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THE FROST RESISTANCE OF CONCRETE SUBJECTED TO A DE-ICING AGENT

A THESIS

Submitted to the Faculty of Graduate Studies through the
Department of Civil Engineering in Partial Fulfillment
of the Requirements for the Degree of
Master of Applied Science at the
University of Windsor

by

James D. Whiting

B.A.Sc., The University of Windsor, 1971

Windsor, Ontario, Canada

1974

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DEDICATED TO

my wife and my family for their

continued encouragement

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Abstract

The first part of this thesis is an appreciation of the work performed by others and deals in great detail with the mechanisms of frost action in concrete, the parameters influencing frost action and the effects of the presence of de-icing agents on the frost resistance of concrete.

The next part includes the experimental programme which was designed to investigate the effect of a de-icing agent (NaCl) on the amount of water retained in different types of concrete under various ambient conditions (i.e., 30%, 47%, 72% and 88% relative humidities), and to evaluate the resultant frost resistance of concrete treated in this manner. The first section of this experimental programme involved the conditioning to equilibrium of two sizes of concrete specimens ($1\frac{1}{8} \times 1 \times 2$ inches and $\frac{1}{2} \times 1 \times 6$ inches) in 30%, 47%, 72% and 88% R.H. chambers. The second section of the experimental programme dealt with the frost resistance of the conditioned specimens as well as fully saturated specimens of comparable size, under five freeze-thaw cycles.

One important finding of this thesis was that concrete specimens saturated in higher salt concentrations were found to retain higher levels of saturation for any given relative humidity

condition. Another important finding was that even when concrete is conditioned in a high R.H. atmosphere (i.e., 98%), it can have its moisture content reduced below critical levels for frost damage.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS.	iv
ABSTRACT.	v
TABLE OF CONTENTS.	vii
LIST OF TABLES.	xiii
LIST OF FIGURES.	xiv
CHAPTER	
I Introduction	1
II Mechanisms of Frost Action in Concrete	3
A. Freezing Mechanisms in Cement Paste.	4
B. Freezing Mechanisms in Rock Particles	8
III Parameters Influencing Frost Action in Concrete.	13
A. Frost Action in Rocks Unconfined in Concrete.	13
(1) Critical Size.	14
(2) Pore Structure and Freezable Water	15
(3) Spontaneous Nucleation	18
(4) Critical Degree of Saturation.	18
Summary.	19
B. Frost Action in Rocks Confined in Concrete	19
(1) Time to Reach Critical Saturation.	19
(2) Permeability and Thickness of Mortar Cover.	20
(3) Expulsion Distances.	20

(4) Air-Entrainment of Surrounding Mortar.	21
(5) Critical Degree of Saturation	22
Summary	22
C. Frost Action in Cement Paste Unconfined in Concrete.	
(1) Freezing Point Depressions.	24
(2) Porosity and Pore Structure	24
(3) Permeability of Cement Paste.	25
(4) Air-Entrainment	25
(5) Critical Degree of Saturation.	27
(6) Environmental Conditions.	27
(7) Autogenous Desiccation and Maturity	28
Summary	29
D. Frost Action in Concrete	29
(1) Air-Entrainment	29
(2) Water-Cement Ratio.	30
(3) Maximum Aggregate Size.	31
(4) Maturity of Concrete.	31
(5) Degree of Saturation.	32
(6) Effect of Drying.	33
(7) Autogenous Desiccation	34
(8) Sheathing of Concrete Surfaces.	35
(9) Rate of Freezing and Low Temperatures	35
Summary	35

IV	Front Action Due to De-Icing Agents on Concrete Surfaces	37
	A. Effect of Ponding Salt Solutions on Concrete Surfaces	38
	B. Salt Penetration Into Concrete	38
	C. Physical Attack by De-Icing Agents	40
	D. Freezing Mechanisms in Concrete Under the Influence of De-Icing Agents	41
	E. Preventive and Remedial Measures	44
	(1) Air-Entrainment	45
	(2) Water-Cement Ratio	45
	(3) Slump	45
	(4) Effect of Drying	46
	(5) Protective Sealants	47
	Summary	47
V	Experimental Program	48
	Introduction	48
	A. Desiccation Tests	49
	(1) Preparation of Concrete Specimens	49
	(a) Small Specimens--a Specimens	49
	(b) Large Specimens--b Specimens	50
	(2) Measurements of Weight Change During Desiccation	51
	(a) a Specimens	51
	(b) b Specimens	52

B. Freeze-Thaw Tests.	52
(I) Preparation of Concrete Specimens	52
(a) <u>o</u> Specimens.	52
(b) "Fully" Saturated Specimens.	53
(2) Testing Procedures.	53
VI. Equipment and Materials.	55
A. Equipment.	55
(1) Clipper	55
(2) Mettler P-1000 Weigh Scale.	55
(3) Sartorius Weigh Scale	55
(4) Rachel Metal Desiccator	57
(5) Vacuum Saturation Equipment.	57
(6) Relative Humidity Chambers.	57
(7) Humidity Temperature Recorder and Sensing Elements.	61
(8) Mitutoyo Vernier Calipers	61
(9) Merser Extensometer	61
(10) Freezing Chamber.	63
(11) DCBT Transducers, Their Frames and the Multipoint Strip Chart Millivolt Recorder (Electronik 16).	63
(12) Temperature Potentiometer	63
(13) Millipoint Strip Chart Temperature Recorder (Electronik 12).	65
B. Materials.	65

	(1) Concrete	65
	(2) Sulfur	67
	(3) Salts	67
VII	Development of Experimental Procedure	68
	A. Vacuum Saturation Procedure	68
	(1) Test A	68
	(2) Test B	69
	(3) Test C	69
	B. Control of the Cooling Rate in the Freezer	70
	C. Temperature Lags	71
	D. Calibration of the DCDT Transducers and the Frames in Which They Were Mounted	72
VIII	Discussion of Results	75
	A. Desiccation Tests	75
	(1) Time to Equilibrium	75
	(2) Degree of Saturation at Equilibrium	77
	(3) Time to 91% Degree of Saturation	81
	(4) Total Water Content at Saturation	80
	(5) Rate of Desiccation From a Saturated Condition Down to the 91% Degree of Saturation Level	87
	B. Freeze-Thaw Tests	88
	(1) First Freeze-Thaw Cycle on "Fully" Saturated Specimens	88
	(a) Cooling Cycle	89
	(b) Warming Cycle	90
	(c) Residual Expansion and Maximum Dilations	91

(2) First Freeze-Thaw Cycle on <u>b</u> Specimens.	91
(a) <u>b</u> Specimens From Chambers 3 and 4.	91
(b) <u>b</u> Specimens From Chambers 1 and 2.	94
(3) Four Subsequent Freeze-Thaw Cycles.	97
(a) Cumulative Residual Expansions of the <u>b</u> Specimens.	97
(b) Cumulative Residual Expansion of "Fully" Saturated Specimens.	100
(4) Assessment of Frost Damage.	101
(a) Cast-In-Place Concrete Specimens	102
(b) "Pressed" Concrete Specimens	103
IX Summary and Conclusions	105
APPENDIX A. Experimental Errors	109
APPENDIX B. Development of Experimental Procedure Data	112
APPENDIX C. Data on Concrete Slabs	139
APPENDIX D. Desiccation and Freeze-Thaw Test Data	149
REFERENCES	284
VITA AUCTORIS	286

LIST OF TABLES

	Page
TABLES I - III Degree of Saturation at Equilibrium.	78 - 80
IV Cumulative Residual Expansions	92
V - VI Cumulative Residual Expansions	95 - 96
VII - VIII Cumulative Residual Expansions	98 - 99
B-I Vacuum Saturation Tests.	135
B-II Average Water Contents at 0% R.H.	136
B-III Solubilities of Salts.	137
B-IV Humidity-Temperature Data.	137
B-V Coefficient of Thermal Expansion	138
B-VI Slope/Length.	138
B-VII Scaling Factors.	138
D-I - D-II Time to Equilibrium.	245 - 246
D-III - D-IV Time to 91% Degree of Saturation	247 - 248
D-V - D-VII Water Content at Saturation.	249 - 251
D-VIII - D-IX Rate of Desiccation.	252 - 253
D-X Temperature Logs.	254
D-XI Freezing Point Depressions.	255
D-XII Maximum Dilations.	255
D-XIII - D-LVIII Length Change Data.	256 - 283

LIST OF FIGURES

	Page
FIGURES 1 - 4 Degree of Saturation at Equilibrium.	82 - 85
5 Maximum Dilations vs Cumulative Residual Expansions.	93
B-1 - B-5 Humidity Calibration Curves.	114 - 118
B-6 - B-7 Coefficient of Thermal Expansion	119 - 120
B-8 - B-21 Millivolt Readings vs Change in Temperature.	121 - 134
D-1 - D-56 Desiccation Curves	151 - 206
D-57 - D-64 Length Change Curves	207 - 235
D-65 Average Freezing Point Depressions	236
D-66 - D-72 Cumulative Residual Expansions vs Freeze-Thaw Cycles.	237 - 243
D-93 Cumulative Residual Expansions vs NaCl Solution Concentrations	244

CHAPTER I

Introduction

Over the past few years there has been a considerably increased usage of de-icing salts on concrete pavements, pedestrian malls, etc., in order to provide safer conditions for drivers and pedestrians. Unfortunately, this has resulted in an increased incidence of damaged concrete, in the form of scaling and surface spalling, which has been attributed to frost action, intensified by the presence of de-icing salts. The concrete structures which have been affected most by the presence of de-icing agents are reinforced bridge decks, highway pavements, sidewalks, patio slabs in pedestrian malls and slabs under slope embankments of bridges. The frost damage generally results in concrete surface scaling and in the case of reinforced concrete bridge decks, corrosion of the steel reinforcement, resulting in rust build-up and eventual cracking of the structure.

Although considerable research has been carried out in this subject there is still considerable disagreement as to which mechanism or mechanisms of frost action are primarily responsible for damage; however, there is fairly general agreement that the

damage produced is primarily one of physical rather than chemical attack.

One aspect of this problem that has not received much attention is the effect that de-icers might have on the amount of water retained by concrete under any given relative humidity condition. As water content of the concrete at the time of freezing has an important bearing on its frost resistance, it was felt that this factor might have a bearing on the increased damage produced by freezing in the presence of de-icing salts. This therefore forms the subject of this thesis.

CHAPTER II

Mechanisms of Frost Action in Concrete

Concrete specimens subjected to continuous wetting on all sides or total inundation in water show various degrees of deterioration and damage when freezing temperatures are incurred below the normal freezing point of water. This is generally the behaviour whether concrete is air-entrained or not. However, concrete structures with one surface exposed continuously to the atmosphere prior to freezing may appear to be completely invulnerable to freezing or may show total destruction due to frost action. Over the years much work has been carried out in this area of research to establish the mechanisms of frost action and the important parameters affecting frost action. Even now there is still much controversy surrounding the various theories of frost action that have been proposed by various investigators. As concrete can show such variable behaviour under frost action, it is important to consider freezing phenomena in the cement paste and in the aggregate individually in order to understand freezing phenomena in concrete.

A. Freezing Mechanisms in Cement Pastes

Originally Powers¹ proposed that frost damage in cement paste was the result of stresses developed in the pores by the generation of hydraulic pressure. This pressure he claimed is due to the resistance of expulsion of gel water away from the freezing zones in the pores. The extent of the hydraulic pressure would depend on the critical thickness of the paste, porosity and permeability of the paste, the degree of saturation of the paste, the rate of freezing and the length of the flow-path to the exterior or to the nearest air bubble..

At the present time many researchers still consider this hydraulic pressure theory to be the most important mechanism for frost action in cement pastes. However, Powers no longer believes this to be true and has introduced a new mechanism of frost action in cement pastes.

In his latest work Powers² observed that the movement of water during freezing in cement paste is, for the most part, not away from the sites of freezing but towards them. Although hydraulic pressure may exist in cement paste during freezing he now claims the principal cause of stress is due to osmotic pressure, which he explains as follows. In cement paste the pore water contains dissolved solutes, mainly the alkalis. This dissolved material lowers the melting point of ice; thus in cement pastes there are

many melting points for ice. For a virtually saturated cement paste; when the temperature has fallen below the highest melting point for the cavities, most of each frozen cavity contains ice and the rest is an increased concentration of the alkali solution in those cavities. Some of the original dilute solution is forced through the cement gel to the exterior; hydraulic pressure is thus developed during this process and if not excessive the structure remains intact. However expansion may still occur since there is now a cavity containing a concentrated solution in contact with a less concentrated solution from the gel pores and from the exterior. The water molecules in the gel pores proceed to dilute the concentrated solution in the cavity by diffusing into it, while the solute ions in the stronger solution proceed to diffuse into the weaker solution of the gel pores. Since the volume of water moving into the cavity is much greater than the volume of solute ions able to move, osmotic pressure is developed in the cavity opposing the diffusion. If the cavities are not completely full of ice and concentrated solution at the time of freezing, then the osmotic pressure will be negligible. However when the cavities become full, osmotic pressure will develop. The magnitude of the osmotic pressure developed depends upon the difference in concentration of the solutions in the cavities and in the surrounding cement gel.

When air bubbles are supplied to the cement paste by air-entraining agents, such cavities are initially empty and because of

their large sizes they are normally difficult to fill with water. The function of entrained air is to provide cavities which can contain ice and displaced pore water solution but which cannot become filled under normal conditions. Even with the presence of saturated capillary cavities in the surrounding cement paste which are able to develop osmotic pressure, water diffuses due to the unfilled air bubble from the cement gel where its diffusion is not opposed by osmotic pressure. Freezing of air-entrained cement paste not only relieves osmotic pressure but desiccates the paste. If the air bubbles are situated such that their spacing is close enough together dilation due to the development of osmotic pressure is eliminated and the net effect of freezing is harmless shrinkage.

Litvan³ has recently proposed a new mechanism for frost action in cement paste. In this theory it is suggested that water which is adsorbed on the surface or contained in the capillary pores does not freeze in situ but must be redistributed. A failure to solidify in situ is caused by a restriction of the mobility of water molecules to form in the required arrangement for crystal lattice formation due to surface forces. Below the normal freezing point of bulk water the unfrozen adsorbed undercooled water has similar properties to bulk supercooled water; however, the freezing of adsorbed undercooled water cannot be initiated by nucleation. Therefore at a temperature below the freezing point of bulk water

there will be present simultaneously adsorbed undercooled water in the cement paste and bulk ice in the surroundings of the paste system. Because the adsorbed undercooled water has a higher vapour pressure than the bulk ice, there exists a non-equilibrium state which cannot be maintained. Since the vapour pressure difference cannot be eliminated by solidification of adsorbed water, a different mechanism is used to create equilibrium. By the expulsion of some of the adsorbed undercooled water the cement paste can equilibrate with the ice crystals in the surroundings or in larger pores of the paste that maintain a relative humidity with reference to bulk water below 100% R.H. Once redistribution has occurred the exuded water immediately freezes and the newly formed ice crystals are indistinguishable from those of the bulk ice. The cement paste is now partially desiccated and is in equilibrium with the bulk ice. This mechanism can damage cement paste or concrete in different ways. If a flaw exists in concrete and is surrounded by a strong sound portion of concrete, water will migrate to the crack during freezing, filling it completely, and on solidifying it causes the crack to propagate. With continued cooling, the mechanism operates with increasing severity until total destruction results. Damage is caused by the rapid accumulation of water beneath a dried-out surface area which impedes moisture flow and this leads to surface scaling. Damage also occurs when the required water expulsion rate necessitated by rapid cooling is so high that the water cannot reach the external surfaces and

solidifies in the large cavities; Litvan claims this results in a large expansion and even damage to the system.

When frost damage occurs in concrete it may be due to the dilation of cement paste alone; however, dilation may also be a result of pressures developing in rock pores. Therefore freezing phenomenon in rock particles must not be excluded from the discussion of frost action.

B. Freezing Mechanisms in Rock Particles

According to Powers² the mechanism by which freezing causes a rock to dilate is less complicated than that causing cement paste to dilate. Whereas, he claims that osmotic pressure is the dominant factor in the mechanism of the frost action in cement paste, he thinks that it is a minor factor, if it exists at all in rock. Frost damage in rock he claims is primarily due to stresses produced in the pores developed by hydraulic pressure. When water freezes, it expands 9.07% by volume; if this expansion of water is prevented forcibly, freezing does not occur. The force required to prevent expansion and freezing is that which raises the hydrostatic pressure to a great degree. A rock able to absorb water contains a system of inter-connected capillaries in which freezing occurs. As freezing progresses in a saturated rock particle, resistance to expulsion of excess water away from the freezing zones develops in the

capillaries. This effect of hydraulic pressure may be very damaging to the rock or the concrete surrounding the rock.

Dunn and Hudon⁴ have also proposed a theory for frost action in rock particles. In the case of carbonate aggregates, they observed using D.T.A. measurements that the majority of frost sensitive aggregates have less than 50% of their contained water freezing, whereas in sound aggregates most of the water freezes rapidly. They found that frost sensitive rocks could be grouped into a two-end member series of unsound rocks, one end being the truly frost sensitive rocks and the other being the sorption-sensitive rocks. Truly frost sensitive rocks were found to saturate critically with water by immersion whereas the sorption sensitive rocks saturated critically by adsorption of water from the atmosphere. They proposed therefore that during freezing, truly frost sensitive rocks fail due to the hydraulic pressure theory, while, the sorption sensitive rocks fail due to some other mechanism. They suggested that the water adsorbed by sorption sensitive rocks is unfreezable, because the relative vapour pressure of adsorbed water is lower than the relative vapour pressure of bulk ice at a given temperature. This adsorbed, non-freezable water, they claim, plays an important role in the failure of certain rock types. Adsorbed water, they suggest, has some rigidity which is imparted to the adsorbed water by the pore surfaces to which it adheres. They claim that there is a strong bond between the water molecule layers and the

pore surfaces and the strength of this bond varies inversely as the distance increases from the surface of the water molecule layers.

This means that adsorbed water is much more securely held in frost sensitive rocks than in sound rocks. Thus when a sorption sensitive rock is saturated, part of the adsorbed water becomes ordered.

With a temperature decrease, the polarity of the water increases causing continued ordering of the adsorbed water. If the specific

volume of the ordered water is larger than that of bulk water, a

temperature decrease will result in a volume increase of the adsorbed pore water. If the ordering forces equals those of ice crystallization

and if the rigid ordered water is not allowed to escape from the pore,

disruptive hydraulic forces will be generated. Repeated cycling of

freezing and thawing fatigues the rock, permanently enlarges the

pores, and allows more water to freeze to produce normal frost-type action.

Everett⁵ has presented a thermodynamic approach to the understanding of frost action in porous materials such as rocks. His basic approach involves the thermodynamics of growth of an ice crystal in a pore which is subjected to an exterior constraint such as the walls of the pore. Consider a simple model of two completely water-filled pores A and B connected by a capillary tube, with the water in both pores subjected to an initial pressure P_1 . As the temperature is lowered to 0°C , freezing is nucleated in pore B and

as freezing proceeds expansion takes place in both pores. When pore B is completely filled with ice, a further temperature decrease could result in ice formation in two ways (assuming no nucleation of ice occurs in pore A): (a) by extension of ice crystals along the connecting capillary or (b) by continued ice crystal growth over the interface between the bulk ice in pore B and the liquid water in the capillary tube accompanied by a flow of water from pore A to pore B and exertion of pressure on the walls of pore B. The bulk ice in pore B now has a pressure P_B exerted on it and the liquid water in pore A and in the capillary tube has a hydrostatic pressure P_A exerted on it. Providing ($P_1 = P_B = P_A$) there will exist a flat plane interface between the bulk ice in pore B and the liquid water in the capillary tube; thus there will be no tendency for the bulk ice to penetrate the capillary. If the pressure P_B remains constant, bulk ice crystals will continue to grow in pore B drawing water from pore A at the desired equilibrium temperature. When the flat plane interface between the bulk ice and the liquid water exists the chemical potential of the bulk ice is much lower than that of water. However, with the continuous growth of ice crystals in pore B, the pressure P_B is progressively increased and the chemical potential of the bulk ice is greatly increased. Now there exists an interface of ice and water with a fully developed hemispherical shape and this ice has a higher chemical potential

than the bulk ice at a new equilibrium temperature. A further increase of the pressure P_B leads eventually to the condition where the chemical potential of the bulk ice in pore B is raised above that of the hemispherical cap of ice in the capillary and the thermodynamically preferred process changes from the growth of bulk ice in pore B to the propagation of ice into the capillary tube. Therefore Everett claims that in rocks, frost damage will occur when the excess pressure ($P_B - P_1$) is built up such that it exceeds the strength of the pore walls. Also he suggests that an equilibrium state in a rock can only be attained when this excess pressure which is applied to the bulk ice to stop ice growth is equal to the tension ($P_1 - P_A$) which is applied to the water to achieve the same result. This model suggests that frost damage is associated with rocks in which their coarse pores are separated from each other by microporous regions. Everett claims further that frost damage of rocks in service is not only associated with the existence of small pores but with the regular occurrence of pores of critical size amidst coarser pores. The factor determining the pressure built up in the macroporous region of rocks will depend on the size of the largest capillary leading out of it.

CHAPTER III

Parameters Influencing Frost Action in Concrete

There are several important parameters which influence the frost resistance of concrete. In order to understand the overall effect of frost action in concrete it is necessary first to examine the factors influencing frost action in the individual constituents of concrete, i.e., the aggregate and cement paste. Subsequently, the parameters influencing frost action in concrete will be discussed.

A. Frost Action in Rocks Unconfined in Concrete

A rock which has the ability to absorb and retain water contains a system of interconnected capillaries in which freezing of the water takes place. According to Powers², during freezing a resistance to the expulsion of excess water develops in these capillaries. Flow lines of expelled water from the frozen zone of a saturated portion of a rock propagate through an unfrozen portion of the rock and these flow lines represent hydraulic pressure. For a given distance of flow and a given rate of flow the maximum pressure is directly proportional to the resistance of

viscous flow which in turn is related to the coefficient of permeability of the rock.

1. Critical Size: Powers² claims that for a saturated rock frozen at a given rate, there exists a critical size or thickness of the rock, above which size the force generated by hydraulic pressure is able to damage the rock particle. These critical sizes or thicknesses are usually in the order of inches or tenths of inches. Vesicular basalts have virtually no critical size because they have a capillary system periodically interrupted by cavities, which remain virtually empty under normal conditions. Therefore the freezing process normally does not harm these rocks; however, in general, most rocks have critical sizes. In the case of instantaneous freezing of saturated aggregates, Verbeck and Landgren³ discovered that rocks of low porosity (0.3% by volume or less) can be accommodated elastically without damage. This is so they claim because the tensile stresses required for elastic accommodation were less or equal to the tensile strengths of the aggregates and these aggregates also have no critical sizes. They state that for saturated rocks freezing at a rate similar to that in nature, the aggregate of moderate porosity but of low permeability such as chert has a very small critical size and may fail by the development of high internal hydraulic pressures. However an aggregate of high porosity and high permeability such as dolomite

has a large critical size and does not fail due to internal pressure developed during freezing. They have also shown in their results that the greater the aggregate size, the greater the probability of it being vulnerable under freezing conditions. This size effect they associated with the need for redistribution of water in the rock.

Powers² implies that frost resistance is reduced when a rock has a relatively small critical size. A small critical size is characterized by (a) a high capacity for freezable water and (b) a low-coefficient of permeability or in other words a high porosity and a fine pore structure.

2. Pore Structure and Freezable Water: The capacity for freezable water refers to the amount of water that will freeze in a unit volume of rock at a specified sub-freezing temperature. Within a rock there are a variety of pore sizes. Not all the water contained in the rock freezes at the bulk freezing point of water. The smaller the capillary diameter, the smaller the radius of curvature of the meniscus and the lower the freezing point of water. In extremely fine pores, where all the water is tightly held adsorbed water, such water virtually will not freeze at any temperature. In the sorption sensitive rocks studied by Hudcok⁴ less than 50% of their contained water is freezable and the rest is unfreezable adsorbed water. In such sorption sensitive rocks, frost deterioration, according to Hudcok⁴ is not a result of hydraulic

pressure but rather due to the tearing apart of the rocks by the constant ordering and disordering of the adsorbed water during temperature changes. This form of deterioration applies to rocks with a fine pore structure, e.g., rocks containing a high percentage of clay minerals. Dunn and Hudc⁷ suggest the pore sizes most likely to cause deterioration by freezing and thawing of adsorbed water are those which are less than 4 to 5 microns in diameter especially when these represent a relatively large volume of pores. Pore sizes less than 4 microns in diameter will empty effectively only at extreme pressures which cause the rock to fail in tension. A harmful pore size is one which is large enough to allow water to enter readily into a high percentage of the pore spaces but not large enough to allow easy expulsion.

Of equal importance to specific capillary pore size is the particular mixture of pore sizes that occur in a rock. Thus, some limestones may have a low porosity and a coarse pore structure but if it contains a thin layer of clay or shale, this layer may have a high porosity and a fine pore structure resulting in a low critical thickness; thus during freezing, the layer fails and splits the limestone. Everett⁵ expressed a somewhat similar idea when he states that frost damage in rock is not only associated with the presence of fine pores but with the simultaneous occurrence of pores of critical size together with coarser pores; in other words, rocks have a poorer frost resistance when the macroporous

structure of the rock is imbedded into the microporous matrix of the rocks. This is the case he claims because the factor establishing the pressure generated in the macroporous region depends on the size of the largest capillary leading out of it.

According to Verbeck and Landgren⁵ fine pore aggregates such as traprock adsorb considerably more water and attain a higher degree of saturation at any given relative humidity condition than aggregates with coarse pore structures such as dolomite. Traprock reaches a high degree of saturation more rapidly than dolomite even if the aggregates have the same porosity and also traprock has a much higher rate of absorption than dolomite even if the aggregates are compared at equal degrees of saturation. For aggregates of similar pore size distribution, the higher porosity aggregates such as dolomite require more time to reach any particular degree of saturation than lower porosity ones like traprock.

Litvan³ suggests that rocks which have a coarse pore structure and a high permeability can exude excess water and when the expelled water freezes on the external surface of the rock there is a large heating effect which is evident in a single pulse denoting the formation of a large amount of ice. However, low permeability rocks cannot reduce their water contents to the required level and the subsequent ice formation in the non-equilibrium state is not abrupt but continuous, with little observable temperature elevation.

3. Spontaneous Nucleation: Dunn and Hudec⁷ claim that when ice forms in the larger pores at a given temperature this initiates freezing in the smaller diameter pores which might not have frozen otherwise until much lower temperatures were reached. Once ice starts to form in supercooled water it does so rapidly, propagating itself through the capillaries and pores until some barrier is confronted to stop or reduce the freezing process. The presence of solutes in the pores of rock will also lower the melting points of ice in rock.

4. Critical Degree of Saturation: Frost resistance in a rock is dependent on the rock's ability to attain and retain a high degree of saturation. Powers² suggests that when a rock particle reaches 91.7% of its capacity for freezable water, with the water evenly distributed, freezing will gradually fill the pores as the freezing advanced with no transfer of water from one section of the rock to another, providing the rock is larger than its critical size. In practice, however, the water is not evenly distributed within the rock; therefore the critical value for degree of saturation may be much less than 91.7%. Thus there can be no exact value for the critical degree of saturation of a rock particle. MacMillan⁸ claims that the value of critical degree of saturation for rocks is inversely proportional to that of porosity.

Summary: The frost resistance of a rock unconfined in concrete can be greatly increased if the rock particle has a large critical size, a low porosity and a coarse pore structure and if it is not critically saturated.

B. Frost Action in Rocks Confined in Concrete

—Verbeck and Landgren⁵ have indicated that the frost resistance of concrete made with different aggregates depends upon the rate at which the different aggregates reach critical saturation in the concrete and upon the different responses of the aggregates during freezing. They have shown that the time required for an aggregate to become critically saturated in concrete is influenced by the thickness and permeability of the mortar cover over the aggregate. There are different factors which affect the freezing of fully saturated aggregates in concrete such as the influence of confining mortar (external expulsion distances and external hydraulic pressures), soluble material, degree of saturation and freezing point depression in fine pores.

1. Time to Reach Critical Saturation: If an aggregate in concrete receives some degree of drying in the summertime, it may react satisfactorily if the required time for it to reach critical saturation is longer than its wintertime exposure to wetting and freezing even though the aggregate would cause damage if it were

frozen while saturated. Powers¹ suggests that once rock particles are dried, they cannot readily be resaturated when embedded in concrete and therefore remain safe during a relatively long soaking period.

2. Permeability and Thickness of Mortar Cover: The permeability of the mortar cover around the aggregate depends on the water-cement ratio and the degree of hydration of the cement paste. The permeability of cement paste is lower--the lower the water-cement ratio and the greater the degree of hydration. The length of time needed to destructively saturate the aggregate in concrete is beneficially lengthened by the use of low water-cement ratio paste and a greater thickness of mortar cover.

3. Expulsion Distances: A saturated aggregate which has a porosity greater than that which can be elastically accommodated and has a size smaller than its critical size must expel excess water during freezing into the surrounding mortar without generating hydraulic pressure exceeding the tensile strength of the aggregate. Verbeck and Landgren⁵ suggest that expulsion distance into the surrounding cement paste are small for moderate porosity aggregates such as chert and are large for high porosity aggregates such as dolomite. The smaller the expulsion distance required and the smaller the maximum size of the aggregate such as dolomite the less

chance there will be for development of stresses in the aggregate. The time required to destructively saturate an aggregate in mortar is significantly longer for smaller size aggregate particles.

4. Air-Entrainment of Surrounding Mortar: Verbeck and Landgren⁵ have shown that air-entrainment of the surrounding mortar reduces the expulsion distances and serves to decrease the high vulnerability of a saturated aggregate considered as unsound when used in non air-entrained concrete. Powers² believes this amount of pressure relief is highly overestimated by Verbeck and Landgren because they assumed that the out-flow through one square centimeter of rock occurred through one square centimeter of paste. According to Powers, if a rock has a capacity for freezable water of say 5% by volume then about 95% of the contact area transmits no water to the surrounding cement paste rather than all of it as assumed in the calculations by Verbeck and Landgren. When air-entrained bubbles are present in the cement paste approximately 50% of the paste area bordering an air bubble can transmit moisture; however the total interfacial area between an aggregate particle and an air bubble is approximately 1.5% because the rock particle is covered with a layer of cement paste. Therefore, compared with the process of expelling water from a saturated thin layer of cement paste into an air bubble, the process of expelling water from a rock to the nearest air bubble must involve extremely high local pressures and if the pressure does not destroy the rock it may

separate the rock from the matrix. Under-aggregate fissures, developed in concrete during bleeding, are no doubt an alleviating factor in reducing hydraulic pressures and may be more effective than air-entrainment.

5. Critical Degree of Saturation: Powers¹ indicates that whether or not air-entrained concrete is ever destroyed during the freezing process depends on whether or not any rock-particles contain dangerous amounts of water at the time of freezing. According to Verbeck and Landgren², if the degree of saturation does not exceed 91.7% then no water has to be expelled, and therefore no hydraulic pressure is developed. However, Powers³ suggests that if the degree of saturation of a rock in concrete is critical then the local rate of flow to relieve hydraulic pressure must be quite high because most of the rock pore water freezes in a narrow temperature range.

Summary: The time required for saturated rock particles confined in concrete to reach a critical level of saturation is dependent on the thickness and the permeability of the mortar cover. The frost resistance of the same rocks is influenced by external expulsion distances, air-entrainment of the surrounding mortar and the critical degree of saturation of the rocks.

C. Frost Action in Cement Paste Unconfined in Concrete

There is general agreement among all researchers in this field that frost resistance of cement pastes is fundamentally related to the pore structure of the paste. Cement paste is composed of (a) cement gel plus gel pores (b) capillary pores and (c) residues of anhydrous cement particles (if any exist). Cement gel is composed of (a) gel particles which are the solid portions of the cement gel and occupy 72% of it and (b) gel pores which occupy the other 28% and are accessible to evaporable water. Powers² claims that gel pores have an average width of 15 Å or 5 times the diameter of a water molecule, whereas the gel particles are only 30 Å to 40 Å thick or 10 to 13 times the diameter of a water molecule. The capillary pores are usually much larger than the gel pores in cement paste. Pore dimensions are emphasized because they have an important effect on the freezing of water in cement paste. There is a range of ice crystal sizes for which the melting point is a function of the size that can exist within a range of pore sizes in cement paste. At 28.4°F an ice crystal of 180 Å can exist in a capillary pore of size 208 Å and at -4°F an ice crystal of 18 Å can exist in a capillary pore of size 35 Å. The capillary pore size must be considerably larger than the ice crystal because of the space required by an adsorbed water layer in the pore which cannot become frozen at the given temperature. This adsorbed water layer has a thickness of about 14 Å at 28.4°F.

and is reduced to about 8 Å at -4°F .

1. Freezing Point Depression: Pore sizes in cement paste (as in aggregate) affect the freezing point of water. In addition the presence of dissolved alkalis lowers the freezing point of water in cement paste. Thus for a given alkali content, Powers² claims, the freezing points of water vary throughout the cement paste according to the differences in pore size. At any given sub-freezing temperature, all the pores too small to accommodate ice crystals of a viable size at a given temperature will not freeze. Except at extremely low temperatures where spontaneous nucleation can take place, freezing is initiated by seeding at the surface and then propagates through the specimen through channels that are large enough to permit it. If cement paste has an extended contact with an outside supply of water, the capillary pores will ultimately become filled because they are so small that they can readily be filled by capillary absorption.

2. Porosity and Pore Structure: According to Powers² cement pastes have a small critical thickness which is accounted for by (a) a high capacity for freezable water and (b) an extremely low coefficient of permeability or in other words a high porosity and an extremely fine pore structure. The critical thicknesses of cement pastes are usually in the order of thousandths

of an inch and probably do not exceed 3 thousandths of an inch. Litvan³ also claims that the pore structure of cement paste is probably the most important property affecting frost resistance. Very large and very small pores are preferable to those of intermediate size between 300 Å and 40 Å because the large pores are seldom full and the small ones become involved in the freezing mechanism only at extremely low temperatures. Pore structure he claims is determined by the water-cement ratio of the paste. Since the drying rates of cement pastes of different water-cement ratios are equal, the higher porosity pastes require a longer time to desiccate and are more susceptible to frost damage for a longer duration of time. The amount of water to be expelled during freezing depends on the porosity of the cement paste.

3. Permeability of Cement Paste: The ease of flow of water through a cement paste depends on the permeability of the paste. Litvan³ implies that it is not the reduction of water content in cement paste that is detrimental during freezing; but it is the restriction of flow which impedes the process that causes the damage. A low permeability cement paste may cause such a condition. Cement pastes with high water-cement ratios (owing to higher water contents) require higher permeabilities if frost damage is to be prevented. Since cement pastes of different water-cement ratios have similar desiccation rates, it follows that with an increase in water-cement

ratio, the required amount of water to be expelled increases considerably without the benefit of increased permeability. In order to prevent destruction in cement paste the rate of cooling has to be less than a limiting value which is determined by its permeability. If the cooling rate is constant, an increase in dilation can be produced by a gain in water content due to an altered permeability and porosity of the paste resulting from frost damage.

4. Air-Entrainment: Air-entrainment in cement paste is a beneficial factor increasing the frost resistance of the paste. In reference to Powers' mechanism of frost action in cement paste, the dilation due to hydraulic pressure and osmotic pressure can be eliminated with the proper amount of air-entrainment. When air bubbles are present, they are empty from the start and are very difficult to fill with water and under normal conditions their water content will be far below critical values at the time of freezing. Even if the surrounding pastes become critically saturated, the overall effect during freezing is shrinkage rather than expansion if the air bubbles are closely spaced, i.e., about 0.006 inches apart. If the air bubbles are close together, this eliminates the need for migration of water to external surfaces during freezing. According to Kelvin's equation⁹, at relative vapour pressures greater than 0.95, pores with radii greater than

300 Å are empty. These pores act as reservoirs and they can accommodate expelled water from the smaller capillaries during freezing temperatures. These large pores constitute the air bubbles produced from air-entrainment.

5. Critical Degree of Saturation: As in rocks the degree of saturation of cement paste is a relevant factor at the time of freezing. If a paste is partially saturated, a fraction of the large pores are empty, thus less water has to be expelled and the partially empty pores act as reservoirs that accommodate the expelled water from nearby pores involved in the freezing process. Litvan³ indicates that the dimensions of the cement paste determine the distance of the migration path of water on wetting and thus affects the degree of saturation for a given soaking period and the expansion on freezing. Even at relatively high water contents, there will be no frost damage occurring if the degree of saturation is less than a critical value. Litvan⁹, MacInnis and Beaudoin¹⁰ believe the critical value to be around 91% and it was found to be accurate for mortar mixes. Powers² has emphasized that this number may be less than 91.7% depending on how the water is distributed within the cement paste.

6. Environmental Conditions: According to Litvan³, after complete hydration the total pore volume and pore size

distribution in cement paste remains unchanged, and whether the pores are filled with water or stay partially filled is decided by environmental conditions such as relative humidity and temperature. The higher the R.H. of the environment the higher the degree of saturation of the paste. Also the lower the temperature attained during freezing the greater the volume of pores that will be involved in the freezing process.

If the rate of cooling is slow, desorption of the paste can take place in an orderly fashion; however, if it increases slightly, this can result in frost damage.

7. Autogenous Desiccation and Maturity: According to Beaudoin and MacInnis¹⁰ two factors which affect the development of a critical pore structure are self-desiccation and maturity of the paste. If there is no water movement to or from the cement paste during hydration, then the hydration reactions continue until little or no water is left to saturate the solid surfaces of the paste and as a result the amount of free water in the paste decreases; this phenomenon is known as self-desiccation or autogenous desiccation. As the water-cement ratio increases so does the time required for the self-desiccation phenomenon to give the cement paste frost resistance. This is so because with a higher water-cement ratio there is more free water available at any given state of hydration to influence dilation behaviour due to temperature

change. The extent of self-desiccation is related to the degree of hydration of the paste which is related to the maturity of the paste.

Summary: The frost resistance of unconfined cement paste is greatly influenced by freezing point depressions, porosity, pore structure, permeability, air-entrainment, critical degree of saturation, environmental conditions, autogenous desiccation and maturity.

D. Frost Action in Concrete

Powers¹ has shown that the effect of freezing in concrete depends on the size or thickness of the concrete and the degree of saturation of the concrete. In air-entrained concrete there is a sequence of reaching saturation. The cement paste, excluding entrained air bubbles, will become almost completely saturated first, then the aggregate (although full saturation will be reached at about the same time for cement paste and the aggregate) and finally the air-entrained bubbles.

1. Air Entrainment: Powers¹¹ suggests that when an aggregate becomes critically saturated, freezing will cause it to try to expel excess water into the already saturated surrounding

cement paste. Although the air bubble system may be adequate for controlling freezing in the saturated pastes, its spacing factor may be too far apart with respect to the excess water expelled from the aggregate. Consequently when freezing occurs, the water expelled from the aggregate produces a force that tends to separate the aggregate particles from the matrix without damaging the aggregate; thus a failure in the matrix may be due to water in the aggregate. If the paste becomes critically saturated and the aggregate does not, entrained air can prevent stress in the concrete during freezing by developing harmless shrinkage in the paste. However if the concrete remains continually wet for a long period with the result that the aggregate gets completely saturated and the entrained air voids in the cement paste become filled with water, then this concrete will ultimately be damaged by frost action. However, it is emphasized that this represents an extreme and rather uncommon environmental situation.

2. Water-Cement Ratio: For concrete specimens made of various water-cement ratios there are varying degrees of frost resistance. Mather¹² suggests that if the total amount of freezable water expressed as a fractional volume of concrete is very low, then no harm will happen to the concrete if all of it freezes, even if the concrete has no entrained air and the pores that can

contain freezable water are full and remain full. MacInnis¹³ has shown that for a water-cement ratio of 0.45, the degree of saturation of air-entrained concrete can be close to 100% and still show no expansion at sub-freezing temperatures.

3. Maximum Aggregate Size: Frost resistance of concrete is very much affected by the maximum size of the aggregate as well as the water-cement ratio. MacInnis and Lau¹⁴ showed that concrete specimens made with $\frac{1}{2}$ inch maximum aggregate size showed expansions during freezing only when the water-cement ratio was greater than or equal to 0.50 and specimens made with $\frac{3}{4}$ inch maximum aggregate size showed expansions only when the water-cement ratio was greater than or equal to 0.45. Therefore the smaller the maximum aggregate size the more frost resistant will be the concrete.

4. Maturity of Concrete: Maturity of concrete means essentially the degree of hydration. Hydration continues until (a) the supply of hydratable cementitious material is exhausted or (b) there remains none of the originally water filled spaces in which to lay down more hydration products. The greater the amount of cement hydration products formed the less freezable water fillable spaces there are. The degree of maturity required is a function of the severity of frost action to be resisted. Powers¹⁵

has shown that for green concrete to be frost resistant its maturity factor must be equal to 53% of the water-cement ratio or its compressive strength must be equal to 430 psi for a prescribed prehardening time of 24 hours. These results are based on the assumption that no water from the surroundings be supplied during this 24 hours. The maturity factor and the prehardening time required for frost resistance increase with an increase in the water-cement ratio.

5. Degree of Saturation: According to Powers¹⁶ the theoretical critical degree of saturation for concrete is 91.7%; however, concrete can be damaged when the overall degree of saturation is far below this value; therefore we must be concerned with the degree of saturation of the vulnerable component. Fagerlund¹⁷ suggests that critical degree of saturation is a material constant that has an individual value for each particular material. If the critical degree of saturation is to be defined it is necessary to know the amount of non-freezable water in the concrete at the lowest temperature and the total open pore volume in the concrete. If the moisture conditions reached in service for concrete are known then the frost resistance is equal to the critical degree of saturation minus the actual degree of saturation.

The critical degree of saturation increases with increasing pore size at a certain critical depth and time. Powers² relates that if the aggregate particles and the capillary pores in the paste remain below the critical saturation point, freezing will not produce stress in concrete, regardless of whether air-entrainment is used or not. Hardened cement paste has no critical saturation point if it contains an adequate air-entrainment system and rock has no critical saturation point if it is smaller than its critical size for its type and for a given rate of freezing.

6. Effect of Drying: Powers¹ suggests that in most cases concrete is usually not perpetually wet. Seasonal drying gives it a reprieve every summer and this drying may be sufficient to lower the degree of saturation below the critical value and thus increase frost resistance. Malisch¹² claimed that the increase in frost resistance as a result of some degree of drying is not due to a reduction in saturation but rather to an increase in the permeability of the concrete resulting in a reduction of the pressure developed. Transpiration according to Powers² can reduce the degree of saturation in a concrete structure. Concrete which has one section of its structure in contact with moisture (say the earth or a hydraulic head) and the other section exposed to the atmosphere can lose water. Water is lost from the concrete by evaporation.

from the exposed surface to the atmosphere providing the internal humidity within the concrete is higher than the humidity of the atmosphere. A continual flow of moisture from the saturated section of the concrete upward and through to the atmosphere can be maintained only if the rate of evaporation at the dry end of the concrete is equal to the rate of flow through the saturated section or any other section of the concrete/structure. This moisture flow develops a hydrostatic pressure and with air-entrained concrete, only where the hydrostatic pressure becomes positive, is it possible for any component of concrete to become critically saturated. Carlson and Davis² indicated that transpiration into a 50% R.H. atmosphere could transfer water through an 8 foot section of concrete more quickly than water could be forced through 4 inches of the same structure under a hydrostatic pressure of 100 psi. For safety from frost action it appears that only a slight desiccation period is necessary.

7. Autogenous Desiccation: In green concrete, Powers¹⁵ suggests that immunity to damage after a certain time is not a result of strength development per se but it is due to the absence of destructive forces during freezing which is accounted for in the reduction of the degree of saturation of the cement paste that develops in the early stages of hydration. During the period prior

to the removal of the moulds, green concrete acquires little or no water from outside sources, so the concrete is subjected to autogenous desiccation where water is being used up in the capillary pores to produce hydration products. Safety from frost damage due to autogenous desiccation may only be temporary because if the concrete receives moisture from the surroundings, the cement paste may render itself vulnerable to the freezing process. This might occur very rapidly if the paste is not air-entrained. Powers¹⁶ explains that there is an advantage to using a low water-cement ratio concrete because during freezing the concrete desiccates to a greater extent thus reducing the possibility of frost damage.

3. Sheathing of Concrete Surfaces: If sheathing is present under concrete structures, such as stay-in-place forms on the underside of bridge decks or the subgrade existing beneath highway pavements, then high moisture contents can be expected in such structures¹⁷. Stay-in-place formed bridge decks have a greater moisture content in them at any depth through the structure than do conventionally formed decks where the forms are removed. The conventionally formed bridge decks are allowed to dry from both surfaces whereas the stay-in-place forms can only dry from the upper exposed surface. The high degree of saturation that can be attained by the stay-in-place form bridge decks can be very

damaging to the structure during winter exposure.

2. Rate of Freezing and Low Temperatures: The rate of freezing and the temperature regime are important factors influencing frost resistance in concrete. According to Powers¹ the length of time at a low temperature is important for development of osmotic pressure primarily in the cement paste and possibly in the aggregate particles. The rate of freezing is important for the development of hydraulic pressure primarily in the aggregate particles and to some extent in the cement paste. Evans and Hesser¹⁸ suggest that the freezing rate of 5°F/hr simulates very well the rates attained in nature and should be used when freeze-thaw tests are prescribed. With a slower rate of freezing, saturated concrete has a better chance to expel its excess water produced during freezing in order to prevent frost damage.

Summary: Frost damage in concrete is greatly reduced if air-entrainment is incorporated with an air bubble spacing of about 0.005 inches and if low water-cement ratios and small maximum aggregate sizes are used. Other factors influencing frost action in concrete are maturity, degree of saturation, effect of drying, autogenous desiccation, shrinkage, rate of freezing, and low temperatures.

CHAPTER IV

Frost Action Due to De-Icing Agents on Concrete Surfaces

During the winter, salts and other agents are often applied to concrete road surfaces, sidewalks and bridge-decks to remove ice from these surfaces. These materials have in many cases caused serious deterioration of the concrete. This deterioration usually takes the form of surface mortar spalling or scaling as well as corrosion of the steel reinforcing bars in concrete bridge decks and cracking of the concrete caused by the build-up of rust from the corrosion of steel. Often these salts are retained or ponded on the surfaces due to lack of good drainage. When frost action takes place in the presence of de-icers the severity and rapidity of scaling is greatly increased. It has been found that greater scaling occurs in non air-entrained concrete.

With repeated salt applications, salt solutions eventually penetrate into the porous concrete structures. In bridge decks, a high salt concentration builds up at the level of the steel reinforcement and corrodes the steel. Ultimately the structure cracks due to the build-up of rust.

Various types of de-icing agents have been used on concrete surfaces in service, e.g., sodium chloride, calcium chloride, ammonium nitrate, ammonium sulfate, urea and ethyl alcohol.

A. Effect of Ponding Salt Solutions on Concrete Surfaces

Neville¹⁹ investigated the effect of ponding salt solutions on the surfaces of concrete structures. His work involved a study on the behaviour of concrete ponded with saturated and 5% CaCl_2 solutions. All his testing was carried out at room temperature. His results showed that exposure to a saturated CaCl_2 solution was highly deleterious even to concretes of low water-cement ratios (0.4 to 0.5) where loss of strength and leaching occurred; in concrete of a higher water-cement ratio (0.7), in addition to loss of strength and leaching, serious expansion was also indicated. However, for concretes exposed to 5% CaCl_2 solution, no damage was observed.

B. Salt Penetration into Concrete

A number of investigators have studied the extent of salt penetration into hardened concrete with a view to determining if there was a relationship between chloride content at any given depth and the corrosion of steel reinforcing bars or surface

mortar deterioration.

Ost and Monfore²⁰ set up laboratory tests to establish the penetration of chloride into cement paste and concrete over a one year period. They found that both 2% and 5% CaCl_2 solutions penetrated concrete more readily than cement paste and they believed this was due to the permeability of the aggregate being greater than that of the cement paste in this particular instance. In concrete, the amount of chloride penetration increased with the salt concentration. After one year's exposure to an 5% CaCl_2 solution, the amount of CaCl_2 at a depth of 2 inches in concrete ranged from 5.3% by weight for a water-cement ratio of 0.6 to 0.1% for a water-cement ratio of 0.4. Thus the water-cement ratio of the paste is obviously an important factor in salt penetration.

A co-operative study²¹ sponsored by the Federal Highway Administration in the U.S.A. revealed that cores removed from bridge decks showed a higher chloride content in the spalled decks than in the sound decks. This reflected the higher permeability of the spalled decks and the placement of more chlorides on spalled decks. The higher chloride content at the steel reinforcement level in bridge decks is, of course, related to corrosion of the steel and resultant spalling of the surface. They concluded that the lower the water-cement ratio, the lower the permeability to chloride penetration and the better the protection to the steel against corrosion. It was discovered that similar scaling is

produced with de-icing agents having different chemical compositions and thus the action was suggested to be one of physical rather than chemical attack.

C. Physical Attack by De-Icing Agents

Previous to 1943, field observations appeared to suggest that concrete surface scaling increased with increasing amounts of de-icing agents. Work performed by Arnfelt²² has proven this to be false. His study indicated that concretes frozen and thawed repeatedly while immersed in solutions of different materials (calcium chloride, sodium chloride, urea and ethyl alcohol) showed more destructive deteriorations for reasonably low concentrations (3.5% by weight) than either weaker or stronger concentrations.

All the materials used for de-icing agents were equally active for the same solution concentrations and caused a similar depression of the freezing point in the concrete.

Verbeck and Klieger²³ confirmed the earlier work done by Arnfelt. They found that the rate of scaling is much greater with salt solution concentrations of 2% and 4% than with 0%, 8% and 16% solutions for chemically dissimilar materials. This is further proof that the mechanism of surface scaling is not primarily chemical but physical.

D. Freezing Mechanisms in Concrete Under the Influence of De-icing Agents

A number of different theories have been proposed as to the mechanisms involved when frost action occurs in concrete under the influence of de-icing agents.

Hartmann²⁴ claims that de-icing agents do not affect concrete to any great extent by chemical attack, crystallization pressure or osmosis, but that damage is due to other causes. She postulated that when de-icers are present, the concrete is cooled more quickly because the heat absorption of the ice thawing on the surface is drawn primarily from the concrete. This sudden cooling results in a rapid change in temperature of the upper layers of concrete causing any unfrozen pore-water in the near surface layers to freeze quickly. If there were insufficient relief to available air bubbles for the resulting hydrostatic pressure, then the upper layer zone of the concrete would be split off from the concrete slab especially if the zone contained a weak plane between the surface mortar layer and the underlying aggregate. The sudden freezing of capillary water due to heat abstraction in the deeper zones parallel to the surface of the concrete could result in whole surface plates splitting from the underlying concrete. If, however, the de-icers are applied previous to ice formation on the surface, then the freezing point of the surface moisture is reduced without rapid cooling and plate-splitting is not produced.

This idea was also expressed by Franklin²⁵ who did an extensive study of air-entrained concrete pavements which had been subjected to a significant number of de-icing salt applications during an unusually severe winter in the U.K.

Powers² has advanced a theory in which it is proposed that scaling is primarily due to a destructive stress in the cement paste although he is aware that freezing of water in the saturated rock particles could be a contributing factor. After the ice has melted on the surface of a non air-entrained concrete, he claims salt in the melt is slowly diffused into the concrete pores. The diffusion rate into the cement gel is very low; therefore the salt concentration is built up in the capillary pores more rapidly than in the dense cement gel. During the winter when de-icers are used, freezings will occur while salt concentration is higher in the capillaries than in the gel pores. Thus, after application of de-icers, osmotic pressure would be greatly increased; however, less ice would be produced than before at a given minimum temperature. According to Powers, a de-icer has two opposing effects. At a given low temperature it reduces the amount of ice that can form in the capillaries of cement paste which in turn reduces the pressure produced during freezing, either osmotic or hydraulic. On the other hand, for a given amount of freezing, it increases the osmotic pressure which is generated by the variation of salt concentration in the capillaries and gel pores and for a given amount of freezing

it tends to increase the maximum pressure that can be generated by hydraulic flow and osmotic pressure. These opposite effects account for the observation that intermediate salt concentrations on the surface and in the capillary spaces have caused the most damage.

Litvan²⁰ claims that when a saturated specimen containing salt solution is cooled below the freezing point of bulk water, the solution contained in the pores remains in a liquid-like state. This phenomenon creates a non-equilibrium condition and instability within the pore liquid solution which is eliminated by mass transfer. If this process of desiccation cannot proceed in an orderly fashion, then mechanical failure occurs. This process is similar to that if water were used as the adsorbate; however, salt solutions impose several variations on the system. The freezing points of salt solutions and the temperatures at which they become unstable in the pores decrease with a corresponding increase in salt concentration. With the exception of cement pastes containing saturated salt solutions and pure water, the pastes containing intermediate salt concentrations exhibit two exothermic heat effects during the cooling cycle from 0°C to -70°C with a slow rate of cooling of 0.33°C/minute. The first exothermic peak indicates the initiation of the freezing process when pure ice starts to form on the external surface of the pastes. The temperatures at which the first peaks occur are

variable and are dependent on the salt solution concentration. The second peaks indicate freezing due to the solutions of the eutectic compositions on the external surfaces and they occur at approximately -25°C for these pastes. In specimens containing low salt concentrations (i.e. 5%) during freezing, a large portion of the water component freezes at the exterior of the capillary channels leading to the surface. A further lowering of the temperature results in a subsequent flow of solution from the interior of the paste and if this process is impeded non-equilibrium exists and extremely large expansions are created.

Inderwick²⁷ suggests that when dissolved solutes, due to the presence of de-icers, are present in excess in concrete and when the water becomes saline, the result of a temperature decrease in the voids is to progressively raise the concentration of the saline solution in the voids by freezing out the water. The ice eventually builds up on the surface of the voids, thereby sealing off the escape channels in the early stages. As the ice formation progresses on the inside of the voids, pressure is exerted until rupture and scaling occurs.

E. Preventive and Remedial Measures

Most if not all recommended measures to be taken to prevent damage due to freezing, also apply to freezing where de-icing salts are present. The only difference between the two cases is that

Frost action produces more damage in the presence of de-icing salts with the result that greater care is necessary in the production and in the maintenance of concrete. The important factors to be considered in the production of concrete to resist freezing in the presence of de-icing salts are covered in the following sections.

1. Air-Entrainment: Air-entrainment is essential but it is not a cure-all for the prevention of scaling and damage influenced by de-icing agents on concrete surfaces. Where air-entrainment can not be used such as in "wet pressed" concrete slabs an important factor for resistance to scaling seems to be the water-cement ratio.

2. Water-Cement Ratio: Indervick²⁷ claims that a water-cement ratio of 0.42 or less must be maintained over every section of the "wet pressed" slab if it is to be durable under critical de-icing salt conditions. This is probably true provided the cement has had a chance to hydrate completely before the onset of freezing cycles. At higher water-cement ratios even if hydration were complete some frost damage would be inevitable if the concrete were saturated when the freezing occurs.

3. Slump: Although consolidation of concrete must be

adequate, high slump concrete results in bleeding with the end result of a higher water-cement ratio paste at the top, exposed surface. It should also be emphasized that overworking and overfinishing should be avoided since the resultant laitance is especially susceptible to deterioration by the applied de-icing agents. Therefore a minimum slump consistent with the placement conditions should be used.

4- Effect of Drying: Proper attention must also be given to the curing conditions of concrete. Continuous moist curing and then immediate application of de-icers during freezing can be very detrimental to concrete. Although moist curing is essential, a period of air drying before the onset of freezing greatly enhances the frost durability of concrete subjected to de-icing agents. Pavements, in service, rarely obtain curing comparable to continuous moist curing in the lab. Generally after a prescribed moist curing period, the concrete is exposed to drying conditions with occasional rewetting during rainfalls. However, the amount of re-absorbed water rarely is equivalent to that lost during the drying period. The overall result is a reduction in the degree of saturation of the concrete. Verbeck and Klieger²³ suggest a drying period of at least one month should elapse in order to minimize the possibility of frost damage.

47

Protective Sealants: If frost damage due to de-icing agents has already occurred, the Federal Highway Administration²⁰ in the U.S.A. suggest that surface treatments such as linseed oil and neutral petroleum oil should be applied to protect the concrete surfaces and to reduce the chances of further deterioration by de-icers. In California, various membranes are being used on reinforced concrete bridge decks. These membranes are made from coal tar, plasticized coal tar, nylon, glass fiber, polyurethane, asbestos asphalt, rubber and epoxy and are used in the mountainous regions to reduce frost damage in the presence of de-icing agents. In the valleys where heavy frost occurs epoxy sealants are used. These protective coatings increase the initial cost of bridge decks; however, they are expected to reduce maintenance costs in the future.

Summary: Frost damage of concrete due to the presence of de-icing agents can be reduced if concrete has adequate air-entrainment, a low water-cement ratio and a minimum slump. A period of drying prior to salt application is also beneficial to concrete. If frost damage has occurred protective sealants can be used to reduce further deterioration.

CHAPTER V

Experimental Programme

Introduction

In the earlier chapters of this thesis it has been shown that the frost resistance of concrete is indeed a complex subject and that the introduction of de-icing salts adds another dimension to the problem. Although it is reasonably well established that de-icing salts increase the damage produced by frost action, there is by no means unanimity as to the mechanism or mechanisms involved in such increased damage. One aspect of this problem which has not been investigated to any extent and which Litvan²⁶ has suggested may be an important factor is the effect that de-icing salts may have on the amount of water retained by concrete under given environmental conditions. The purpose of this experimental programme, therefore, was to study the effect of one de-icing agent (NaCl) at different solution concentrations on the amount of water (or salt solution) retained by concrete under a variety of relative humidity conditions. Also, the programme was designed to investigate the effects of freezing on the specimens so conditioned. In specific terms, therefore,

the programme is divided into two parts, namely:

- A. Desiccation Tests and
- B. Freezing Tests

The variables which were included in the programme are:

1. Concrete Slabs:
 - 4 types of air-entrained precast slabs designated A, D, E and I
 - 5 types of wet pressed precast slabs designated B, C, G, H and J
 - 1 type of dry pressed precast slab designated F
2. NaCl Solution Concentrations:
 - 0%, 1½%, 3% and 10%
3. Relative Humidities:
 - 30%, 47%, 72% and 88% designated chambers 1 to 4 respectively

A. Desiccation Tests

1. Preparation of Concrete Specimens: All concrete specimens were sawn from the central portions of each of the ten types of concrete slabs procured from various plants across the country. Two sizes of specimens were prepared for the desiccation tests. It should be noted that the larger specimens were also subsequently used for the freeze-thaw tests.

(a) Small Specimens -- a Specimens: In

total 112 small specimens, $1/8 \times 1 \times 2$ inches in size, were cut through the 2 inch depth of the slabs. These small ($1/8$ inch thick) specimens will be referred to as the a specimens for the remainder of the experimental programme. All the a specimens were conditioned for 2 days at 0% R.H. prior to saturation. After conditioning, one specimen each, from slab types A to J was "fully" saturated in water and in the 3% NaCl solution and one each of slabs types A, C, E and G was "fully" saturated in the $1\frac{1}{2}$ % and 10% NaCl solutions. After saturation the a specimens were surface dried and weighed. Of the 112 a specimens, 20 were placed in each R.H. chamber for the desiccation test.

(b) Large Specimens -- b Specimens: In total 112 specimens, $\frac{1}{2} \times 1 \times 6$ inches in size, were cut from the top $\frac{1}{2}$ inch of the slabs. To simulate conditions found in practice it was deemed desirable to use specimens of $\frac{1}{2}$ inch thickness because Ost and Monfort²⁰ had found that salt penetrated only $\frac{1}{2}$ inch below the top surface of concrete after one year's exposure. The top surfaces were used because it was felt that the condition of the original finished surface may have some effect on the frost resistance of the various types of concrete used. After these specimens were cut, a hole was drilled in the ends of each specimen in which a stud was secured with epoxy glue to facilitate the measuring of length

changes during the subsequent freeze-thaw tests. These $\frac{1}{2}$ inch thick specimens will hereafter be referred to as the b specimens. Prior to saturation these b specimens were also conditioned at 0% R.H. for 2 days. After conditioning, the identical saturation procedure was applied to the b specimens as to the a specimens with the same number of specimen types saturated in the same concentrations of salt solutions and in water. After saturation the b specimens were surface dried, weighed and immediately sealed on all surfaces but the top surface which was to be exposed to the various atmospheres within the R.H. chambers. The surfaces were sealed with 2 mil polyethylene and fastened with elastic rubber bands, then aluminium foil was moulded around the exterior of the polyethylene of each specimen in order to hold the polyethylene secure to the concrete surfaces; the foil was also held with elastic bands. All the sealing materials used for each specimen were pre-weighed prior to the sealing procedure. Twenty-eight of the 112 b specimens were then placed in each of the four R.H. chambers for the desiccation test.

To summarize the chamber loading procedure, chambers 1 to 4 were each loaded with 28 a specimens and 28 b specimens.

2. Measurements of Weight Changes During Desiccation

(a) a Specimens: These specimens were weighed

three times a day for the first two days and daily after that until equilibrium weights were reached. The equilibrium point for each specimen was determined when the weight of the specimen stayed constant for 7 days. Upon completion of the desiccation test the a specimens were oven dried for one day at 105°C; the specimens were then removed from the oven and placed in a desiccator at 0% R.H. to cool down for at least 30 minutes. After cooling they were removed from the desiccator and weighed.

(b). b Specimens: During desiccation these specimens were also weighed three times a day for the first two days and daily after that until equilibrium was reached. The equilibrium point was determined when the specimens had a weight of water loss which was less than 0.002 g/day.

B. Freeze-Thaw Tests

1. Preparation of Concrete Specimens: For the freeze-thaw tests only the b specimens conditioned at various relative humidities and "fully" saturated specimens were tested.

(a). b Specimens: After the desiccation tests terminated these specimens were removed from the R.H. chambers and

their exposed surfaces were immediately sealed with polyethylene and fastened with elastic bands.

(b) "Fully" Saturated Specimens: A total of 28 specimens, $1 \times 1 \times 6$ inches in size, were cut from the ten types of concrete slabs, 4 each from slab types A, C, E and G, 2 each from the others. Studs were inserted in these specimens and then they were conditioned at 9% R.H. for two days prior to saturation. One specimen each from slab types A to J was saturated in water and 3% NaCl solution and one each of types A, C, E and G was saturated in 1% and 10% NaCl solutions. After saturation these specimens were surface dried, weighed and completely sealed in 2 mil polyethylene secured with elastic rubber bands.

2. Testin; Procedure: Prior to the first freeze-thaw cycle, each specimen was weighed and its length was recorded at room temperature (70°F). Each specimen was subjected to five freeze-thaw cycles from 70°F down to 0°F and back to 70°F . The freezer was set by an automatic timer for a 24 hour temperature cycle. The cooling cycle took 11 hours. The cooling rate of the specimens was about 10°F/hr from 70°F down to 40°F and about 5°F/hr from 40°F down to 0°F . The warming cycle took 13 hours from 0°F to 70°F .

The "fully" saturated specimens and the specimens from

chambers 3 and 4 (72% and 68% conditioning) had their length changes monitored continuously during the first cycle. For the other specimens only the residual length change was recorded. In the subsequent four cycles only cumulative residual length changes were recorded for all specimens.

Upon completion of all the freeze-thaw tests the specimens were oven dried at 105°C for two days, cooled down in a desiccator at 0% R.H. for at least one hour and then weighed.

CHAPTER VI

Equipment and Materials

A. Equipment

1. Clipper Saw: The saw (illustration 1) which was used to cut all the concrete specimens to the required dimensions for the entire testing programme is operated by a 230 volt, 60 cycle, 3 H.P. motor and is equipped with a diamond studded blade, 0.05 inches thick and 14 inches in diameter. During the sawing procedure the saw blade is lubricated with water.

2. Mettler P-1200 Weigh Scale: This instrument (illustration 2) was used to weigh all the concrete specimens in the preliminary tests as discussed in the subsequent chapter. The scale has a maximum capacity of 1200 g and a precision of ± 0.005 g.

3. Sartorius Weigh Scale: This scale (illustration 3) was used for all weighings throughout the main programme of

Illustration 1. Saw

Illustration 2. Mettler Weigh Scale

testing. It had two functions, weighing specimens sealed within the relative humidity chambers and weighing specimens outside the chambers during the freeze-thaw tests. The instrument has a precision of ± 0.05 mg. with a maximum capacity of 200 g.

4. Boekel Metal Desiccator: The desiccator used (illustration 4) has dimensions of approximately 24 x 16 x 18 inches high. CaSO_4 crystals were used to produce a 0% R.H. condition within the desiccator. The desiccator was used to condition concrete specimens for two days prior to saturation and to cool the specimens after oven drying and before weighing. This instrument was also used in the preliminary studies to determine the water content of various concrete specimens conditioned for one day at 0% R.H.

5. Vacuum Saturation Equipment: The vacuum saturation equipment (illustration 5) consisted of a vacuum pump (capable of creating a vacuum of 30 inches of Hg) attached by a rubber hose to a metal seal-proof specimen container, the lid valve of which is attached by a transparent plastic hose to a 5 gallon capacity collapsible plastic water or solution container.

6. Relative Humidity Chambers: Four identical relative

Illustration 3. Sartorius Weigh Scale

Illustration 4. Boekel Metal Desiccator

humidity chambers (illustration 6) were built for the desiccation tests. The major portions of the chambers (framing, top, bottoms, ends, shelves and trap doors) were constructed of $\frac{1}{2}$ inch fir plywood and the sides were covered with 6 mil. transparent polyethylene. The outside dimensions for each chamber were 28 x 22 x 12 inches high. The interior of each chamber contained a shelf (27 x 15 inches) placed $4\frac{1}{2}$ inches below the top surface. The purpose of the shelf was to support the a and b specimens and to shield them from a direct blast of air by the fan. The shelf was situated such that total circulation could be maintained over the surface of the specimens. The a specimens were supported slightly above the surface of the shelf so that they could dry from all sides. In each chamber, a fan (4 inches in diameter) was mounted on the inside wall of one end of the chamber just below the shelf and just above the top surface of the glass pans containing supersaturated salt solutions. The purpose of the fan was to circulate air across the top of the salt solutions and around the shelf. At the bottom of the opposite end wall of each chamber, a trap door (15 x 3 inches) was located such that it allowed access to the glass pans for the purpose of stirring or replacing the salt solutions. The top surface of each chamber contained three trap doors, each 6 x 6 inches covering three holes 5 x 5 inches. Flexible transparent plastic bags were inserted into the two outside holes and were

Illustration 5. Vacuum Saturation Equipment

Illustration 6. R.H. Chambers and Weigh Scale

scaled along the outside edges of each hole with industrial tape. These bags were needed to allow access of hands to the specimens for the purpose of weighing them within the chambers. The top central hole of each chamber contained a weighing pan. All the trap doors were lined along their edges with $\frac{1}{8}$ inch rubberized weather stripping and were clamped down with wing nut fasteners. The Sartorius weigh scale was used in conjunction with these chambers.

7. Humidity--Temperature Recorder and Sensing Elements:

Model 15-5040E humidity-temperature recorder (illustration 7), manufactured by Hygro Dynamics Inc., was used with the type TH, class A, narrow-range sensing elements to measure the relative humidities and temperatures inside the four relative humidity chambers, the Boekel metal desiccator and the control room used in the preliminary studies discussed in the subsequent chapter.

8. Mitutoyo Vernier Calipers:

The overall lengths of the concrete and sulfur specimens used in the freeze-thaw tests were measured using these vernier calipers (illustration 8). The instrument has a range of 12 inches with a readability to 0.001 inches.

9. Mercor Extensometer:

This equipment was used for

Illustration 7. R.H. Chambers and H-T Recorder

Illustration 8. Extensometer and Vernier Calipers

measuring length changes of sulfur and concrete specimens over specified temperature ranges. It consists essentially of a Mercer extensometer mounted on a metal stand (see illustration 8) and has a gauge length of 7 inches with a range of 0.4 inches and a readability of 0.0001 inches.

10. Freezing Chamber: All the freeze-thaw tests were carried out in a 6.7 cubic foot capacity freezer (illustration 9) manufactured by Lab-Line Instruments Inc. The freezer is equipped with a 115 volt, 60 cycle, 1 H.P. motor. A fan was located in the freezer to eliminate temperature fluctuations at various locations.

11. DCDT Transducers, Their Frames and the Multipoint Strip Chart Millivolt Recorder (Electronik 10): The millivolt recorder was manufactured by Honeywell and it was used along with the five transducers, their frames and a Harrison power input source to record millivolt readings for the concrete and sulfur specimens during the freeze-thaw cycles (illustration 10).

12. Temperature Potentiometer: The temperature potentiometer used (illustration 11) was made by Leeds and Northrup and it was used along with thermocouples for the determination of the

Illustration 29. Freezing Chamber

Illustration 30. Processing Equipment

coefficient of thermal expansion for pure sulphur in the preliminary studies. The potentiometer is calibrated to read directly in °F.

12. Millipoint Strip Chart Temperature Recorder (Electronic)

12): The temperature recorder used (illustration 12) was produced by Honeywell and it was used along with the thermocouples for determining the temperature changes of the concrete specimens used in the freeze-thaw tests. The instrument was also used in the preliminary tests (discussed in the subsequent chapter) with the sulfur bars.

B. Materials

1. Concrete: Ten different types of concrete slabs were prepared from various industrial concrete producing plants across Canada. The slabs received were typical of those produced and sold commercially at the various plants. The main types of slabs were included, i.e., "pressed" slabs and cast-in-place slabs. The "pressed" slabs were made either by the "wet press" method on a Fielding machine or by the "dry press" method using a Rino press. The dimensions of all slabs were similar, 30 inches long, 24 inches wide and a nominal 4 inches thick. The ten different types of concrete are coded with letters from A to J. On request from the

Illustration 11. Temperature Potentiometer

Illustration 12. Temperature Recorder

individual manufacturers, their names will not be given; however, pertinent data is available for all the concrete types except Type II (see Appendix C). Type H is produced by the "wet press" process.

2. Sulfur: A two pound bag of sulfur was obtained from Golder Associates. The sulfur was 99.9% pure and was used for the preparation of the sulfur bars.

3. Salts: Twelve pounds of $MgCl_2 \cdot 6H_2O$, twenty-two pounds of $Ca(NO_3)_2 \cdot 4H_2O$ and eight pounds of KNO_3 were obtained from Can. Lab. The NaCl was available from the laboratory. These four salts were used with distilled water to produce supersaturated salt solutions to be used in the relative humidity chambers. NaCl was also used with water to produce the various concentrations of salt solutions for saturation purposes. $CaSO_4$ crystals used in the Bockel metal desiccator were also obtained in the laboratory.

CHAPTER VII

Development of Experimental Procedures

In order to obtain accurate measurements on the various experimental instruments used, it was necessary to perform preliminary tests on these instruments and in some cases to develop new experimental procedures.

A. Vacuum Saturation Procedure

Three different saturation procedures were investigated in order to arrive at the best procedure. These were designated as tests A, B and C and are described in the following sections.

1. Test A: Initially 20 concrete specimens of size $\frac{1}{2} \times 1 \times 6$ inches were inundated in the container of water; then they were subjected to a full vacuum of 30 inches of Hg for two hours with the vacuum pump running. After two hours under vacuum, the pump was turned off and the specimens were allowed to soak for 48 hours under partial vacuum. After this soaking period

the specimens were removed from the water container, surface dried and weighed. The specimens were then dried for seven days in a room with a controlled environment of 42% R.H. and 72°F.

2. Test B: Immediately following the seven days of drying the same specimens were subjected to a different method of vacuum saturation. They were placed in the same container except that this time it was empty and then they were subjected to a full vacuum for one-half hour. After one-half hour the pump was turned off and water was allowed to enter the empty container under vacuum until all the specimens were submerged. The specimens were allowed to soak for one-half hour under partial vacuum, and then were removed from the container, surface dried and weighed. The specimens were again dried for seven days in the control room.

3. Test C: Following the seven days of drying the same procedure as in test B was followed except that this time the specimens were subjected to a full vacuum for one hour with the pump running; and one hour soaking under partial vacuum with the pump turned off. Weights were again recorded.

As seen in table B-I the results show that the specimens vacuum saturated in test C generally reached the highest level of saturation. As a result it was decided to use procedure C plus

three further days of soaking in the appropriate solution in order to achieve the fullest saturation possible. Specimens which were used in the experimental programme and which were saturated by this method have been labelled as "fully" saturated specimens.

B. Control of the Cooling Rate in the Freezer

In order to develop a cooling rate that would relate reasonably well with an average maximum rate found in nature, different added weights of scrap concrete were placed in the freezing chamber and were subjected to numerous cooling cycles. For these tests, five thermocouples were attached to sealed saturated concrete specimens which were placed at various locations within the freezing chamber. The freezer was loaded with the appropriate number of specimens and transducer frames that would be present throughout all the freeze-thaw tests as well as the additional pieces of scrap concrete. It was found that if the freezing chamber was loaded with 72 pounds of additional concrete, then the cooling rate of the specimens was about constant at 5 °F/hour throughout the range from 40°F down to 0°F. Therefore throughout all the experimental freeze-thaw tests, including the tests for the calibration of the transducers, the freezing chamber was loaded in this fashion.

C. Temperature Lags

In order to determine whether or not there would be a significant temperature differential between the interior and the surface of freeze-thaw specimens during testing, preliminary freeze-thaw tests were run on 16 concrete specimens on which interior and surface temperatures were monitored continuously. The specimens chosen ($\frac{1}{2} \times 1 \times 6$ inches in size) were from slab types A and C because these slabs were typical of cast-in-place and "wet pressed" concretes respectively. A hole was drilled about 1 $\frac{1}{2}$ inches deep into one end of each specimen to accommodate the interior thermocouple. Another thermocouple was glued along one outside surface of each specimen.

These specimens were conditioned for two days at 0% R.H. After conditioning, two specimens each of types A and C were saturated in 0%, 1%, 3% and 10% NaCl solutions respectively. The specimens then were sealed on all sides except the top surface. Half the specimens were then placed in chamber 1 (R.H. of 30%) and half in chamber 4 (R.H. of 90%). After the specimens were conditioned to equilibrium, they were removed from the R.H. chambers and were completely sealed, as they would be in the normal freeze-thaw tests. The thermocouples from each specimen were connected to the temperature recorder and the specimens were

placed in the freezer for a freeze-thaw cycle.

As shown in table D-X the temperature lags on the cooling cycle range from 0.0 to 0.5°F with an average lag of 0.3°F. For the warming cycle the range is from 0.0 to 0.4°F with an average lag of 0.2°F. On the average, therefore, these temperature lags were almost negligible so it was deemed justifiable in the freeze-thaw experimental programme to measure only the temperatures of the exterior surface of all the specimens during the freeze-thaw tests.

D. Calibration of the DCDT Transducers and the Frames in Which They Were Mounted

Four pure sulfur bars, 1 x 1 x 6 inches in size were moulded for the calibration of the five transducers each mounted in its own frame. The sulfur bars were moulded with a thermocouple placed longitudinally along the central interior axis of each bar in order to obtain the internal temperature of each, and with a stud situated in each end of the bars to enable length changes to be made while the specimens were cycled through a temperature range. The inside lengths between the studs for each bar were recorded and are shown in table B-V.

Sulfur bars 2 and 3 were used to calculate the coefficient of thermal expansion of the pure sulfur. Both sulfur bars were

sealed in one inch thick insulating material and then sulfur bar 2 was placed in the freezing chamber at 70°F. The thermocouple of sulfur bar 2 was connected to the potentiometer and then the temperature in the freezing chamber was lowered to 0°F. When the temperature reading on the potentiometer was constant at 0°F the freezer door was opened and sulfur bar 2 was removed and placed in the extensometer at 70°F. Length changes and temperature changes were recorded as sulfur bar 2 warmed up to 70°F. These points were plotted and are shown in figure B-6. Sulfur bar 3 was similarly tested with only one variation, the temperature recorder was used instead of the potentiometer. The points for sulfur bar 3 were plotted and are shown in figure B-7. The coefficients of thermal expansion were calculated for both sulfur bars and are shown in table B-V.

For successive calibration tests sulfur bars 1 and 2 were placed in frames 1 to 4, and sulfur bars 1, 3 and 4 were placed in frame 5 with the respective transducers of each frame connected to the millivolt recorder and with the thermocouple of each bar connected to the temperature recorder. The different frames were placed in the freezer and were subjected to a freeze-thaw cycle. Millivolt readings and temperature changes were recorded simultaneously for the different sulfur bars and frames. These readings were noted and then plotted and are shown in

Figures B-3 to B-21. From these graphs, slopes were taken and from the slopes scaling factors were calculated for the five frames and transducers. These values are shown in tables B-VI and B-VII.

CHAPTER VIII

Discussion of Results

A. Desiccation Test

The desiccation curves or weight of water loss per weight of saturated specimen per day for all the a and b specimens are shown in Figures D-1 to D-50. From these curves it is observed that for all the a and b specimens (comparing the same concrete types) desiccation increases with a decrease in relative humidity. Also, for any one concrete type, it can be seen that the higher the concentration of salt solution, the higher the percentage of water retained for any given R.H. condition. The reason for this will be discussed later. It can be seen that water loss from saturated specimens under the various R.H. atmospheres occurs exponentially. In the first few days the a and b specimens lose most of the water that they are going to lose permanently and from this point forward until equilibrium is reached water loss is extremely slow and gradual. This initial pattern is primarily due to the mass expulsion of water from the larger size pores in each specimen when they are introduced into

an atmosphere of less than 100% R.H. After the larger pores have expelled most of their water, the smaller pores gradually empty until an equilibrium condition is reached for each specimen. The amount of water lost and the rate of water lost are dependent on the total porosity and the permeability of the specimen.

1. Time to Equilibrium: A point of clarification should be introduced before the discussion continues. The equilibrium points determined for these specimens were not actually the points where no more water was lost but the points where the water loss was less than .002 /day. This was a cut-off point and it is realized by the author that a little more water would be lost by each specimen; however, for all practical purposes it is felt that equilibrium had been reached and that there would be no appreciable differences between the degrees of saturation at the cut-off points and the actual equilibrium points. Hereafter the cut-off points will be referred to as the equilibrium points for the b specimens.

As shown in tables D-I and D-II it can be observed that the times to equilibrium increased on the average with a decrease in R.H. conditions for all the a and b specimens. The average times to equilibrium for the b specimens in each R.H. chamber were 3 to 4 times longer than for the a specimens in the same R.H. chamber. This is accounted for by the fact that the $1/8$ inch

thick a specimens were drying from the top and bottom surfaces so their maximum water expulsion distance was $1/16$ inches. On the other hand the $\frac{1}{2}$ inch thick b specimens were drying only from the top surface; therefore their maximum water expulsion distance was $\frac{1}{2}$ inch. In chamber 1 (30% R.H.) the average times to equilibrium were 26 days for the a specimens and 20 days for the b specimens. In chamber 2 (50% R.H.) the average times were 25 days and 73 days; in chamber 3 (70% R.H.) they were 16 days and 62 days and in chamber 4 (90% R.H.) they were 5 days and 20 days.

2. Degree of Saturation at Equilibrium: It can be seen from tables I and II that (when comparing the same concrete types) for all the a and b specimens there is an increase in the degree of saturation at equilibrium for an increase in the R.H. of the chambers. Table III shows that the average degree of saturation for the A, C, E and G specimens increases as the salt concentration increases for each R.H. condition. The A, C, E and G specimens were considered because they are the only specimens that were saturated in the four different solvents (water, 1%, 5% and 10% NaCl solution). Salt solutions lower the vapour pressures within the concrete specimens; therefore a specimen saturated in a higher salt concentration will maintain a

TABLE I
DEGREE OF SATURATION AT EQUILIBRIUM

SPEC TYPE	SAT IN NaCl SOLN (%)	DEG OF SAT AT EQUIL (%)			
		CHAMBER 1	CHAMBER 2	CHAMBER 3	CHAMBER 4
A	0	27.1	40.3	58.4	80.0
B	0	16.2	24.7	41.9	60.3
C	0	33.1	49.0	69.1	87.4
D	0	17.9	22.5	45.6	67.4
E	0	23.9	38.4	54.7	72.6
F	0	24.7	33.3	48.9	65.1
G	0	26.2	39.4	57.8	71.7
H	0	20.6	29.7	44.7	67.3
I	0	31.4	41.2	60.7	81.0
J	0	20.2	29.9	42.9	63.5
A	1.5	30.4	42.0	57.1	75.5
C	1.5	33.3	49.5	66.9	78.2
E	1.5	26.7	39.8	53.8	66.1
G	1.5	29.8	42.5	56.5	72.3
A	3	32.3	44.4	60.6	80.6
B	3	21.3	29.1	47.9	66.4
C	3	37.6	51.2	68.7	85.2
D	3	22.5	30.4	49.1	63.0
E	3	29.7	41.3	54.0	70.3
F	3	27.5	35.7	49.1	62.0
G	3	32.1	45.5	62.0	76.6
H	3	25.4	33.0	50.1	67.0
I	3	32.5	45.3	62.7	82.2
J	3	24.3	32.0	50.0	66.3
A	10	38.1	48.8	64.2	96.6
C	10	44.0	54.0	70.5	94.2
E	10	35.5	42.7	59.1	88.9
G	10	35.3	50.7	63.3	88.2
TOTAL AVE		30.2	40.4	57.7	77.3

a SPECIMENS

TABLE II

SPEC TYPE	SAT IN NaCl SOLN (%)	DEG OF SAT AT EQUIL (%)			
		CHAMBER 1	CHAMBER 2	CHAMBER 3	CHAMBER 4
A	0	27.7	38.8	51.4	69.2
B	0	19.4	26.8	39.7	56.8
C	0	35.8	55.4	67.2	85.9
D	0	19.5	26.4	39.7	62.4
E	0	25.5	39.0	47.4	57.5
F	0	26	36.1	45.3	62.7
G	0	32.0	44.8	58.6	77.7
H	0	24.3	35.8	50.9	72.8
I	0	30.3	39.3	55.1	68.5
J	0	26.2	34.9	44.3	57.1
A	1.5	27.9	37.8	51.2	73.1
C	1.5	36.5	48.6	67.2	89.2
E	1.5	27.5	37.1	49.7	68.2
G	1.5	30.1	45.4	59.3	77.3
A	3	29.9	40.4	53.8	75.5
B	3	21.0	27.7	43.5	68.5
C	3	35.4	49.0	70.1	91.6
D	3	21.5	27.3	43.8	68.3
E	3	29.0	36.7	50.9	69.2
F	3	26.6	36.5	40.4	63.7
G	3	34.5	43.2	53.0	81.5
H	3	27.6	36.5	51.0	77.1
I	3	33.6	41.4	57.5	76.7
J	3	28.6	34.1	51.3	72.0
A	10	33.9	40.1	50.5	80.9
C	10	39.8	51.2	75.3	97.7
E	10	29.7	39.2	56.4	89.0
G	10	38.3	46.9	69.6	91.3
TOTAL AVE		29.8	40.4	56.2	76.3

b. SPECIMENS

TABLE III

AVERAGE DEGREE OF SATURATION AT EQUILIBRIUM

SPEC CODE	SAT IN NaCl SOLN (%)	AVE DEG OF SAT AT EQUIL FOR THE A,C,E&G SPECS (%)			
		CHAMBER 1.	CHAMBER 2.	CHAMBER 3.	CHAMBER 4.
a	0	30.4	41.5	56.1	75.1
a	1.5	30.5	42.2	56.8	77.2
a	3	32.2	42.8	57.0	79.5
a	10	35.4	44.3	65.5	92.4
b	0	27.6	41.8	58.0	73.0
b	1.5	30.1	43.5	58.6	73.1
b	3	32.9	45.5	61.3	78.2
b	10	38.2	49.1	64.3	92.0

higher degree of saturation at a particular relative humidity equilibrium condition. The average of the degrees of saturation in the 30% R.H. chamber were 30.2% for the a specimens and 29.6% for b specimens; in the 50% R.H. chamber they were 40.4% and 40.4%; in the 70% R.H. chamber they were 57.7% and 56.2% and in the 90% R.H. chamber they were 71.3% and 70.3%. This indicates that there is a ~~good~~ correlation between the a and b specimens. From figures 1 to 4 it is observed that for the a specimens only the A and C concretes saturated in 10% NaCl solution and conditioned in the 90% chamber had degrees of saturation greater than 91% at equilibrium. For the b specimens, only the C specimens saturated in ~~the~~ 10% NaCl solutions and conditioned in the 90% R.H. chamber and the C specimen saturated in 10% NaCl solution and conditioned in the 90% chamber had degrees of saturation greater than 91%.

3. Time to 91% Degree of Saturation: As shown in tables D-III and D-IV for all the a and b specimens the average times required to reach 91% saturation increases for decreasing relative humidities. Therefore, although it takes longer for the a and b specimens in the 90% R.H. chamber to reach equilibrium than ~~in~~ in the 30% R.H. chamber, the initial rate of desiccation is much faster in the lower R.H. chambers than in the higher

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

R.H. chambers. The a specimens reached 91% saturation, 6 to 8 times faster than the b specimens in each relative humidity condition. The average times in the 30% R.H. chamber were 1 hour for the a specimens and 6 hours for the b specimens; in the 50% R.H. chamber they were 1 hour and 6.5 hours; in the 70% R.H. chamber they were 2 hours and 12 hours and in the 90% chamber they were 11 hours and 3.47 days.

4. Total Water Content at Saturation: All the water contents at saturation for the a and b specimens are shown in tables D-V and D-VI and the average water contents for each specimen type are shown in table D-VII. The range of average water contents was from 4.4% to 7.6% for the a specimens and from 4.3% to 7.8% for the b specimens. The total water content at saturation represents the total available space capable of occupying water or in other words the total porosity of the concrete specimen (provided it is fully saturated). Specimen I showed the highest porosity (represented by a water content of 7.8%), specimens A, B, E, F, H and J had intermediate porosities (represented by water contents of 5.9% to 6.3%), and specimens C, D and G had the lowest porosities (4.3% to 4.8%). There is a trend for the amount of water lost during desiccation to increase with an increase in water contents at saturation. Therefore it can be stated that as the

total porosity increases so does the rate of moisture lost.

5. 2. Rate of Desiccation From a Saturated Condition Down to the 91% Degree of Saturation Level: The rates of desiccation expressed as weight of water loss per weight of the saturated specimen per day from a "fully"-saturated condition down to the 91% degree of saturation level are presented in tables D-VIII and D-IX. These rates are considered important because they represent the speed of water expulsion for each specimen from a "fully" saturated condition down to what many authorities consider a critical saturation level. From tables D-VIII and D-IX it is observed that for the a and b specimens there is a decrease in the rate of desiccation for an increase in relative humidity. The average rates are 3 to 5 times quicker for the a specimens than for the b specimens in each R.H. condition. The a specimens are important only in that they have shown good correlation with the b specimens. The b specimens are more important because they were subsequently used in the freeze-thaw tests, so only these specimens will be discussed for the remainder of this section. In each chamber the b specimens follow a trend in the rates of desiccation and on the average the concrete types ranging in order from the fastest rates to the slowest rates are I, B, E, A, D, J, F, H, G and C. From this list it can be seen that the cast-in-place specimens I, E, A and D have

83

faster rates than the "pressed" concrete specimens, with the exception of type B. The rate of desiccation is probably a good indicator of the permeability (both to water flow and vapour flow) of the concrete; thus it would appear that specimens I, B and E have the highest permeabilities, specimens A, D, J and F have intermediate permeabilities and specimens H, G and C have the lowest permeabilities.

B. Freeze-Thaw Tests

1. First Freeze-Thaw Cycle on "Fully" Saturated

Specimens: The curves of $\Delta L/L$ vs temperature for the "fully" saturated specimens are presented in figures D-57 to D-84. These curves represent the first freeze-thaw cycle of the "fully" saturated specimens. Length changes were monitored continuously during the freeze-thaw cycle.

(a) Cooling Cycle: As the temperature of the freezing chamber was lowered during the cooling cycle, these specimens experience a normal, almost linear, thermal contraction from 70°F down to about 24°F. With further lowering of the ambient temperature they undergo dilation anomalies of a positive nature. Simultaneously slight exothermic heat effects are produced within

the specimen (noted as a temperature increase in the specimen).

Upon completion of the exothermic heat reactions some specimens endure further expansions with a decrease in temperature. When maximum dilations are reached the specimens begin to contract and continue to do so until the completion of the cooling cycle. The slopes of the final contractions are similar to those of the original thermal contractions.

The initiation of the dilation anomalies occurs at the freezing point depending upon the various concentrations of salt solutions in which the specimens were saturated as well as on the size of pores in which freezing is initiated. The freezing point depressions are shown in table D-XI for the different types of concrete saturated in the various salt concentrations. The freezing point decreased for each specimen with an increase in NaCl concentration. From Figure D-85 it can be seen that when the A, C, E and G specimen types were saturated in water the average freezing point was 10°F lower than that of bulk water; however, when these same specimen types were impregnated with the 10% NaCl solution the average freezing point was depressed only 5°F below the corresponding bulk freezing point for a 10% NaCl solution. Thus, the freezing point depression produced by NaCl in bulk water is much greater than it is when the water is present in concrete pores.

The maximum dilations experienced during the cooling cycle are shown in table D-XII. The range for the maximum dilations was from 0.0 to 15.7×10^{-4} in/in and this indicates that some of the "fully" saturated specimens were relatively unaffected by the freezing phenomenon while others suffered large expansions.

(b) Warming Cycle: On the warming cycle the "fully" saturated specimens initially experience expansions as the temperature begins to increase. The expansions are slightly greater than the normal thermal expansions and this is probably due to the re-adsorption of some original gel pore water back into the gel pores. The expansions are not too large and are similar to a swelling effect within the specimens. As the temperature increases the bulk ice within the large pores and on the external surfaces of the specimens begin to melt and at this point the specimens tend to contract. Contraction continues until a low point is reached at about 32°F at which point the bulk ice melts regardless of whether the specimens are saturated in water or in any concentration of NaCl solution. From 32°F to 70°F the specimens undergo almost normal linear thermal expansions.

C. Residual Expansions and Maximum Dilations: At 70°F residual expansions were measured from the freeze-thaw curves for the "fully" saturated specimens and are marked on each curve. These values coincide very well with the residual expansions measured using the extensometer at the end of the first freeze-thaw cycle, see table IV. The maximum dilations developed by the "fully" saturated specimens during the first cycle show a linear relationship with the residual expansions exhibited by the specimens at the end of the first cycle and these values are plotted in figure 5. However, after only one freeze-thaw cycle the results from the residual expansions did not demonstrate definite trends as to which type of concrete (cast-in-place or "pressed") suffered the most frost damage or which strength of solvent was the most detrimental.

2. First Freeze-Thaw Cycle on b Specimens:

(a) b Specimens from Chambers 3 and 4: The b specimens conditioned in the 70% and 90% R.H. chambers also had their length changes monitored continuously during the first freeze-thaw cycle. On the cooling cycle from 70°F down to about 0°F these specimens experienced only the normal linear thermal contractions with no dilation anomalies occurring at all. On the warming cycle back to 70°F the specimens undergo normal linear thermal expansions along almost the same slopes as the contractions.

TABLE IV

92

CUMULATIVE RESIDUAL EXPANSIONS

SPEC TYPE	SAT IN NaCl SOLN (%)	CUMULATIVE RESIDUAL EXPANSIONS $\frac{\Delta L}{L} \times 10^4 \left(\frac{1N}{IN} \right)$				
		CYCLE 1	CYCLE 2	CYCLE 3	CYCLE 4	CYCLE 5
A	0	3.6	8.6	14.3	21.5	25.6
B	0	1.1	1.7	3.0	3.2	4.0
C	0	0.9	1.7	2.6	3.6	4.2
D	0	1.3	2.8	4.7	6.4	10.0
E	0	4.9	10.5	15.4	23.6	27.6
F	0	1.7	4.0	7.0	9.4	11.8
G	0	0.6	2.3	4.3	6.3	10.4
H	0	7.7	11.1	13.3	15.2	16.9
I	0	2.8	5.6	10.0	11.7	14.1
J	0	0.6	1.5	2.2	2.2	2.2
A	1.5	2.1	6.0	10.3	11.5	13.5
C	1.5	0.2	1.3	1.9	2.1	2.3
E	1.5	0.6	1.7	2.8	4.0	4.0
G	1.5	2.3	4.7	6.8	8.5	9.1
A	3	5.7	15.1	23.3	27.0	33.4
B	3	0.5	0.8	1.0	1.3	3.3
C	3	0.4	1.5	3.6	5.1	5.2
D	3	1.0	1.7	2.9	3.4	5.1
E	3	0.8	3.0	5.7	7.2	7.9
F	3	4.5	6.0	8.5	10.4	13.2
G	3	1.0	1.5	5.1	8.4	11.0
H	3	0.2	3.0	6.4	9.6	14.8
I	3	4.0	6.1	10.5	15.2	23.6
J	3	0.4	2.3	2.7	3.0	3.4
A	10	1.1	1.5	1.9	2.3	2.5
C	10	0.6	2.3	3.2	3.6	3.6
E	10	0.4	2.3	2.3	2.3	2.4
G	10	1.3	2.3	3.6	5.3	7.7

FULLY SAT SPECS

FIGURE 5

The resistance to frost action exhibited by these specimens could be attributed to the fact that 53 of the 56 specimens conditioned in chambers 3 and 4 had attained degrees of saturation below 91% at equilibrium and hence prior to the first freeze-thaw cycle. Only the C and G specimens saturated in 10% NaCl solution and the C specimen saturated in 3% NaCl solution from chamber 4 attained degrees of saturation higher than 91%. These three specimens probably did not suffer expansions because of their low total porosities. Although the degrees of saturation were high in the C and G specimens, there obviously was not enough total water in each specimen to create expansive pressures during freezing. Since there were no length change anomalies occurring during the cycle no curves for them are presented in this thesis; however, the length change-temperature data is recorded in tables D-III to D-LVI. For the b specimens from chambers 3 and 4 residual expansions were also measured mechanically after the first freeze-thaw cycle. Some of the specimens showed no length changes at all while others displayed slight fluctuations either above or below the zero residual point. In any case these residual expansions are considered to be negligible; see tables V and VI.

(b) b Specimens From Chambers 1 and 2: The

TABLE V

SPEC TYPE	SAT. IN NaCl SOLN (%)	CUMULATIVE RESIDUAL EXPANSIONS $\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$				
		CYCLE 1	CYCLE 2	CYCLE 3	CYCLE 4	CYCLE 5
A	0	-0.0	0.0	-0.2	-0.2	-0.2
B	0	0.0	+0.2	0.0	0.2	0.0
C	0	0.0	-0.4	-0.2	-0.2	-0.4
D	0	0.0	0.0	-0.2	-0.4	-0.2
E	0	0.0	0.0	0.0	-0.4	-0.4
F	0	0.0	0.2	-0.2	-0.4	0.0
G	0	-0.4	-0.2	-0.6	-0.6	-0.6
H	0	-0.4	0.0	-0.8	-0.8	-0.8
I	0	-0.4	-0.2	-0.8	-0.6	-0.4
J	0	-0.4	-0.6	-1.0	-1.0	-0.8
A	1.5	-1.0	-1.0	-1.3	-1.3	-1.1
C	1.5	-0.6	-0.6	-0.8	-1.0	-0.8
E	1.5	-0.6	-0.6	-0.4	-0.8	-0.8
G	1.5	-0.6	-0.6	-0.6	-0.8	-0.8
A	3	-0.6	-0.6	-0.2	-0.2	-0.2
B	3	-0.4	-0.6	-0.6	-0.8	-0.8
C	3	-0.4	-0.4	-0.2	-0.8	-0.8
D	3	-1.0	-0.8	-0.2	-0.6	-0.4
E	3	-1.0	-0.8	-0.6	-1.1	-1.1
F	3	-0.6	-0.6	-0.6	-1.0	-1.0
G	3	-0.4	-0.4	-0.4	-0.8	-0.6
H	3	-0.2	-0.2	-0.2	-0.4	-0.4
I	3	0.2	0.2	0.0	-0.4	0.0
J	3	-0.2	0.0	0.0	-0.4	-0.2
A	10	-0.6	-0.6	-0.6	-0.8	-0.4
C	10	0.0	-0.2	-0.2	0.0	0.0
E	10	-0.8	-0.4	-1.0	-1.0	-0.6
G	10	-0.4	-0.6	-0.8	-1.0	-0.6

B. SPECS

CHAMBER 1

TABLE VI

SPEC TYPE	SAT IN NaCl SOLN (%)	CUMULATIVE RESIDUAL EXPANSIONS $\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$				
		CYCLE 1.	CYCLE 2.	CYCLE 3.	CYCLE 4.	CYCLE 5.
A	0	0.0	0.4	0.2	0.0	0.5
B	0	-0.6	-0.2	-0.6	-0.2	0.0
C	0	-0.2	-0.2	-0.4	-0.4	0.2
D	0	-0.4	-0.4	-0.2	-0.4	0.8
E	0	0.0	0.2	-0.2	0.0	0.5
F	0	0.0	0.0	0.4	0.4	0.9
G	0	-0.4	0.0	-0.4	0.0	0.6
H	0	-0.4	-0.2	-0.4	-0.2	0.0
I	0	-0.6	0.0	-0.4	-0.2	0.2
J	0	-0.2	0.0	-0.2	0.2	0.6
A	1.5	-0.2	0.0	-0.2	0.0	0.0
C	1.5	-0.4	0.0	-0.2	0.2	0.2
E	1.5	-0.4	-0.4	-0.4	-0.2	0.0
G	1.5	-0.2	0.4	-0.2	0.0	0.2
A	3	0.0	0.4	0.0	0.4	0.4
B	3	0.2	0.0	-0.4	0.0	0.0
C	3	-0.2	0.0	-0.2	0.2	0.2
D	3	-0.2	-0.2	0.2	0.2	-0.2
E	3	0.2	0.2	-0.2	0.2	0.2
F	3	0.0	0.2	-0.4	0.0	0.0
G	3	0.0	-0.2	-0.2	0.0	0.0
H	3	-0.2	-0.2	-0.6	0.0	0.0
I	3	0.4	0.2	0.0	0.2	0.6
J	3	-0.2	0.0	0.0	0.0	0.2
A	10	0.2	0.4	0.0	0.2	0.6
C	10	0.0	0.0	-0.2	0.2	0.6
E	10	-0.2	0.0	-0.4	0.0	1.2
G	10	-0.6	-0.0	-0.2	0.2	0.4

b SPECS
CHAMBER 2

b specimens conditioned in the 30% and 50% R.H. chambers did not have their length changes monitored continuously during the first freeze-thaw cycle. As the results of the b specimens from the 70% and 90% R.H. chambers showed no dilation anomalies and negligible residual expansions after the first cycle, it was thought that similar behavior would be obtained for the b specimens from chambers 1 and 2. This was discovered to be the case so only the residual expansions were measured for these specimens and the results are shown in tables VII and VIII.

3. Four Subsequent Freeze-Thaw Cycles: The "fully" saturated specimens and all the b specimens from the four R.H. chambers were each measured for residual expansions (using the extensometer) after each of the four subsequent freeze-thaw cycles. The cumulative residual expansions were compiled for each specimen and are included in tables IV to VIII.

(a) Cumulative Residual Expansions of the b Specimens: The results clearly show that even after five freeze-thaw cycles the b specimens were still immune to frost action. Their immunity is definitely due to the lowered degrees of saturation attained prior to the freeze-thaw test. Therefore it can be concluded that partial desiccation of concrete slabs

TABLE VII.

SPEC TYPE	SAT IN NaCl SOLN (%)	CUMULATIVE RESIDUAL EXPANSIONS: $\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$				
		CYCLE 1.	CYCLE 2.	CYCLE 3.	CYCLE 4.	CYCLE 5.
A	0	0.2	0.2	0.2	0.2	0.4
B	0	-0.2	-0.4	-0.2	0.2	0.4
C	0	0.2	-0.2	0.0	0.6	0.6
D	0	0.0	-0.2	-0.2	0.2	0.2
E	0	-0.2	0.8	0.8	1.0	0.6
F	0	-0.2	0.2	0.2	0.2	0.2
G	0	-0.2	0.2	0.2	0.4	0.6
H	0	0.4	0.4	0.8	0.8	0.8
I	0	0.4	1.1	1.1	1.1	1.1
J	0	-0.4	0.8	0.8	1.0	1.0
A	1.5	-0.2	1.0	1.1	1.3	1.3
C	1.5	-0.2	0.4	0.6	1.0	1.0
E	1.5	0.2	0.2	1.1	1.1	1.1
G	1.5	0.0	0.0	0.2	0.4	0.4
A	3	0.4	0.6	0.6	0.8	0.8
B	3	0.2	0.4	0.8	0.8	0.8
C	3	0.4	0.8	0.8	0.8	0.8
D	3	0.2	-0.2	-0.2	-0.2	0.0
E	3	0.4	0.4	0.4	0.4	0.4
F	3	0.2	0.8	0.6	0.8	0.8
G	3	0.0	0.4	0.4	0.4	0.4
H	3	-0.4	1.0	1.1	1.1	1.1
I	3	0.2	1.0	1.0	1.1	1.1
J	3	0.2	0.6	0.9	1.1	1.1
A	10	0.0	0.6	1.0	1.1	1.1
C	10	0.8	1.1	1.3	1.3	1.1
E	10	0.0	0.8	1.0	1.3	1.1
G	10	-0.4	0.8	1.0	1.1	1.1

5 SPECS
CHAMBER 3

TABLE VIII

SPEC TYPE	SAT IN NaCl SOLEN (%)	CUMULATIVE RESIDUAL EXPANSIONS $\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$				
		CYCLE 1.	CYCLE 2.	CYCLE 3.	CYCLE 4.	CYCLE 5.
A	0	-0.4	-0.4	-0.4	-0.4	-0.4
B	0	0.6	1.1	1.1	1.1	1.1
C	0	0.4	0.2	0.0	0.2	0.4
D	0	0.2	0.4	0.0	0.0	0.0
E	0	0.6	0.2	0.0	0.2	0.2
F	0	0.0	-0.8	-0.8	-0.8	-0.6
G	0	0.2	-0.6	-0.6	-0.6	-0.6
H	0	-0.2	-0.6	-0.6	-0.6	-0.6
I	0	0.3	-0.4	-0.4	-0.6	-0.6
J	0	0.2	-0.4	-0.4	-0.4	-0.6
A	1.5	0.6	1.2	1.2	1.2	1.2
C	1.5	0.4	1.1	1.0	1.1	1.1
E	1.5	-0.2	1.0	1.0	1.1	1.1
G	1.5	0.4	1.0	1.0	0.8	1.0
A	3	0.8	0.0	-0.2	0.0	-0.4
B	3	0.4	-0.2	-0.2	-0.2	-0.2
C	3	0.2	-0.4	-0.2	-0.4	0.2
D	3	0.4	-0.2	-0.4	-0.4	0.2
E	3	0.4	-0.2	-0.4	-0.4	0.0
F	3	0.2	0.2	0.2	0.6	0.6
G	3	0.4	-0.2	-0.2	0.2	0.2
H	3	0.0	0.4	0.6	0.6	0.6
I	3	0.8	0.9	0.8	0.9	0.9
J	3	0.4	0.6	0.4	0.4	0.4
A	10	0.4	0.8	0.8	0.8	0.8
C	10	0.4	0.8	1.1	1.0	0.8
E	10	0.4	0.8	1.3	1.1	1.1
G	10	0.6	0.6	0.6	0.6	0.6

b SPECS

CHAMBER 4

is not beneficial to the performance of the slabs under frost action regardless as to whether or not the slabs are impregnated with salts.

(b) Cumulative Residual Expansion of "Fully"

Saturated Specimens: These specimens showed variable behavior after five freeze-thaw cycles. Curves of cumulative residual expansions vs. freeze-thaw cycles are shown in Figures D-65 to D-72. From these curves it can be seen that most of the specimens continue to expand during each successive cycle. The amount of expansion, however, is dependent on the solution contained within each "fully" saturated specimen. It is observed that after five cycles, specimen types A, C, E, G, I and J produce their greatest cumulative residual expansions when they are saturated in 3% NaCl solution and their second largest expansions when saturated in water. For the ~~A, C, E, G, I and J~~ specimens the lowest expansions were produced when they were saturated in 1% and 10% NaCl solutions. The B, D, F and H specimen types exhibited their largest expansions when saturated in water and second largest when saturated in 1% NaCl solution. The trends, however, for all the "fully" saturated specimen types A to J indicate that if projections of these curves were extrapolated into further successive freeze-thaw cycles along the same slope gradients that exist between the fourth and fifth cycle of each curve, there would be

reatest expansions developing in all the specimens when saturated in a 3% NaCl solution. The concentrations of the solvents ranging from most destructive to least destructive for frost damage would be 3% NaCl solution, water, 1 1/2% NaCl solution and finally 10% NaCl solution. There is one specimen, however, that tends not to follow the previously mentioned pattern. Specimen type E saturated in water shows a cumulative residual expansion after five cycles far greater than the same specimen type saturated in 3% NaCl solution. It is also observed that if the specimen were subjected to more freeze-thaw cycles the results would probably still be in the same relative order. Visual observation of specimen E saturated in water showed that it contained two very large pieces of aggregate, i.e., in excess of one inch in diameter whereas the average maximum size of the aggregates of the other three E specimens was approximately 1/2 inch. It is felt, therefore, that the presence of these two large aggregate pieces in this specimen was the cause of the excessive expansion that was observed. Thus, it is felt that this specimen was not very representative of the E type concrete tested.

4. Assessment of Frost Damage: All further discussions will be centered on specimens which were "fully" saturated in water or in the 3% NaCl solution as specimens conditioned in these two solvents suffered the greatest expansions. Specimen E saturated

in water will be excluded from the discussions for reasons previously mentioned. The order of magnitude of expansions from highest to lowest after five freeze-thaw cycles are shown in Figure D-23 and the specimens are A, I, H, F, G, E, D, C, B and J respectively. Specimen types A, I, E and D are cast-in-place concretes while H, F, G, C, B and J are "pressed" concretes.

(a) Cast-In-Place Concrete Specimens:

Consider first the cast-in-place specimens all of which were air-entrained. Air-entrainment is beneficial for improving the frost resistance of concrete when the concrete is not fully saturated; however, when concrete is fully saturated, air-entrainment can be more harmful than beneficial. If prior to the freezing process the air bubbles and the larger aggregate pores are all full, then, when freezing occurs, ice would form readily in the saturated entrained air voids and capillary cavities, causing expansion. Therefore, expansions of a high degree may take place in fully saturated air-entrained concrete. The magnitude of the expansions would depend on the total porosity and permeability of the concrete. Fully saturated air-entrained concrete would suffer a large expansion if it had a very high total porosity with a very low permeability. Specimen type A suffered the most damage because it has a medium to high total porosity and only a medium permeability. Although specimen type I has a high permeability it

suffered the second largest expansion because of its very high total porosity. Specimen type E has a medium total porosity with a high permeability so it suffered the third largest expansion. Specimen type D has a medium permeability and it experienced the least damage of the cast-in-place specimens because of its very low total porosity.

(b) "Pressed" Concrete Specimens: The "pressed" concrete specimens, in general, showed less expansion after five freeze-thaw cycles than the cast-in-place specimens. During freezing, the "fully" saturated "pressed" specimens experience expansions in much the same manner as the air-entrained specimens do, except that they do not contain the large water filled entrained air voids. However, it is felt that the magnitude of expansion is largely dependent on the total porosity and permeability of the concrete. Specimen type H experienced the largest expansions because it had a medium to high porosity with a low permeability. Next was specimen type F which has a medium to high porosity with a medium permeability. Specimen type G had the third largest expansion and this is a result of its low total porosity and low permeability. Specimen type C also has a low total porosity and a low permeability but it showed less expansion than type G. This is probably due to its lower water-cement ratio of 0.43. Specimen type B had the second lowest expansion and this is probably

due to its medium to high porosity with its high permeability. Specimen type J was by far the most frost resistant; it has a medium total porosity with a medium permeability.

It can be seen that permeability as determined by the rate of desiccation appears to be a big factor in establishing the frost resistance of "fully" saturated concrete whether it is air-entrained or not. Total porosity also appears to be important.

In order to check if there was significant moisture loss from the specimens during the freeze-thaw tests each specimen was weighed before and after each freeze-thaw cycle. For all the b specimens and "fully" saturated specimens tested there was only an average moisture loss of 0.2% by weight from the beginning of cycle 1 to the completion of cycle 5. This small amount would be negligible in altering the degree of saturation for each specimen during the freeze-thaw tests.

CHAPTER IX

Summary and Conclusions

This experimental program was designed to investigate the effect of a de-icing agent (NaCl) on the amount of water retained in different types of concrete under a variety of ambient relative humidities 30%, 47%, 72% and 80%, and to evaluate the resultant frost resistance of concrete thus treated. Following are the pertinent findings and conclusions of this study:

1. The higher the salt concentration of the solution with which the concrete specimens were saturated, the higher was the degree of saturation retained in the concrete under any given ambient relative humidity. For example, the average degree of saturation retained under 80% R.H. conditions for the concrete specimens saturated in 10% NaCl solution was 92% compared with an average of 73% for specimens saturated in water.

2. As would be expected, the lower the R.H. atmosphere

in which the saturated concrete was placed, the faster was the rate at which the degree of saturation was brought below a critical level (from the viewpoint of frost resistance). For example, in the $\frac{1}{2}$ inch thick concrete specimens drying from one side, on the average, the specimens desiccating in the 30% R.H. chamber took only six hours to get below the critical level of saturation, compared with 3.5 days for the specimens desiccating in the 90% R.H. chamber. It is thus obvious that the lower the R.H. atmosphere in which concrete is exposed after it has been saturated by unusually wet weather conditions, the sooner it will be brought below a critical degree of saturation.

3. Specimens from the cast-in-place concrete slabs (which, incidentally, were air-entrained); in general, showed faster rates of desiccation down to the critical level of saturation than did the specimens from the "pressed" concrete slabs. This would seem to be a reflection of greater permeability in the former slabs.

4. The higher the concentration of the NaCl solution used for saturating the specimens the greater was the freezing point depression indicated in the freeze-thaw tests. However, these freezing point depressions were lower than those indicated for NaCl solutions of bulk water.

5. There was found to be a linear relationship between the maximum dilation of "fully" saturated specimens and residual expansions of the same specimens after one freeze-thaw cycle. This would indicate that either criterion is a good parameter for assessment of frost damage.

6. All the specimens conditioned to equilibrium at the different relative humidities (30%, 47%, 72% and 88%) showed almost complete immunity to frost action even after five freeze-thaw cycles. This shows dramatically that even when concretes are conditioned in an atmosphere as high as 88% R.H., they can have their retained moisture contents reduced below critical levels for frost damage.

7. The curves of cumulative residual expansions vs freeze-thaw cycles show that concrete specimens "fully" saturated in 3% NaCl solution exhibited greater expansions for successive freeze-thaw cycles than they did in higher or lower NaCl concentrations. This confirms the findings of others and is explainable by Powers' theories regarding the effect of de-icing salts on freezing mechanisms in concrete (see page 42).

8. In general, for a "fully" saturated condition, the

cast-in-place concrete specimens showed greater cumulative residual expansions than did the "pressed" concrete specimens. Although the cast-in-place specimens were air-entrained, it is felt that the effective saturation procedure employed in this programme would almost completely fill the entrained air voids, and under freezing conditions water in such voids would be the first to freeze, causing considerable expansions.

9. For a continuous wet environment, it is concluded that in order to produce a more frost resistant concrete, the concrete should have a low total porosity with a high permeability. It is also understood that in nature air-entrained concrete is rarely ever virtually saturated because the larger air bubbles are very difficult to fill. Therefore, an air-entrained concrete, in service, would probably be more frost resistant than the same concrete completely saturated for the laboratory tests especially if it received periodic drying.

APPENDIX A

Experimental Errors

A. Cartorius Weigh Scale

The sensitivity control was checked on this instrument before and after each set of readings for the duration of the main experimental programme. A weight of 1 g, equivalent to the optical scale range, was used to ensure correct control of the sensitivity. At the beginning of the testing procedure the sensitivity was checked to give an exact scale of 1 g. It was not necessary to adjust the scale throughout the programme thus indicating exact reliability to 0.1 mg.

B. Mercer Extensometer

Sulfur bars were used to establish the accuracy of this instrument. In the determination of the coefficient of thermal expansion of two different sulfur bars the same value of 35.8×10^{-5} in/in/°F for the coefficient was established to an accuracy of 0.1×10^{-5} in/in/°F. The actual value of the coefficient is 35.6×10^{-5} in/in/°F. Since the extensometer was only used to record length changes this small error in accuracy would result in negligible variations of the recorded values.

C. DCDT Transducers, Their Frames and the Multipoint Strip
Chart Millivolt Recorder (Electronik 16)

The accuracies of the five transducers and their frames were established by the use of four sulfur bars. In establishing scaling factors for each transducer and frame it was discovered that for testing with different sulfur bars the same slope/length to an accuracy of 0.1×10^4 volts/°F/in was obtained for the different bars in each of the five frames. This indicated adequate accuracies to be obtained from the transducers and their frames. The transducers each had a stroke of ± 0.5 inches with a linearity of $\pm 0.5\%$ of the full scale. The calibrated accuracy of the millivolt recorder was ± 0.25 mv for a 100 mv span. In the calculations for the scaling factors ± 0.25 mv would make no difference at all in the calculated values.

APPENDIX B

117

CALCULATIONSTest to Establish Water Contents of Specimens
Conditioned in a Desiccator at 0% RH

Refer to Table B-II.

$$\text{WATER CONTENT (\%)} = \frac{\text{COLUMN 1} - \text{COLUMN 3}}{\text{COLUMN 2} - \text{COLUMN 3}}$$

Calibrations for DCDT Transducers and Their
Frames

Refer to Table B-V, Figures B-6 and B-7.

$$\text{COEFF. OF THERMAL EXP} \frac{\text{IN}}{\text{IN}^\circ\text{F}} = \frac{\text{SLOPE}}{\text{LENGTH}}$$

Refer to Tables B-VI and B-VII, Figures B-8 to B-21.

$$\text{SCALING FACTOR} \frac{\text{V}}{\text{IN}} = \frac{\text{SLOPE}}{\text{LENGTH}} \frac{1}{\text{COEFF. OF EXP}}$$

TEMPERATURE CURVE

DIRECTIONS FOR READING

1. See measuring instrument instructions for correct connections and switch position for temperature.
2. When indicating meter pointer is stable read its dial number.
3. Refer to dial reading scale on extreme left side of chart running vertically from 0 to 100, to find corresponding dial indication.
4. From dial reading scale follow horizontally to right to intersection of temperature curve. From point of intersection proceed vertically down to bottom where temperature is given in degrees Fahrenheit.
5. Example: Let's say step No. 3 is 60, dial reading scale (step No. 3) would then be value A. Following horizontal line (step No. 4) we intersect temperature curve at B. A vertical line down from B (step No. 4) to C will then give you degrees Fahrenheit temperature or 70°F.

FIGURES LISTED VERTICALLY ALONG THIS SIDE REPRESENT DIAL NUMBER TAKEN FROM YOUR INDICATOR OR RECORDER AFTER TURNING SELECTOR SWITCH TO TEMPERATURE

FIGURE 86

FIGURE 87

FIGURE 88

FIGURE B9

FIGURE 810

FIGURE BII

FIGURE B12

FIGURE 813

FIGURE B14

FIGURE B15

FIGURE B 16

FIGURE B17

FIGURE B18

FIGURE 819

FIGURE B20

FIGURE 821

TABLE B-I
VACUUM SATURATION TESTS

SPEC TYPE	TEST A WT OF SPEC (G)	TEST B WT OF SPEC (G)	TEST C WT OF SPEC (G)
A1	138.23	138.70	139.16
A2	129.93	131.41	131.44
B1	130.76	131.86	131.59
B2	128.58	128.89	128.94
C1	148.65	149.17	149.17
C2	153.75	154.08	154.07
D1	128.41	128.46	129.17
D2	131.44	132.34	132.30
E1	144.15	145.08	144.39
E2	131.30	132.92	132.68
F1	127.89	128.01	127.96
F2	127.11	127.49	127.47
G1	140.00	140.42	140.37
G2	144.92	147.32	147.35
H1	137.00	136.82	136.80
H2	137.70	136.12	136.16
I1	128.09	128.85	129.12
I2	117.74	119.78	119.76
J1	134.00	135.21	135.21
J2	129.71	130.43	130.45

TABLE B-II
AVERAGE WATER CONTENTS AT 0% R.H.

SPEC TYPE	WT AFTER 1 DAY AT 0% RH (G)	WT AFTER VACUUM SAT (G)	WT AFTER OVEN DRYING (G)	WATER CONTENT AT 0% RH (%)	AVE WATER CONTENT (%)
A1	64.04	65.52	62.65	21.0	20.6
A2	77.07	61.15	75.01	20.6	
A3	70.14	74.45	69.57	20.2	
B1	28.14	30.04	27.87	12.4	12.5
B2	29.01	30.65	28.74	12.8	
B3	28.95	30.24	28.29	12.2	
C1	34.33	35.74	33.94	20.8	21.0
C2	45.35	46.54	45.78	21.0	
C3	47.12	49.27	48.54	21.2	
D1	51.12	53.31	50.71	15.8	15.7
D2	53.00	73.83	54.29	15.4	
D3	74.85	78.43	74.15	15.6	
E1	76.45	82.29	77.49	20.8	20.4
E2	75.09	79.53	74.72	20.2	
E3	76.45	80.05	75.94	20.4	
F1	50.89	53.51	50.20	20.9	20.1
F2	35.03	38.95	34.34	20.2	
F3	50.21	53.05	49.54	19.1	
G1	124.94	129.90	123.53	21.6	21.4
G2	125.41	130.05	124.01	21.2	
G3	107.00	112.01	100.41	21.3	
H1	25.77	27.32	25.47	16.2	16.1
H2	39.81	42.30	39.34	15.9	
H3	39.70	41.71	38.83	16.3	
I1	55.44	60.70	55.29	21.3	21.6
I2	2.39	60.77	51.16	21.9	
I3	57.75	61.76	59.55	21.7	
J1	32.57	34.10	32.41	15.4	15.2
J2	32.76	34.17	32.51	15.1	
J3	32.00	34.13	32.42	15.2	

TABLE B-III
SOLUBILITIES OF SALTS

SALT	TYPE	SOLUBILITY RANGE (G/100 cc OF WATER)	EXACT SOLUBILITY (G/100 cc OF WATER)
$\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$		157 - 357	329.1
$\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$		275 - 660	506.6
NaCl		35.7 - 39.12	39.1
KNO_3		13.3 - 247	47.7

TABLE B-IV
HUMIDITY - TEMPERATURE DATA

CHAMBER NO	SENSING PROBE	DIAL RDGS		CALIBRATED RDGS	
		TEMP	RH	TEMP (°F)	RH (%)
		1ST SET OF READINGS			
1	YELLOW	34.0	34.0	79.5	30.3
2	GREEN	34.5	37.5	82.0	47.3
3	VIOLET	54.0	20.5	61.0	72.2
4	GRAY	54.0	55.0	61.0	83.0
2ND SET OF READINGS					
1	YELLOW	34.0	32.0	61.0	30.0
2	GREEN	34.0	37.5	61.0	47.0
3	VIOLET	55.0	27.5	61.5	72.0
4	GRAY	61.5	52.0	62.0	67.0

TABLE B-V
COEFFICIENT OF THERMAL EXPANSION

SULFUR BAR NO	LENGTH (IN)	COEFF OF THERMAL EXP (IN/IN/°F) X 10 ⁶
1	4.950	—
2	4.950	35.0
3	5.002	35.0
4	5.003	—

TABLE B-VI
SLOPE/LENGTH

FRAME NO	SLOPE / LENGTH (MV/°F / IN)			
	SULFUR BAR 1.	SULFUR BAR 2.	SULFUR BAR 3.	SULFUR BAR 4.
1	0.27 0.26 0.27	0.27	—	—
2	0.21 0.21	0.21	—	—
3	0.34	0.34	—	—
4	0.33	0.33	—	—
5	0.92	—	0.92	0.92

TABLE B-VII
SCALING FACTORS

FRAME NO	SCALING FACTORS (VOLTS/IN.)				
	SULFUR BAR 1.	SULFUR BAR 2.	SULFUR BAR 3.	SULFUR BAR 4.	AVE
1	7.50	7.50	—	—	7.5
2	8.27	8.27	—	—	8.2
3	9.50	9.50	—	—	9.5
4	9.22	9.22	—	—	9.2
5	20.70	—	20.70	20.70	20.7

APPENDIX C

CONCRETE TYPE A

Process of Manufacture	cast-in-place (broomed surface)
Mix Design	unknown
Curing Method	sprinkled surface then covered with polyethylene film
Cement Type	Normal Portland
W/C Ratio	unknown
Slump	3.5 inches
Air Entrainment	2.5%
Air Bubble Spacing	0.000 inches

CONCRETE TYPE B

Process of Manufacture	wet press
Mix Design	2350 lbs. of aggregate 350 lbs. of cement 40 gals. of water
Curing Method	air.
Cement Type	High Early
Pressing Time	0 seconds + 2 seconds full pressure
Pressure	1000 psi
Original W/C Ratio	1.05
Final W/C Ratio	unknown

CONCRETE TYPE C

Process of Manufacture	wet press
Mix Design	regular mix 325 lbs. of stone 380 lbs. of crusher dust 210 lbs. of cement
Curing Method	air
Cement Type	Normal
Pressing Time	unknown
Pressure	unknown
Original W/C Ratio	unknown
Final W/C Ratio	0.43

CONCRETE TYPE D

Process of Manufacture	cast-in-place
Mix Design	600 lbs. of sand 1000 lbs. of gravel 240 lbs. of cement 12 gals. of water
Curing Method	kila
Cement Type	Pronto
W/C Ratio	unknown
Air Entrainment	5%

CONCRETE TYPE E

Process of Manufacture	cast-in-place (traughed surface)
Mix Design	unknown
Curing Method	sprinkled surface then covered with polyethylene film
Cement Type	Normal Portland
W/C Ratio	unknown
Air Entrainment	3.2%
Air Bubble Spacing	0.0072 inches

CONCRETE TYPE F

Process of Manufacture	dry press (Rino)
Mix Design	220 lbs. of cement 600 lbs. of sand 390 lbs. of 5/8 inch stone
Curing Method	air
Cement Type	Normal Portland
Pressing Time	12 seconds with continued tamping
Pressure	unknown
Original W/C Ratio	no slump mix
Final W/C Ratio	unknown

CONCRETE TYPE G

Process of Manufacture	wet press
Mix Design	low cement mix 325 lbs. of stone 140 lbs. of crusher dust 170 lbs. of cement
Curing Method	air
Cement Type	Normal
Pressing Time	unknown
Pressure	unknown
Original W/C Ratio	unknown
Final W/C Ratio	0.53

CONCRETE TYPE I

Process of Manufacture

cast-in-place

Mix Design

120 lbs. of cement
275 lbs. of stone
100 lbs. of sand
5.5 gals. of water

Curing Method

12 hours at 50 C

Cement Type

Type III

W/C Ratio

0.45

Air Entrainment

5 to 7%

CONCRETE TYPE J

Process of Manufacture

wet press

Mix Design

1050 lbs. of stone
450 lbs. of sand
900 lbs. of stone dust
350 lbs. of cement

Curing Method

air

Cement Type

Normal Portland

Pressing Time

5 seconds of full pressure

Pressure

1250 psi

Original W/C Ratio

unknown

Final W/C Ratio

unknown

APPENDIX D

9

APPENDIX D

Calculations:

$$\text{Deg of Sat at Equil} = \frac{\text{Wt of Spec at Equil} - \text{Wt of Dry Spec}}{\text{Wt of Sat Spec} - \text{Wt of Dry Spec}}$$

$$\text{Water Content at Sat} = \frac{\text{Wt of Sat Spec} - \text{Wt of Dry Spec}}{\text{Wt of Sat Spec}}$$

$$\text{Rate of Desiccation} = \frac{\text{Wt of Water Lost}}{\text{Wt of Sat Spec}} \times \frac{1}{\text{Time}}$$

$$\frac{\Delta L}{L} \times 10^4 = \frac{\text{MV Reading}}{\text{Scaling Factor}} \times \frac{1}{\text{Total Length of Spec}}$$

$$\text{Cum. Res. Exps.} = \frac{\text{Change in Length}}{\text{Total Length of Spec}}$$

FIGURE D1

FIGURE D2

FIGURE 03

FIGURE D4

FIGURE D5

FIGURE D6

FIGURE D7

FIGURE D8

FIGURE D9

FIGURE D10

FIGURE D11

FIGURE D12

FIGURE D13

FIGURE D14

FIGURE D15

FIGURE D16

FIGURE D17

FIGURE D18

FIGURE D19

FIGURE D20

FIGURE D21

FIGURE D22

FIGURE D23

FIGURE D24

FIGURE D25

FIGURE D26

FIGURE D27

FIGURE D28.

FIGURE D29

FIGURE D30

FIGURE D.31

FIGURE D32

FIGURE D33

FIGURE D34

FIGURE D35

FIGURE D36

FIGURE D37

FIGURE D38

FIGURE D39

FIGURE D40

FIGURE D41

FIGURE D42

FIGURE D43

FIGURE D44

FIGURE D45

FIGURE D46

FIGURE . D47

FIGURE D48

FIGURE D49

FIGURE D50

FIGURE D51

FIGURE D52

FIGURE D53

FIGURE 054

FIGURE D55

FIGURE D56

FIGURE D58

FIGURE 059

FIGURE D60

FIGURE D61

FIGURE D62

FIGURE D63

FIGURE D64

FIGURE D 65

FIGURE 066

FIGURE D67

FIGURE D68

FIGURE D69

FIGURE 070

FIGURE D71

FIGURE D72

FIGURE 073

FIGURE D74

225

FIGURE 075

FIGURE D76

FIGURE D77

FIGURE D78

FIGURE D79

FIGURE D 80

FIGURE DB1

FIGURE D 82

FIGURE D 82

FIGURE D-83

FIGURE D84

FIGURE D85

FIGURE D86

FIGURE D87

FIGURE D88

FIGURE D89

FIGURE D90

FIGURE D91

FIGURE 092

FIGURE D93

TABLE D-I
TIME TO EQUILIBRIUM

SPEC TYPE	SAT ^a IN NaCl SOLN (%)	TIME TO EQUILIBRIUM (DAYS)			
		CHAMBER 1.	CHAMBER 2.	CHAMBER 3.	CHAMBER 4.
A	0	27	31	15	6
B	0	18	26	6	6
C	0	26	27	7	2
D	0	21	21	14	4
E	0	2	27	15	4
F	0	23	24	14	2
G	0	23	26	16	4
H	0	21	32	9	6
I	0	20	32	10	3
J	0	16	24	3	3
A	1.5	25	24	25	6
C	1.5	2	24	19	3
E	1.5	20	24	21	6
G	1.5	25	24	16	6
A	3	25	24	17	3
B	3	25	24	10	3
C	3	27	32	11	4
D	3	25	24	10	4
E	3	25	24	17	5
F	3	20	24	11	4
G	3	25	29	10	4
H	3	20	24	11	7
I	3	26	24	21	4
J	3	25	24	6	4
A	10	27	24	24	6
C	10	26	24	9	5
E	10	2	24	22	6
G	10	33	23	22	6
TOTAL AVE		26	25	16	5

^a SPECS

TABLE D-II

SPEC TYPE	SAT IN NaCl SOLN (%)	TIME TO EQUILIBRIUM (DAYS)			
		CHAMBER 1.	CHAMBER 2.	CHAMBER 3.	CHAMBER 4.
A	0	60	73	65	12
B	0	76	69	60	13
C	0	62	73	64	14
D	0	64	74	31	11
E	0	62	76	53	12
F	0	62	76	70	19
G	0	61	72	65	10
H	0	63	74	77	25
I	0	62	79	69	20
J	0	81	77	62	16
A	1.5	60	71	60	15
C	1.5	62	75	64	15
E	1.5	62	76	60	14
G	1.5	61	71	62	22
A	3	62	75	53	16
B	3	61	70	71	10
C	3	63	77	61	15
D	3	70	74	39	14
E	3	60	75	74	18
F	3	62	75	56	31
G	3	62	76	61	22
H	3	60	76	70	35
I	3	63	70	63	15
J	3	77	73	67	22
A	10	79	76	66	34
C	10	62	73	64	12
E	10	79	74	60	34
G	10	61	71	62	24
TOTAL AVE		60	73	62	20

b SPECS

TABLE D-III
TIME TO 91% DEGREE OF SATURATION

SPEC TYPE	SAT. IN NaCl SOLN (%)	TIME TO 91% DEG OF SAT (DAYS)			
		CHAMBER 1.	CHAMBER 2.	CHAMBER 3.	CHAMBER 4.
A	0	0.04	0.04	0.03	0.13
B	0	0.04	0.04	0.03	0.13
C	0	0.04	0.05	0.13	0.25
D	0	0.04	0.04	0.03	0.13
E	0	0.04	0.04	0.03	0.13
F	0	0.04	0.04	0.03	0.13
G	0	0.04	0.04	0.03	0.13
H	0	0.04	0.04	0.03	0.19
I	0	0.04	0.05	0.03	0.13
J	0	0.04	0.04	0.03	0.13
A	1.5	0.04	0.04	0.03	0.13
C	1.5	0.04	0.04	0.03	0.13
E	1.5	0.04	0.04	0.03	0.13
G	1.5	0.04	0.04	0.03	0.13
A	3	0.04	0.05	0.03	0.13
B	3	0.04	0.04	0.03	0.13
C	3	0.04	0.05	0.13	0.25
D	3	0.04	0.04	0.03	0.13
E	3	0.04	0.04	0.03	0.13
F	3	0.04	0.04	0.03	0.13
G	3	0.04	0.04	0.03	0.19
H	3	0.04	0.04	0.03	0.13
I	3	0.04	0.04	0.03	0.25
J	3	0.04	0.04	0.03	0.13
A	10	0.04	0.05	0.13	*
C	10	0.04	0.05	0.13	*
E	10	0.04	0.04	0.13	4.13
G	10	0.04	0.04	0.13	3.75
Total Ave		0.04	0.04	0.09	0.44

a SPECS

* Specimen did not reach 91% deg of saturation

TABLE D-IV

SPEC TYPE	SAT IN NaCl SOLN (%)	TIME TO 91% DEG OF SAT (DAYS)			
		CHAMBER 1.	CHAMBER 2.	CHAMBER 3.	CHAMBER 4.
A	0	0.19	0.13	0.13	0.45
B	0	0.17	0.15	0.13	0.46
C	0	0.52	0.55	1.00	2.33
D	0	0.11	0.11	0.11	0.29
E	0	0.14	0.13	0.13	0.45
F	0	0.19	0.19	0.19	0.45
G	0	0.45	0.46	0.71	1.00
H	0	0.27	0.27	0.25	0.45
I	0	0.19	0.24	0.33	0.45
J	0	0.15	0.14	0.13	0.58
A	1.5	0.11	0.13	0.17	0.50
C	1.5	0.32	0.39	1.00	6.92
E	1.5	0.11	0.13	0.15	0.58
G	1.5	0.13	0.29	0.67	1.29
A	3	0.17	0.19	0.23	1.00
B	3	0.15	0.16	0.17	0.71
C	3	0.31	0.38	1.33	* —
D	3	0.12	0.13	0.15	0.50
E	3	0.17	0.17	0.17	1.29
F	3	0.27	0.28	0.31	1.33
G	3	0.66	0.56	1.17	2.71
H	3	0.23	0.23	0.29	1.79
I	3	0.17	0.17	0.29	0.79
J	3	0.17	0.17	0.45	1.38
A	10	0.19	0.20	0.42	34.0
C	10	0.50		2.38	* —
E	10	0.15		0.33	25.0
G	10	0.50		1.92	* —
Total Ave		0.25	0.27	0.49	3.47

b. SPECS

* Specimen did not reach 91% deg of saturation

TABLE D-V
WATER CONTENT AT SATURATION

SPEC TYPE	SAT IN NaCl SOLN (%)	WATER CONTENT AT SAT (%)			
		CHAMBER .1.	CHAMBER .2.	CHAMBER .3.	CHAMBER .4.
A	0	5.8	5.6	5.9	5.5
B	0	6.8	6.4	6.5	6.5
C	0	4.5	4.1	4.3	4.1
D	0	6.1	4.7	5.2	5.8
E	0	5.7	4.5	5.0	5.2
F	0	6.6	6.5	6.5	6.3
G	0	4.8	4.8	4.9	4.7
H	0	6.4	6.3	6.7	6.5
I	0	6.0	7.0	7.7	7.7
J	0	5.9	6.0	6.0	5.6
A	1.5	5.7	6.2	6.1	5.6
C	1.5	4.6	4.3	4.8	4.6
E	1.5	5.4	5.0	5.9	5.5
G	1.5	4.3	4.0	4.4	4.7
A	3	5.7	5.8	5.5	5.6
B	3	6.4	6.3	6.3	6.6
C	3	4.5	5.2	4.8	4.5
D	3	5.5	5.3	4.3	5.6
E	3	5.0	4.8	4.7	5.1
F	3	6.6	6.4	6.6	6.5
G	3	4.4	4.8	4.6	5.0
H	3	6.1	6.0	6.4	6.5
I	3	7.5	7.2	7.6	6.2
J	3	5.9	6.2	6.0	5.8
A	10	5.4	5.7	5.5	5.4
C	10	4.2	4.6	4.1	3.9
E	10	5.2	5.4	5.1	4.6
G	10	4.3	4.2	4.6	4.2

a SPECS

TABLE D-VI

SPEC TYPE	SAT IN NaCl SOLN (%)	WATER CONTENT AT SAT (%)			
		CHAMBER 1.	CHAMBER 2.	CHAMBER 3.	CHAMBER 4.
A	0	5.3	6.4	6.4	6.4
B	0	6.4	6.7	6.4	6.4
C	0	4.7	4.5	4.3	4.9
D	0	4.3	4.3	4.4	4.4
E	0	5.6	6.3	5.9	6.0
F	0	6.5	6.6	6.2	6.6
G	0	5.0	5.0	4.8	4.8
H	0	6.2	6.5	6.2	6.4
I	0	7.5	8.1	7.9	8.2
J	0	5.6	6.1	6.0	6.0
A	1.5	5.3	6.3	6.1	6.3
C	1.5	4.6	5.3	4.7	4.7
E	1.5	5.9	6.3	5.8	5.4
G	1.5	4.4	4.9	4.7	4.8
A	3	6.0	6.3	6.4	6.3
B	3	6.4	6.6	6.2	6.2
C	3	5.1	4.9	4.8	5.1
D	3	4.1	4.0	4.7	4.3
E	3	6.3	5.9	5.9	5.6
F	3	6.0	6.2	6.1	6.3
G	3	5.0	4.8	4.6	4.8
H	3	6.3	5.4	6.3	5.9
I	3	7.7	7.9	7.8	7.4
J	3	5.7	6.2	5.6	5.6
A	10	6.1	5.3	6.3	6.1
C	10	4.8	4.7	4.8	4.9
E	10	5.9	6.2	6.0	5.7
G	10	4.6	4.5	4.7	4.4

b SPECS

TABLE D-VII

SPEC TYPE	SPEC CODE	AVE WATER CONTENT AT SAT (%)
A	<u>a</u>	5.7
B	<u>a</u>	6.5
C	<u>a</u>	4.4
D	<u>a</u>	5.4
E	<u>a</u>	5.1
F	<u>a</u>	6.5
G	<u>a</u>	4.6
H	<u>a</u>	6.4
I	<u>a</u>	7.6
J	<u>a</u>	6.0
A	<u>b</u>	6.3
B	<u>b</u>	6.4
C	<u>b</u>	4.8
D	<u>b</u>	4.3
E	<u>b</u>	5.9
F	<u>b</u>	6.3
G	<u>b</u>	4.7
H	<u>b</u>	6.3
I	<u>b</u>	7.8
J	<u>b</u>	5.9

TABLE D-VIII
RATE OF DESICCATION

SPEC TYPE	SAT IN NaCl SOLN (%)	RATE OF DESICCATION AT 91% DEG OF SAT (G/G/DAY) X 10 ²			
		CHAMBER 1.	CHAMBER 2.	CHAMBER 3.	CHAMBER 4.
A	0	13.0	12.8	6.6	3.8
B	0	15.3	14.5	7.4	4.5
C	0	10.0	7.4	2.9	1.5
D	0	13.8	10.5	6.1	4.0
E	0	12.8	10.3	5.6	3.6
F	0	14.8	14.5	7.4	4.4
G	0	10.8	10.8	5.5	2.2
H	0	14.3	14.3	7.5	4.5
I	0	18.0	12.6	8.8	5.3
J	0	13.3	13.5	6.8	3.8
A	1.5	12.0	14.0	6.9	3.8
C	1.5	10.3	9.5	5.4	3.2
E	1.5	12.3	11.3	6.6	3.8
G	1.5	9.8	9.0	5.0	3.2
A	3	12.8	13.0	6.1	3.8
B	3	14.3	14.0	7.1	4.5
C	3	10.0	9.2	3.3	1.6
D	3	12.3	11.5	4.9	3.8
E	3	11.3	11.0	5.3	3.5
F	3	14.0	14.5	7.5	4.5
G	3	9.0	10.8	5.1	2.4
H	3	13.8	13.5	7.3	4.5
I	3	17.0	16.3	8.5	3.0
J	3	13.3	13.8	7.4	4.0
A	10	12.3	10.2	3.8	* —
C	10	9.5	8.2	2.8	* —
E	10	11.8	12.3	3.5	0.1
G	10	9.8	9.5	3.2	0.1
TOTAL	AVL	12.6	11.9	5.9	3.0

a SPECS

* Specimen did not reach 91% Deg of Saturation

TABLE D-IX

SPEC TYPE	SAT IN NaCl SOLN (%)	RATE OF DESICCATION AT 91% DEG OF SAT (G/G/DAY) X 10 ²			
		CHAMBER 1.	CHAMBER 2.	CHAMBER 3.	CHAMBER 4.
A	0	3.1	4.5	4.5	1.3
B	0	3.4	4.0	4.5	1.2
C	0	0.8	0.6	0.4	0.2
D	0	3.5	4.3	3.6	1.3
E	0	3.6	4.3	4.1	1.2
F	0	3.1	3.1	2.9	1.3
G	0	1.0	1.0	0.6	0.4
H	0	2.1	2.3	2.2	1.3
I	0	3.5	3.0	2.2	1.6
J	0	3.3	3.9	4.2	0.9
A	1.5	5.2	4.3	3.2	1.0
C	1.5	1.3	1.2	0.4	0.1
E	1.5	4.6	4.4	3.5	0.2
G	1.5	3.1	1.5	0.6	0.3
A	3	3.2	3.0	2.5	0.6
B	3	3.8	3.7	3.3	0.8
C	3	1.5	1.2	0.3	*
D	3	3.0	2.8	2.8	0.6
E	3	3.3	3.1	3.1	0.4
F	3	2.0	2.0	1.8	0.4
G	3	0.7	0.8	0.4	0.2
H	3	2.5	2.5	2.0	0.3
I	3	4.1	4.2	2.5	0.9
J	3	2.3	2.7	1.1	0.4
A	10	2.9	2.9	1.4	0.01
C	10	0.9	0.6	0.2	*
E	10	3.5	3.1	1.6	0.01
G	10	0.7	0.6	0.2	*
TOTAL	AVL	2.7	2.7	2.1	0.7

b SPECS

* Specimen did not reach 91% Deg of Saturation

TABLE D-X.
TEMPERATURE LAGS

SPEC TYPE	CHAMBER NO.	SAT IN. NaCl SOLN (%)	TEMPERATURE LAG	
			TEMP DECREASE (°F)	TEMP INCREASE (°F)
A	1	0	0.5	0.4
A	1	1.5	0.3	0.3
A	1	3	0.3	0.3
A	1	10	0.5	0.4
A	4	0	0.5	0.3
A	4	1.5	0.3	0.3
A	4	3	0.2	0.4
A	4	10	0.3	0.2
C	1	0	0.1	0.0
C	1	1.5	0.0	0.0
C	1	3	0.0	0.0
C	1	10	0.4	0.3
C	4	0	0.2	0.4
C	4	1.5	0.3	0.3
C	4	3	0.5	0.3
C	4	10	0.5	0.0
AVE TEMP LAG			0.3	0.2

TABLE D-XI
FREEZING POINT DEPRESSIONS

SPEC TYPE	FREEZING POINT DEPRESSIONS (°F)			
	SAT IN 0% NaCl SOLN	SAT IN 1.5% NaCl SOLN	SAT IN 3% NaCl SOLN	SAT IN 10% NaCl SOLN
A	21.5	21.0	20.4	16.0
B	23.5		19.8	
C	20.9	19.7	19.0	12.5
D	24.2		20.6	
E	21.9	21.0	20.5	16.0
F	22.9		19.6	
G	23.8	20.0	19.7	16.4
H	24.0		20.7	
I	24.3		19.5	
J	24.3		20.5	

FULLY SAT SPECS

TABLE D-XII
MAXIMUM DILATIONS

SPEC TYPE	MAXIMUM DILATIONS (IN/IN X 10 ⁴)			
	SAT IN 0% NaCl SOLN	SAT IN 1.5% NaCl SOLN	SAT IN 3% NaCl SOLN	SAT IN 10% NaCl SOLN
A	5.4	1.9	5.4	0.0
B	1.9		0.4	
C	1.3	0.1	0.3	0.0
D	1.2		0.1	
E	6.6	0.5	0.3	0.5
F	0.9		6.5	
G	0.5	3.7	0.0	2.1
H	16.0		0.4	
I	2.4		4.5	
J	0.6		0.3	

FULLY SAT SPECS

TABLES D-XIII & D-XIV
LENGTH CHANGE DATA

255

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-4.7	-0.4
-0.1	61.8	-4.4	3.9
-1.1	51.6	-4.3	8.5
-1.9	42.1	-4.1	12.7
-2.5	33.8	-3.8	16.5
-2.9	25.4	-3.6	20.0
-3.3	19.8	-3.4	23.0
-3.7	13.8	-3.3	25.8
-4.0	9.1	-3.1	28.3
-4.2	5.3	-2.9	30.7
-4.3	2.2	-2.7	33.2
-4.4	1.0	-0.7	50.0
-4.7	-0.4	1.2	70.0

D SPECS CHAMBER . 3 . FRAME . 2 .
SPEC TYPE A SAT IN 0 % NaCl SOLN

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-9.4	4.0
-0.5	55.5	-9.0	5.5
-1.5	44.9	-7.9	10.2
-2.5	45.3	-7.1	14.5
-3.5	36.5	-6.4	18.2
-4.7	29.0	-5.9	21.7
-5.8	22.3	-5.7	24.7
-6.8	16.4	-5.1	27.4
-7.8	11.2	-4.6	30.0
-8.8	7.2	-4.3	32.4
-8.9	6.0	-4.0	34.8
-9.1	5.0	-2.3	50.0
-9.4	4.0	-0.1	70.0

D SPECS CHAMBER . 3 . FRAME . 4 .
SPEC TYPE B SAT IN 0 % NaCl SOLN

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-6.1	0.0
-0.2	63.2	-5.0	3.5
-1.1	53.0	-4.9	8.0
-1.9	43.5	-4.8	12.1
-2.7	34.6	-4.2	16.0
-3.6	27.5	-3.9	18.9
-4.2	21.0	-3.6	22.5
-4.7	15.0	-3.4	25.2
-5.1	9.8	-3.1	27.9
-5.3	6.8	-3.0	30.5
-5.6	2.7	-2.8	32.8
-5.9	1.0	-1.3	50.0
-6.1	0.0	0.3	70.0

b SPECS CHAMBER . 3 . FRAME . 1 .
 SPEC TYPE C SAT IN 0 % NaCl SOLN

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-6.0	1.5
-0.4	65.5	-5.2	5.5
-1.3	54.9	-4.5	10.2
-2.1	45.3	-4.2	14.5
-2.9	35.6	-4.1	18.2
-3.5	29.0	-3.9	21.7
-3.8	22.3	-3.8	24.7
-4.4	16.4	-3.5	27.4
-4.8	11.2	-3.4	30.0
-5.3	7.2	-3.3	32.4
-5.7	4.0	-3.1	34.8
-5.8	3.0	-1.9	50.0
-6.0	1.5	-0.1	70.0

b SPECS CHAMBER . 3 . FRAME . 3 .
 SPEC TYPE D SAT IN 0 % NaCl SOLN

TABLES D-XVII^B D-XVIII

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{IN}{IN} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{IN}{IN} \right)$	TEMP (°F)
0.0	70.0	-6.3	10.0
-1.2	60.1	-5.7	13.0
-2.1	51.2	-5.2	18.0
-3.0	43.6	-4.8	22.7
-3.7	37.2	-4.4	26.6
-4.1	31.0	-4.0	30.3
-4.4	25.7	-3.8	33.4
-4.6	22.3	-3.4	35.3
-5.1	18.8	-3.2	36.8
-5.4	15.5	-3.0	41.2
-5.9	12.8	-2.7	43.8
-6.2	10.0	-2.5	44.2
-6.6	6.0	-1.0	70.0

D SPECS CHAMBER. 3. FRAME. 1.
SPEC TYPE E SAT IN 0 % NaCl SOLN

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{IN}{IN} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{IN}{IN} \right)$	TEMP (°F)
0.0	70.0	-8.1	7.6
-1.2	58.4	-7.3	10.4
-2.3	49.0	-6.4	15.3
-3.2	41.5	-5.8	19.7
-4.2	34.9	-5.4	23.6
-4.9	29.2	-4.9	27.1
-5.5	24.2	-4.5	30.3
-6.2	20.0	-4.1	33.3
-6.7	16.3	-3.6	36.0
-7.2	13.3	-3.5	38.5
-7.6	10.6	-3.3	40.8
-8.1	7.5	-3.0	43.2
-8.4	5.0	-0.2	70.0

D SPECS CHAMBER. 3. FRAME. 3.
SPEC TYPE F SAT IN 0 % NaCl SOLN

TABLES D-XIX B D-XX

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-8.6	7.6
-1.0	58.4	-7.8	10.4
-2.0	49.0	-6.6	15.3
-2.9	41.5	-5.9	19.7
-3.7	34.9	-5.2	23.6
-4.6	29.2	-4.7	27.1
-5.4	24.2	-4.3	30.3
-6.1	20.0	-3.9	33.3
-6.8	16.3	-3.6	36.0
-7.4	13.3	-3.3	38.5
-8.0	10.6	-3.1	40.8
-8.6	7.6	-2.7	43.2
-9.9	6.0	-0.6	70.0

D SPECS CHAMBER . 3 . FRAME . 4 .
 SPEC TYPE G SAT IN 0 % NaCl SOLN

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-3.5	6.5
-1.1	58.5	-3.4	9.5
-1.5	47.5	-3.3	14.5
-1.9	40.2	-3.1	19.2
-2.2	33.7	-2.8	23.1
-2.6	28.2	-2.7	26.6
-2.8	23.2	-2.5	29.9
-3.0	18.6	-2.3	31.8
-3.2	15.3	-2.1	35.3
-3.3	12.0	-1.9	37.7
-3.4	9.3	-1.8	40.3
-3.5	6.5	-1.6	42.7
-3.6	6.0	0.4	70.0

D SPECS CHAMBER . 3 . FRAME . 2 .
 SPEC TYPE H SAT IN 0 % NaCl SOLN

TABLES D-XXI & D-XXII

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-6.1	10.1
-0.9	63.2	-5.6	14.3
-1.7	53.5	-5.2	16.8
-2.5	45.0	-4.7	22.6
-3.1	39.5	-4.4	26.4
-3.6	34.0	-4.1	29.6
-4.1	29.3	-3.7	32.7
-4.5	25.0	-3.5	35.3
-5.0	21.1	-3.2	37.7
-5.3	17.7	-3.0	39.9
-5.5	14.0	-2.7	42.3
-5.9	12.2	-2.5	44.7
-6.5	0.0	-0.3	70.0

D. SPECS CHAMBER, 3 . FRAME, 1 .
 SPEC TYPE I SAT IN 0 % NaCl SOLN

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-7.4	10.0
-0.7	63.3	-5.5	13.5
-1.6	54.7	-5.3	17.9
-2.5	45.9	-5.3	21.7
-3.3	40.2	-4.9	25.3
-4.0	34.5	-4.5	28.6
-4.5	29.5	-4.2	31.6
-5.2	25.2	-3.9	34.2
-5.5	21.3	-3.6	36.6
-6.2	17.6	-3.3	39.0
-6.5	14.9	-3.1	41.2
-7.0	12.4	-2.8	43.5
-8.0	0.0	-0.3	70.0

D. SPECS CHAMBER, 3 . FRAME, 3 .
 SPEC TYPE J SAT IN 0 % NaCl SOLN

TABLES D-XIII B D-XIV

COOLING	CYCLE	WARMING	CYCLE
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-5.4	11.6
-1.7	50.7	-4.9	22.3
-2.5	50.0	-4.4	27.6
-3.1	44.0	-3.9	32.6
-3.5	34.2	-3.7	37.3
-3.9	33.0	-3.4	40.8
-4.3	30.7	-3.2	44.2
-4.5	25.1	-2.9	47.5
-4.7	21.7	-2.6	51.0
-4.9	18.3	-2.4	54.0
-4.9	15.7	-2.1	56.5
-5.1	13.2	-1.6	65.0
-5.6	0.0	-1.2	70.0

D SPECS CHAMBER. 3. FRAME. 2.
SPEC TYPE A SAT IN 1.5 % NaCl SOLN

COOLING	CYCLE	WARMING	CYCLE
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-7.7	10.0
-1.4	55.1	-6.3	15.7
-2.4	49.5	-5.4	24.3
-3.2	42.2	-4.0	29.3
-3.9	36.6	-4.3	33.0
-4.5	31.5	-3.0	37.3
-5.2	27.1	-3.5	40.7
-5.7	23.4	-3.0	44.1
-6.2	19.8	-2.0	47.5
-6.7	15.7	-2.2	50.5
-7.1	14.0	-1.9	53.3
-7.4	11.5	-1.2	60.0
-8.3	0.0	-0.2	70.0

D SPECS CHAMBER. 3. FRAME. 3.
SPEC TYPE C SAT IN 1.5 % NaCl SOLN

TABLES D-XXV & D-XXVI

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-6.4	7.8
-1.5	55.0	-5.5	15.0
-2.3	48.0	-4.9	20.8
-3.3	38.7	-4.5	25.6
-3.9	32.0	-3.9	30.0
-4.4	27.0	-3.6	33.5
-4.8	23.3	-3.2	36.7
-5.3	19.5	-3.0	40.2
-5.9	15.0	-2.7	43.5
-6.9	12.0	-2.3	46.3
-7.8	10.5	-2.1	49.0
-8.4	7.8	0.9	60.0
-6.0	5.0	0.2	70.0

D SPECS CHAMBER. 3 . FRAME. 1 .
SPEC TYPE E SAT IN 1.5 % NaCl SOLN

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-7.3	9.8
-1.0	59.1	-6.3	15.3
-2.1	49.5	-5.4	21.2
-3.0	42.5	-4.7	25.2
-3.7	38.1	-4.1	30.5
-4.4	30.5	-3.7	34.0
-5.0	25.0	-3.4	37.3
-5.5	22.0	-2.9	40.8
-6.1	16.5	-2.5	44.0
-6.6	15.1	-2.2	47.0
-6.9	12.5	-1.9	49.0
-7.2	9.0	-0.9	60.0
-7.0	5.0	0.1	70.0

D SPECS CHAMBER. 3 . FRAME. 3 .
SPEC TYPE G SAT IN 1.5 % NaCl SOLN

TABLES D-XXVII & D-XXVIII

253

COOLING	CYCLE	WARMING	CYCLE
$\frac{\Delta L}{L} \times 10^4 \left(\frac{IN}{IN} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{IN}{IN} \right)$	TEMP (°F)
0.0	70.0	-4.3	0.3
-1.0	57.0	-3.9	15.3
-1.8	47.0	-3.5	21.2
-2.2	40.2	-3.1	26.2
-2.3	34.0	-2.8	30.5
-3.2	28.7	-2.0	34.0
-3.5	24.2	-2.3	37.3
-3.7	20.3	-2.0	40.0
-3.9	15.6	-1.8	44.0
-4.0	13.4	-1.6	47.0
-4.1	10.0	-1.4	49.5
-4.3	0.3	-0.4	50.0
-4.5	0.0	0.4	70.0

b. SPECS CHAMBER. 3. FRAME. 2.
SPEC TYPE A SAT IN 3 % NaCl SOLN

COOLING	CYCLE	WARMING	CYCLE
$\frac{\Delta L}{L} \times 10^4 \left(\frac{IN}{IN} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{IN}{IN} \right)$	TEMP (°F)
0.0	70.0	-9.0	0.0
-1.3	55.2	-7.9	14.3
-2.3	40.0	-5.7	20.2
-3.4	31.5	-5.0	25.2
-4.3	20.2	-3.1	29.5
-5.1	10.0	-4.0	33.0
-5.8	0.0	-4.0	36.3
-6.7	0.0	-3.0	40.0
-7.3	0.0	-3.4	44.0
-7.9	13.2	-2.7	47.0
-8.4	11.5	-2.3	49.0
-9.0	0.0	-1.0	0.0
-9.5	0.0	0.2	70.0

b. SPECS CHAMBER. 3. FRAME. 4.
SPEC TYPE B SAT IN 3 % NaCl SOLN

TABLES D-XXIX B D-XXX

COOLING	CYCLE	WARMING	CYCLE
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-7.1	12.6
-1.1	59.1	-5.7	20.7
-1.2	48.2	-4.9	25.8
-2.5	41.9	-4.2	30.1
-3.3	35.5	-3.6	34.0
-4.0	29.0	-3.3	37.2
-4.5	27.7	-2.8	40.5
-5.2	23.5	-2.4	43.5
-5.7	20.1	-2.1	45.5
-6.2	16.8	-1.5	49.5
-6.9	14.0	-1.5	52.1
-7.1	12.6	-0.5	60.0
-7.8	0.0	0.3	70.0

b SPECS CHAMBER. 3 . FRAME. 4 .
SPEC TYPE C SAT IN 3 % NaCl SOLN

COOLING	CYCLE	WARMING	CYCLE
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-4.0	10.3
-1.4	52.9	-3.4	20.5
-2.0	45.2	-3.2	25.0
-2.3	39.1	-2.9	30.0
-2.7	34.0	-2.7	33.5
-2.9	29.0	-2.4	37.0
-3.2	25.4	-2.2	40.5
-3.4	21.5	-2.0	43.7
-3.5	17.0	-1.5	45.7
-3.7	14.5	-1.7	49.5
-3.9	11.5	-1.5	52.0
-4.0	10.3	-0.7	60.0
-4.3	0.0	0.2	70.0

b SPECS CHAMBER. 3 . FRAME. 2 .
SPEC TYPE D SAT IN 3 % NaCl SOLN

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-5.9	10.5
-1.6	52.9	-4.5	21.1
-2.4	45.5	-4.5	26.1
-3.4	39.3	-3.9	30.5
-3.5	34.5	-3.5	34.2
-4.0	30.0	-3.2	37.5
-4.3	25.9	-2.8	40.9
-4.6	22.0	-2.5	44.3
-5.1	18.3	-2.2	47.2
-5.4	15.1	-1.9	49.8
-5.7	12.3	-1.6	52.5
-5.9	10.8	-0.7	60.0
-6.3	5.0	0.4	70.0

D SPECS CHAMBER 3 FRAME 1
 SPEC TYPE E SAT IN 3 % NaCl SOLN

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-7.4	12.0
-1.5	55.1	-6.0	20.7
-2.4	48.2	-5.2	25.8
-3.0	41.9	-4.5	30.1
-3.9	36.5	-4.1	34.0
-4.5	32.0	-3.5	37.2
-5.1	27.7	-3.1	40.5
-5.6	23.8	-2.7	43.6
-6.2	20.1	-2.3	46.6
-6.7	16.6	-2.0	49.5
-7.2	14.0	-1.7	52.1
-7.4	12.6	-0.6	60.0
-8.4	6.0	0.2	70.0

D SPECS CHAMBER 3 FRAME 3
 SPEC TYPE F SAT IN 3 % NaCl SOLN

COOLING	CYCLE	WARMING	CYCLE
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-7.1	15.7
-1.3	57.3	-5.9	22.1
-2.1	49.6	-5.0	27.1
-3.0	43.0	-4.3	31.3
-3.4	38.0	-3.8	34.6
-4.0	34.2	-3.3	38.4
-4.6	30.2	-2.9	42.0
-5.1	26.4	-2.5	45.1
-5.8	23.2	-2.2	48.2
-6.2	20.3	-1.9	50.8
-6.7	17.7	-1.6	53.3
-7.1	15.7	-1.0	60.0
-8.0	0.0	0.0	70.0

D SPECS CHAMBER. 3. FRAME. 4.
SPEC TYPE G SAT IN 3 % NaCl SOLN

COOLING	CYCLE	WARMING	CYCLE
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-3.3	16.3
-0.6	55.0	-2.6	25.1
-1.3	49.2	-2.4	30.1
-1.7	43.2	-2.2	34.3
-2.2	40.5	-1.9	37.6
-2.4	34.2	-1.7	41.2
-2.6	30.2	-1.5	45.0
-2.8	26.7	-1.1	48.2
-2.9	23.0	-0.9	51.2
-3.0	20.6	-0.7	53.8
-3.2	18.2	-0.6	56.3
-3.3	15.3	-0.3	60.0
-4.0	0.0	0.4	70.0

D SPECS CHAMBER. 3. FRAME. 2.
SPEC TYPE H SAT IN 3 % NaCl SOLN

COOLING	CYCLE	WARMING	CYCLE
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-4.8	16.7
-1.2	55.2	-4.1	25.2
-1.9	46.5	-3.5	30.2
-2.3	43.0	-3.2	34.5
-2.8	35.2	-2.5	37.9
-3.2	34.0	-2.4	41.5
-3.6	30.2	-2.1	45.0
-3.9	29.7	-1.7	48.4
-4.2	23.0	-1.4	51.3
-4.4	21.0	-1.2	54.0
-4.7	18.5	-0.8	56.5
-4.8	15.7	-0.5	60.0
-5.2	6.0	0.0	70.0

D SPECS CHAMBER. 2. FRAME. 1.
SPEC TYPE I SAT IN 3 % NaCl SOLN

COOLING	CYCLE	WARMING	CYCLE
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-7.1	15.7
-1.7	57.3	-6.1	22.1
-2.0	49.8	-5.3	27.1
-3.5	43.0	-4.7	31.3
-3.8	34.5	-4.2	34.0
-4.4	34.2	-3.9	38.4
-5.0	30.2	-3.3	42.0
-5.4	29.4	-2.8	45.1
-5.9	23.2	-2.5	48.2
-6.6	20.5	-2.2	50.8
-6.8	17.7	-1.9	53.3
-7.1	15.7	-1.1	60.0
-3.0	6.0	0.0	70.0

D SPECS CHAMBER. 3. FRAME. 3.
SPEC TYPE J SAT IN 3 % NaCl SOLN

TABLES D-XXVII D-XXVIII

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{IN}{IN} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{IN}{IN} \right)$	TEMP (°F)
0.0	70.0	-4.1	12.1
-0.8	65.2	-3.7	16.3
-1.3	59.5	-3.3	20.8
-1.6	47.8	-3.2	24.8
-2.2	41.5	-2.9	28.4
-2.7	36.0	-2.6	31.8
-2.9	31.3	-2.4	34.7
-3.2	27.0	-2.2	37.3
-3.4	23.1	-2.0	39.7
-3.6	19.7	-1.9	41.9
-3.8	15.8	-1.7	44.3
-3.9	14.2	-1.5	45.7
-4.4	0.0	0.0	70.0

D SPECS CHAMBER 3 / FRAME 2
 SPEC TYPE A SAT IN 10 % NaCl SOLN

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{IN}{IN} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{IN}{IN} \right)$	TEMP (°F)
0.0	70.0	-7.9	7.0
-0.7	61.0	-7.2	10.5
-1.4	52.9	-6.9	14.9
-2.3	44.5	-5.2	18.7
-3.0	37.7	-4.7	22.3
-3.3	31.7	-4.2	25.0
-4.5	24.7	-3.8	28.5
-5.2	22.2	-3.4	31.2
-5.8	18.3	-3.1	33.5
-6.4	14.6	-2.8	36.0
-7.0	11.9	-2.5	38.2
-7.4	9.4	-2.3	40.5
-8.1	0.0	0.7	70.0

D SPECS CHAMBER 3 / FRAME 4
 SPEC TYPE C SAT IN 10 % NaCl SOLN

TABLES D-XXXIX & D-XL

COOLING	CYCLE	WARMING	CYCLE
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-5.2	13.0
-1.3	60.0	-5.1	23.5
-2.3	50.7	-4.5	29.2
-3.1	44.0	-4.0	34.0
-3.7	39.5	-3.4	38.5
-4.1	35.9	-3.0	42.0
-4.5	29.7	-2.9	45.2
-5.0	26.1	-2.7	49.0
-5.3	22.6	-1.9	52.3
-5.5	19.7	-1.4	55.3
-5.7	17.0	-1.2	58.2
-5.9	14.5	-0.6	65.0
-5.9	0.0	-0.1	70.0

D SPECS CHAMBER. 3 . FRAME. 1.
SPEC TYPE B SAT IN 10 % NaCl SOLN

COOLING	CYCLE	WARMING	CYCLE
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-3.5	20.5
-1.5	63.5	-3.9	18.5
-2.3	50.5	-5.9	24.2
-3.1	45.6	-4.5	29.3
-3.9	37.7	-4.4	33.0
-4.5	32.0	-3.7	37.5
-5.2	26.1	-3.3	41.0
-5.9	24.2	-2.9	44.3
-5.9	20.0	-2.4	47.0
-7.1	17.5	-2.1	50.7
-7.7	14.7	-1.7	53.2
-7.7	12.1	-1.2	58.0
-7.7	0.0	-0.3	70.0

D SPECS CHAMBER. 3 . FRAME. 4
SPEC TYPE G SAT IN 10 % NaCl SOLN

TABLES D-XLI & D-XLII

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-4.9	7.4
-0.5	5.2	-4.4	14.7
-1.0	9.6	-4.1	20.1
-2.0	40.3	-3.8	24.3
-3.0	30.5	-3.5	29.1
-4.0	31.2	-3.3	32.5
-4.0	24.7	-3.0	35.0
-4.4	19.3	-2.5	39.3
-4.5	14.6	-2.3	40.5
-4.7	10.7	-2.0	45.6
-4.8	7.0	-1.9	40.3
-4.9	7.5	-1.7	40.7
-5.0	5.0	-0.4	70.0

D SPECS CHAMBER. 4 FRAME. 2
 SPEC TYPE A SAT IN 0 % NaCl SOLN

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-5.4	0.6
0.5	59.7	-5.4	14.2
-1.0	29.0	-7.4	19.0
-2.0	50.0	-5.4	24.6
-3.0	41.5	-5.5	29.0
-4.0	35.5	-5.0	32.7
-5.0	26.9	-4.2	35.0
-6.0	21.2	-2.5	39.4
-7.0	16.7	-2.2	42.0
-8.0	12.1	-2.0	45.9
-9.0	7.7	-2.4	40.7
-10.0	5.0	-2.0	40.7
-11.0	5.0	0.0	70.0

D SPECS CHAMBER. 4 FRAME. 4
 SPEC TYPE A SAT IN 0 % NaCl SOLN

COOLING	CYCLE	WARMING	CYCLE
$\frac{\Delta L}{L} \times 10^4 \left(\frac{IN}{IN} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{IN}{IN} \right)$	TEMP (°F)
0.0	70.0	-4.0	70.0
0.0	67	-4.0	14.2
-0.6	65	-3.5	12.5
-1.2	60.5	-3.1	24.5
-1.5	41.5	-2.6	29.0
-2.4	33.5	-2.4	32.7
-3.0	30.7	-2.1	35.0
-3.4	21.0	-1.5	39.5
-3.5	15.0	-1.5	42.0
-4.2	12.1	-1.4	45.9
-4.5	10.7	-1.3	46.7
-4.5	9.6	-1.1	50.7
-5.0	9.0	0.1	70.0

b SPECS CHAMBER. 4. FRAME. 2.
SPEC TYPE C SAT IN 0 % NaCl SOLN

COOLING	CYCLE	WARMING	CYCLE
$\frac{\Delta L}{L} \times 10^4 \left(\frac{IN}{IN} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{IN}{IN} \right)$	TEMP (°F)
0.0	70.0	-7.2	70.0
-0.5	65.0	-6.0	14.7
-1.5	60.0	-5.0	20.1
-2.4	50.5	-4.0	24.0
-3.0	40.0	-3.7	29.1
-3.5	30.0	-3.0	32.0
-4.0	20.0	-2.1	35.0
-4.5	15.0	-1.5	39.5
-5.0	10.0	-1.5	42.0
-5.5	5.0	-1.1	45.9
-6.0	0.0	-1.1	46.7
-6.5	0.0	-0.1	50.7
-7.0	0.0	0.0	70.0

b SPECS CHAMBER. 4. FRAME. 3.
SPEC TYPE D SAT IN 0 % NaCl SOLN

TABLES D-ALV 8 D-ALVI

COOLING	CYCLE	WARMING	CYCLE
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.6	70.0	-5.0	14.2
0.0	59.7	-4.0	19.5
-0.4	50.6	-3.4	24.6
-1.0	41.5	-3.0	29.0
-1.6	33.6	-2.6	32.7
-2.1	25.9	-2.3	35.0
-2.7	21.2	-2.0	39.3
-3.1	14.2	-1.7	45.9
-3.5	10.1	-1.5	46.7
-3.7	7.7	-1.3	50.7
-4.0	5.0	-1.0	54.5

D SPECS CHAMBER. 4 FRAME. 1.
SPEC TYPE 2 SAT IN 0 % NaCl SOLN

COOLING	CYCLE	WARMING	CYCLE
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-4.7	19.6
-0.5	1.4	-4.0	14.5
-1.0	51.7	-3.0	20.1
-1.5	43.0	-2.4	24.0
-2.0	37.0	-2.0	28.2
-2.5	31.0	-1.7	30.0
-3.0	24.0	-1.4	35.2
-3.5	17.5	-1.1	42.0
-4.0	14.5	-1.0	46.7
-4.5	11.5	-0.8	48.5
-4.7	10.0	-0.7	50.5
-5.1	5.0	0.0	70.0

D SPECS CHAMBER. 4 FRAME. 5.
SPEC TYPE 2 SAT IN 0 % NaCl SOLN

TABLES D-ALVII & D-ALVIII

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-7.4	16.6
-0.7	1.4	-6.7	14.6
-1.5	11.7	-5.7	20.1
-2.4	45.0	-4.9	24.1
-3.3	37.3	-4.2	29.5
-4.2	4.2	-3.7	32.0
-5.7	20.0	-3.2	30.2
-6.5	22.3	-2.5	32.3
-7.1	17.3	-2.4	42.0
-7.7	14.3	-2.1	40.7
-7.8	11.3	-1.6	41.3
-7.4	10.3	-1.5	30.7
-6.3	10.0	0.1	70.0

D SPECS CHAMBER. 4 . FRAME. 4 .
 SPEC TYPE : SAT IN 0 % NaCl SOLN

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.3	70.0	-1.4	1.2
-1.0	1.7	-1.0	13.7
-1.5	34.1	-0.7	13.9
-2.7	41.3	-0.2	18.9
-3.4	34.3	-2.1	2.3
-3.8	21.0	-3.4	32.1
-4.2	34.3	-3.2	30.4
-4.2	1.3	-2.3	4.3
-4.3	11.1	-2.5	10.1
-5.1	11.3	-2.4	30.3
-5.3	10.0	-2.1	41.3
-5.4	1.3	-1.9	0.0
-5.5	1.0	-0.3	70.0

D SPECS CHAMBER. 4 . FRAME. 1 .
 SPEC TYPE : SAT IN 0 % NaCl SOLN

TABLES INDEX 8 D-L

COOLING	CYCLE	WARMING	CYCLE
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-3.7	9.7
-1.0	50.0	-3.0	14.3
-1.0	40.0	-3.0	20.3
-1.1	41.7	-2.7	24.9
-1.5	30.0	-2.0	29.3
-2.0	20.0	-2.0	32.7
-2.0	14.4	-2.0	35.9
-2.0	10.0	-1.0	39.3
-2.4	10.0	-1.0	42.1
-2.0	13.0	-1.4	47.0
-2.0	10.0	-1.2	40.1
-2.0	9.0	-1.0	40.4
-2.0	10.0	0.6	70.0

D SPECS CHAMBER. 4 FRAME. 2
 SPEC TYPE I SAT IN 0 % NaCl SOLN

COOLING	CYCLE	WARMING	CYCLE
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-3.0	10.6
-0.0	11.3	-0.1	14.5
-1.0	11.7	-0.2	20.1
-1.0	15.0	-4.7	24.3
-2.0	17.0	-4.0	29.3
-2.0	11.2	-3.0	32.6
-2.0	16.0	-3.0	36.2
-2.0	11.0	-2.0	39.5
-2.0	17.0	-2.0	42.6
-2.1	14.0	-2.1	45.7
-2.0	11.0	-1.0	40.3
-2.0	10.0	-0.5	50.7
-2.0	10.0	0.0	70.0

D SPECS CHAMBER. 4 FRAME. 3
 SPEC TYPE I SAT IN 0 % NaCl SOLN

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-3.7	17.8
0.0	61.0	-3.3	22.1
-0.7	52.1	-3.0	27.5
-1.2	44.9	-2.7	31.6
-1.6	40.4	-2.5	35.0
-2.0	36.7	-1.9	40.1
-2.4	37.4	-1.1	45.2
-2.9	33.0	-1.1	49.3
-3.1	29.7	-0.9	52.3
-3.7	25.0	-0.7	54.9
-3.9	21.6	-0.6	57.3
-3.6	17.0	-0.5	70.0
-4.0	0.0	0.0	70.0

b SPECS CHAMBER. 1. FRAME. 2.
SPEC TYPE A SAT IN 1.5 % NaCl SOLN

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-2.0	20.6
-0.2	61.1	-2.8	24.3
-0.4	51.0	-2.2	27.1
-0.7	43.7	-1.9	32.1
-1.0	36.7	-1.6	35.0
-1.3	31.3	-1.4	39.7
-1.6	25.0	-1.1	43.7
-1.9	20.0	-1.0	45.2
-2.2	15.0	-0.9	49.3
-2.5	10.0	-0.8	52.3
-2.8	5.0	-0.7	55.3
-3.0	0.0	-0.6	57.1
-4.0	0.0	0.0	70.0

b SPECS CHAMBER. 1. FRAME. 3.
SPEC TYPE C SAT IN 1.5 % NaCl SOLN

COOLING		WARMING	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-5.2	17.3
-0.8	62.1	-4.6	22.1
-1.4	54.9	-4.1	27.3
-2.0	45.4	-3.4	31.0
-2.7	43.7	-3.2	35.0
-3.1	37.4	-2.5	39.1
-3.4	33.0	-2.5	42.8
-3.9	28.7	-2.0	46.2
-4.2	25.0	-1.8	49.3
-4.5	21.5	-1.6	52.3
-4.8	18.5	-1.4	54.9
-5.2	17.3	-1.1	57.5
-5.5	5.0	-0.2	70.0

D SPECS CHAMBER. 4. FRAME. I.
SPEC TYPE E SAT IN 1.5 % NaCl SOLN

COOLING		WARMING	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-5.4	20.6
-0.2	66.5	-5.1	23.4
-0.5	62.1	-4.3	28.1
-1.1	55.0	-3.7	32.3
-1.9	47.1	-3.1	35.0
-2.4	41.5	-2.6	39.0
-3.0	37.0	-2.1	43.4
-3.5	35.0	-1.9	46.7
-4.0	30.5	-1.4	50.0
-4.7	25.2	-1.2	52.5
-5.2	21.3	-1.0	55.3
-5.4	20.6	-0.7	57.7
-5.5	5.0	0.3	70.0

D SPECS CHAMBER. 4. FRAME. 4
SPEC TYPE G SAT IN 1.5 % NaCl SOLN

COOLING	CYCLE	WARMING	CYCLE
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-5.2	5.0
-1.2	57.0	-4.7	10.9
-2.1	48.0	-3.8	22.1
-2.8	39.3	-3.2	30.9
-3.4	32.7	-2.5	38.2
-3.8	29.5	-1.9	45.2
-4.2	21.2	-1.3	51.0
-4.5	14.4	-0.6	55.2
-4.7	12.3	-0.4	60.4
-4.8	9.1	0.1	64.0
-4.8	8.0	0.4	67.2
-5.1	6.3	0.6	69.7
-5.2	5.6	0.8	70.0

D SPECS CHAMBER. 4. FRAME. 2.
SPEC TYPE A SAT IN 3 % NaCl SOLN

COOLING	CYCLE	WARMING	CYCLE
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-9.9	6.6
-1.2	60.5	-9.1	11.1
-2.3	50.5	-6.7	22.0
-3.4	42.1	-5.1	31.0
-4.5	35.0	-3.8	37.7
-5.5	28.3	-2.7	44.5
-6.6	22.5	-2.0	50.6
-7.5	17.7	-1.3	55.0
-8.4	13.9	-0.5	60.3
-9.1	10.0	-0.3	64.0
-9.7	7.3	0.0	67.2
-9.9	6.0	0.2	69.9
-10.0	5.0	0.3	70.0

D SPECS CHAMBER. 4. FRAME. 4.
SPEC TYPE B SAT IN 3 % NaCl SOLN

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-4.3	6.6
-0.6	60.5	-4.4	11.1
-1.2	50.6	-3.4	22.0
-1.8	42.1	-2.7	31.0
-2.3	35.0	-2.1	37.7
-2.9	28.3	-1.6	44.6
-3.3	22.5	-1.2	50.5
-3.7	17.7	-0.8	55.8
-4.1	13.5	-0.6	60.3
-4.4	10.0	-0.4	64.0
-4.7	7.3	-0.2	67.2
-4.8	6.5	0.0	69.5
-4.8	5.0	0.0	70.0

D. SPECS CHAMBER. 4 FRAME. 5.
SPEC TYPE C SAT IN 3 % NaCl SOLN

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-4.4	6.6
-0.5	59.3	-3.9	11.0
-0.9	49.2	-2.0	22.1
-1.4	41.0	-2.1	31.0
-1.9	34.0	-1.7	36.2
-2.3	28.1	-1.3	45.2
-2.8	22.3	-0.9	51.0
-3.2	17.7	-0.7	55.0
-3.7	13.5	-0.5	60.5
-3.9	10.0	-0.2	64.0
-4.2	7.3	0.1	67.2
-4.4	6.5	0.2	69.5
-4.5	5.0	0.3	70.0

D. SPECS CHAMBER. 4 FRAME. 3.
SPEC TYPE D SAT IN 3 % NaCl SOLN

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{IN}{IN} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{IN}{IN} \right)$	TEMP (°F)
0.0	70.0	0.0	70.0
-1.2	50.1	-5/4	10.4
-2.0	45.4	-4.1	21.5
-2.9	38.4	-3.2	30.5
-3.0	31.5	-2.0	37.7
-4.1	29.5	-1.7	44.7
-4.0	20.2	-1.4	50.7
-5.0	19.0	-0.9	55.5
-5.4	11.5	-0.5	60.2
-5.0	5.2	-0.1	63.3
-5.1	7.5	0.2	67.0
-5.0	5.4	0.4	69.0
-5.0	4.5	0.5	70.0

b SPECS CHAMBER. 4 . FRAME. 1 .
SPEC TYPE E SAT IN 3 % NaCl SOLN

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{IN}{IN} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{IN}{IN} \right)$	TEMP (°F)
0.0	70.0	-3.4	25.2
-0.2	60.2	-3.2	27.7
-0.7	50.0	-2.0	32.1
-1.2	43.3	-2.4	35.7
-1.5	37.2	-2.1	39.5
-2.0	31.7	-1.0	43.2
-2.4	37.1	-1.0	45.0
-2.7	33.2	-1.3	49.0
-3.0	29.5	-1.1	52.5
-3.3	25.3	-0.9	55.1
-3.4	25.2	-0.7	57.7
-3.0	20.0	-0.0	59.0
-5.0	5.0	0.1	70.0

b SPECS CHAMBER. 4 . FRAME. 5 .
SPEC TYPE F SAT IN 3 % NaCl SOLN

TABLES D-LXI 8 D-LXII

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-4.7	22.2
-0.2	65.2	-4.3	27.7
-0.5	60.0	-3.9	32.1
-1.4	53.3	-3.1	35.7
-1.9	47.2	-2.5	39.5
-2.5	41.7	-2.2	43.5
-3.1	37.1	-1.9	45.5
-3.6	33.2	-1.5	49.6
-4.1	29.5	-1.2	52.5
-4.5	25.3	-1.0	55.1
-4.7	22.2	-0.8	57.7
-5.2	18.0	-0.5	59.5
-7.4	0.0	0.4	70.0

D SPECS CHAMBER. 4. FRAME. 4.
 SPEC TYPE 3 SAT IN 3 % NaCl SOLN.

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-4.0	23.1
-0.7	63.9	-4.2	28.1
-1.4	59.3	-3.6	31.0
-2.1	49.5	-3.2	34.5
-2.5	47.2	-2.6	38.9
-3.1	36.5	-2.5	42.0
-3.5	34.3	-2.3	45.0
-3.9	30.5	-1.9	49.0
-4.2	30.9	-1.5	52.0
-4.4	28.9	-1.4	54.5
-4.5	23.1	-1.1	57.0
-4.7	18.0	-0.9	59.3
-5.3	0.0	0.0	70.0

D SPECS CHAMBER. 4. FRAME. 1.
 SPEC TYPE 3 SAT IN 3 % NaCl SOLN

TABLES D-LXIII & D-LXIV

COOLING	CYCLE	WARMING	CYCLE
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-2.8	23.2
-0.3	64.6	-2.5	27.3
-0.9	55.7	-2.1	32.0
-1.3	49.5	-1.6	35.7
-1.5	42.6	-1.3	39.6
-1.6	40.9	-1.2	43.4
-2.1	34.6	-1.0	45.7
-2.4	30.7	-0.7	49.6
-2.5	27.2	-0.5	52.7
-2.7	24.2	-0.3	55.2
-3.0	23.2	-0.2	57.7
-3.0	15.0	0.0	59.0
-4.1	5.0	0.5	70.0

D SPECS CHAMBER. 4 . FRAME. 2 .
 SPEC TYPE I SAT IN 3 % NaCl SOLN

COOLING	CYCLE	WARMING	CYCLE
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-4.7	24.3
-0.4	66.3	-4.3	27.0
-1.1	51.5	-3.0	32.0
-1.0	51.7	-3.3	35.6
-2.4	45.5	-2.6	39.6
-2.9	40.3	-2.4	43.4
-3.3	35.0	-2.0	45.7
-3.9	32.1	-1.7	49.6
-4.3	25.5	-1.4	52.7
-4.5	25.3	-1.0	55.3
-4.7	24.3	-0.9	57.7
-5.2	15.0	-0.5	59.0
-5.2	5.0	0.5	70.0

D SPECS CHAMBER. 4 . FRAME. 3 .
 SPEC TYPE J SAT IN 3 % NaCl SOLN

TABLES D-LXV 8 D-LXVI

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-3.1	24.5
-0.2	69.9	-2.5	26.1
-0.9	60.0	-2.4	33.2
-1.3	53.0	-2.2	35.9
-1.6	44.7	-1.9	40.9
-1.9	43.0	-1.6	44.5
-2.2	39.1	-1.3	47.8
-2.5	35.2	-1.1	50.3
-2.7	31.5	-0.9	53.7
-2.9	26.3	-0.5	56.3
-3.0	25.4	-0.5	59.7
-3.1	24.5	-0.3	60.0
-4.3	0.0	0.4	70.0

D SPECS CHAMBER. 4 FRAME. 2
 SPEC TYPE A SAT. IN 10 % NaCl SOLN

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-2.2	26.0
0.0	69.2	-2.0	29.5
-0.2	62.4	-1.7	33.0
-0.5	55.5	-1.4	37.3
-0.7	51.2	-1.2	41.2
-0.9	47.1	-1.0	44.0
-1.1	41.5	-0.8	48.0
-1.3	37.4	-0.7	50.7
-1.6	33.2	-0.5	53.7
-1.9	30.4	-0.5	56.3
-2.1	27.0	-0.4	59.7
-2.3	25.0	-0.3	60.0
-3.7	0.0	0.3	70.0

D SPECS CHAMBER. 4 FRAME. 3
 SPEC TYPE C SAT IN 10 % NaCl SOLN

TABLES D-LVII & D-LVIII

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-4.2	23.0
-0.4	61.1	-3.4	27.0
-1.0	59.0	-3.3	32.3
-1.4	52.0	-3.0	35.0
-2.1	47.5	-2.5	40.0
-2.5	42.0	-2.2	43.8
-3.0	39.0	-2.0	47.1
-3.3	34.0	-1.6	50.2
-3.5	30.5	-1.2	53.0
-3.8	27.3	-0.9	55.5
-4.1	24.4	-0.7	58.0
-4.2	23.6	-0.5	60.1
-5.5	6.0	0.4	70.0

D SPECS CHAMBER. FRAME.
SPEC TYPE SAT IN %NaCl SOLN

COOLING CYCLE		WARMING CYCLE	
$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)	$\frac{\Delta L}{L} \times 10^4 \left(\frac{\text{IN}}{\text{IN}} \right)$	TEMP (°F)
0.0	70.0	-4.4	27.1
0.0	69.0	-4.1	29.9
-0.5	63.3	-3.4	33.0
-1.0	57.7	-2.9	37.3
-1.5	52.5	-2.4	41.2
-1.9	47.3	-2.0	44.6
-2.4	42.6	-1.7	47.9
-2.9	38.4	-1.4	52.0
-3.4	34.5	-1.0	53.7
-4.2	31.5	-0.6	56.3
-4.2	26.1	-0.5	58.7
-4.4	27.1	-0.3	60.3
-7.0	6.0	0.5	70.0

D SPECS CHAMBER. FRAME.
SPEC TYPE SAT IN %NaCl SOLN

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