure that plastering is satisfactorily carried out and heat maintained until the completion of hydration. Provide and maintain necessary heating appliances, taking care to avoid excessive localised drying out, and provide adequate artificial or other ventilation."[4]*

Netherlands

The study by OECD found that the basic additional measures required for plastering in the winter were simple: "Openings should be closed and adequate heating and ventilation provided. In the Netherlands warm water is used (not above +20°C (68°F), if gypsum is added, +40°C (96°F), if no gypsum is used)."[9]

Russia

Sizov[8] discusses plastering operations in the USSR. They desire that an effort be made for a maximum decrease in the volume of wet plastering in finishing buildings during winter.

Using mortars to plaster rooms during winter is permitted in special cases, if this is required in the conditions of their use. "For these operations, the winter periods begin from the time that an average daily temperature below 5°C (41°F) is established during autumn and ends with the attainment of an average daily temperature above 5°C during spring. During this period, plastering operations using ordinary mortars must be carried out within heat-insulated and warmed rooms."[8]

Sizov continues by stating that if, within the room, surfaces and the structures themselves are not exposed to below-zero (°C) temperatures for more than a day, plastering can be begun immediately after heating has begun. Otherwise, "Preliminary heating of the room is required until the temperature of the outer wall surface to a height of 0.5 meters from the floor will not be less than 5°C."[8] This temperature is to be sustained 2 days for simple plastering, 5 days for decorative plastering.

Walls are dried by establishing within the room as high a temperature as possible with a maximum of 50°C (122°F). The mortar must be at least 8°C (46°F) for manual and 10°C (50°F) for mechanized plastering. However, plastering mortars containing gypsum must not be prepared at temperatures above 25°C (77°F), since then rapid setting would take place.

United States

It is generally considered that indoor construction operations are not significantly affected by weather. However, indoor plastering requires sensitive control of the environment regarding temperature and humidity. The cost of doing so appears to be sufficiently substantial and should be considered as a significant influence.[7]

Construction Methods

A general approach to the process of plastering includes the following classifications: selection of material, provision of enclosure, and provision of heating and ventilation.

Selection of material

The plaster used should be suitable for the weather conditions. Special plasters are now available which obviate the need to wet high suction backgrounds. "The rapid hardening properties of gypsum based plasters make these plasters more suitable for winter conditions than those containing lime and cement."[1]

In exceptionally cold weather, traditional sand, lime or cement-lime plasters are prone to frost and their use may halt plastering. Such plasters also need application and drying times seldom acceptable today. Background materials that permit one- or two-coat application such as plasterboard or blockboard should be used.

"When it is not possible to avoid the use of lime and cement plasters, considerations should be given to ready-mixed mortars which may be made up under conditions free from frost."[1]

The Canadian building code requires plaster to be at least ⅝ in. thick at any point and to conform to the following requirements:

"1. Plaster shall be applied in three coats consisting of a scratch coat, brown coat and finish coat, except that where the base consists of gypsum lath or unit masonry other than concrete, a two coat application may be used in which a brown coat is doubled back over the scratch coat.

"2. When plaster is applied over concrete or concrete masonry a special bond coat shall be used as the first coat.

"3. When 3 coat plaster is used, the first or scratch coat shall consist of 1 part gypsum plaster to 2 parts sand by weight. The second or brown coat shall consist of 1 part gypsum plaster to 3 parts sand by weight. The finish coat shall consist of 1 part gypsum plaster to 3 parts lime by volume.

"4. When 2 coat plaster is used, the first coat shall consist of 1 part gypsum plaster to 2½ parts sand by weight. The finish coat shall consist of 1 part gypsum plaster to 3 parts lime by volume."[2]

The Russians found that the drying of plaster, applied on porous water-absorbing surfaces, proceeds more intensely than on a flat base. "Plastering on wood-fiber and gypsum slabs dries especially well, requiring only thin covering or spackling for final finishing."[4]

Sizov reports that purely lime mortars may not be used in the USSR nor are lime-gypsum formulations containing plaster gypsum in the ratio of more than 0.3 parts per one part of cement paste used. He states that mortars must be prepared with the minimum mortar content in accordance with the formulation chosen and the workability required.

Provision of enclosure

The part of the building to be plastered should be completely enclosed. "If glazing has not been completed, then some form of translucent sheet should be used over the window openings. All external door openings should also be suitably covered, while the number of entrances should be restricted; these should be fitted with self-closing devices."[1]

Provision of heating and ventilation

Interior plastering during the winter is made especially difficult by the fact that the moisture must be eliminated. There are two types of moisture: water contained in the mortar, and water which forms in the process of carbonization.

The measures which are taken during the winter, while interior plaster work is carried on, are intended to protect and heat the plaster itself and to provide protection and heat during the setting time of the plaster.

Protection and heat for the plaster itself. As previously noted, Canada requires a minimum application temperature of 50°F. In Britain a "temperature of 50°F (10°C) is best for traditional plasters. . . ."[4]

The Russians preheat the water and aggregate to obtain a mortar of at least 8° (46°F) to 10°C (50°F). They find that at temperatures less than 10°C, mortars are reduced in plasticity and are poorly suited for mechanized feeding.

The United States military requires heating when the ambient temperature falls below 55°F.

Protection and heat during the setting time of the plaster. Fresh plaster must not be allowed to freeze since this results in damp, dark-colored walls with inadequate strength. "During the first twenty-four hours the plaster should be kept warm and moist. After the plaster has hydrated, which will be within the 24 hours, ventilation must be provided to permit drying of the plaster."[3]

High humidity conditions, particularly at temperatures of 40° to 50°F, may prevent drying of the plaster; this greatly weakens the bond of the plaster to the base.

Canada requires heat when the outside temperature falls below 40°F. However, Canadians warn against artificial temperatures above 65°F "to prevent too rapid drying of the plaster which often results in the formation of shrinkage cracks."[3]

The British strive for maintaining a 50°F temperature, and they consider it critical that an even level of heat be maintained.

Russia does not desire curing temperatures higher than 50°C (122°F). However, this maximum is much higher than the others, about twice as much.

Sizov stated that at a height of 0.5 m from the floor, a temperature of at least 5°C (41°F) must be maintained for 2 days for simple plastering and up to 5 days for plastering of brick walls.

The United States Army code requires adequate heating: 1 week prior to, during, and for at least 1 week after plastering.

Since in most cases the permanent heating system is in operation when the plastering is started, no trouble is found in maintaining proper temperatures. Warm air heating systems also permit the introduction of fresh air directly to the furnace. "When temporary heaters are used, care must be taken to provide careful supervision since smoke or fumes may stain the plaster."[3]

Ventilation. Ventilation should be provided to combat condensation and help dry out the plaster. Condensation on windows is a problem during the first 24 hours. Water dripping from windows may cause permanent damage to the plaster or to woodwork.

Ventilation should be so arranged that air currents do not impinge on a freshly plastered surface, causing localized drying. In very cold weather, air for ventilation should be introduced at some point away from the area to be dried.

Research and Observations

The most comprehensive study to date is probably the one carried out by Naslund in 1955.[6] Although the results may no longer be valid, this study should be mentioned for its theoretical value. According to this study, the fact that plastering is one of the operations least suited for winter work is not due to technical difficulties but entirely due to the high additional costs. He found total costs for wintertime plastering increasingly higher, by 70%. This amounted to 6.1% of the total building costs on the projects studied.

These figures refer to Swedish conditions, but nevertheless indicate that plastering is a very expensive winter operation. "Owners and builders should be recommended to avoid traditional plastering as far as possible. and to examine the possibilities of replacing plaster by dry techniques."*

Summary

There are two basic problems associated with plastering at low temperatures: The rate of drying-out is considerably reduced, and there is a risk of the plaster freezing. The former problem occurs from the usually high humidity within a building; the latter occurs when the combination of ambient and surface temperature is low enough to retard or stop hydration.

The military requires the application of heat to the building when the ambient temperature falls below 55°F; Canada, 40°F; Britain, 40°F; and Russia, 41°F. Optimum minimum curing is generally at 50°F for 4 days.

A general approach to the process of plastering includes selection of material, provision of enclosure, and provision of heating and ventilation.

Interior plastering during the winter is made especially difficult by the fact that moisture must be eliminated. This entails controlling the water in the mortar as well as the water which forms in the process of carbonization. The cost of doing so appears to be sufficiently substantial and should be considered as a significant influence.

Obviously, material (plaster) is the initial limiting resource input. Because of the sensitive protection required, plastering is a very expensive winter operation. Consequently, owners and contractors should be urged to avoid traditional plastering as much as possible.

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EXTERIOR PAINTING

Under winter conditions, the presence of moisture in or on the surface to be painted causes most painting failures. Paint applied in cold weather does not dry properly and loses its durability and resistance to weathering; and, if allowed to freeze before drying, it separates.

Military Requirements

The Department of the Army has several guides covering paint and the conditions of its application. Its general regulation on the subject is CE-250, dated September 1968, which contains the following:

> "3.7. *Cementitious paint* shall conform to Federal Specification TT-P-35 and shall be applied to provide uniform coverage of not less than one gallon per forty square feet. . . . This paint shall be used for masonry surfaces only, and shall not be used for applications where the ambient temperature is below 40°F or above 85°F or where the relative humidity is below 40%.
>
> "6.4. *Atmospheric conditions*: Paints other than water-thinned coatings shall be applied only to surfaces that are completely free of surface moisture as determined by sight or touch. In no case shall paint be applied to surfaces upon which there is visible frost or ice. While painting is being done, the temperature of the surfaces to be painted and of the atmosphere in contact therewith shall be at or above 50°F for water-thinned coatings and 45°F for other coatings.
>
> "6.9. *Epoxy and moisture cure polyurethane coatings* will only be applied where an average temperature of 55°F or higher can be maintained during the application and for a five day period subsequent to application of any coat. Adequate ventilation will be provided. . . . The moisture cure polyurethane coating will not be used where the relative humidity is below 30%."[4]

A December 1968 Army guide (CE-505) specifies the application of paint to elevated steel water tanks:

> "10. *Painting* shall be done in a workmanlike manner. All coats shall be applied in such manner as to produce an even film of uniform thickness. . . . Pa[illegible] shall be applied under dry and dust free conditions, and unless other-[illegible]roved, shall not be applied when the temperature is below 45°F or a[illegible]°F. Sufficient time shall elapse between coats to permit satisfactory re[illegible]nce commenced, the complete painting operation shall be co[illegible]out undue delay."[5]

A similar guide for painting of steel standpipes and ground storage reservoirs (CE-506), dated October 1968, has the same paragraph on painting as CE-505.

A somewhat dated (April 1957) guide for painting protective coats on metal is CE-249. It reads as follows:

> "-05. *Application*: The specified prime coat of paint shall be applied by brush. Paint shall not be applied when the temperature is below 40°F. Painting shall be done in a workmanlike manner so as to produce an even film of uniform thickness."[6]

The military requirements apparently can be summarized as follows: "Application of paint to dry surfaces within a 45-85°F range and at a relative humidity of 35% or greater."

Civilian Requirements

Canada

The Canadian building bulletin on winter construction recommends that exterior paint not be applied at temperatures below 50°F.[1] It does not mention a maximum temperature or a minimum relative humidity condition. However, it states that fresh plaster should not be painted.

Britain

A British article in the *Architects' Journal*[2] mentions (under "Specifications") that quick drying and porous paints should be specified wherever possible and that all surfaces must be completely dry and free of efflorescence and condensation.

Russia

Sizov[7] describes Russian guidelines for painting:

> "Painting work can be begun only after moisture has ceased to condense. Carrying out painting within rooms is permitted when the temperature of the coolest surfaces is not under 8°C (46°F). However, painting work at 8°C must be avoided, since the temperature of the surface, being close to the dew point, cannot possibly take on a satisfactory coat. The surfaces painted within the rooms must not be subjected to sharp fluctuations in temperature to avoid damage from settling condensation. . . . Preparation, storage, and use of emulsion dilutents and water-emulsion paints is permitted at temperatures not lower than 12°C (54°F).
>
> "The water formulations for painting are prepared and stored in a heated room. The temperature of these formulations when used must not be lower than 8°C (46°F); priming coats must not be under 5°C (41°F) and nonaqueous formulations not lower than 10°C (50°F). . . . The final water paint coat is allowed to dry at the temperatures indicated for not less than two days. Thereafter, only in emergency cases can negative temperature be permitted in the room."[7]

The following quotation is a surprising one. Note the extremely low temperatures.

> "In urgent cases painting is permitted at lower temperatures, but only when limited surfaces are being covered. In this case, painting must be carried out only in dry weather at temperatures not lower than -10°C (14°F); the surfaces being treated must be dry, free of ice; the temperature of the oil and lacquer formulations, diluted with turpentine or white spirit, must be not less than 15°C (59°F).
>
> "Exterior painting using lime formulations is permitted on the conditions that the air temperature during the day must not fall below 5°C (41°F).
>
> "The length of time each paint coat is allowed to dry (primer, spackling, paint) at below-zero (°C) conditions is not less than 24 hours as against 4-8 hours during the summer."[7]

United States

The Travelers Research Center, Inc. found that painting is seldom attempted at temperatures below 45° to 50°F in this country (Russo[6]).

Construction Methods

The basic considerations in exterior painting are the perishable product, the quality of the work, and worker efficiency.[6]

Basically, the procedure involves application of the paint according to the appropriate specification. For outside painting there are many quick drying paints on the market; but if the weather is bad, the wise contractor organizes alternative work under cover.

Introduction of heat and ventilation or use of dehumidifiers speeds drying time; porous coatings such as emulsion paints allow drying to continue after application.

Control of temperature for interior painting presents no problem if the heating system is operating. Ventilation is desirable not only to assist in the drying of the paint, but also to remove the solvent fumes which are sometimes toxic.

Summary

The basic considerations in exterior painting are the perishable product, the quality of the work, and worker efficiency.

Under winter conditions, the presence of moisture in or on the surface to be painted causes most painting failures. Paint applied in cold weather does not dry properly and loses its durability and resistance to weathering; and, if allowed to freeze before drying, it separates.

The military requirements apparently can be summarized as follows: "Application of paint to dry surfaces within a 45-85°F range and at a relative humidity of 35% or greater."

Very little civilian data are available. However, Canada does not recommend exterior painting at temperatures below 50°F. Normally, Russia prefers the same 50°F. The Travelers Research Center, Inc. found that painting is seldom attempted at temperatures below 45° to 50°F in the United States.

The obvious initial limiting resource input is material (paint), occurring at approximately 50°F. Procedures and methods are available to lower this temperature limit somewhat: the use of quick-drying (porous) paints, introduction of heat and ventilation, and/or the use of dehumidifiers. However, it is doubtful that exterior painting will ever be done at, or below, freezing temperatures.

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ROOFING

Early completion of the roof is useful as it affords cover for other trades. However, roofing is very sensitive to weather conditions because of the use of perishable asphalt material and constant exposure of the worker. The operation is highly sensitive to precipitation of any type or intensity. Strong winds and icy conditions are also major detrimental factors.[11]

Every effort should be made to construct a built-up roof in warm dry weather. Freezing or frozen precipitation necessitates additional operations and increased cost to satisfactorily complete the operation. However, when this is not possible, precautions must be taken to keep water, snow, and ice off the roof deck and the roofing.

Military Requirements

The Army has many guides describing roof decking, built-up roofing, elastomeric roofing, and corrugated steel roofing.

Roof decking

The military has four guides for construction of roof decking; by using cast-in-place gypsum, cast-in-place perlite concrete, cast-in-place vermiculite concrete, and cast-in-place foam concrete. The use of gypsum concrete allows the most liberal conditions of placement as indicated in CE-219.02, 1967:

> "11.4. *Cold-weather placement*: Gypsum concrete shall not be mixed or poured during weather when the temperature and job exposure will allow the concrete to freeze before the chemical set of the concrete is complete."[7]

The remaining three guides contain basically the same conditions for placement:

> ". . .concrete shall not be placed when the ambient temperature is below 40°F. When it is anticipated that temperatures will be 40°F or below after placing of the concrete, the mixing water shall be heated to a temperature of 75 to 100°F. The concrete shall be protected from freezing during and at least 48 hours after placing."[8]

Built-up roofing. CE-220.11, 1968, states that:

> "The entire roof-deck construction of any bay or section of the building shall be completed and the ambient temperature shall be 40°F or above, before installation of the vapor barrier or insulation of underlayment is started in that area. The roof-deck surface shall be free from ice, frost, and surface moisture and shall be smooth, firm, free from dirt, projections, and foreign materials."[3a]

Elastomeric roofing

This type of roofing, fluid and sheet, applied on concrete roof-decks, is described in 1967 guides CE-220.13 and CE-220.15. Both guides essentially say the following:

> "6. *Preparation*: The entire roof-deck construction of any bay or section of the building shall be completed before roofing work commences. Ambient temperature, for applications using hot asphalt, shall be not lower than 40°F. Ambient temperature for applications using cold adhesive exclusively, shall be not less than 20°F. The surface on which the roofing or flashing is to be applied shall be smooth and firm, free of projections, and free from ice, frost, moisture, dirt, and foreign materials. . . ."[6]

Corrugated steel roofing

Corrugated steel roofing is specified in CE-222.01, January 1961, which states that "Sheets shall not be installed, fabricated, or otherwise handled when the temperature is below 32°F unless authorized by the Contracting Officer."[4] In addition, requirements for shipment and storage are provided.

Civilian Requirements

Most publications available on roofing describe only built-up roofing. Consequently, discussion of roofing in this section generally implies built-up roofing.

Canada desires that "Roofing felts and asphalt shingles during cold weather should be kept at a temperature of 70°F until they are ready to be used. Gravel or slag, used to surface built-up roofs, must be dry and should be heated when the air temperature is below 40°F. to ensure proper penetration into the bitumen."[2]

Britain follows these general rules:

"1. Roof screeds are subjected to similar precautions as for concreting, and are protected against rain.

"2. Absorbent underlays, such as strawboard and other forms of insulation, are kept covered and dry.

"3. Felt or asphalt finishes are not applied when the roof decking is wet."[3]

Generally, all restrictions on roofing concern water. Water trapped under or between the plies of built-up roofing invariably gives trouble. It is important, therefore, that the roof deck be dry when the roofing is applied and that no water get between the layers of roofing felt. It is necessary to have dry weather for 2-3 days before built-up roofing application.

Russia permits placement of roofing materials "during frosts not more severe than -20°C (-4°F). At temperatures below -5°C (23°F), operations must be carried out with special requirements met."[12] The roofing material consists of Ruberoid surfaced with asphalt mastic.

Construction Methods

Military guides develop the following general method of roof construction:

1. The roof decking is cast in place using concrete and is allowed to cure until it is dry as possible.

2. Upon completion of the roof-deck, the roof surfaces are cleaned of debris and other foreign matter and left ready to receive the built-up roofing.

3. Membrane vapor barriers are applied directly on the roof-deck, except that they are not required on steel decks. A vapor barrier usually consists of laid saturated felt, covered by hot bitumen which is mopped on.

4. Instead of the felt vapor barrier, a single wrinkle-free sheet of polyvinyl membrane can be laid directly on the deck.

5. Board-type insulation is then laid in one or more layers in hot bitumen.

6. Elastomeric fluid- and sheet-applied roofing are laid to form an integral waterproof membrane.

The Russian approach is similar.[12] After the roof deck is dry and cleaned of debris, the individual members of the roof are applied. These members are supporting base, thermal insulation, roofing cover, and layer of water impermeable membrane. Each is bound to the other and must be placed in a specified sequence.

Research and Observations

Taking into consideration the difficulty of delivering construction materials, their high cost, the short construction season, and the presence of permafrost, the Russians feel that there is a case for recommending new structures in the form of suspended roofs.[1] The advantages listed are slightly lower outlay of materials per area of floor, need for fewer supports in construction, and no need for complex, heavy and expensive erection equipment.

In 1960, new designs for roofs of industrial buildings emerged and are now used by the Russians for construction.[9] They include:

1. Cold roofs made of sheets of grade aluminum alloy.
2. Insulated roofs made of aluminum sheets.
3. Roofs assembled from precast reinforced concrete plates for unheated buildings.
4. Roofs with precast reinforced concrete plates for heated buildings.

A 1963 Canadian Housing Note describes roofing techniques for asphalt shingles.

> "Asphalt shingles are very sensitive to weather and must be carefully handled when cold and brittle, but the roof deck itself can keep snow out and the house dry until the weather is suitable for shingling while work goes on indoors. Staplers simplify cold weather shingling, allowing gloves to be worn. Low slope asphalt shingles are more difficult to apply as the asphalt adhesives are stiff when cold and must be trowelled on. Built-up roofing should be protected by shelter if done in winter; otherwise damage from entrapped water and from overheated asphalts is very difficult to avoid."[10]

It is common practice for contractors in Canada to heat asphalt and tar to higher temperatures than normal to compensate for the lower winter air temperatures. "This is not good practice since overheating changes the physical properties of these materials and will reduce roof life."[2]

Summary

Roofing is very sensitive to weather conditions. Generally, all restrictions on roofing are aimed at that old nemesis – water. Water trapped under or between the plies of built-up roofing invariably gives trouble. Therefore, it is important that the roof deck be dry when the roofing is applied and that no water get between the layers of roofing felt.

Russia permits placement of roofing materials at temperatures down to -4°F. The U.S. military restricts built-up roofing operations below 40°F; 32°F for corrugated steel roofing. Canada requires the introduction of heat to the gravel or slag used to surface built-up roofs when the ambient temperature approaches 40°F.

The initial limiting resource input is material (asphalt); this occurs at approximately 40°F. Protection and heat allow operations at lower temperatures. However, overheating the asphalt may change the physical properties of the material and reduce roof life.

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WATERPROOFING, DAMPPROOFING AND CALKING

Waterproofing, dampproofing, and calking entail the positioning of an impervious layer to prevent the ingress of moisture into a structure. The layer may be a plastic sheet of bitumen mastic which is painted, spread, or troweled into position.

The Travelers Research Center reports that "Low temperatures will adversely affect both worker efficiency and the working characteristics of the material, which hardens and tends to lose its adhesive properties while becoming difficult to apply."[8]

A Canadian contractor who has designed, manufactured, and erected close to 300 buildings in the North, claims that "Condensation is probably the greatest source of difficulty with northern buildings."[6] In particular, he considers concealed condensation within the structure more damaging than surface condensation.

In a Russian publication, Suvorov[9] concluded that all underground premises in permafrost and in ground subject to deep seasonal freezing are exposed to extremely difficult hydrogeological conditions. "In addition to the ordinary pressure of the ground, they are subject to the hydrostatic pressure of groundwater."[9]

The presence of this hydrostatic pressure determines whether the operation will be waterproofing or just dampproofing. According to the Canadian building code,[1] in the north where hydrostatic pressure *is* likely to occur, all exterior surfaces of basement or cellar walls below grade shall be *waterproofed*. Where hydrostatic pressure *is not* likely to occur, all exterior surfaces of foundation walls below grade shall be *dampproofed*.

According to the same authority, "Calking shall be provided at any location where necessary to prevent the entrance of water into the structure."[1]

Military Requirements

The Department of the Army guide specifications for waterproofing, CE-212.01 and CE-212.02, dated 1960 and 1964, cover bituminous-membrane and metallic waterproofing. They read in part as follows:

> "03. *General*: Waterproofing shall be installed where indicated. Waterproofing may be either asphalt or coal-tar type and shall be applied when the ambient temperature is 40°F or above. . . ."[2]

> "03. *General*: Metallic waterproofing shall be applied in the locations shown. . . . Metallic waterproofing shall not be applied until the surfaces to be waterproofed are protected from excessive change in temperature. Waterproofing shall be applied only when the ambient temperature is above 40°F. Temperature shall be maintained above 40°F during the curing period."[3]

The 1959 guide on dampproofing is under revision and thus unavailable for examination by the writer.

Department of the Army guide specification for calking and sealing (CE-239, August 1968) places temperature restrictions on a few of the sealants. The applicable portions follow:

"3.8. *No. 10 sealant* shall be. . . . The ambient temperature shall be within the limits of -20°F and +190°F when the sealant is installed. . . .

"8.1. *Sealant No. 1*: The ambient temperature shall be between 40 and 100°F when the sealant is applied. Compound shall be gun-applied with. . . .

"8.2. *Sealants Nos. 2 and 4*: The ambient temperature shall be between 40 and 100°F when the sealant is applied."[4]

Civilian Requirements

As previously mentioned, the Canadian building code for the north devotes a section to dampproofing and waterproofing. However, it does not place temperature limitations on their application. Instead the components of each are described as follows: ". . .waterproofed by covering the walls with two layers of bitumen-saturated membrane, with each layer being cemented in place with bitumen and coated overall with a heavy coating of bitumen."[1]

The code continues: ". . . dampproofed by applying at least one heavy coat of bituminous or other acceptable dampproofing."[1]

Describing calking, it states that "Calking materials shall be of a type suitable for the temperature conditions prevailing at the time of application, and which will remain pliable after completion throughout the range of temperatures encountered in service."[1]

More specific direction is provided for bituminous dampproofing by the National Concrete Masonry Association, which states:

"Bituminous dampproofing shall be applied to the outside surfaces of the below-grade portion of all exterior basement walls and to other walls below grade for which dampproofing is shown on the drawings. . . . Dampproofing shall not be applied when the air temperature is less than 32°F or is less than 40°F and falling. . . ."[5]

The guidance on calking mentions no temperature limitation in application.

Construction Methods

The construction methods for waterproofing are hinted at by the previously mentioned requirements. However, the following general method of application is presented for clarity:

1. Preparing the surfaces by removing dust and foreigh matter.

2. Applying the solid base coat by mopping with bitumen.

3. Placing the desired type of membrane in the bitumen base, usually by the shingle method with each strip lapping over the preceding strip.

4. Protecting, when necessary, with insulating board.

Dampproofing procedures are basically the same with the use of less membrane protection.

Calking is generally gunned into joints subject to structural movement to provide a firm, flexible, weathertight seal.

Research and Observations

Very little information is recorded on the subject. One manufacturer claims that his calking product can be gunned on at any temperature. He further asserts that "The sealant will not harden (down to -40°F) or soften (up to 200°F)."[7]

An arctic contractor, building small structures in the north, uses foamed polystyrene in his wall panels. This is a "breathing-drainage type panel which employs an interior vapor seal but allows for condensation within the panel."[6] Convinced by its workability, he has a patent pending on this panel, his prime weapon against condensation within the walls.

Summary

Waterproofing, dampproofing, and calking entail the positioning of an impervious layer to prevent the ingress of moisture into a structure. The layer may be a plastic sheet or bitumen mastic which is painted, spread, or troweled into position.

Low temperatures adversely affect both worker efficiency and the working characteristics of the material, which hardens and tends to lose its adhesive properties while becoming difficult to apply.

The initial limiting resource input for waterproofing is the material (bitumen) at 40°F. If the impervious layer were plastic, then man might be considered the limiting factor. Dampproofing is subject to the same constraints as waterproofing; however, calking is not. Dependent upon the sealant used, calking may be initially detained by either man or material. Consequently, the choosing of limits may be arbitrary; but it is doubtful that quality work may be performed in these areas at temperatures below freezing.

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ECONOMIC FEASIBILITY

During recent years, greater economic prosperity has brought in its wake a demand for increased winter building activity. However, opinions have differed as to the best methods of winter construction, and no single concept has been formulated. Those in favor of winter construction point to the progress made in other countries as an example, while their opponents claim that local conditions render winter construction impossible. Each side supports its arguments with proof from the technical, economic and climatic, as well as the social, traditional and psychological viewpoints. Any extra costs incurred by constructing during the winter, once definitively identified, become a significant factor in these arguments.

The term "cost" has different connotations to different people; it is used regularly with tone of authority, although rarely understood. There are a multitude of meanings for the word "cost": outlay, opportunity, fixedcost, increment, amount sunk, price, charge, expense, etc.

One form of cost involves the concept of interest, or the "time value of money." Interest has been defined as "a rental for the use of money." Time value of money implies that a dollar to be received one year from now is not as valuable (in terms of its ability to satisfy immediate wants) as a dollar to be received today. This concept exists entirely distinct from any inflationary or deflationary trends.

If the contractor understands what "costs" mean for him, he can then apply basic methods of comparing the financial implications of alternative working plans (such as winter construction). His analysis must give serious attention to "cash flows," rather than concentrate exclusively on "book profit." A book profit is a stylized representation of the recorded difference between revenues collected and the costs supposedly incurred in producing these revenues, measured over any given period. It is not a measure of the actual cash involved. Cash flows are the actual dollar and cents amounts coming into and going out of the firm–the actual money transactions which take place – and it is these flows that are of prime concern to a contractor.

Because of the clouded meaning and disparate connotations of the term "costs," a comparison of the costs incurred by various countries in constructing different types of buildings, with variations in construction materials, construction methods and winter protection measures, seems an impossible–if not fruitless – endeavor.

In sympathy with these views Stegemann wrote:

> "The additional costs quoted by contractors are purely coincidental, depending on the stage of construction and the type of weather, and may therefore never be taken as a general guideline. Were the reader given quotes between 5-100% or 8-120% additional charges, these individual quotes would be of no value to him whatever. Similar fluctuations are encountered when trying to measure the drop in output. Even itemised quotations for certain services such as the construction of protective roofs, the covering up of building machinery, installing sheltered sheds for storing material, etc., are of no value to the reader because the costs of all these items depend on the local conditions, the measurement of the items and various other circumstances. Any information about the costs of single items would be inadmissible because it would lead to confusing generalisations."[7]

Nevertheless, an attempt will be made to review analyses made in various countries to clarify the problem of the economic feasibility of winter construction. Following this, the apparent advantages to the owner and contractor will be identified.

International Economic Review

USSR

According to the Organization for Economic Cooperation and Development (OECD), the Soviet Union has investigated extra costs during the last few years, applying them to overall costs. The figure obtained, varying according to climatic conditions, was found to be between 0.8 and 8.9% for industrial installation, 0.8 and 7.8% for cemented apartment houses, and 0.8 and 6.3% for scaffolding work.

Germany

For the German Federal Republic, OECD analyzed data which indicated that the extra winter construction charges are about 0.42 to 6.46% for rough brickwork.

Austria

In Vienna extra winter costs of building apartment houses are at 1 to 1.2% of the overall construction costs per winter.

Poland

The Warsaw Institute for Building Techniques has also started to analyze extra winter costs during the last few years. According to this body, as reported by OECD, work carried out in closed rooms is 8% more costly, in temporary weather shelters 20% more costly, in the open air (for brickwork) 17.1% more costly, and for concrete scaffolding 20.5% more costly – an average of 1[illegible]7% above normal construction prices.

United Kingdom

Table XXXII[3] reflects the results of a study done for the Ministry of Public Building and Works. The project covered 79 weeks at a cost of $100,000 for a precast concrete frame building with *in-situ* concrete floors and brick partitions.

Table XXXII. Comparative cost to the builder per week (after ref 3).

	Cost of not taking precautions	*Cost of precautions to maintain output*
In normally inclement weather	$ 89	$ 79
In exceptionally inclement weather	890	220

Sweden

The percentage increases in costs for various types of work associated with road building when done in the bad seasons in Sweden are shown in Table XXXIII.[5]

Table XXXIII. Percentage increase in costs (after ref 5).

Operations	Summer	Autumn	Winter	Spring
	Cost of work performed during (as percentages of normal summer costs)			
Excavation (excavator) in				
gravel (depth 2½ m)	100	103	113	108
quicksand (depth 2½ m)	100	133	117	145
Dozing (tractor) in				
gravel (layer depth ½ m)	100	101	179	113
quicksand (layer depth ½ m)	100	156	209	165
Profiling and compacting embankment of				
gravel	100	106	154	127
quicksand	100	152	179	167
Rock blasting	100	100	103	102
Laying concrete pipe ducts	100	110	111	139
Gravel subbase	100	101	102	106
Spreading topsoil on slopes	100	117	181	141

By planning a road job or succession of jobs on a year-round basis, the total cost of the project, as estimated by the Swedish Organization of Road Builders, would be between 86% and 93% of the cost of building only in the most favorable weather (Table XXXIV).[5]

An extension of the work season increases gross revenue in Sweden at a rate estimated at 2% and more of total annual construction costs for each month in which work continues. The following are a few examples of increased gross revenues obtained by extending the work season in Sweden (Table XXXV).[5]

Table XXXIV. Swedish economic feasibility study (after ref 5).

Times during which construction proceeds	Nature of costs	Central Sweden	Upper northern Sweden
Summer and autumn only	Total cost of project	100%	100%
Year-round with steady employment of labor	Increased costs for operations started at most suitable times (June or July)	+6%	+12%
	Reduced costs for elimination of start and stop	−3%	− 6%
	better use of contractor's resources	−8%	−14%
	better use of owner's resources	−1%	− 2%
	lower interest charges	−1%	− 4%
	Total costs of project	93%	86%

Table XXXV. Increased gross revenues (after ref 5).

From	Season extended To 12 months	To 10 months	To 8 months
6 months	12%[a]	9%	5%
8 months	7%	4%	
10 months	4%		

[a] Percentage of total annual construction costs, added to gross revenue.

Canada

C.R. Crocker, in a speech before the Building Research Advisory Board's "Year-round all weather construction" conference in 1968, argued strongly for economical construction in the winter.

> "... the Canadian Construction Association which represents the entire construction industry in Canada conducted a survey among the general contractor members to find out how much extra these contractors provided in their bids for winter work. One hundred and six jobs were studied, ranging in size from about $20,000 to $2.8 million. It was found that on jobs valued at over $500,000, the extra cost averaged less than 1% of the total cost; for smaller jobs, the average extra cost was 1.31%."[2]

He made the statement that, because of the highly competitive business of construction, even an extra 1 to 2% would, in most cases, lose a contractor the job on which he was bidding. This assumes that he can do the job at a later date at the lower price – which is false thinking. It is false if for no other reason than the rising cost of construction (a subject which will be covered shortly).

United States

OECD states that cement and brickwork constructions in the United States cost 0.63 to 6.61% more during the winter and gives an average of 3.5% on 30 projects.

Studies directed by Professor C.W. Lovell, Jr.,[6] in the Purdue School of Civil Engineering, reveal that benefits accrued from winter highway construction for a geographic location like northern Indiana amount to 5 to 15% of the total project cost; whereas, the extra costs needed amount to no more than 5 to 10% of the total project cost.

Economic Advantages

Several variables influence the extra costs of winter construction, but could probably be summarized in these classifications: severity of the climate, size of the construction project, type of project, and starting date of project.

Efforts to combat these variables have discouraged many contractors; but, as more experience is gained, it is increasingly suspected that the only alternative to winter construction – waiting until spring – may be an even more expensive proposition. An economic advantage seems to exist for the contractor to meet his schedule and for the owner to obtain the earlier use of his facility.

Could this be the case? After scanning the available literature, the authors compiled a list of the advantages of winter construction which were mentioned by most sources

Fights inflation

Perhaps the most important factor, which may not have been given due consideration in the past, is the continually rising costs of construction. The building cost index has risen at an annual rate of 5% per year since 1945 and a forecast by *Engineering News-Record*[4] indicates an annual increase of at least 9.2% for 1969. This continual and apparently inevitable annual increase in building costs is a significant factor in determining the optimum date for starting a building project. For example, the cost of building index in January is approximately 4.6% lower than in the following summer.

According to Crocker, "The cost of building in winter must be compared with the cost of building next summer – not last summer."[2]

Restricts extra costs

The next point to remember is that the extra costs of wintertime construction are "related only to those portions of the project carried out in the adverse winter period – not to the whole job."[2]

Retains key personnel

A contractor who shuts down in winter is forced to recruit a new working force each spring. The best workers, naturally, seek work with firms that offer year-round employment.

Spreads overhead costs

Even for the contractor who shuts down in winter, the cost of maintaining a skeleton staff, an office and other overhead expenses during the off season continues.

Speeds up supply deliveries

Supplies are often easier to obtain during the winter because of the suppliers' "slack period."

Reduces summer overtime

According to Bone,[1] Canadian Construction Association, the need to pay costly premium wages for overtime work during the summer peak period is reduced.

Performs work adapted to winter

Working in muskeg areas is much easier in the winter because of the frozen-ground stability. Other tasks may be easier as well.

Maintains productivity of machines and men

According to Crocker, "A start-and-stop operation will be unable, even during comparable periods in the summer, to match the productivity of a competitor who works the year-round."[2]

Eliminates costs of startup and shutdown

Swedish authorities estimate this at 3 to 6% of the project cost.

Provides better use of owner resources

When owners consider the earlier entry into a market, the earlier return on their investment, and the reduced financing costs related to an earlier completion date for their construction project, the factors favoring winter work are usually very obvious. These and other factors encourage an owner and his contractor not to be apprehensive of the financial aspects of winter work.

Summary

Because of the clouded meaning and disparate connotations of the term "costs," a comparison of the costs incurred by various countries in constructing different types of buildings, with variations in construction materials, construction methods, and winter protection measures, seems an impossible, if not fruitless, endeavor.

Nevertheless, if a contractor understands what "costs" mean for him, he can then apply basic methods of comparing the financial implications of alternative working plans (such as winter construction). However, his analysis must give serious attention to "cash flows," rather than concentrating exclusively on "book profit"; for it is these flows that are of prime concern to a contractor.

Of the listed economic advantages for winter construction, perhaps the most important factor is the continually rising costs of construction. The cost of building *this* winter must be compared with the cost of building *next* summer, not *last* summer. The economic advantages of timely completion of construction by the contractor and earlier occupancy by the owner are apparent.

A study of these economic advantages should encourage an owner and his contractor not to be apprehensive of the financial aspects of winter work.

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CONCLUSIONS

During recent years, greater economic prosperity has created a demand for increased winter building activity. However, opinions have differed as to the best methods of winter construction, and no single concept has been formulated. The state of the art is not very far advanced and much study and experimentation are still required.

There is no mystery about winter construction. Each construction task is well defined, as are the winterizing procedures for relaxing the limits otherwise imposed by winter construction on the resources: men, material and equipment.

If winter construction is performed knowledgeably, construction quality does not suffer and costs are usually competitive. These conclusions were reached as early as 1920 by the Honorable Herbert C. Hoover, then Secretary of Commerce, who said:

> "Summarizing the question of winter construction, it may be stated without fear of contradiction that both from an engineering and a quality standpoint any type of modern building construction can be accomplished fully as well, in the winter months as at other seasons, if the proper protection during the progress of certain parts of the work is provided."*

Construction seasonality in the United States is a major economic problem that has been largely neglected. Reducing seasonality and overcoming its effects remain major tasks for the future. Cold weather construction, although not a panacea for seasonal unemployment, would help to alleviate it.

RECOMMENDATIONS

Based upon the findings of this study, further research should concentrate on:

1. topics of significant interest for which the state-of-the-art literature is scarce

2. tasks with the most extreme low-temperature restraints, imposed upon them by the resources (men, material, and equipment)

3. tasks whose existing cold-temperature limits might be lowered through further research

4. military specifications for cold-weather construction which seem unduly conservative or inappropriate in comparison with the consensus of the best construction plans

5. a more comprehensive economic feasibility study.

As an illustration, specific examples of these recommended research items are presented in the following paragraphs:

1. There seem to be three "weak" areas in the present state-of-the-art report on cold-weather construction. Literature concerning plastics, soil stabilization, and the inherent advantages of winter construction (e.g., high, steep frozen cuts) is scarce or nonexistent.

2. Painting and plastering require high temperatures of about 50°F for best application. The initial limiting resource input for both is the material involved (plaster and paint). Because of the sensitive nature of the operations, painting and plastering are expensive when done in cold environments. Therefore, further research aimed towards lowering the existing 50°F limitation should prove helpful.

* Crocker, C.R. (1968) Winter construction in Canada. Paper presented at the *Building Research Advisory Board's Conference, Year-round all weather construction.* 30 Apr.

3. Other tasks are optimally winterized to subfreezing temperatures but possibly could be conducted at still lower temperatures with further research and study. Such tasks include:

a. satisfactory placement of fill at temperatures below 20°F
b. excavation at temperatures below 10°F
c. practicable portland cement concreting below 10°F and bituminous concreting below 45°F
d. practicable masonry construction below 20°F.

4. Existing military guides restrict placing of fills to temperatures above freezing. Successfully constructed embankments at temperatures below this limit are becoming common. Therefore, the military guides concerning this task might be conservative.

U.S. *military specifications* require concrete curing for a considerably longer time and at higher temperature than those found in many European countries and in civilian activities in many of the United States. This suggests that military requirements are possibly conservative in this respect.

Additionally, civilian bituminous concreting is performed at temperatures lower than those allowed by existing U.S. military guides.

The required placing and curing conditions for masonry construction by government organizations within the United States are stricter than those required by other countries. The effects of cold weather on masonry are not well understood; further research in the area is needed.

5. Little pertinent economic analysis has been done in this country. Existing analyses from Europe are helpful but are too far removed from conditions in this country to be applicable. Therefore, further research in this area should be performed.