DEVELOPMENT
OF A
CONDUCTOMETRIC TEST
FOR
FROST RESISTANCE OF CONCRETE

FINAL REPORT
JANUARY 31, 1988

IOWA DOT PROJECT HR-272
ERI PROJECT 1775

Sponsored by the Highway Division of the
Iowa Department of Transportation and the
Iowa Highway Research Board.

ENGINEERING RESEARCH
INSTITUTE
iowa state university
DEVELOPMENT OF A CONDUCTOMETRIC TEST FOR FROST RESISTANCE OF CONCRETE

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"The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Highway Division of the Iowa Department of Transportation."
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INTRODUCTION

This report describes the research completed under the research contract entitled "Development of a Conductometric Test for Frost Resistance of Concrete" undertaken for the Iowa Highway Research Board. The objective of the project was to develop a test method which can be reasonably and rapidly performed in the laboratory and in the field to predict, with a high degree of certainty, the behavior of concrete subjected to the action of alternate freezing and thawing. The significance of the results obtained, and recommendations for use and the continued development of conductometric testing are presented in this final report.

In this project the conductometric evaluation of concrete durability was explored with three different test methods. The test methods and procedures for each type of test as well as presentation of the results obtained and their significance are included in the body of the report. The three test methods were:

1) Conductometric evaluation of the resistance of concrete to rapid freezing and thawing,

2) Conductometric evaluation of the resistance of concrete to natural freezing and thawing, and

3) Conductometric evaluation of the pore size distribution of concrete and its correlation to concrete durability.

The report also includes recommendations for the continued development of these test methods.
DESCRIPTION OF CONCRETE MIXES FOR CONDUCTOMETRIC TESTING

In the project proposal it was stated that testing would begin with concrete containing a class III aggregate and Type I portland cement and that two sets of specimens would be prepared at four different entrained air contents, the first set with constant slumps and the second with constant water-cement ratios. In review of early test data obtained in Phase II of this project it was decided to deviate from the original mix plan. This was based on the desirability to determine if conductometric analysis could be used to distinguish between durable and nondurable coarse aggregates. It was recommended that mixes be formulated using three different coarse aggregates of varying durability. This new plan required nine mixes for each aggregate with three different water-cement ratios and three different entrained air contents bringing the total number of mixes to 27.

Constituent Materials

The portland cement used for the first part of this project was Lehigh Type I. It was used with all mixes containing Alden aggregate. Concrete specimens subjected to natural freezing and thawing and those for which conductometric pore size distributions were determined also contained Lehigh cement. The remaining mixes contained blended Type I portland cement provided by the Iowa DOT.

The fine aggregate used was from the Cordova quarry. It is the same sand the IDOT uses for its durability testing. For coarse aggregate three different aggregates were tested. The first aggregate was from the Alden quarry. This Class III limestone has a 3/4 inch maximum aggregate size and IDOT durability
tests have shown that the durability of concretes containing this aggregate is largely independent of air content and water-cement ratio provided the mix contained a minimal amount of entrained air. The second aggregate selected was an oolitic limestone from the Montour quarry. The maximum aggregate size for this aggregate was also 3/4 inch. Iowa DOT durability studies have shown that concretes containing this aggregate have durability factors that vary quite markedly with changes in water-cement ratio and air content. Also, the Montour oolite has a much better field service record than measured laboratory durability factors would indicate. The final aggregate tested was from the Crescent quarry. It is a nondurable Class I aggregate. In accordance with IDOT specifications this aggregate has a 3/8 inch maximum aggregate size.

Mixing water was tap water from the Town Engineering Building. Blended with the water was the air-entraining agent Protex Pro-Air. This admixture was used at concentrations of 0 ml/100 lbs. cement, 49.8 ml/100 lbs. cement and 74.7 ml/100 lbs. cement. These concentrations resulted in total air contents of approximately 2, 6, and 8 percent, respectively.

Mix Proportions

Volumetric mix proportions centered around the IDOT C3 mix. In fact, the conductometric test mix designation LM used in this report has the same volumetric proportions as the IDOT C3 mix. All mixes have the same cement content of 605 lbs. per cubic yard. For each mix, the coarse aggregate occupies 55% of the total aggregate volume and the fine aggregate the remaining 45%. All combinations of three different water-cement ratios (0.43, 0.51 and 0.60) and three target air contents (1.5%, 6% and 9%) were used for making concrete mixes with each coarse aggregate. This made a total of 27 different concrete mixes.
The actual mix volumes are shown in Table 1. Mixes were given designations consisting of a three letter code. The first letter (L, M or H) is indicative of the water-cement ratio of the mix. The letter L indicates a low water-cement ratio equal to 0.43 with the letters M and H indicating a medium (0.51) and high (0.60) water-cement ratio, respectively. Similarly, the second letter is indicative of the total air content of the mix with the letters L, M, and H representing a low (1.5%), medium (6%) and high (9%) total air content, respectively. The last letter in the designation represents the coarse aggregate used with the letters A, C, and M representing the Alden, Crescent, and Montour aggregates, respectively. Mix designations thus reflect low (L), medium (M) and high (H) water-cement ratios and air contents along with aggregate types Alden (A), Montour (M) and Crescent (C) in the following order:

(WATER-CEMENT RATIO) (AIR CONTENT) (AGGREGATE TYPE)

Mix proportions were strictly adhered to and no attempt was made to control the slump of the different mixes. As a result some of the mixes had rather high slumps and molding specimens without segregation was difficult for some of the mixes. These mixes were those with high air contents and high water-cement ratios. Since all mixes had the same cement content the amount of air-entraining admixture added did not vary with water-cement ratio. Properties of the mixes tested are listed in Tables 2, 3, 4, and 5. Tables 2, 3 and 4 list the properties of the mixes used for conductometric evaluation of freeze-thaw resistance of concrete. Properties of mixes used for conductometric evaluation of the resistance of concrete to natural freezing and thawing, and conductometric evaluation of concrete pore size distribution and correlation to concrete durability are shown in Table 5.
Table 1. Volumetric mix proportions for conductometric tests.

<table>
<thead>
<tr>
<th>Materials</th>
<th>LL</th>
<th>LM**</th>
<th>LH</th>
<th>ML</th>
<th>MM</th>
<th>MH</th>
<th>HL</th>
<th>HM</th>
<th>HH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>.1142</td>
<td>.1142</td>
<td>.1142</td>
<td>.1142</td>
<td>.1142</td>
<td>.1142</td>
<td>.1142</td>
<td>.1142</td>
<td>.1142</td>
</tr>
<tr>
<td>Water</td>
<td>.1538</td>
<td>.1538</td>
<td>.1538</td>
<td>.1834</td>
<td>.1834</td>
<td>.1834</td>
<td>.2158</td>
<td>.2158</td>
<td>.2158</td>
</tr>
<tr>
<td>Fine Agg.</td>
<td>.3221</td>
<td>.3019</td>
<td>.2885</td>
<td>.3088</td>
<td>.2886</td>
<td>.2752</td>
<td>.2943</td>
<td>.2741</td>
<td>.2606</td>
</tr>
<tr>
<td>Coarse Agg.</td>
<td>.3949</td>
<td>.3701</td>
<td>.3535</td>
<td>.3786</td>
<td>.3538</td>
<td>.3372</td>
<td>.3607</td>
<td>.3359</td>
<td>.3194</td>
</tr>
<tr>
<td>Air</td>
<td>.015*</td>
<td>.06</td>
<td>.09</td>
<td>.015*</td>
<td>.06</td>
<td>.09</td>
<td>.015*</td>
<td>.06</td>
<td>.09</td>
</tr>
<tr>
<td>Total</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
</tr>
<tr>
<td>W/C ratio</td>
<td>0.43</td>
<td>0.43</td>
<td>0.43</td>
<td>0.51</td>
<td>0.51</td>
<td>0.51</td>
<td>0.60</td>
<td>0.60</td>
<td>0.60</td>
</tr>
</tbody>
</table>

*No air entraining admixture added  

**Volumes same as for IDOT C3 mix.
Table 2 - Properties of mixes containing the Alden aggregate from which beams were cast and subjected to rapid freezing and thawing.

<table>
<thead>
<tr>
<th>Mix Designation</th>
<th>Water-Cement Ratio</th>
<th>Air Content</th>
<th>Slump (inches)</th>
<th>Unit Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>LLA</td>
<td>0.43</td>
<td>2%</td>
<td>2</td>
<td>151.4 pcf</td>
</tr>
<tr>
<td>LMA</td>
<td>0.43</td>
<td>5.8%</td>
<td>4.5</td>
<td>142.3 pcf</td>
</tr>
<tr>
<td>LHA</td>
<td>0.43</td>
<td>6.8%</td>
<td>6.5</td>
<td>141.0 pcf</td>
</tr>
<tr>
<td>MLA</td>
<td>0.51</td>
<td>2%</td>
<td>6.5</td>
<td>152.2 pcf</td>
</tr>
<tr>
<td>MWA</td>
<td>0.51</td>
<td>5.8%</td>
<td>&gt;8</td>
<td>141.1 pcf</td>
</tr>
<tr>
<td>MHA</td>
<td>0.51</td>
<td>7.8%</td>
<td>&gt;8</td>
<td>138.9 pcf</td>
</tr>
<tr>
<td>HLA</td>
<td>0.60</td>
<td>2%</td>
<td>&gt;8</td>
<td>148.7 pcf</td>
</tr>
<tr>
<td>HWA</td>
<td>0.60</td>
<td>5.9%</td>
<td>&gt;8</td>
<td>139.9 pcf</td>
</tr>
<tr>
<td>HHA</td>
<td>0.60</td>
<td>7.9%</td>
<td>&gt;8</td>
<td>136.1 pcf</td>
</tr>
</tbody>
</table>

Table 3 - Properties of mixes containing the Crescent aggregate from which beams were cast and subjected to rapid freezing and thawing.

<table>
<thead>
<tr>
<th>Mix Designation</th>
<th>Water-Cement Ratio</th>
<th>Air Content</th>
<th>Slump (inches)</th>
<th>Unit Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>LLC</td>
<td>0.43</td>
<td>1.75%</td>
<td>1.75</td>
<td>146.9 pcf</td>
</tr>
<tr>
<td>LMC</td>
<td>0.43</td>
<td>5.5%</td>
<td>3</td>
<td>145.5 pcf</td>
</tr>
<tr>
<td>LHC</td>
<td>0.43</td>
<td>9.5%</td>
<td>6</td>
<td>136.5 pcf</td>
</tr>
<tr>
<td>MLC</td>
<td>0.51</td>
<td>1.5%</td>
<td>6</td>
<td>152.1 pcf</td>
</tr>
<tr>
<td>MMC</td>
<td>0.51</td>
<td>6.4%</td>
<td>7</td>
<td>139.6 pcf</td>
</tr>
<tr>
<td>MHC</td>
<td>0.51</td>
<td>8.5%</td>
<td>&gt;8</td>
<td>136.2 pcf</td>
</tr>
<tr>
<td>HLC</td>
<td>0.60</td>
<td>2%</td>
<td>&gt;8</td>
<td>150.6 pcf</td>
</tr>
<tr>
<td>HMC</td>
<td>0.60</td>
<td>7%</td>
<td>&gt;8</td>
<td>144.3 pcf</td>
</tr>
<tr>
<td>HHC</td>
<td>0.60</td>
<td>9%</td>
<td>&gt;8</td>
<td>142.6 pcf</td>
</tr>
</tbody>
</table>
Table 4 - Properties of mixes containing the Montour aggregate from which beams were cast and subjected to rapid freezing and thawing.

<table>
<thead>
<tr>
<th>Mix Designation</th>
<th>Water-Cement Ratio</th>
<th>Air Content</th>
<th>Slump (inches)</th>
<th>Unit Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>LLM</td>
<td>0.43</td>
<td>1.5%</td>
<td>6.5</td>
<td>152.1 pcf</td>
</tr>
<tr>
<td>LMM</td>
<td>0.43</td>
<td>5.5%</td>
<td>&gt;8</td>
<td>144.9 pcf</td>
</tr>
<tr>
<td>LHM</td>
<td>0.43</td>
<td>8%</td>
<td>&gt;8</td>
<td>140.2 pcf</td>
</tr>
<tr>
<td>MLM</td>
<td>0.51</td>
<td>1.5%</td>
<td>&gt;8</td>
<td>150.5 pcf</td>
</tr>
<tr>
<td>MMM</td>
<td>0.51</td>
<td>5%</td>
<td>&gt;8</td>
<td>145.5 pcf</td>
</tr>
<tr>
<td>MHM</td>
<td>0.51</td>
<td>8.5%</td>
<td>&gt;8</td>
<td>137.8 pcf</td>
</tr>
<tr>
<td>HLM</td>
<td>0.60</td>
<td>1.5%</td>
<td>&gt;8</td>
<td>149.5 pcf</td>
</tr>
<tr>
<td>HMM</td>
<td>0.60</td>
<td>---</td>
<td>&gt;8</td>
<td>143.2 pcf</td>
</tr>
<tr>
<td>HHM</td>
<td>0.60</td>
<td>---</td>
<td>&gt;8</td>
<td>142.7 pcf</td>
</tr>
</tbody>
</table>

Table 5 - Properties of mixes from which beams were cast and subjected to natural freezing and thawing and from which cylinders were cast and conductometric pore size distributions determined.

<table>
<thead>
<tr>
<th>Mix Designation</th>
<th>Water-Cement Ratio</th>
<th>Air Content</th>
<th>Slump (inches)</th>
<th>Unit Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>LLA</td>
<td>0.43</td>
<td>1.8%</td>
<td>3</td>
<td>150.2 pcf</td>
</tr>
<tr>
<td>LMA</td>
<td>0.43</td>
<td>6.0%</td>
<td>7.5</td>
<td>141.2 pcf</td>
</tr>
<tr>
<td>LLC</td>
<td>0.43</td>
<td>2.0%</td>
<td>2.5</td>
<td>152.2 pcf</td>
</tr>
<tr>
<td>LMC</td>
<td>0.43</td>
<td>5.0%</td>
<td>3.5</td>
<td>146.6 pcf</td>
</tr>
<tr>
<td>LLM</td>
<td>0.43</td>
<td>2.0%</td>
<td>1.5</td>
<td>152.7 pcf</td>
</tr>
<tr>
<td>LLC</td>
<td>0.43</td>
<td>6.5%</td>
<td>6.5</td>
<td>139.0 pcf</td>
</tr>
</tbody>
</table>
It was stated in the project proposal:

"The ultimate goal of the proposed research is to establish specifications for concrete quality control in respect to its freeze-thaw durability. It appears to the authors of this proposal that a plausible solution (probably the only solution) to this problem could be achieved by continuously monitoring the physicochemical state of concrete during freezing and thawing cycles as a function of all the variables such as temperature, rate of cooling and warming, degree of saturation, air content, pore structure and the type of freezing-thawing medium. By physicochemical state of a sample we mean the dimensional stability and integrity of its solid and void spaces, the frozen and unfrozen fractions of its water content, and the sizes of its voids occupied by air, water (liquid) and ice. When the functional relationships between the physicochemical state and the variables are developed extrapolations can be made to various field conditions. Once these studies are completed we anticipate being able to develop a reasonably rapid test for predicting the freeze-thaw durability of concrete on the basis of changes occurring under a fixed set of ambient conditions in its physicochemical states during a limited number of cycles. Extrapolations to a different set of ambient conditions will then be possible to make using the functional relationship established as mentioned above."

The progress made during the course of this research project has allowed us to make significant steps towards the achievement of this ultimate goal. As stated earlier the three types of testing undertaken were:

1) Conductometric evaluation of the resistance of concrete to rapid freezing and thawing,

2) Conductometric evaluation of the resistance of concrete to natural freezing and thawing,

3) Conductometric evaluation of concrete pore size distributions and correlation to concrete durability.

In the first type of testing, relative dynamic moduli of elasticity, as evaluated by ASTM Method C666-84, (Standard test method for resistance of concrete to rapid freezing and thawing) are correlated to changes in the electrical conductance of concrete beams subjected to repeated freezing and
thawing. In this report we will show that these changes can be used to predict the durability of concrete in much the same manner as changes in fundamental transverse frequency or pulse velocities.

In the second test (evaluation of resistance to natural freezing and thawing) the same conductometric changes were monitored in concrete beams exposed to the ambient conditions imposed by a Iowa winter. Continued development of this type of testing could allow functional relationships between the physicochemical state of the concrete and the environmental variable to be developed.

The last type of testing (conductometric pore size analysis) is the most versatile of the three. With the methodology developed for the conductometric porosimeter the physicochemical state of the concrete can be monitored under a nearly limitless variety of laboratory and field freeze-thaw conditions.

Obviously a complete investigation of all the variables contributing to the freeze-thaw durability could not be accomplished during the time duration of this research project. The purpose of this report is to present and analyze results of testing undertaken and illustrate how the experimental techniques developed during this project can be used in further investigations of concrete durability.

All mixes were tested after 28 days of moist curing. The saturation state of the concretes tested was limited to the degree of saturation that a concrete would attain at ambient temperatures if a limitless supply of water was available. Finally, two freeze-thaw conditions were imposed. For all laboratory tested samples this was the 40°F to 0°F cycle established by ASTM C666-84. For samples exposed to natural freezing and thawing the cycling was imposed by weather conditions.
Conductometric Evaluation of the Resistance of Concrete to Rapid Freezing and Thawing

Methods and Procedures

For this type of testing 1/8 inch diameter stainless steel rods were cast in one end of 3" by 3" by 16" concrete beams. To do this the 1/4" steel bottoms of the beam molds recommended by ASTM were replaced with 1" thick Plexiglas bottoms. Holes the same size as the 1/8" stainless steel electrodes were drilled in the Plexiglas bottom plates at the desired spacing. The electrode geometry for the beam samples is shown in Figure 1. The electrodes were force fitted into the holes to provide a secure geometry. The molds were then assembled and specimens were cast and allowed to cure for 24 hours in a humid curing room. The molds were then disassembled and the Plexiglas bottoms were tapped off with a rubber hammer and each electrode cut flush with the bottom of the beam.

The samples were subjected to rapid freezing and thawing in accordance with ASTM C666-84. Samples were frozen in water and thawed in water. Initially measurements were taken at 5 to 6 cycle intervals. As testing continued the number of cycles between testing was increased. The fundamental transverse frequency for each beam was measured on the half of the beam containing no electrodes. Conductance measurements were taken using each possible pair of electrodes using a Solomat model 2009 conductivity meter. Conductance measurements are particularly sensitive to changes in temperature. Thus, at the end of a cycle for which conductance readings were to be taken, samples were placed in an ice bath for at least 30 minutes to assure all testing was conducted at nearly the same concrete temperature.
Figure 1. Electrode geometry for beam samples.
Results and Discussion

A total of 27 different mixes containing three different aggregates and having three different water-cement ratios and air contents were tested in this manner. In this report a parameter termed inverse relative conductance (IRC) is used to evaluate the data. This parameter is defined as:

\[ \text{IRC}_x = \frac{C_0}{C_x}, \]

where \( \text{IRC}_x \) is the inverse relative conductance at the end of \( x \) number of freeze-thaw cycles, \( C_0 \) is the conductance prior to any freeze-thaw cycling, and \( C_x \) is the conductance at the end of \( x \) number of freeze-thaw cycles. Also, test data indicated that the inverse relative conductance is independent of electrode geometry, consequently, only data for one particular electrode geometry for each mix will be presented. Thus, data presented herein are for the electrode geometry labeled A in Figure 1.

Appendix A contains graphs of inverse relative conductance versus the number of freeze-thaw cycles for all the mixes tested. Table 6 lists the number of freeze-thaw cycles, the inverse relative conductance and relative dynamic modulus of elasticity at the termination of testing for each mix. Figure 2 presents this information in a graphical format. From the examination of Figure 2 it is clear that the inverse relative conductance is directly related to relative dynamic modulus and could be used as an index of concrete durability. The solid line through the points in this graph represents a linear regression of the data. This regression results in a correlation coefficient of 0.761.

There were three mixes (mix designation HMM, HHM, and HHC) tested for which the relative dynamic modulus decreased with increasing number of freeze-thaw cycles while their electrical conductances practically remained constant (see Appendix A for these mixes). In these instances the concrete mixes had a combination of
Table 6 - Inverse Relative Conductances and Relative Dynamic Moduli for concrete beam samples at the termination of freeze-thaw cycling.

<table>
<thead>
<tr>
<th>Mix Designation</th>
<th># of Cycles at Termination</th>
<th>Inverse Relative Conductance</th>
<th>Relative Dynamic Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>LLA</td>
<td>36</td>
<td>0.462</td>
<td>0.287</td>
</tr>
<tr>
<td>LMA</td>
<td>195</td>
<td>0.899</td>
<td>0.948</td>
</tr>
<tr>
<td>LHA</td>
<td>121</td>
<td>0.944</td>
<td>0.910</td>
</tr>
<tr>
<td>MLA</td>
<td>28</td>
<td>0.430</td>
<td>0.308</td>
</tr>
<tr>
<td>MMA</td>
<td>112</td>
<td>0.946</td>
<td>0.900</td>
</tr>
<tr>
<td>MHA</td>
<td>108</td>
<td>0.928</td>
<td>0.909</td>
</tr>
<tr>
<td>HLA</td>
<td>32</td>
<td>0.412</td>
<td>0.389</td>
</tr>
<tr>
<td>HMA</td>
<td>108</td>
<td>0.930</td>
<td>0.894</td>
</tr>
<tr>
<td>HHA</td>
<td>108</td>
<td>0.900</td>
<td>0.905</td>
</tr>
<tr>
<td>LLC</td>
<td>26</td>
<td>0.531</td>
<td>0.350</td>
</tr>
<tr>
<td>LMC</td>
<td>301</td>
<td>0.694</td>
<td>0.559</td>
</tr>
<tr>
<td>LHC</td>
<td>301</td>
<td>0.626</td>
<td>0.715</td>
</tr>
<tr>
<td>MLC</td>
<td>42</td>
<td>0.593</td>
<td>0.361</td>
</tr>
<tr>
<td>MMC</td>
<td>311</td>
<td>0.862</td>
<td>0.932</td>
</tr>
<tr>
<td>MHC</td>
<td>311</td>
<td>0.769</td>
<td>0.846</td>
</tr>
<tr>
<td>HLC</td>
<td>42</td>
<td>0.223</td>
<td>0.250</td>
</tr>
<tr>
<td>HMC</td>
<td>254</td>
<td>0.817</td>
<td>0.777</td>
</tr>
<tr>
<td>HHC</td>
<td>254</td>
<td>1.023</td>
<td>0.776</td>
</tr>
<tr>
<td>LLM</td>
<td>92</td>
<td>0.453</td>
<td>0.235</td>
</tr>
<tr>
<td>LMM</td>
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<td>0.895</td>
</tr>
<tr>
<td>LHM</td>
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<td>0.598</td>
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</table>
Figure 2. Correlation between inverse relative conductance and relative modulus.

\[ Y = 0.723X + 0.257 \]

\[ R^2 = 0.761 \]
high air content and high water-cement ratio which resulted in an extremely high initial conductance and extremely fluid mix with a slump which would be unacceptable for normal concrete applications. Such mixes should be expected to be nondurable due to possible segregation of the aggregate from the mortar phase on the one hand and to the high initial water content as evidenced by the high value of initial conductance on the other.

Our concrete durability research during the last six years has shown that the susceptibility of concrete to saturation (controlled by both the rate with which moisture absorption occurs and the final degree of saturation) plays a major role in the assessment of freeze-thaw durability of concrete. Recently, we have been the recipient of a National Science Foundation (NSF) grant entitled "Frost Susceptibility of Concrete in Near-Saturated States" (see Appendix D). Future activities of this new project are expected to help expand on the scope of the research conducted under the present project HR-272.

Since both freeze-thaw durability and conductance of concrete should depend on its degree of saturation and how fast this saturation occurs, conductance measurements should reflect the durability of concrete subjected to ingress of water without a recourse to freeze-thaw cycles. Although the results of the present study support this hypothesis, more work is needed to establish a functional relationship. This is one of the objectives of our NSF project. The present study concentrated on electrical conductance of concrete subjected to freeze-thaw cycles. Thus, efforts were devoted to determination of the degree of degradation caused by freeze-thaw cycles by using electrical conductance.

For concrete mixes that have acceptable values for slump, an open pore structure and aggregate segregation are not expected to occur. Therefore, for such mixes changes in electrical conductance can be used to predict their durability much in the manner as is done with dynamic modulus. Indeed, this is the case for mixes that have acceptable slumps.
In Figure 3, inverse relative conductance is plotted against relative dynamic modulus as in Figure 2 except the values for the three previously mentioned mixes (HMM, HHM and HHC) have been omitted. A linear regression of this data results in a correlation coefficient of 0.866.

Figures 4, 5, and 6 illustrate the variation of conductance with air content and water-cement ratio for mixes containing the Alden, Crescent, and Montour aggregates, respectively. Initial observations that the conductance of a concrete increases with increasing water-cement ratio seems to apply to all mixes although one deviation from this is observed in the case of the Crescent aggregate. This deviation may be due to the high absorption particles of the aggregate. As one might expect the increasing amount of excess water that is present in mixes containing absorptive aggregates and high water-cement ratios results in a concrete with a larger amount of conducting capillary pores. The variation of conductance with air content is more interesting. In the case of the durable Alden aggregate conductance increases with increasing air contents, however for the Montour and Crescent aggregates this is not the case. For both of these aggregates in the mixes with a water-cement ratio equal to 0.43 the conductance decreases with increasing air content. This suggests that there are fundamental differences in the interactions of the air void and capillary void systems of the different aggregates. In the case of mixes containing the Alden aggregate the air void system provides additional conductive paths suggesting that capillary voids and air voids are interconnected. However for mixes containing the Montour and Crescent aggregates with low water-cement ratios the presence of air voids decreases the conductance suggesting these air voids are isolated from the capillary void system. Continued investigations of these
Figure 3. Correlation between inverse of relative conductance and relative modulus (same as Figure 2 except three data points are removed).
Figure 4. Variation of conductance with air content and W/C for mixes made with Alden aggregate.
Figure 5. Variation of conductance with air content and W/C for mixes made with Crescent aggregate.
Figure 6. Variation of conductance with air content and W/C ratio for mixes made with Montour aggregate.

Approximate Air Content (%)

Initial Conductance (micro-siemens)

- W/C ratio = 0.43
- W/C ratio = 0.51
- W/C ratio = 0.60

0 2 4 6 8 10
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
relationships should result in a better understanding of the relationship of the air void and capillary void system to the mechanics of freeze-thaw deterioration. Finally it appears that the overall electrical conductance of the least durable Crescent is less than that of the most durable Alden with the conductance value for the Montour being in between.

Conductometric Evaluation of the Resistance of Concrete to Natural Freezing and Thawing

Methods and Procedures

Beam specimens were prepared in the same manner as outlined previously and were placed in a bed of saturated sand in a tank and exposed to the freeze-thaw cycles of an Iowa winter. The electrical conductance of the beams was measured several times during the course of the winter. An attempt was made to take measurements when the beams were at or near 32°F. The temperature at the time of measurements varied from 28.9°F to 36.4°F. Six beams from six different concrete mixes were tested in this manner. Three of the mixes had the same proportions as the IDOT C3 paving mix. The other three had similar proportions except that they contained no air entraining admixture. Tables 1 and 5 list the mix proportions and mix properties, respectively, for these mixes.

Results and Discussion

Initially it was hoped frequent monitoring of temperatures and conductance would allow us to develop functional relationships between ambient conditions and concrete durability and allow us to modify laboratory testing procedures to these ambient conditions. It was also hoped that monitoring both the temperature and conductance would allow us to monitor the length of natural freeze-thaw cycles, the rate of cooling and warming, changes in the degree of saturation and the number of freeze-thaw cycles. It became apparent very soon
after placing the samples that to follow the rapidly changing environmental conditions imposed on the samples would require nearly continuous monitoring of these measurements. This is largely due to the unanticipated variation in electrical conductance due to continued hydration and variation in the degree of saturation of the concrete. Although current technology would allow these types of continuous measurements to be taken such equipment was not available to us. Consequently, we began taking measurements over longer periods of time. We felt comparative analysis of conductance measurements taken on durable and nondurable concretes, over time, would reveal fundamental differences in the conductometric changes which occurred in these concretes. Figure 7 illustrates the results of this testing. As can be seen from this graph there is little distinguishable difference between the conductometric behavior of the nondurable non-air entrained mixes (labeled LLA, LLM and LLC) and that of the more durable air entrained counterparts (labeled LMA, LMM and LMC). Because of the short time over which these samples were monitored and especially because of the very mild winter we had in Iowa, there seems to be no discernable difference in the conductometric behavior of the different concretes. We plan to include this type of experiment in our NSF project. Copies of the reports for the NSF project will also be submitted to the IDOT.

Conductometric Evaluation of Concrete Pore Size Distributions and Correlation to Concrete Durability

Methods and Procedures

A new method for determining the pore structure of porous materials has been developed. The methodology combines relationships correlating the volume of unfrozen pore solution to electrical conductance, the pore solution freezing temperature to electrical conductance, the pore solution freezing temperature to pore radii, and the electrical conductivity of the pore solution to temperature as illustrated below:
Figure 7. Relative conductance of samples subjected to natural freezing and thawing as a function of date.

MEASUREMENT DATE

PERCENTAGE OF ORIGINAL CONDUCTANCE

Dec 01
Dec 23
Dec 26
Jan 6
Jan 12
May 12

LLA + LMA △ LMC ▲ LML ⊗ LLM

23
These relationships are used with measurements of the electrical conductance and temperature to obtain pore size distributions of saturated porous materials subjected to a cycle of capillary freezing and melting.

Based on this methodology, a conductometric phase transition porosimeter was constructed. The pore size distribution of porous Vycor glass (a standard for pore size calibration) was measured using this porosimeter. The modal neck and body radii measured by this method are 28 and 55 angstroms, respectively. The modal neck and body radii of the same Vycor sample as determined by mercury intrusion porosimetry are 30 and 85 angstroms and by dilatometric phase transition porosimetry, 27 and 49 angstroms, respectively. Modal neck sizes determined by all three methods are comparable. Modal body sizes determined by the two phase transition methods are also comparable. The modal body size determined by mercury porosimetry is significantly larger. This difference is due to problems arising from the entrapment of mercury during the extrusion phase of mercury porosimetry testing. A complete discussion of conductometric phase transition porosimetry is included in Appendix B and for the sake of brevity will not be included in the main body of this report.

The conductometric phase transition porosimeter consists of a conductance meter, a cryostat, a thermistor, the measurement circuitry, a microcomputer, and a plotter.
Conductance measurements are made with a Solomat 2009 conductivity meter. This meter's high frequency alternating current excitation and the use of stainless steel or tungsten electrodes minimizes polarization effects. The instrument has a resolution of 0.1 micro-siemens. Digitized conductance output from the meter is relayed to the computer.

A thermistor manufactured by Thermometrics is used to measure the temperature of the sample. The thermistor is used as a variable resistor in a square wave oscillator. The oscillator's output frequency varies with corresponding changes in the resistance of the thermistor. The computer then measures the period of the square wave.

The temperature of the sample is controlled by placing the sample in a suitable container and immersing that container in a Haake cryostat filled with iso-propyl alcohol. The temperature of the cryostat is controlled by the computer through a digital to analog converter.

The computer used is an Apple IIe computer equipped with two input/output cards from John Bell Engineering. These cards serve as an interface between the measurement circuitry and the computer. Software was developed to allow the computer to control the temperature of the cryostat, gather test data, perform necessary data processing, and output the processed data to either the computer's video monitor or a Hewlett-Packard plotter. Cycle starting and ending temperatures, cooling rates, and data collection intervals are all input by the user. In addition, the user can input the total number of cycles for a test sequence and designate different cycle parameters for each cycle within the sequence. These features allow the user to tailor the test sequence to a particular pore system. They also allow periodic determinations of pore size distribution to be made for samples subjected to repeated cycles of freezing and thawing. With this system, a wide range of ambient freezing and thawing conditions can be simulated.
Appendix C of this report contains a user's manual for the conductometric phase transition porosimeter. This manual contains instructions for the operation of the porosimeter, porosimeter circuitry schematics, computer program descriptions, and computer program listings. A patent application is being made for this methodology by Iowa State University. Earlier, a patent for the phase transition porosimeter developed under IDOT project HR-258 and utilized in the present investigation was obtained and licensed to OMICRON Company by ISU.

Two of the most significant advantages the conductometric phase transition porosimeter has over currently available commercial porosimeters, including the phase transition porosimeter, are the minimal sample preparation procedure which results in less disturbance of pore structure; and the ability to determine pore size distributions of large samples, much larger than other porosimeters can accommodate, thus minimizing sampling error.

For the evaluation of pore size distributions of portland cement concrete, 4-inch diameter by 4-inch high cylinders were molded with an imbedded electrode configuration as shown in Figure 8. The electrodes are fixed in a Plexiglas bottom plate during molding. To prevent surface conductance at the bottom of submersed specimens the bottom portions of the electrodes were embedded in small Plexiglas studs. These studs, when inserted in holes cut in the mold bottom, also held the electrodes in place during casting. Also, the upper portion of the electrodes were covered with nonconductive plastic shrink tubing to eliminate conductance between the exposed electrodes. Electrodes were cut from 1/8 inch diameter stainless steel rods. After curing, a 1 1/2 inch deep hole is drilled in the cylinder to accommodate a plastic termistor housing. The thermistor is placed in the housing to obtain the necessary temperature measurements.
Figure 8. Electrode geometry of concrete samples for measurement of conductometric pore size distribution.
During testing, the cylinder is placed in a thin-walled plastic container, and the void between the walls of the cylinder and the container are filled with Ottawa sand. The sand is then saturated with water. Experimentation has shown that the silica crystals in the sand prevent supercooling of the bulk water surrounding the sample. This allows both warming and cooling data to be gathered.

Test sequences for the concretes tested in this manner involved alternating diagnostic cycles and rapid freeze-thaw cycles. For the diagnostic cycles the temperature of the bath was lowered from $7^\circ C$ to $-30^\circ C$ at the rate of $3^\circ C$ per hour. Conductance and temperature data collected at $0.1^\circ C$ intervals composed the cooling portion of the diagnostic cycle. These data are used to calculate the pore neck size distribution for the concrete. The temperature is then raised to $7^\circ C$ at the same rate. Again, conductance and temperature data were collected at $0.1^\circ C$ intervals composing the warming portion of the diagnostic cycle. The latter data were used to calculate the pore body size distribution of the concrete. Diagnostic test runs were made with a 7 kilo-ohm resistor connected in series with the cylinder allowing the more sensitive range on the conductance meter to be used. Data processing routines calculated the conductance of the cylinder alone from the measured conductance. The concretes were subjected to several rapid ($20^\circ C$ per minute) freeze-thaw cycles between each diagnostic cycle. For these rapid freeze-thaw cycles the upper and lower limits of temperature for each cycle were $4^\circ C$ and $-16^\circ C$, respectively. This temperature range along with the $20^\circ C$ per hour rate of temperature change resulted in cycles conforming with the specifications set by ASTM C666.

Six cylinders from six different mixes were tested in this manner. Three mixes had the same proportions as the IDOT C3 paving mix. The other three had similar proportions except they contained no air entraining admixture. Three
different coarse aggregates were used (Alden, Crescent, and Montour). Tables 1 and 5 list the mix proportions and the mix properties of samples tested in this manner. For all samples tested the first cycle was a diagnostic cycle. Subsequent diagnostic cycles were the 5th, 10th, 15th, 20th and 25th cycles. After 25 cycles, testing for the non-air entrained concretes was discontinued. For the air-entrained concretes cycling was continued until 100 cycles with diagnostic cycles at 35, 45, 55, 75 and 100 cycles. At this point test cylinders were stored for a period of approximately three months. Later cycling was restarted for the three air-entrained concretes and continued until 250 cycles had been completed. During this stage of testing diagnostic cycles were run at 150, 200 and 250 cycles.

Results and Discussion

In Figures 9 and 10 the conductance of the cylindrical samples measured at 0°C is plotted versus the number of freeze-thaw cycles the sample had been subjected to at the time of the measurement. The lines drawn on these graphs represent linear regressions of the data. Figure 9 presents this information for the concrete cylinders which contained no entrained air. It can be seen from this plot that the conductance increases rapidly with the increasing number of freeze-thaw cycles for all mixes without entrained air. The behavior of the concretes containing entrained air differs, however. Figure 10 presents the same information for these mixes. From this figure it can be seen that conductance remains nearly constant for the mix containing the Alden aggregate while for the mixes containing the Montour and Crescent aggregates the conductance increases with increasing number of freeze-thaw cycles. This behavior is as expected for these mixes. IDOT durability testing has shown the Alden aggregate to have a high durability factor while the Montour and Crescent have lower durability factors. In Figures 11 and 12 the parameter inverse
Figure 9. Variation of conductance with number of F/T cycles for mixes (IDOT C3) prepared without air entrainment.
Figure 10. Variation of conductance with number of F/T cycles for air-entrained mixes (IDOT C3).
Figure 11. Inverse relative conductance versus number of freeze-thaw cycles for mixes (IDOT C3) without air entrainment.
Figure 12. Inverse relative conductance versus number of F/T cycles for air-entrained mixes (DOT C3).
relative conductance (IRC) is plotted against the number of freeze-thaw cycles for samples without and with entrained air, respectively. Again the lines in these graphs represent linear regressions of the data.

The conductometric phase transition porosimeter is capable of providing much more detailed information about the changes in the physicochemical state of a concrete subjected to repetitive freeze-thaw cycles than those provided in Figures 11 and 12. In Figure 13 the log of the conductance is plotted versus the negative inverse of the absolute temperature for the concrete cylinder containing the Montour aggregate and without entrained air. Plotted are two sets of curves. The curve represented by a solid line is that for the sample prior to any freeze-thaw cycling, while the curve represented by the dashed line is that for the sample after 25 freeze-thaw cycles. For both curves the upper branch represents data gathered during the cooling portion of the test and the lower branch represents data gathered during the warming portion of the test. Several observations can be made concerning the physicochemical changes which have occurred in this nondurable concrete. First, as previously observed the conductance at above freezing temperatures \((-1/T > -36.63 \times 10^{-4})\) has increased after being subjected to repetitive freezing and thawing. Secondly, at temperatures slightly below freezing \((-1/T \text{ slightly less than } -36.63 \times 10^{-4})\) the curves are much steeper after the sample was subjected to repetitive freezing and thawing than they were prior to freezing and thawing. Finally, at lower temperatures \((-1/T \text{ much less than } -36.63 \times 10^{-4})\) the conductance of the concrete after exposure to repetitive freezing and thawing is much less than prior to this exposure.

The methodology supporting conductometric phase transition porosimetry can be used to process data such as that presented in Figure 13 to give the observed conductometric changes some physical significance. The increase in total
Figure 13. Variation of conductance with temperature for Montour aggregate mixes (IDOT C3) prepared without air entrainment.
conductance of the sample implies that the concrete is becoming more porous and that the degree of saturation is increasing. Or otherwise stated the conductive paths are increasing. Processing the data further allows the presentation of changes in pore size distribution illustrated in Figure 14. In this figure the cumulative relative pore volume is plotted against pore radius for the concrete at several points during the repetitive freeze–thaw exposure sequence. Points on these curves represent the fraction of the total pore volume containing pores smaller than the corresponding pore radius. From this plot the progressive nature of the failure is observable. As the concrete deteriorates the volume of small gel size (less than 100 angstrom radius) pores decreases while the volume of pores in the capillary size range (between 100 and 10,000 angstrom radius) increases. As it can be seen from Figure 14 for example, the volume of gel pores (volume of pores smaller than 100 angstroms) decreases from about 45% for cycle 1 to about 15% for cycle 25 while volume of all capillary pores (volume of pores having sizes between 100 and 10,000 angstroms) increases from 50% for cycle 1 to 80% for cycle 25. This behavior differs from the behavior of a durable concrete (mix containing the Alden aggregate and entrained air) as is illustrated in Figure 15. For this durable concrete, no significant change in the volume of gel pores is observable. The capillary size pores have increased somewhat in size but only in the range of the large capillaries without a systematic dependence on the number of F/T cycles. This would indicate that in the case of the nondurable concrete the portland cement paste has been subjected to a mechanical degradation and is no longer sound while in the durable concrete the portland cement gel structure remains intact.

Conductometric phase transition porosimetry can also be used to contrast the differences between the physicochemical changes which occur in concretes containing different aggregates. Figures 16 and 17 show the pore body size
Figure 14. Effect of the number of F/T cycles on total volume distribution of sizes of body pores for the mix (IDOT C3) prepared using Montour aggregate without air entrainment.
Figure 12. Effect of the number of P1 cycles on total volume distribution of stages smaller than 1 Angstrom.

Relative Pore Volume (Cumulative)

Radius Smaller Than (Angstroms)
Figure 16. Total volume-size distribution of pore bodies prior to freezing and thawing for mixes prepared without air entrainment.
Relative Pore Volume

Figure 17. Total volume-size distribution of pore bodies prior to freezing and thawing for air-entrained mixes.

Alden (Cycle 1)
Montour (Cycle 1)
Crescent (Cycle 1)
distributions measured prior to any freeze-thaw cycling for mixes from which concrete cylinders were cast and tested. Figure 16 contrasts distributions for mixes without any entrained air while Figure 17 contrasts distributions for mixes with entrained air. There are no significant differences between the distributions for the mixes containing the Crescent aggregate with and without air, the Alden aggregate without air and the Montour aggregate with air. The mix containing the Montour aggregate without air has a somewhat smaller initial size distribution while the mix containing the Alden aggregate with air has a somewhat larger distribution. It is not discernable from the limited data collected whether or not these differences are significant or not. However, the changes in the physicochemical state observed for the cylinder cast from concrete containing the Alden aggregate with air were less than those observed for any of the other tested cylinders and the changes in the physicochemical state observed for the cylinder cast from concrete containing the Montour aggregate without air were greater than those observed for any of the other tested cylinders. Therefore, it is possible that continued investigations may allow researchers to imply something about differences in the durability of the concretes containing different coarse aggregates from examinations of initial pore size distributions determined in this manner. However, these differences may also be due to sampling errors resulting from inhomogeneities of concrete between the electrodes.

Since electrical conductance behavior of concrete should be largely controlled by the physicochemical state of cement matrix such differences, if not due to inhomogeneity, should reflect the effect of aggregate on the cement matrix, such as absorptivity or reactivity of the aggregate. Further studies in this area will be carried out under our recent NSF project.
It is significant to note that the pore size distribution of the cylinders with entrained air does not vary as much from those cylinders without entrained air as may be expected. This is not too surprising because the cylinders were saturated by only immersing them in water for an extended period of time. Therefore, pore size distribution determined by the conductometric method is exclusive of entrained air pores. If it were possible to saturate the entrained air voids in this manner they would not be effective in protecting the concrete from damage due to freeze-thaw action. Recalling, however, that the overall conductance of concrete containing the Alden aggregate increases with the addition of entrained air while for concretes containing the other two coarse aggregates it remains constant or decreases slightly and that the concrete containing the Alden aggregate had a somewhat larger pore size distribution than the other concretes may suggest a fundamental difference exists between how the aggregate paste and air voids interact in concretes containing different aggregates.

While the importance of differences in initial pore size distributions is somewhat speculative, interpretation of the changes which occur in pore size distributions as a concrete is subjected to repetitive freezing and thawing is more conclusive. The progressive changes which occur in the pore size distribution of a deteriorating concrete were discussed earlier and illustrative examples of the changes which occur in durable (air-entrained containing Alden aggregate) and nondurable (non air-entrained containing Montour aggregate) concretes were contrasted. These same changes, namely deterioration of the gel pore system, are observable for concrete with entrained air but containing nondurable coarse aggregates. In Figures 18 and 19 the first derivative of the relative pore volume with respect to the log of the pore radius (first derivative of Figures 14 and 15, respectively) is plotted against pore radius.
Figure 18. Variation of true pore size distribution of mix made with Montour aggregate without entrained air with F/T cycles.
Figure 19. Variation of true pore size distribution of air.

Pore volume corresponding to the size on the abscissa.

Cycle 1

Cycle 25
Figure 18 represents behavior of a typical nondurable concrete while Figure 19 represents behavior of a durable concrete. Note that for the durable concrete the size distribution remains unchanged for pores smaller than approximately 200 angstroms. Figures 20 and 21 give comparable information for air entrained mixes containing the Crescent and Montour aggregates. In both these plots some degradation of the small gel pores is observable. It would appear that the degradation is more extensive in the case of the Crescent aggregate. Also, the modal peak in the larger capillary pore range is less pronounced for the Montour aggregate. This would indicate that the extent of damage is less for the concrete containing the Montour aggregate. These observations provide some additional information not apparent from monitoring the conductance of the concrete at above freezing temperatures alone. The rate of change of conductance with number of freeze-thaw cycles for these two concretes was the same (see Figure 12) and the inverse relative conductance for the concrete containing the Montour aggregate was also nearly the same for both mixes.

**SUMMARY AND CONCLUSIONS**

During this research project several significant research advances have been made towards the development of superior test methods for evaluating the durability of portland cement concrete.

Monitoring the changes in the conductance of samples of portland cement concrete at above freezing temperatures provides an index of the concretes durability. Evaluation of concrete durability from conductance measurements can be used as a supplement to or replacement for more traditional measurements such as fundamental transverse frequency and pulse velocity. Measurements of electrical conductance could be easily incorporated into a completely automated
\[ \frac{d(\text{Pore Volume})}{d(\log \text{Radius})} \]

(Pore volume corresponding to the size on abscissa)

Figure 20. Variation of true pore size distribution of air-entrained mix made with Crescent aggregate with P/T cycles.
Figure 21. Variation of true pore size distribution of air-entrained mix made with Montour aggregate with F/T cycles.
repetitive freeze-thaw testing apparatus eliminating the need for removal of
samples from the cabinet and manually taken measurements. These types of
measurements are time intensive and increase both the cost and length of this
type of test. For such an automated system measurements could easily be taken
at the end of each cycle. In addition, such a system could also measure the
conductance of a concrete sample at a temperature corresponding to the freezing
point of pores having a radius equal to approximately 100 angstroms
(approximately -5°C). The conductance of a nondurable concrete at this
temperature will decrease as the concrete is exposed to repetitive freezing and
thawing. This is in contrast to the conductance of the concrete at above
freezing temperatures which for a nondurable concrete will increase as the
concrete deteriorates.

A new method for determining pore size distributions of saturated porous
materials has been developed. Based on this newly developed methodology, a
conductometric phase transition porosimeter was constructed. The porosimeter is
capable of determining the pore size distributions for a broad range of pore
radii ranging from 12 to 5000 angstroms. The porosimeter has been used to
determine the pore size distributions of portland cement concretes and monitor
the changes in the distributions as the concretes are subjected to repetitive
freeze-thaw cycles. This information provides a fingerprint of the changing
physicochemical state of the concrete that is not available using other
analytical techniques.

Conductometric porosimetry has shown that for a concrete susceptible to
freeze-thaw deterioration capillary pores grow at the expense of gel pores. An
early detection of this behavior during freeze-thaw cycles may help to identify
nondurable concrete mixes in a much shorter time than required by the dynamic
modulus method presently in use.
RECOMMENDATIONS

In order to make the transition from research to application it will be necessary to expand the data base of concretes tested by these newly developed conductometric methods. This will be necessary to establish design limits for the parameter inverse relative conductance (IRC) such as those in use for durability factors. This will be possible only as more concretes are tested in this manner. Also, it is suggested that the undertaking of such a task include concretes containing the same component materials as evaluated during this project. Mixes for these tests should be prepared at a constant slump.

Researchers at Iowa State have begun to take conductance measurements along with weight and pulse velocity measurements of concretes being subjected to repetitive freezing and thawing as a part of other research activities. This will expand the current data base of information for this type of testing.

The pore size distributions of larger numbers of concrete samples need to be determined using the conductometric phase transition porosimeter. This is necessary to evaluate the amount of sampling error present due to current sample preparation techniques and to make improvements in these techniques that reduce errors if it is appropriate. These may include larger sample sizes and different electrode configurations.

Conductometric testing can also be used to determine rate and ultimate degree of saturation of concrete exposed to the ingress of water. It appears from our investigations during the last six years that there is a critical level of the free water in concrete at which a concrete mix becomes nondurable. The sooner the water content reaches this level the more susceptible a concrete is to freezing and thawing damage.
Collaboration between the Iowa State Civil Engineering Materials research team and the Iowa DOT researchers has been very productive. Continuation and furtherance of this collaboration will help Iowa further establish its leadership in transportation materials research and testing.

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APPENDIX A

Graphs of conductance data obtained from concrete beams subjected to rapid freezing and thawing.
Graphs of conductance data obtained from concrete beams subjected to rapid freezing and thawing
ALDEN W/ LOW W/C AND LOW AIR

\[ y = -0.012x + 0.911 \]
ALDEN W/ LOW W/C AND HIGH AIR

\[ Y = -0.00053 \times + 0.986 \]

RELATIVE FRACTION

NO. OF FREEZE THAW CYCLES

INV. REL. COND.  \quad +  \quad REL. SONIC MOD.
ALDEN W/MEDIUM W/C AND MEDIUM AIR

\[ y = -0.00006x + 0.904 \]

RELATIVE FRACTION

NO. OF FREEZE THAW CYCLES

INV. REL. COND. + REL. SONIC MOD.
ALDEN W/ HIGH W/C AND LOW AIR

\[ Y = -0.01579 \times + 0.835 \]

RELATIVE FRACTION

NO. OF FREEZE THAW CYCLES

INV. REL. COND. + REL. SONIC MOD.
ALDEN W/ HIGH W/C AND HIGH AIR

\[ Y = -0.00040 \times + 0.958 \]

RELATIVE FRACTION

NO. OF FREEZE THAW CYCLES

- INV. REL. COND.
- REL. SONIC MOD.
Y = -0.00910 X + 0.910

CRESCEMT W/ LOW W/C AND LOW AIR
Crescent W/ Medium W/C and Low Air

$Y = -0.00631 \times + 0.952$

RELATIVE FRACTION

NO. OF FREEZE THAW CYCLES

□ INV. REL. COND.

+ REL SONIC MOD.
CRESCENT W/ MEDIUM W/C AND HIGH AIR

$Y = -0.00064 \times + 0.911$

![Graph with data points and line equation](image-url)
MONTOUR W/ LOW W/C AND LOW AIR

\[ Y = -0.00454 \times + 0.907 \]

- \[ \square \] INV. REL. COND.
- \[ + \] REL. SONIC MOD.

RELATIVE FRACTION

NO. OF FREEZE THAW CYCLES
MONTOUR W/ LOW W/C AND HIGH AIR

\[ Y = -0.00034 \times + 0.943 \]

RELATIVE FRACTION

NO. OF FREEZE THAW CYCLES

INV. REL. COND.  REL. SONIC MOD.
MONTOUR W/ MEDIUM W/C AND MEDIUM AIR

\[ y = -0.00015 \times + 0.940 \]

RELATIVE FRACTION

NO. OF FREEZE THAW CYCLES

INV. REL. COND. + REL. SONIC MOD.
MONTGOMERY W/ MEDIUM W/C AND HIGH AIR

\[ y = -0.00040x + 0.989 \]
MONTOUR W/ HIGH W/C AND LOW AIR

\[ Y = -0.01779 \times + 0.961 \]

RELATIVE FRACTION

NO. OF FREEZE THAW CYCLES

INV. REL. COND. + REL. SONIC MOD.
MONTOUR W/ HIGH W/C AND MEDIUM AIR

\[ y = 0.00224x + 0.941 \]
Montour W/ High W/C and High Air

\[ Y = 0.000017 \times + 0.987 \]

- INV. REL. COND.
- REL. SONIC MOD.

Relative Fraction vs. No. of Freeze Thaw Cycles
APPENDIX B

Determination of the pore structure of porous materials using electrical conductance

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DETERMINATION OF THE PORE STRUCTURE OF POROUS MATERIALS USING ELECTRICAL CONDUCTANCE

by

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ABSTRACT

A new method for determining the pore structure of porous materials has been developed. The methodology combines the plastic ice model for solid-liquid phase transitions of pore water with relationships between conductance and temperature, and conductance and pore structure. With these relationships and measurements of the electrical conductance and the corresponding temperature of a saturated porous material subjected to a cycle of capillary freezing and melting, a pore size distribution is obtainable.

Based on this methodology a conductometric phase transition porosimeter was constructed. The pore size distribution of porous Vycor glass was measured using this porosimeter. The modal neck and body radii measured by this method are 28 and 55 angstroms respectively. These results are comparable to those obtained using other techniques. The modal neck and body radii measured on the same sample by mercury porosimetry are 30 and 85 angstroms and by phase transition porosimetry, 27 and 49 angstroms, respectively.
1. INTRODUCTION

Two independent methods which have found large scale application exist for pore-size distribution analysis. The first is mercury porosimetry. Two problems associated with this method have not been solved satisfactorily: (i) the mercury/matrix contact angle, and (ii) the entrapment of mercury during extrusion. The second method, the capillary condensation method makes use of the well known Kelvin equation. It is an elaborate and time consuming method. A discussion of the limitations of these two powerful methods of porosimetry has been presented elsewhere (1,2).

Recently a method was developed based on observation of the liquid-solid phase transition point of pore water in a porous sample at the saturated state and dilatometric measurements (1,2). The method is similar to "Thermoporometry" proposed by Brun et al. (3) which is based on calorimetrically measured freezing points of water in a saturated porous material and assumes freezing is initiated by homogeneous in-situ nucleation. It is in this latter aspect phase transition porosimetry (PTP) differs from "Thermoporometry". It has been shown previously (4) that the model of plastic ice put forward by Everett (5) was applicable to freezing and melting of the pore water in a saturated porous material. In PTP the process of the phase change is followed by measuring the volume change of the sample. The principles of PTP have been discussed in detail elsewhere (1,2).

The purpose of this paper is to introduce another phase transition porosimetry method which is also based on the plastic ice model of Everett
but differs from PTP in that the phase change is followed by measuring the change in electrical conductance of the sample and is referred to in this paper as conductometric phase transition porosimetry, CPTP.

2. CAPILLARY FREEZING AND MELTING

Assuming that the pore geometry of the sample can be represented by randomly intersecting spheres or cylindrical capillaries with or without constrictions, it can be shown using the plastic ice model, that the solid-liquid phase transition of water in a pore having an effective radius of \( r \) takes place at a temperature, \( t \) (°C) given by (4.5):

\[
t = -2\gamma T_0 / (\rho \lambda r)
\]

where \( T_0 \) is the normal melting point of ice in °K, \( \lambda \) is the heat of fusion of ice per unit mass, \( \rho \) is the density of water and \( \gamma \) is the ice/water interfacial tension at temperature \( t \). In melting, \( r \) is the pore body radius, while in freezing it is the radius of the pore constriction.

3. PRINCIPLES OF ELECTRICAL CONDUCTANCE OF POROUS MATERIALS

Many porous materials consist of a non-conducting solid phase and a void system of randomly intersecting capillaries of various sizes. If the material is saturated the pore solution generally will exhibit electrolytic conductance, which results from the mobility of ions in the solution.

Sunberg (6), Archie (7), Winsauer et al. (8), and Perkins et al. (9) used a parameter called resistivity factor in their investigations of the resistivity
of porous geomaterials. Resistivity factor is defined as the ratio of the resistivity, $\rho_p$, of a porous material completely saturated with an electrolyte to the resistivity, $\rho_e$, of the electrolyte itself.

Winsauer et al. (8) and later Perkins et al. (9) expressed a relationship between resistivity factor, $F$, and pore structure where

$$ F = \frac{\rho_p}{\rho_e} = \frac{\tau}{\psi} \quad (2) $$

where $\tau$ is the tortuosity, defined as the ratio of the mean tortuous length, $L'$, of the pore channels in a brine-saturated rock sample traversed by an electrical current flowing between the two ends of the sample separated by a distance, $L$, and $\psi$ is the ratio of the apparent cross-sectional area, $A'$, of the conducting electrolyte to the total cross-sectional area, $A$, of the sample. Also these investigators related the resistivity factor to the tortuosity, $\tau$, and porosity, $\eta$, of the sample by

$$ F = \frac{\tau^2}{\eta} \quad (3) $$

In a commentary of the paper by Perkins et al. (9), Wyllie and de Witte (10), pointed out that this was true only if $\eta$ equaled $\tau$ times $\psi$, or otherwise stated, the pore volume, $V_p$, was equal to the product of $A'$ and $L'$. It can be shown that this is only true for pores with uniform cross-sectional areas.

Consider a cylindrical container of volume $V$ having a cross-sectional area, $A$, and length, $L$, made of an insulating material, but with ends of a conducting material and filled with a solution of conductivity, $\kappa$. The conductance, $C$, of the container is then
Let the same container be filled with a porous material saturated with the same solution. The conductance will now be considerably less since (i) the mean length of path traversed by the current is longer and (ii) the cross-sectional area which is available to current flow is smaller.

Let's define the conductance of a porous material, $C'$, as

$$C' = \kappa V_p/(L^2 \omega)$$  \hspace{1cm} (5)

where $\kappa$ and $L$ are as defined for equation 4, $V_p$ is the pore volume and $\omega$ is a dimensionless pore geometry factor.

An expression for the conductance of a pore system consisting of $X$ number of parallel conducting pores can be developed from equation 5 where

$$C' = \kappa \frac{V_p}{L^2 \omega} = \sum_{j=1}^{X} \frac{\kappa V_{pj}}{L^2 \omega_j}.$$  \hspace{1cm} (6)

where $C'$, $\kappa$, $V_p$, $L$, and $\omega$ are defined earlier and $V_{pj}$ and $\omega_j$ are the pore volume and pore geometry factor for individual conducting pore $j$. From this relationship it can be shown that if the pore geometry factor for each parallel conducting pore, $\omega_j$, is the same then the pore geometry factor for the pore system, $\omega$, is equal to $\omega_j$.

Let us now consider an irregular single conducting pore channel of the
porous material as shown in figure 1a. This pore can be represented by a pore with equivalent circular cross-sectional areas as shown in figure 1b. Such a pore would have the same volume and conductance as the original irregular pore. If this circular pore is then stretched so the curve connecting the centers of the circular cross-sections is a line, the pore can be represented by a series of right angle truncated cones as shown in figure 1c without a change in the volume or conductance. The volume of each cone, \( V_j \), can be expressed as

\[
V_j = L_i (\pi/3) r_{oi} r_{ni} \left( (r_{oi}/r_{ni}) + 1 + (r_{ni}/r_{oi}) \right). \tag{7}
\]

It can be shown, using equation 4 for infinitesimally small slices, that the conductance of each cone, \( C_j \), can be expressed as

\[
C_j = \kappa (\pi r_{oi} r_{ni})/L_i'. \tag{8}
\]

where \( \kappa \) is the conductivity of the pore solution, \( L_i' \) is the length of the right truncated cone, and \( r_{oi} \) and \( r_{ni} \) are the radii of the ends of the cone.

By combining equations 5, 7, and 8 it can be shown that if the pore system of a porous material when stretched consists of a single right angle truncated cone, then the dimensionless pore geometry factor, \( \omega \), can be expressed as

\[
\omega = (1/3) (L'/L)^2 \left( (r_o/r_n) + 1 + (r_n/r_o) \right). \tag{9}
\]
Figure 1 - Right angle truncated cone modeling of irregular pore
Using the same approach the pore geometry factor, \( \omega \), for a pore system consisting of a singular irregular pore (represented by \( z \) right angle truncated cones in a series connection, figure 1) can be expressed as

\[
\omega = \frac{\sum_{i=1}^{i=z} (L'_i r_{oi} r_{ni}) ((r_{oi}/r_{ni}) + 1 + (r_{ni}/r_{oi}))}{3L^2}.
\]

This relationship for a pore of uniform cross-sectional area is simplified to

\[
\omega = (L'/L)^2,
\]

where \( L' \) is the sum of the lengths of the component cylinders (right angle cones with uniform cross-sectional areas) and \( L \) is the distance between the ends of the pores as defined previously. The quantity \( (L'/L) \) has been commonly referred to as tortuosity. Also for a pore consisting of uniformly sized right angle truncated cones (\( r_{oi} \) and \( r_{ni} \) are constant) equation 10 is simplified to the relationship expressed in equation 9. Further, if the connected cones lie in a straight line perpendicular to the end planes of the conducting material \( L' \) will equal \( L \) and the pore geometry factor, \( \omega \), will be a function of the ratio of the pore neck radii to the pore body radii only or a parameter heretofor referred to as necking. This illustrates two fundamental characteristics of a pore system, tortuosity and necking, exist which effect the value of the pore geometry factor, \( \omega \). Later in this paper these two parameters, tortuosity and necking, will be referred to in a qualitative sense.
in discussing the importance of the pore geometry factor in conductometric phase transition porosimetry.

Finally, considering any pore system to consist of \( x \) number of irregular conducting pore channels connected in parallel, an expression for the pore geometry factor, \( \omega \), for any pore system as modeled by an agglomeration of right angle truncated cones is

\[
\omega = \frac{\sum_{j=1}^{x} \sum_{i=1}^{z} L_i r_{oi} r_{ni} \left( \frac{r_{oi}}{r_{ni}} \right)^{1+(r_{ni}/r_{oi})} }{3L^2} \]

Thus, equation 5 provides a relationship between electrical conductance and pore structure.

Equation 12 provides a rather complicated expression for the pore geometry factor for any pore system. If the parallel conducting pores within the system have equivalent pore geometry factors the pore geometry factor for the system could be evaluated using the relationship given for a single parallel conducting pore (equation 9). Pore systems for which this would be true would contain geometrically similar pores, or otherwise stated all pores in the system would have the same tortuosity and necking. This does not imply that all the pores in the system are identical but rather that large pores are essentially magnifications of smaller pores.
4. CONDUCTOMETRIC PHASE TRANSITION POROSIMETRY

In conductometric phase transition porosimetry it is assumed that the electronic conductance through the solid phases of a porous material is negligible when compared to the electrolytic conductance of the pore solution. Thus, when the temperature of a mass of saturated porous material is raised from sub-freezing temperatures the frozen pore solution will melt, and an increase in electrical conductance will be observed. Capillaries will begin to melt with smaller sizes melting at lower temperatures in accordance with the plastic ice theory as expressed in equation 1.

The theory behind conductometric phase transition porosimetry is developed from a few basic relationships. First, it is assumed the relationship between the electrical conductivity of an electrolyte and the absolute temperature of the electrolyte is an Arrhenius type relationship and can be expressed as

\[ \ln \kappa = \frac{a}{T} + b, \]  

(13)

where

- \( \kappa \) = electrical conductivity,
- \( T \) = absolute temperature,
- \( a \) = physical constant, and
- \( b \) = physical constant.

By combing equations 5 and 13 the following equation is derived

\[ y = mx + d + \log_{10} \left( \frac{V_p}{(L^2 \omega)} \right) \]  

(14)
where $L$, $V_p$ and $\omega$ are as defined earlier,

\[ x = -1/(\text{absolute temperature}), \]
\[ y = \log_{10}(\text{conductance}), \]
\[ m = \text{physical constant}, \text{ and} \]
\[ d = \text{physical constant}. \]

A plot of the $\log_{10}$ of the conductance versus the negative inverse of the absolute temperature ($y$ versus $x$) for which no phase change occurs will result in a line with a slope equal to $m$. Below freezing temperatures the phase change which occur in a certain range of pores will effectively decrease the volume of conducting pores. Thus, $V_p$ at below freezing temperatures can be considered to be the volume of conducting pores, $V_{cp}$.

Taking the first derivative of equation 14 yields

\[
\frac{dy}{dx} = m + \frac{d\left(\log_{10}(V_p/(L^2\omega))\right)}{dx}
\]

(15)

Integrating equation 15 over the definite interval, $x$ to $x_0$, yields the following:

\[
\log_{10} \left[ \begin{array}{c}
\frac{V_{cp}(x_0)}{L^2\omega_{x_0}} \\
\frac{V_{cp}(x)}{L^2\omega_x}
\end{array} \right] = \int_{x}^{x_0} \frac{dy}{dx}\, dx - \int_{x}^{x_0} m\, dx
\]

(16)

The right half of equation 16 can be calculated numerically from
conductance test data by graphical integration as shown in figure 5 (page 19, results and discussion) and is given the variable name $Z$. Also, if $x_0$ is the value of $x$ at the pore solution melting point, then $V_{cp}(x_0)$ is simply the total conducting pore volume, $V_p$. Rearranging equation 16 and referring to pore volume by radius we obtain:

$$\frac{V_{cp}(r)}{V_p} = \frac{-Z(x, x_0)}{10},$$

(17)

where $V_{cp}(r)$ is the volume of the pores with radii smaller than or equal to $r$ containing unfrozen pore solution, $V_p$ is the total pore volume and $\alpha$ is the ratio of the pore geometry factor of the total pore system, $\omega$, to the pore geometry factor of the pores smaller than $r$, $\omega_r$. If it is assumed that the shape factor, $\omega$, is independent of pore size, then $\alpha$ is equal to unity and equation 17 can be reduced to

$$\frac{V_{cp}(r)}{V_p} = \frac{-Z(x, x_0)}{10}.$$

(18)

Assuming $\alpha$ to be equal to unity implies the pore system has a certain degree of homogeneity. This does not imply that all the conducting pores are exactly the same but rather that the tortuosity and necking inherent to a given pore structure is uniform throughout the pore size distribution.

These relationships provide the theoretical background for conductometric phase transition porosimetry.
5. EXPERIMENTAL METHOD

5.1. Apparatus

The conductometric phase transition porosimeter consists of a conductance meter, a cryostat, a thermistor, the measurement circuitry, a microcomputer, and a plotter.

Conductance measurements are made with a Solomat 2009 conductivity meter. This meter's high frequency alternating current excitation and the use of stainless steel or tungsten electrodes minimize polarization effects. The instrument has a resolution of 0.01 micro-siemens (μS). Digitized conductance output from the meter is relayed to the microcomputer.

A thermistor manufactured by Thermometrics is used to measure the temperature of the sample. The thermistor is used as a variable resistor in a square wave oscillator. The oscillator's output frequency varies with corresponding changes in the resistance of the thermistor. The computer then measures the period of the square wave.

The temperature of the sample is controlled by placing the sample in a suitable container and immersing that container in a Haake cryostat filled with iso-propyl alcohol. The temperature of the cryostat is controlled by the computer through a digital to analog converter.

The computer used is an Apple IIe personal computer equipped with two input/output cards from John Bell Engineering. These cards serve as an interface between the measurement circuitry and the computer. Software was developed to allow the computer to control the temperature of the cryostat, gather test data, perform necessary data processing, and output the
processed data to either the computer's video monitor or a Hewlett-Packard plotter.

5.2. Experimental Procedure

The conductometric phase transition porosimeter was used to test a Vycor glass sample obtained from the Corning Glass Company. This porous glass was selected because extensive pore size information is available for it and thus comparative analysis with other techniques is available. A 14mm diameter and 4mm thick disk was saturated with a 0.01 molar ammonium nitrate solution. By saturating the sample with this solution measurable conductance was provided with negligible freezing point depression.

For many materials sample preparation necessary for this type of porosimetry will be minimal. It is simply a matter of embedding electrodes in a mass of the material. However, for the brittle Vycor glass a more complex electrode configuration and containment apparatus was devised (see figure 2). It consisted of a large glass test tube and two smaller sections of glass tubing. The Vycor disk was press fitted into one end of the larger tubing with a short piece of tygon tubing serving as a gasket. The smaller tubing was located at the opposite end. This tube provided the inlet for the electrode connections and thermistor. The upper end of it was filled with a dessicant and cotton to prohibit condensation inside the tubes. These two sections of tubing were then placed in the test tube. The electrical contacts with the Vycor disk were provided by mercury placed inside the tubes in contact with the top and bottom surfaces of the Vycor disk. Tungsten wires inserted through tygon tubing provided the electrical connections between the mercury contacts and the conductance meter. Finally, a thermistor was
Figure 2 - Electrode configuration and containment apparatus for Vycor glass sample
placed in the mercury immediately above the Vycor sample to provide necessary temperature measurements.

The assembled apparatus was then placed in the cryostat and the testing cycle begun. The temperature of the bath was lowered from 70°C to -300°C at the rate of 30°C per hour. Conductance and temperature measurements were taken at 0.1°C intervals. These data composed the cooling portion of the test. The bath temperature was then raised from -300°C to 70°C at the same rate. Again data was gathered at 0.1°C intervals and these data composed the warming portion of the test.

After some initial experimentation a test run was made with a 5 kilo-ohm resistor connected in series with the Vycor sample. This allowed the test to be run in the more sensitive conductance range available on the conductance meter (0.01 μS resolution). Experimentally obtained values of conductance were then converted to quantitative conductance values using known relationships for conductors connected in series. The results from this testing follow.
6. RESULTS AND DISCUSSION

In figure 3 the logarithm of the conductance is plotted against the negative inverse of the absolute temperature for the Vycor sample tested. A temperature scale as measured in degrees Celsius is also included for reference purposes. The linearity of the curves prior to freezing or after melting of capillary water supports the relationship between electrical conductivity of an electrolyte and temperature as defined in equation 13. The sharp drop in conductance which occurs at approximately -80°C on the cooling curve is due to the rapid freezing of supercooled bulk water.

Figure 4 illustrates graphically the calculation of the parameter Z which is defined in equation 16. Plotted on this graph is the first derivative of the \( \log_{10} \) of the conductance with respect to the negative inverse of the absolute temperature versus the negative inverse of the absolute temperature for the warming cycle of the test conducted on Vycor glass. The integration of these data over finite intervals as illustrated in figure 4 give the parameter Z as a function of the negative inverse of the absolute temperature. Combining this relationship with the plastic ice model relationship expressed in equation 1 gives Z as a function of pore radius. The relative conducting pore volume as a function of pore radius is then calculated using equation 18.

Figures 5 and 6 illustrate two graphical means of presenting conductometric pore size distributions.

Evaluations of these results were made by comparing them with results obtained on the same sample by phase transition porosimetry and mercury porosimetry. Figures 7 and 8 contrast the pore size distributions obtained from conductometric phase transition porosimetry, phase transition porosimetry, and mercury porosimetry for neck and body sizes respectively.
Figure 3 - Logarithm of the conductance versus negative inverse of absolute temperature (T vs. 1/absolute temperature) for Vycor glass.
Porous Vycor Glass
Warming Cycle

\[ X = \left( -\frac{1}{T} \right) \quad Y = \log C \]

\[ z \left( -\frac{1}{T_1}, -\frac{1}{T_0} \right) = \int \frac{d \left( \log C \right)}{d \left( -\frac{1}{T} \right)} - \int \frac{d \left( -\frac{1}{T} \right)}{d \left( -\frac{1}{T} \right)} - \int m d \left( -\frac{1}{T} \right) \]

Figure 4 - Illustration of the calculation of the parameter Z in Conductance Phase Transition Porosimetry.
Figure 5 - Conductometric pore size distribution of Vycor glass
Figure 6 - Conductometric pore size distribution of Vycor glass.
Figure 7 - Comparative neck size distributions for Vycor glass
Figure 8 - Comparative body size distributions for Vycor glass
It can be seen from these figures that all three methods of porosimetry give comparable results for neck sizes. For body sizes some difference is observed. It is believed that the difference between the body size distribution as determined by phase transition techniques and that determined by mercury porosimetry is due to uncertainties involved in the entrapment of mercury during extrusion in mercury porosimetry.

7. REFERENCES


APPENDIX C

Conductometric phase transition porosimeter users manual

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CONDUCTOMETRIC
PHASE TRANSITION POROSIMETER

USER'S MANUAL
Volume 1
Operation Instructions
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Conductometric phase transition porosimetry is based on the assumption that the electronic conductance through the solid phases of a porous material is negligible when compared to the electrolytic conductance of the pore solution. Thus, when the temperature of a mass of saturated porous material is raised from sub-freezing temperatures the frozen pore solution will melt, and an increase in electrical conductance will be observed. As ice in capillaries melts at temperatures below the normal melting point of ice, the change in electrical conductance of the material with temperature will be a function of the pore structure of that material. The methodology combines the plastic ice model for solid-liquid phase transitions of pore water with relationships between conductance and temperature, and conductance and pore structure. The theory behind conductometric phase transition porosimetry is developed from a few basic relationships.

Assuming that the pore geometry of the sample can be represented by randomly intersecting spheres or cylindrical capillaries with or without constrictions, it can be shown using the plastic ice model, that the solid-liquid phase transition of water in a pore having an effective radius of \( r \) takes place at a temperature, \( t \) (°C) given by:

\[
t = \frac{-2\gamma T_0}{(\rho \lambda r)}
\]

where \( T_0 \) is the normal melting point of ice in °K, \( \lambda \) is the heat of fusion of ice per unit mass, \( \rho \) is the density of water and \( \gamma \) is the ice/water interfacial tension at \( t \). In melting, \( r \) is the pore body radius, while in freezing it is the radius of the pore constriction.

A relationship between the ice/water interfacial tension, \( \gamma \), and temperature is used where

\[
\gamma = \gamma_0 + kt
\]
where \( t \) is the temperature in °C, \( k \) is a dimensional constant with a value of 0.25 ergs cm\(^{-1}\) K\(^{-1}\), and \( \gamma_0 \) is the value of \( \gamma \) at 0 °C. Also, for conductometric phase transition porosimetry it is helpful to develop a relationship between pore radius, \( r \), and the negative inverse of the absolute temperature, \( X \). With this information equation 1 can be rewritten as

\[
\frac{-2T_0(k - \gamma_0X + kT_0X)}{\rho\lambda(1 + T_0X)}
\]

where \( r, T_0, \gamma_0, k, \rho, \) and \( \lambda \) are as defined earlier and \( X = (-1/T) \), where \( T \) is the phase transition temperature in °K.

The numerical values of the various constants used in computations contained in this document were as follows:

\[
\begin{align*}
\gamma_0 &= 29 \text{ N m}^{-1} \\
T_0 &= 273.16 \text{ 0K} \\
\rho_w &= 1.000 \text{ gm cm}^{-3} \\
\lambda &= 333.3 \text{ J gm}^{-1}.
\end{align*}
\]

These values were obtained from physical and chemical handbooks.

The relationship between conductance of a porous material, \( C' \), and pore structure for a cylindrical sample of porous material with cross-sectional area, \( A \), and length, \( L \), is defined as

\[
C' = \kappa \left( \frac{V_p}{(L^2 \omega)} \right)
\]

where \( \kappa \) is the electrical conductivity of the pore solution, \( V_p \) is the pore volume and \( \omega \) is a dimensionless pore geometry factor.
Also, it is assumed the relationship between the electrical conductivity of an electrolyte and the absolute temperature of the electrolyte is an Arrhenius type relationship and can be expressed as

\[
\ln \kappa = \frac{a}{T} + b
\]

(5)

where

- \( \kappa \) = electrical conductivity,
- \( T \) = absolute temperature,
- \( a \) = physical constant, and
- \( b \) = physical constant.

By combining equations 4 and 5 the following equation is derived

\[
Y = mX + d + \log_{10}\left( \frac{V_p}{L^2 \omega}\right)
\]

(6)

where \( L, V_p \) and \( \omega \) are as defined earlier,

- \( X = -1/(\text{absolute temperature}) \),
- \( Y = \log_{10} \text{(conductance)} \),
- \( m \) = physical constant, and
- \( d \) = physical constant.

A plot of the \( \log_{10} \) of the conductance versus the negative inverse of the absolute temperature (\( Y \) versus \( X \)) for which no phase change occurs will result in a line with a slope equal to \( m \). Below freezing temperatures the phase changes which occur in a certain range of pores will effectively
decrease the volume of conducting pores. Thus, $V_p$ at below freezing temperatures can be considered to be the volume of conducting pores, $V_{cp}$.

Taking the first derivative of equation 6 yields

$$\frac{dY}{dX} = m + \frac{d\left(\log_{10}\left(V_p/(L^2\omega)\right)\right)}{dX} \tag{7}$$

Integrating equation 7 over the definite interval, $X$ to $X_o$, yields the following:

$$\log_{10}\left[\frac{V_{cp}(X_o)}{L^2\omega X_o} \right] = \int_X^{X_o} \frac{dY}{dX} dX - \int_X^{X_o} m dX \tag{8}$$

The right half of equation 8 can be calculated numerically from conductance test data and is given the variable name $Z$. Also, if $X_o$ is the value of $X$ at the pore solution melting point ($273.15 \,^\circ\text{K}$ for water), then $V_{cp}(X_o)$ is simply the total conducting pore volume, $V_p$. Rearranging equation 6 and referring to pore radius instead of temperature in light of equation 1 we obtain:

$$\frac{V_{cp}(r)}{V_p} = \frac{-Z(X, X_o)}{\alpha} \tag{9}$$

where $V_{cp}(r)$ is the volume of the pores with radii smaller than or equal to $r$ containing unfrozen pore solution, $V_p$ is the total pore volume and $\alpha$ is the ratio of the pore geometry factor of the total pore system, $\omega$, to the pore geometry factor of the pores smaller than $r$, $\omega_r$. If it is assumed that the
shape factor, $\omega$, is independent of pore size, then $\alpha$ is equal to unity and equation 9 can be reduced to

$$\frac{V_{cp}(r)}{V_p} = \frac{-Z(X, X_0)}{10}$$

Assuming $\alpha$ to be equal to unity implies the pore system has a certain degree of homogeneity. This does not imply that all the conducting pores are exactly the same but rather that the tortuosity and necking inherent to a given pore structure is uniform throughout the pore size distribution or otherwise stated that they are geometrically similar.

These relationship provide the theoretical background for conductometric phase transition porosimetry.

The Apple IIe computerized data acquisition system has been developed. The system consists of the Apple IIe computer (with two disk drives, a monitor, a parallel interface card, and a serial interface card), a cooling bath, a temperature interface box, and a Solomat conductance meter. The computer controls the bath and records the data for a typical experiment.
This section will take a step by step look at a typical multicycle conductance test. For further information on any step refer to the detailed descriptions in the program or interface sections.

1. Place program disk in drive 1 and raw data disk in drive 2, then reboot the computer by pressing the CTRL, open-Apple, and RESET keys simultaneously. The computer will restart and load the Main Menu program from the program disk. The programs used in this system are menu based. By choosing a number (to change a parameter) or a letter (to choose an action) the program is controlled. While inputting a selection or data, the left and right arrows on the lower right hand corner of the keyboard may be used to correct mistakes. Press the RETURN key to enter your selection.

2. Place the sample in an appropriate container and immerse in the cooling bath. The sample should be saturated with water and surrounded by bulk water. The container should be slightly larger than the sample and able to separate the cooling fluid from the sample. Connect the leads from the Solomat conductance meter to the probes mounted in the sample. If better resolution is needed at the lower end of the conductance scale place a resistor in series with the sample to lower the overall conductance below 160 μS and set the scale on the Solomat to 160 μS for the 1.0 cell. If a series resistor is used, the sample’s conductance will be calculated by the data processing programs when the appropriate data are entered in the Main Menu before processing. If a series resistor is not used set the scale on the conductance meter to 16000 μS for the 1.0 cell. The thermistor should be placed adjacent to the sample. Turn the cooling bath on by using the green main switch first followed by the black compressor switch. Manually set the bath’s temperature to the maximum temperature of the first cycle. It will take about 20 to 30 minutes for the temperature of the sample to reach that of the bath.

3. Start the controlling program by entering C for Run Conductance Test. The program will allow some notes to be entered. Then enter the number of cycle types and define each of the types by entering the maximum temperature, minimum temperature, rate of temperature change, and temperature interval between readings for each cycle type. If data collection is not needed for a particular cycle type enter the number 0 as the
temperature interval. Next enter the total number of cycles for the test sequence and the cycle type for each cycle. Finally, enter the sample's base file name and the starting cycle number for the test sequence. The test sequence will begin. Place the temperature preset switch on the rear of the cooling bath in the ON position. The computer will control the entire test and return to the Main Menu when finished. When the test sequence is completed, turn off the cooling bath and remove the sample.

4. The next step is to process the data. The parameters shown on the Main Menu control the processing. First choose 1 for File Name. If the name of the file you wish to process is unknown, press RETURN and a catalog of the disk in drive 2 will be displayed. Enter the base file name and the cycle number. For example, Mortar.25 would be entered for the 25th cycle of the sample named mortar. If a resistor was connected in series with the sample indicate so and input the CONDUCTANCE of the resistor (mS). The derivative programs use a moving average in their algorithms to smooth the data. Enter the desired moving average for each of the derivative steps. Some of the intermediate steps generate data that may or may not be of interest. Respond with a Y to a Save File option and the data for that file will be saved to a disk. The temperature of TO is the normal freezing point of the pore solution in degrees Kelvin (usually 273.15 K). Once the parameters are set in the desired manner, enter A and calculations will be performed.

5 About one minute into the processing the program will prompt the user to remove the raw data disk and insert a Caldat disk. The processed information is stored on a different disk than the raw data and the raw data has been loaded and processed at this point. The total process takes roughly 7-8 minutes for a cycle with 350 points per portion (warming and cooling) and the program returns to the Main Menu when finished.

6. To make plots of the data choose B for Plot Curves. The computer will load the Plotting Program and display a menu of data file types (from X.Y through R.DVPDLR). If selection 6 or 7 is chosen, the option of plotting the radius on a log scale is available. The plotting menu will then be displayed. Both the warming and the cooling data, may be plotted simultaneously. Enter the file name(s) of the data (base filename, cycle number, and W for warming or C for cooling, i.e., Mortar .25C for the cooling portion of the 25 cycle of a sample named mortar). Plotting parameters may be adjusted to the user's preference and the range of the data. It is advisable to make a
plot on the computer screen to ensure the parameters are set up correctly before making a plot on the plotter. The computer may be stopped while plotting to the screen at any time by pressing the ESC key. The plot is finished when the computer beeps several times. Pressing any key will return the computer to the menu.

7. When all of the necessary plots have been made, enter E to Exit Program and return to the Main Menu. When finished, return the disks to the cases and turn off the computer monitor. The computer itself is left on to maintain the stability of the amplifier circuits.
In this section the purpose, operation, and the structure of each program will be discussed. The structure will be given to help understand the program and solve possible problems. Each program will be listed with the following information:

Main Menu. [Startup], (Convert TC,...), (general sample file)
\data files accessed\programs it may branch to\file name stored on program disk as\program name

Most programs are menu based, the user options are listed on the screen by number or letter. Choosing a number allows you to edit the data or a parameter and selecting a letter chooses a particular action. While inputting a selection or data, the left and right arrows on the lower right hand corner of the keyboard may be used to correct mistakes. Press the RETURN key to enter the selection.

There are three types of disks in this system. One of the disks contains the programs to control the tests, process the data and output the results. The other two types are data disks. The raw data disk contains the temperature vs. conductance information for all cycles and the general sample file. The CALDAT disk contains the processed data for the directories listed in the introduction section. Due to disk space limitations, only about two fully processed cycles (all directories saved) or 3 partially processed cycles (only saving X.Y, R.VP, and X.DYDX) may be saved on one CALDAT disk (assuming 340 points per portion of the cycle or 680 points per cycle). More cycles may be stored on a disk if the number of points per cycle is decreased.
<table>
<thead>
<tr>
<th>DIRECTORY</th>
<th>CONTENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>X.Y</td>
<td>Converted temperature and Conductance</td>
</tr>
<tr>
<td>X.DYDX</td>
<td>$d(Y)/d(X)$</td>
</tr>
<tr>
<td>X.Z</td>
<td>Integral of $Y$</td>
</tr>
<tr>
<td>X.VP</td>
<td>Pore Volume</td>
</tr>
<tr>
<td>R.VP</td>
<td>Pore Volume vs. Radius</td>
</tr>
<tr>
<td>R.DVPDR</td>
<td>$d($Pore Volume$)/d($Radius$)$</td>
</tr>
<tr>
<td>R.DVPDLR</td>
<td>$d($Pore Volume$)/d($Radius$)$</td>
</tr>
</tbody>
</table>

The control program will be discussed first, followed by the data processing and output programs. Program listings can be found in volume 2 of this manual.
MAIN MENU, [Startup], (Plotter, Controller, Convert XY, Derivative XY, Integrate, Convert VP, Convert R, Derivative VP), (raw data file)

PURPOSE: Main Menu is the central program of the entire system. From Main Menu a new test sequence may be started, data plotted, or data calculations initiated.

OPERATION: Main Menu is the first program that will appear upon starting the system. From Main Menu a test may be started, data calculations initiated, or plots of data made. To start a new test press "C" and you will proceed directly to Controller. To make a plot press "B" and Plotter will be run. The format of the test may be printed on the plotter by entering "D" to run the Test Format program.

The items that appear on the screen initially are only used to control the calculation process. This data is only used for current control purposes and is not stored for each file. To load a file input a "1" for File Name and enter a file name consisting of a base file name and the cycle number. If the name or cycle number of the file is unknown, press RETURN and a catalog of the data disk will be shown. If a resistor was placed in series with the sample enter a "Y", if not a "N". If there was a resistor in series enter the conductance (not the resistance) of the resistor in uS. This data will be used to calculate the conductance of the sample. Both derivative programs use an algorithm that averages the data over a specified interval which may be adjusted. Several of the intermediate programs offer the option of saving the file. If the data from these programs is not important enter a "N" in the appropriate spaces. Not saving the intermediate data will speed the calculations and save disk space. When the temperature data is converted to radius the file may be thinned out so that there is at least one Angstrom between each of the data points. Thinning the file will cut the plotting time and also save disk space. The temperature T0 is the pore solution melting point in degrees Kelvin. A sample menu is shown on the next page.
**CONDUCTANCE MENU**

1. File Name
   : Mortar.25

2. T.C to X.Y
   : Series Resistor : Y
   : Cond of Resistor : 144.3

3. X.Y to X.DYDX
   : Moving Average : 3
   : Save File : N

4. X.DYDX to X.Z
   : Save File : N

5. X.Z to X.VP
   : Save File : N

6. X.VP to R.VP
   : Thin File Out : Y
   : Temp of T0 : 273.15

7. R.VP to R.DVPDR
   : Moving Average : 3

8. R.VP to R.DVPDLR
   : Moving Average : 3

A. Calculate the data
B. Plot data
C. Run Conductance test
D. Print Test Format
E. Exit to system

Enter your menu choice :
CONTROLLER, [Cond2], (Main Menu, Clock, Temp Timer), (raw data, general sample file, CAL)

PURPOSE: Controller controls the cooling bath and records data during a conductance test of the sample.

OPERATION: At the beginning of the program will prompt the user to enter some information about the sample and specify the testing parameters. The computer will first prompt the user to enter some notes on the sample. Typical information would be the date and sample material. Don't put any commas into the information or the computer will ignore the rest of the line after the comma. At the end of each line press RETURN.

Now the program prompts the user to enter the number of cycle types. Any number of cycle types may be specified. For each cycle type enter the maximum temperature, minimum temperature, rate of temperature change, and the temperature interval between data readings. The computer will check the input values to insure the minimum temperature is above the maximum, a negative rate of temperature change is not entered, a rate greater than 30 C/hr is not entered, and that the temperature interval for data readings isn't greater than the difference between the maximum and minimum temperature or negative. If a temperature interval of zero is entered the program will not record any data on that cycle. This feature is useful for multiple cycle runs when only data at certain cycle intervals is needed. All of the maximum temperatures must be the same so that when the computer switches from one cycle type to another there is a smooth transition. If the current cycle has a maximum lower than the next cycle's the computer will begin taking data as soon as the current cycle is over and continue until the temperature is above the level of the next reading.

Once the data for all of the cycle types has been entered the program will prompt the user to input a test profile consisting of a sequence of the cycle types. Input the total number of cycles in the test profile and the cycle type for each cycle. The cycle types are described by number, the first one entered being number one.

Now that the test profile is completed, input the base file name for the sample and the cycle number the test is starting on. For example if a previous test of 45 cycles was run on the sample, input the same base file name and then enter the starting cycle as 46 and the cycle number of the data will now be correct.
The test will now start and a status screen will be displayed. A sample status screen is shown below.

<table>
<thead>
<tr>
<th>COOL</th>
<th>Press F to stop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mortar Sample 1</td>
<td>Temp (C)</td>
</tr>
<tr>
<td>\</td>
<td>-10.22</td>
</tr>
<tr>
<td>\</td>
<td>\</td>
</tr>
<tr>
<td>\</td>
<td>\</td>
</tr>
<tr>
<td>\</td>
<td>\</td>
</tr>
<tr>
<td>\</td>
<td>\</td>
</tr>
</tbody>
</table>

CYCLE NUMBER 11 OF 45

Maximum Temp : 4
Minimum Temp : -30
Temp Rate : 3
Temp Interval between readings : .1

The display shows the current temperature of the sample, the conductance of the last data point taken, and the number of that point. The screen also displays the cycle parameters, the current portion of the cycle (heat or cool), and the progress of the overall test (in this case on the 11th of 45 cycles).

To discontinue the experiment at any time press F and the computer will stop at the end of the cycle. The computer must stop at the end of a cycle to save the data for that cycle.

The data is saved at the end of each cycle and when the test is complete the program returns to the Main Menu.

STRUCTURE: Controller allows the user to input notes on the sample, the parameters each cycle type, and the cycle types that make up the test profile. This information is stored on the raw data disk as the CT file.

The cycle type parameters are stored in the arrays TP, BTTM, INVL, and RA for maximum temperature, minimum temperature, temperature interval and the rate of temperature change respectively. The TDS array is used to tell the program whether data should be taken during the cycle. If the temperature interval is set at 0 then TDS is set to tell the computer not to take data during the cycle, otherwise TDS is always set for taking data.
The test profile is stored in the array TC. Each element contains the cycle type corresponding to the cycle number.

The sample descriptions are used for the base file name. The starting cycle number will be one unless previous tests were run on the sample. If previous tests were run the starting cycle number is added to the current cycle number to get the cycle number the file is saved under (see the introduction for an explanation of the file names). For example if the starting cycle number is 10 the first cycle will be stored under cycle 10 and the second under 11 and so on.

When all of the data are entered the computer begins the test. There are two parts to each cycle, cooking and warming. During both portions of a cycle the same type of control cycle is performed. The temperature interval of the next reading is set and the temperature is continuously monitored. When the temperature passes the interval a conductance reading is taken and both the temperature and conductance are stored in the array SDT. The temperature of the interval is checked to see if it is past the end temperature for the current portion of the cycle. If the interval is past the end temperature then that portion of the cycle is completed. If the interval is not past the end temperature, then the next interval is set and the control cycle is repeated. While cooling a reading is taken when the temperature is lower than the temperature interval set and the cycle ends when the interval is less than the minimum temperature for the cycle. While warming, the temperature must be greater than the interval and the interval must be greater than the maximum temperature for the cycle.

The temperature of the cooling bath is controlled throughout the cycle. The bath is either cooled or warmed at the rate of temperature change specified. The temperature is controlled by sending a number between 0 and 255 to the temperature controller card. The card then converts the digital input to a voltage output that is sent to the cooling bath (for more information see the hardware section). A 0 represents 7 °C and 255 represents -35 °C. The temperature can be controlled in integer steps between these two values for a resolution of .164 °C/integer. For example 0 °C would be set by sending a 42.6 but really either a 42 or 43 would be sent for .112 or -.052 °C respectively. At the beginning of either portion of the cycle the starting and ending temperature points are set and and the time (in seconds) between integer steps is calculated. If a cycle has end points, for example, of 4 and -16 °C, the corresponding integers would be 18 and 141. If the rate of temperature change was 20 °C/hr then the time between integer steps would be
Each time the sample temperature is read the time is checked to see if it is time for the next temperature step. The bath temperature will continue to change until the end of the cycle even if it passes one of the end points. The bath would only stop if one of the limiting end points (7 or -35 °C) is reached.

The clock for controlling the rate of temperature change is produced by the temperature controller card. An machine language program, Clock, is loaded from the program disk converts one of the timers on the temperature controller card to a clock.

The temperature of the sample is measured by a thermistor. The variable resistance of the thermistor is converted to variable frequency by an square wave oscillator. The period of the square wave is then measured by the interface card using a machine language program, Temp Timer, loaded from the program disk. The length of the period is then read by the program. The period is converted back to a temperature by linear interpolation of a temperature table read from the CAL file on the program disk.

The conductance is measured by the Solomat conductance meter. The meter's reading is transmitted in parallel to the interface card. The conductance may then be read directly from the interface card by the program.

When the cooling portion of a test cycle is completed the data are saved to the disk, the temperature controller parameters are set for the warming portion, and the controlling loop is started. At the end of a warming portion there is one extra thing that is checked. The data is saved, but then the cycle number is checked to see if the test is completed. If there are still cycles left to complete, the next cycle type is loaded, the temperature controller parameters for the cooling portion are set, and the controlling loop is started.

At the end of a test the program returns to the Main Menu.
PLOTTER, [Plot], (Main Menu, HP Plotter), (general sample file, V, PCV, DVDP, DVR, DSR, S)

PURPOSE: Plotter allows the user to load a sample's data files from any of the directories and plot the data on the computer screen. The plotting parameters may be changed. Plotter may also pass the data to HP Plotter to make a plot of the data on a Hewlett Packard plotter.

OPERATION: Plotter first prompts the user to enter the directory to plot from. The menu below will appear.

MENU OF SUBDIRECTORIES

1. X.Y
2. X.DYDX
3. X.Z
4. X.VP
5. R.VP
6. R.DVPDR
7. R.DVPDLR
8. EXIT TO MAIN MENU
ENTER NUMBER OF YOUR CHOICE

Choose a type of data. If 6 or 7 is selected the user has the option of plotting the radius on a log scale. The plotting menu will then be displayed (a sample is shown).
Enter the letter of any value that you wish to change and press RETURN.

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Title</td>
<td>Concrete Mortar 27 March 87</td>
</tr>
<tr>
<td>2.</td>
<td>Filename</td>
<td>Mortar.25W</td>
</tr>
<tr>
<td>3.</td>
<td>Label</td>
<td>Warming</td>
</tr>
<tr>
<td>4.</td>
<td>Linetype</td>
<td>7</td>
</tr>
<tr>
<td>5.</td>
<td>Filename</td>
<td>Mortar.25C</td>
</tr>
<tr>
<td>6.</td>
<td>Label</td>
<td>Cooling</td>
</tr>
<tr>
<td>7.</td>
<td>Linetype</td>
<td>0</td>
</tr>
<tr>
<td>8.</td>
<td>Minimum X</td>
<td>10</td>
</tr>
<tr>
<td>9.</td>
<td>Maximum X</td>
<td>10000</td>
</tr>
<tr>
<td>10.</td>
<td>X-Interval Size</td>
<td>10</td>
</tr>
<tr>
<td>11.</td>
<td>Minimum Y</td>
<td>0</td>
</tr>
<tr>
<td>12.</td>
<td>Maximum Y</td>
<td>1</td>
</tr>
<tr>
<td>13.</td>
<td>Y-Interval Size</td>
<td>.1</td>
</tr>
<tr>
<td>14.</td>
<td>Paper Length</td>
<td>8.5</td>
</tr>
</tbody>
</table>

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Onscreen Plotting</td>
<td>D</td>
</tr>
<tr>
<td>B</td>
<td>HP722 Plotting</td>
<td>E</td>
</tr>
<tr>
<td>C</td>
<td>View Graphics Screen</td>
<td>F</td>
</tr>
</tbody>
</table>

Enter your choice and press RETURN.

Choices from this menu may either load data files, change plotting parameters, or choose an action. Two files may be plotted at the same time, usually the warming and cooling data from the same sample and cycle. To load a file enter 2 or 5, and enter the complete file name for the data. When a file name is entered, the computer does not load the file into an array but instead loads it during plotting. The label and the type of line associated with each file may be changed by choosing 3, and 4 or 6, and 7.

The other parameters are for adjusting the X and Y axis. The minimum and maximum value for each axis scale and also the spacing between scale markings may be adjusted. If the X axis is radius and a log scale is chosen, the interval for the X axis is not used so changes to the interval will have no effect on the plot. The paper size is normally set for the smaller plotters and 8.5 X 11 paper. If a larger plotter is used the paper length may be changed to 14 for 11 X 14 paper.

Now that the plotting parameters and file names have been entered, the data may be plotted. It is recommended to first plot the data on the computer screen to insure the parameters are set correctly before starting a more time consuming plot on a plotter. If a "TRUE" appears after "D - Clear Graphics Screen", the graphics screen will be cleared before the new data is plotted. To plot a second set of data on top of the previous plot, make sure
it says "FALSE". At any time after the axis are drawn pressing the ESC key will discontinue the plot. The computer will stop plotting and by pressing another key, the plotting menu will reappear. This escape feature only works while plotting on the computer screen.

To make the plot on paper, choose B to transfer the data to HP Plotter. HP Plotter will plot the data on the plotter and then return the data to Plotter.

To load a different sample or a different directory of files from the same sample, choose F. The program will start over by prompting the user to select a file directory.

Select E to return to the Main Menu.

STRUCTURE: The user is first prompted to select the directory of the files to plot. When the file name is entered (must include sample name, cycle number, and portion of the curve) data isn't loaded but it is ready to be loaded during plotting. Two files may be loaded and plotted at the same time. The top file is plotted first followed by the lower.

The plotting parameters set the X and Y axis. If a plot with a log scale X axis is selected the X interval is not used by the computer. The computer automatically sets up a log scale plot from the minimum X to the maximum X, but if either of these values are not a power of ten the computer rounds down to the next lowest power of ten. For example if the minimum X is set at 15 and the maximum is set at 15000 the computer will plot from 10 to 10000 with a log scale.

Line types for each of the files may be chosen from the following list.

<table>
<thead>
<tr>
<th>Pattern #</th>
<th>Line Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>only the data points are plotted</td>
</tr>
<tr>
<td>1</td>
<td>. . . . . . . . . . . . .</td>
</tr>
<tr>
<td>2</td>
<td>--- --- --- --- --- ---</td>
</tr>
<tr>
<td>3</td>
<td>--- --- --- --- --- ---</td>
</tr>
<tr>
<td>4</td>
<td>--- --- --- --- --- ---</td>
</tr>
<tr>
<td>5</td>
<td>--- --- --- --- --- ---</td>
</tr>
<tr>
<td>6</td>
<td>--- --- --- --- --- ---</td>
</tr>
<tr>
<td>7</td>
<td>--- --- --- --- --- ---</td>
</tr>
</tbody>
</table>

→ | ← one pattern length

The arrays are passes to HP Plotter when a hard plot is desired.
HP PLOTTER, [Hpplot], (Plotter), (none)

PURPOSE: HP Plotter receives the parameters passed from Plotter and makes a plot on a plotter.
OPERATION: HP Plotter requires no user input.

STRUCTURE: The file names and parameters are passed to HP Plotter by Plotter. HP Plotter then initializes the Plotter and begins to draw the plot. A sample plot is shown below.
CONVERT XY, [T.C.to.X.Y], (Main Menu), (raw data file, X.Y)

PURPOSE : Convert XY reads in the raw temperature vs. conductance data from the disk and converts it to the X vs. Y format for further processing.

OPERATION : Convert XY requires no user input.

STRUCTURE : Convert XY is the first in a string of data processing programs. Therefore Convert XY is responsible for loading the data from the disk and converting it into the format required for the rest of the processing programs. The Main Menu sends the file name to Convert XY. Convert XY loads the raw data from the warming and cooling files into the two-dimensional arrays A and B for the temperature and the conductance respectively. The first dimension of the array indicates whether the data are from the warming (0) or cooling (1) portion of a cycle. The second element is the numerical value of the data.

The raw data are converted to the X vs. Y format where

\[ X = (-1 / T) \times 10000 \]

and T is the temperature in degrees Kelvin. During the conductance test you a resistor may be connected in series with the sample to narrow the conductance range of the test. This allows a lower scale on the conductance meter to be used and thus resolution is better at lower temperatures where low conductances occur. During the calculation of Y values the effect of the conductance of the series resistor is compensated for and the conductance of the sample alone is determined. The following relationships apply.

\[ Y = \log (CT) \], and \[ CT = (C \times R) / (C - R), \]

where R is the conductance of the resistor in \( \mu \)S, and C is the conductance of the resistor and sample in \( \mu \)S. With the effect of the resistor is removed, CT is the conductance of the sample.

The new X vs. Y data are stored in the X.Y directory and the data are passed back to the Main Menu for further processing.
DERIVATIVE XY, [Der.X.Y], (Main Menu), (X.DYDX)

PURPOSE: Derivative XY calculates the derivative of Y with respect to X, \( \frac{dY}{dX} \), for both the warming and the cooling data. The derivative algorithm also smooths the data using the moving average set in the Main Menu. The relationship between the derivative, \( \frac{dY}{dX} \), and the samples pore volume is expressed in equations 7 and 8 in the Introduction.

OPERATION: Derivative XY requires no input by the user.

STRUCTURE: The data are passed from Main Menu through arrays A and B for X and Y respectively. The derivatives, \( \frac{dY}{dX} \), are calculated and stored in the conductance array, therefore the conductance data in the array are lost, but the data are still in the disk file. The derivative is found with an algorithm that uses a moving average to smooth the data somewhat. The moving average (MA) is set in the Main Menu. If the user has chosen to save the data, they are stored in the X.DYDX directory. When the program is finished the data are passed back to the Main Menu for further processing.
INTEGRATE XDYDX, [Int], (Main Menu), (X.Z)

PURPOSE: Integrate XDYDX perform 2 integrations on the X, DYDX data, resulting with the calculation of the parameter Z expressed in equation 8 of the Introduction.

OPERATION: Integrate XDYDX requires no user input.

STRUCTURE: The arrays A and B are passed from the Main Menu containing the information X and dY/dX respectively. The Z values are cumulative totals of the integral and replace the dY/dX values in the array B.

The warming file is processed first with the data pairs processed sequentially from right to left on a X vs. dY/dX plot (the larger X value pairs first). The Z value for all pairs with an X greater than -36.5 are set equal to 0. The average value of Y on the dY/dX interval from -36 to -36.5 is found and stored in Y1 as the slope m. For the rest of the file the Z value is calculated using the following formula:

\[
Z\left(\frac{-1}{T}, \frac{-1}{T_0}\right) = \int_{\frac{-1}{T}}^{\frac{-1}{T_0}} \frac{d(\log C)}{d\left(\frac{-1}{T}\right)} \text{ } d\left(\frac{-1}{T}\right) - \int_{\frac{-1}{T}}^{\frac{-1}{T}} m \text{ } d\left(\frac{-1}{T}\right)
\]

where

The calculations are graphically shown on the graph below.
The cooling portion is processed next, in a left to right manner. The same base \( m \) is used on the cooling curve. The data pairs with a \( \frac{dY}{dX} \) value greater than -36.5 receive the \( Z \) value of the last pair less than -36.5. When the cooling curve is complete the data are passed back to the Main Menu and stored in the directory \( \text{Xi?} \), if the user has directed the computer to save the \( XZ \) File in the Main Menu.
CONVERT VP, [X.VP.from.X.Z], (Main Menu), (X.VP)

PURPOSE: Convert VP calculates the total conducting pore volume from the X vs. Z data. The total conducting pore volume is the ratio of $V_{cp} / V_p$ as shown in equation 10 in the Introduction.

OPERATION: Convert VP requires no user input.

STRUCTURE: The data are passed into Convert VP via the arrays A and B for X and Z, respectively. The pore volume is found using the equation,

$$V_p = \frac{1}{10} Z$$

and replaces Z in the B array. If the user chooses to save the data, they are stored in the X.VP directory. The data are passed back to the Main Menu when the program has completed the calculations.
CONVERT R, [R.VP.from.X.VP], (Main Menu), (R.VP)

PURPOSE: Convert R changes the X variable to a pore radius. Relative conducting pore volume is now expressed as a function of radius, as shown on the left hand sides of equations 9 and 10 in the Introduction.

OPERATION: Convert R requires no user input.

STRUCTURE: The data are passed to Convert R via two arrays, A and B containing X and VP respectively. The X data are converted from a temperature to radius using the equation

\[ R = \frac{-2 \times T_0 \times (0.25 - (29 \times X) + (0.25 \times T_0 \times X))}{(0.9998 \times 3.335 \times 10^9 \times (1 + T_0 \times X)) \times 10^8} \]

where \( T_0 \) is the pore solution melting point (273.15 °K for water) which is entered in the Main Menu and X is the X variable. All data points with an original temperature greater than 0 °C are meaningless and removed from the arrays. If you have chosen to "thin" the file, the program only saves points that are spaced at least one Angstrom apart. The data are saved in the R.VP directory on the data disk and then passed back to the Main Menu for further processing.
DERIVATIVE VP, [Der.R.VP], (Main Menu), (R.DVPDR)

PURPOSE: Derivative VP calculates the derivative of Vp with respect to R, dVp/dR, for both the warming and the cooling data. The derivative algorithm also smooths the data using the moving average entered in the Main Menu.

OPERATION: Derivative VP requires no input by the user.

STRUCTURE: The data are passed from Main Menu through arrays A and B for R and Vp respectively. The derivative, dVp/dR, is calculated but not stored in the conductance array. The arrays are passed back to the Main Menu without any changes so that the derivative with respect to the log(R) can be computed. The derivative is found with an algorithm that uses a moving average to smooth the data somewhat. The moving average (MA) is set in the Main Menu. The data are stored in the R.DVPDR directory. When the program is finished the R and Vp data are passed back to the Main Menu for further processing.
DERIVATIVE LVP, [Der.LR.VP], (Main Menu), (R.DVPDLR)

PURPOSE: Derivative LVP calculates the derivative Vp with respect to log (R), dVp/dLR, for both the warming and the cooling data. The derivative algorithm also smooths the data using the moving average entered in the Main Menu.

OPERATION: Derivative LVP requires no input by the user.

STRUCTURE: The data are passed from Main Menu through arrays A and B for R and Vp respectively. The radius is converted to the log (R) before any of the calculations and then the derivative of Vp is computed with respect to the log10 (R). The derivative, dVp/dLR, is calculated and stored in the conductance array. The derivative is found with an algorithm that uses a moving average to smooth the data somewhat. The moving average (MA) is set in the Main Menu. The data are stored in the R.DVPDLR directory. This is the last step in the data processing cycle and the program returns to the Main Menu when finished.
SURFACE AREA, [Int.Sa], (none), (R.VP)

PURPOSE: Surface Area loads the radius vs. relative pore volume data and after the actual sample pore volume is entered calculates the surface area of the sample.

OPERATION: Surface Area is not offered as an option on the Main Menu, therefore to load and run the program, first exit the menu and type "RUN INT.SA,D1". Once the program is started, input a file name consisting of the base file name for the sample and the cycle number. After the R.VP file for the sample is loaded for the warming portion, enter the pore volume of the sample. The relative pore volume is multiplied by the actual total pore volume to get the pore volume at any given point. The computations will be performed and the surface area printed on the screen.

STRUCTURE: Surface area computations are only performed on the warming portion of the curve. Once the file name is entered, the pore volume data from the warming portion is loaded into an array for processing. Then a modified version of the data, changed to pore volume vs. 1/radius, is integrated from 0 to 1/12 using a method of rectangles. The change in 1/radius between points is multiplied by the height of the larger pore volume to get the area of a rectangle. The total integral is the sum of all of the rectangles. The area will be overestimated using this method but as the number of points increases and therefore the width of the rectangle decreases, the error becomes negligible. The integration method is illustrated on the next page. The width of the rectangles is exaggerated for clarity.
The surface area of the sample (excluding pores less than 12 Angstroms) is found to be the area under the curve multiplied by 2.5. The surface area is graphically represented on the next page.
The surface area is then printed to the screen and the program ended. To return to the Main Menu type "RUN STARTUP,D1"
TEST FORMAT, [Sample.Data], (Main Menu), (general sample file)

PURPOSE: Test Format prints out the test format, the cycle types and the cycles, for a test sequence.

OPERATION: To run Test Format enter a "D" in the Main Menu. Test Format will be loaded and the computer will prompt the user to insert the appropriate raw data disk. Enter the test format file name including the sample name, starting cycle number, and CT (for example Mortar.25.CT). The file will be loaded into memory and displayed on the computer screen. The user may choose to either quit and return to Main Menu or print the information on the plotter.

STRUCTURE: The data is loaded into an array and displayed on the screen. Due to limitations of screen size only 48 cycles may be displayed, the cycles over 48 will be loaded from the disk but not be shown on the screen. The program sends the data to the plotter.
CLOCK, [10.Clock.Slot1], (Controller), (none)

PURPOSE: Clock generates a system clock that is accessed by Controller to maintain the rate of temperature change.

OPERATION: Clock requires no user input.

STRUCTURE: The operation of Clock is described in detail in Byte, March 1982 in an article by Ned Rhodes, the author of the program. The clock uses one of the 16-bit timers on the parallel interface card located in slot 1. The timer generates an interrupt every 1/60 of a second and calls Clock. Clock then displays the time on the screen and maintains a register which can be read by the program. The number in the register represents the number of interrupts since the clock was reset. Controller then divides the number in the register by 60 to get the number of seconds.
TEMP MEASUREMENT, [Cap.Res.2], (Controller), (none)

PURPOSE: Temp Measurement determines the period of the square wave generated by the thermistor's oscillator. The period is used to determine the temperature of the sample.

OPERATION: Temp Measurement requires no user input.

STRUCTURE: Temp Measurement uses one of the 16-bit timers from the parallel interface card located in slot 1. The program turns the timer on when it senses a rising edge on the signal. The timer then counts down until a falling edge is detected. The computer can then access the counter and subtract the initial value to get the half period of the wave.
CALIBRATE, [Calibrate], (none), (Cal)

PURPOSE: Calibrate is a data editing program to allow the user to change the temperature calibration data for the thermistor.

OPERATION: Calibrate is not an option on the Main Menu. To load and run the program exit the Main Menu and type "RUN CALIBRATE,DI". The program will automatically load the Cal file and display it on the screen. The method of determining the calibration data is described in the Appendix. By using the arrows the cursor can be moved around the screen. When the cursor is at the desired location, type in the new data and press RETURN. The new data will then replace the old in the file located in the computer. When editing is completed the new version of the file in the computer may be saved to the disk, by pressing CTRL and S. If the user doesn't want the changes made to the data to be saved pressing CTRL and Q will exit the program without saving the changes (NOTE: the data in the disk file is NOT changed in this case). In both cases you are returned to the Main Menu when finished.

STRUCTURE: The Cal file is automatically loaded into an array when the program is started. The user is then allowed to change the data in the array by moving the cursor on the screen to the data to be changed and entering the new data. The number of data points in the file is set at 22 and may not be changed using this program. When editing is finished the data is either written back to the file on the disk or discarded. The program returns to the Main Menu when completed.
The Conductance Porosimeter system consists of a Solomat conductance meter, an Apple IIe (with 2 disk drives, a monitor, and 2 parallel interface cards), an interface box, and a cooling bath. This section will mainly discuss the interface box but will also look at some of the aspects of the rest of the system. The main components are shown below.

The Solomat measures the conductance of the sample and sends the digital data to the parallel interface card located in slot 4 of the Apple IIe. The temperature is converted from the variable resistance of the thermistor to a variable frequency square wave. The period of the square wave is found by a timer on the parallel interface card located in slot 1 of the Apple. Control of the cooling bath is accomplished by the parallel interface card in slot 1 sending a digital number to the temperature control circuit in the interface box. The temperature control circuit converts the digital data to a voltage level which is sent to the cooling bath. The voltage level represents the temperature level of the bath.

The following sections will take a closer look at each of these main functions of the interface.
INTERFACE BOX

PURPOSE: The interface box provides the circuitry to control the cooling bath and record temperature readings.

OPERATION: The interface circuits are housed in a low profile box with connections for the computer cable, the thermistor, and the temperature control cable. The cables should be connected as shown.

STRUCTURE: There are two main components of the interface box, the thermistor and temperature control circuits. The thermistor circuit converts the variable resistance of the thermistor to a variable frequency square wave. The temperature control circuit converts the digital output from the computer to a voltage level that is sent to the cooling bath.

The main component of the thermistor circuit is a 556 timer chip. The chip is wired as a square wave oscillator with its frequency dependent on the capacitance and resistance on pins 6, 1, and 4. Since the resistance of the thermistor is dependent on temperature, and the frequency of the oscillator is dependent on resistance, the frequency is a function of the temperature of the thermistor. The square wave is sent to the parallel interface card in slot 1. The thermistor circuit is shown on the next page.
The temperature control circuit consists of a Digital-to-Analog (D/A) converter and three operational amplifiers (op amps). The temperature control output from the computer is in the form of a number from 0 to 255 corresponding to 7 and -33 °C respectively. The 8-bit number is transferred through the parallel interface card in slot 1 of the Apple. Lines PA0-7 are used to represent the 8 bits (see the parallel interface card section). The 8-bit number is converted to an analog voltage output by the D/A converter (MC1408L8).

Adjusting the voltage on pin 14 of the D/A converter controls the range of voltage from the maximum to minimum inputs. The voltage on pin 14 is controlled by the voltage divider and op amp. Adjusting the 10 KΩ trim pot changes the voltage sent to the op amp. The op amp is configured as a voltage follower (just maintains the voltage input) and is connected to pin 14.

The D/A converter outputs a voltage on pin 4. The output is then amplified by the first op amp and reduced by the second one in line. The 100 Ω trim pot controls the offset voltage of the second op amp. The offset voltage is used to move the output voltage range to the proper level. The output should be .07 to -.33 V corresponding to 7 and -33 °C respectively. In practice, the 10 KΩ trim pot is used to set the low voltage and the 100 Ω for the high voltage (see the Appendix for calibrating the circuit).
The output is then connected by cable to a socket on the back of the cooling bath. The format of the socket may be found in the cooling bath's manual. The schematics of the temperature circuit are shown on the next page.

The cable connecting the interface box to the computer is a DB 25 connector configured as follows. The cable is connected to the other DB 25 connector on the back of the Apple.
<table>
<thead>
<tr>
<th>Pin #</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+ 5 V</td>
<td>Power supply</td>
</tr>
<tr>
<td>2</td>
<td>+ 12 V</td>
<td>Power</td>
</tr>
<tr>
<td>3</td>
<td>- 12 V</td>
<td>Power</td>
</tr>
<tr>
<td>4</td>
<td>GND</td>
<td>Common or Ground</td>
</tr>
<tr>
<td>5</td>
<td>PA0</td>
<td>Data line 0 for temperature control</td>
</tr>
<tr>
<td>6</td>
<td>PA1</td>
<td>&quot;1&quot;</td>
</tr>
<tr>
<td>7</td>
<td>PA2</td>
<td>&quot;2&quot;</td>
</tr>
<tr>
<td>8</td>
<td>PA3</td>
<td>&quot;3&quot;</td>
</tr>
<tr>
<td>9</td>
<td>PA4</td>
<td>&quot;4&quot;</td>
</tr>
<tr>
<td>10</td>
<td>PA5</td>
<td>&quot;5&quot;</td>
</tr>
<tr>
<td>11</td>
<td>PA6</td>
<td>&quot;6&quot;</td>
</tr>
<tr>
<td>12</td>
<td>PA7</td>
<td>&quot;7&quot;</td>
</tr>
<tr>
<td>13-21</td>
<td>Unused</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>CA1</td>
<td>Square wave output of temp oscillator</td>
</tr>
<tr>
<td>23-25</td>
<td>Unused</td>
<td></td>
</tr>
</tbody>
</table>
PARALLEL INTERFACE CARD

PURPOSE: The parallel interface card is used to input and output data in a parallel fashion (simultaneously on many lines rather than serially one bit at a time on one line), provide the system clock, and measure the period of the temperature signal square wave.

OPERATION: The parallel interface cards require no user intervention other than attachment of cables.

STRUCTURE: The parallel interface card used in this system is supplied by John Bell Engineering, 1014 Center St, San Carlos, CA 94070 (Tel: 415-592-8411). The card consists mainly of two 6522 Versatile Interface Adapters (VIA) with a total of four 8-bit bidirectional I/O ports and four independent 16-bit timers. More information may be found in the manuals supplied by the manufacturer.

Two parallel interface cards are used in the system. One of the cards in slot 1 of the Apple, controls the cooling bath, supplies the system clock, and measures the period of the thermistor's square wave. The other is located in slot 4 and is used to interface the Solomat conductance meter.
The card located in slot 1 generates the system clock through a program published in Byte, March 1982 by Ned W. Rhodes (Clock). Using the Apple's interrupts one of the 16-bit timers is triggered every 1/60 of a second. The program then reads the time from the timer. This is why the IRQ and NMI must be configured correctly. The period measurement for the thermistor is accomplished by triggering a timer on the rising edge and stopping on the falling edge. The timer counts down while operating and the program reads the timer. The temperature control data is simply passed in parallel through port 1. The connections are as shown, note the connector on port 4 and the fact that the -12 V line must be directly connected to pin 33.
The parallel interface card in slot 4 is used exclusively for interfacing with the Solomat. The Solomat is powered by the 5 volt line from the parallel interface card. The data is then sent back in parallel through ports 1, 2, and 3. The connections should be made as shown.

Parallel Interface Card in Slot 4
SOLOMAT CONDUCTANCE METER

PURPOSE: The Solomat conductance meter measures the conductance of the sample and sends the digital data to the Apple.

OPERATION: The conductance cables should be attached to the probes in the sample and the cable from the computer plugged into the socket on the side of the meter. The conductivity scale should be set to 16000 μS for the 1.0 cell unless a series resistor is used. A resistor is sometimes put in series with the sample to give better resolution at the lower end of the conductance cell. If a series resistor is used set the scale to 160 μS again for the 1.0 cell. The meter is powered by the computer and doesn't need to be switched on.

STRUCTURE: The Solomat is described in detail in the manufacturer's manual. The configuration of the socket is described in the section 6. All five digits are passed through the parallel interface. Power is supplied through pin 19. The configuration of the DB 25 connector on the back of the Apple is shown below. The digits are sent in Binary Coded Decimal (BCD) requiring 4 bits per digit except for digit 5 (digit 1 being the least significant) which only requires 1 bit as it can only be a one or a zero.

[Diagram of DB 25 connector with labels 1, 13, 14, 25]
<table>
<thead>
<tr>
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<tr>
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<td>3</td>
<td>-12 V</td>
<td>Power</td>
</tr>
<tr>
<td>4</td>
<td>GND</td>
<td>Common or Ground</td>
</tr>
<tr>
<td>5</td>
<td>PA0</td>
<td>Digit 1 Bit 0</td>
</tr>
<tr>
<td>6</td>
<td>PA1</td>
<td>Digit 1 Bit 1</td>
</tr>
<tr>
<td>7</td>
<td>PA2</td>
<td>Digit 1 Bit 2</td>
</tr>
<tr>
<td>8</td>
<td>PA3</td>
<td>Digit 1 Bit 3</td>
</tr>
<tr>
<td>9</td>
<td>PA4</td>
<td>Digit 2 Bit 0</td>
</tr>
<tr>
<td>10</td>
<td>PA5</td>
<td>Digit 2 Bit 1</td>
</tr>
<tr>
<td>11</td>
<td>PA6</td>
<td>Digit 2 Bit 2</td>
</tr>
<tr>
<td>12</td>
<td>PA7</td>
<td>Digit 2 Bit 3</td>
</tr>
<tr>
<td>13</td>
<td>GND</td>
<td>Common or Ground</td>
</tr>
<tr>
<td>14</td>
<td>PB0</td>
<td>Digit 3 Bit 0</td>
</tr>
<tr>
<td>15</td>
<td>PB1</td>
<td>Digit 3 Bit 1</td>
</tr>
<tr>
<td>16</td>
<td>PB2</td>
<td>Digit 3 Bit 2</td>
</tr>
<tr>
<td>17</td>
<td>PB3</td>
<td>Digit 3 Bit 3</td>
</tr>
<tr>
<td>18</td>
<td>PB4</td>
<td>Digit 4 Bit 0</td>
</tr>
<tr>
<td>19</td>
<td>PB5</td>
<td>Digit 4 Bit 1</td>
</tr>
<tr>
<td>20</td>
<td>PB6</td>
<td>Digit 4 Bit 2</td>
</tr>
<tr>
<td>21</td>
<td>PB7</td>
<td>Digit 4 Bit 3</td>
</tr>
<tr>
<td>22</td>
<td>PC0</td>
<td>Digit 5 Bit 0</td>
</tr>
<tr>
<td>23-25</td>
<td>Unused</td>
<td></td>
</tr>
</tbody>
</table>
COOLING BATH

PURPOSE: The cooling bath controls the temperature of the sample and allows the computer to cycle the sample through a freeze-thaw cycle while monitoring the conductance of the sample.

OPERATION: The controls of the cooling bath are shown below.

To turn on the bath, first place the main switch in the on position and then turn the compressor on. Turning them both on at the same time causes a large power surge on the power line. When turning the bath off turn off the compressor before turning the main power off.

The bath's display serves two purposes. It usually displays the current temperature of the bath, but when the set temp display button is pressed the display shows the temperature the bath has been set at. To set the bath temperature press the set temp display button and adjust the temperature set knob until the desired temperature is shown.

The external control socket is located on the rear of the bath. The cable from the temperature control circuit should be connected to the external socket. To place the bath under external control place the temperature preset switch in the ON position. The temperature of the bath will now be set by an external device, in this case the computer. A small mark will appear in the upper left hand corner of the bath's display indicating external
control. The temperature the external device is setting may be shown on the bath's display by pressing the set temp display button.

STRUCTURE: The cooling bath contains a refrigerating unit and a circulator for the bath's fluid. The bath currently contains isopropyl alcohol. The bath is a Haake model A 82 supplied by Haake Inc., 244 Saddle River Road, Saddle Brook, NJ 07662. For further information of the bath see the manufacturer's manual. The format of the external socket is as shown below.

![Diagram of external socket](image)

The temperature voltage is sent into the bath using pin 3. The output pin is not used but could be used to externally monitor the bath's temperature. Both the output and the input represent temperature with voltages, 0.00 volts corresponding to 0 °C and 1.00 volts for 100 °C. Therefore for our range of 7 and -33 °C, we use .07 and -.33 volts respectively.
THERMISTOR

PURPOSE: The thermistor is a temperature dependent variable resistor used to measure the temperature of the sample.

OPERATION: The thermistor requires no intervention.

STRUCTURE: The thermistor used in model SP85DA102FA1 supplied by Thermometrics, 808 U.S. Highway 1, Edison N. J. 08817. It is .085" in diameter and 1/2" long with a nominal resistance of 1 kΩ at 25 °C and stable to ±.02% per year.
INITIALIZING DISKS

The data disks used by this system need to be initialized and directories established before data may be stored on them. To initialize a disk the user needs the ProDOS User's Disk and the /Caldat master disk. Insert the ProDOS User's Disk in drive one and press the CTRL and open-Apple, and RESET keys to reboot the system. The main menu for the ProDOS User's Disk will be displayed on the screen. Select F for ProDOS Filer (Utilities). This is a set of programs to allow the manipulation of disks. The next menu will be the ProDOS Filer menu. This time select V for Volume commands. This will further define the programs to those that manipulate entire disks rather than single files. When the Volume Commands menu is displayed select C for Copy a Volume. This program will copy the contents of an entire disk to another. This program will be used to copy the contents of the /Caldat master disk to the blank disk. The Copy a Volume screen will be displayed next. The program prompt the user to enter "THE VOLUME IN SLOT:" with a "6" being displayed. The program is asking what slot the disk drive controller card is in which in this case is the default value, slot 6. The copying will be done from drive 1 to drive 2 so answer the prompts respectively. Place the /Caldat master disk in drive 1, the blank disk in drive 2 and press RETURN. The volume name "/Caldat" will appear for the new volume name. Press RETURN to accept this as the new volume name for the blank disk. The program will format the blank disk and proceed to copy the contents from the /Caldat master disk to the blank disk. When the program is finished remove the disks and reboot the system with the porosimeter programs disk or initialize more disks. It is a wise idea to have a number of initialized data disks available.
CALIBRATING TEMPERATURE CONTROL

As described in the interface box section, the temperature of the bath is controlled by sending a number from 0 to 255 representing 7 and -33 °C respectively. The interface converts the number to a voltage level that is sent to the bath. To set the proper voltage levels the adjustment of two trim pots in the interface box will be necessary to send the appropriate maximum and minimum numbers.

The program used to calibrate the temperature control circuit isn't an option on the Main Menu. To run the program exit the menu and type "RUN I.O.CARD.TEST,D1". This program will allow the user to send a number from the parallel interface card to the interface box. The program will prompt the user to enter the port, enter 1 for port 1. Then enter the letter 0 for output on port 1. Only port 1 needs to be addressed as this is the port used to send the data to the interface box, so type a number 0 to begin the calibration.

The user will now need to remove the cover of the interface box to expose the trim pots that will be adjusted.

Turn the cooling bath on (the compressor doesn't need to be running) and place the external temperature preset switch (see cooling bath section)
to the ON position. By pressing the temperature set button on the front of the bath (and holding it in), the temperature the control circuit is sending in will be shown on the bath's display.

To set the trim pots, alternate between sending a 0 and a 255 to the temperature control circuit and adjusting the appropriate trim pot so that the correct temperature will be displayed on the bath. Enter 1/0 into the computer for port 1 with a 0 output. Then adjust the 100 Ω trim pot (High Temp Set) until 7°C is shown on the display. Now enter 1/255 and adjust the 10 kΩ trim pot (Low Temp Set) until -35°C is displayed. Repeat these steps until no adjustments to the trim pots need to be made.

Replace the cover on the interface box. To return to the Main Menu type "RUN STARTUP,DL" and the calibration is completed.
NEW THERMISTOR

New thermistors do not have the same temperature-resistance characteristics and individual thermistors themselves change over time. Therefore the calibration file may need to be updated occasionally. The thermistor circuit converts the variable resistance of the thermistor to a variable frequency square wave. The period of the square wave is then measured by the parallel interface card so that the program may read the period. The program converts the period back to temperature using the table of values in the Cal file.

The Cal file contains 22 period-temperature pairs. The controlling program reads a period and then searches the table. If the period is within the range of the table, the program linearly interpolates between the two closest points of the table to calculate the temperature of the sample. If the period is outside of the boundaries of the table, either the maximum temperature or minimum is assumed accordingly.

To find the 22 data points needed place a thermocouple and the thermistor in a test tube and immerse the tube in the cooling bath. The thermocouple is used to determine the temperature of the thermistor. Exit the Main Menu and type "RUN TEMP.PERIOD,D1" to load a program that will display the square wave's period. Two numbers will be shown on the screen, the top number is the current reading of the thermistor and the lower a moving average of 30 readings.

Turn the bath on and set the temperature at 7 °C. When the temperature of the thermocouple stabilizes record the temperature and the period of the thermistor's square wave shown on the screen. This is the first data pair. Continue changing the bath's temperature and making readings until you have taken 22 pairs. The readings should be spread over the range of 7 and -33°C with a higher concentration near zero where the temperature is critical in the data processing. Press the ESC key to exit the program.

The program Calibrate will automatically be loaded. As described in the software section, Calibrate allows you to view and edit the Cal file. Enter the new data points into the Cal file. Make sure to keep the order straight and put the highest temperature pair at the beginning of the file (point 1). The algorithms in the controlling program assume this order. When finished save the file and return to the Main Menu. The calibration is now completed.
SIMPLIFICATIONS

The conductance porosimeter system uses two parallel interface cards because the original system was designed to handle both conductance PTP and phase transition porosimetry. In phase transition porosimetry the height of mercury in a capillary tube is monitored using capacitance. The variable capacitance was converted to a variable frequency square wave by a circuit similar to the one used for the thermistor. Because the amount of capacitance is so small, the noise from the temperature circuit necessitated two separate interface boxes and separate parallel interface cards. Therefore the conductance system can be set up so that only one parallel interface is used.

There are some changes to the programs and to the wiring to convert to only one interface card. The Solomat data must now be channelled through the card in slot 1 along with the thermistor input and the temperature control output. In the controlling program, Controller, change A1, B1 and C1 in lines 2040-2057 to these new values:

```
2040  A1 = -16256 + ISLOT * 256 + 1: B1 = -16384 + ISLOT * 256
2050  A3 = A1 + 2: B3 = B1 + 2
2057  C1 = -16256 + ISLOT * 256 : C3 = C1 + 2
```

This changes the addresses the computer reads from the location in slot 4 to the card in slot 1. A1 is the location of port 1 and lines PA 0 - 7. It is used to send the digits 1 and 2 from the Solomat. Since the temperature control circuit uses port 1 of the card in slot 1 to send the control data to the temperature control circuit, A1 is also changed to port 3 and C1 (PC 0 or digit 5) is moved to port 4. The power line (+ 5V) remains with port 1. The +12 V line is not used and therefore eliminated. The computer connector for the interface box doesn't change but the new connector for the Solomat is as shown on the next page.
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CONTROLLER
PLOTTER HP PLOTTER
CONVERT XY
DERIVATIVE XY
INTEGRATE XDYDX
CONVERT VP
CONVERT R
DERIVATIVE VP
DERIVATIVE LVP
SURFACE AREA
TEST FORMAT
TEMP MEASUREMENT
CALIBRATE
MAIN MENU

100 REM  **********************************************************************
110 REM  * MAIN MENU FOR COND CALC  *
120 REM  * DOES ALL OF THE CALCULATIONS IN ORDER  *
130 REM  * BASED ON THE INPUT PARAMETERS SET HERE  *
140 REM  **********************************************************************
150 D$ = CHR$(4): SPEED= 255: PRINT D$"PR#3"
160 SR$ = "Y": CR$ = "144.3": M1$ = "7": S1$ = "N"
170 S2$ = "N": S3$ = "N": K$ = "Y": M2$ = "3": C$(1) = "C": C$(0) = "W"
172 M3$ = "3"
175 TO$ = "273.15"
180 GOSUB 3000: REM PRINT MENU OUT
190 VTAB 21: INPUT "Enter your menu choice ":; MN$
200 IF MN$ = "" THEN 190
210 IF LEN (MN$) > 1 THEN 190
220 IF ASC (MN$) > 56 OR ASC (MN$) < 49 THEN 250
230 ON ASC (MN$) - 48 GOSUB 400,700,850,1000,1100,1200,1300,1362
240 GOTO 190
250 IF ASC (MN$) < 65 OR ASC (MN$) > 68 THEN 190
260 ON ASC (MN$) - 64 GOTO 1400,1700,1800,270
270 END
400 REM  **********************************************************************
410 REM  * ENTER THE FILENAME  *
420 REM  **********************************************************************
430 VTAB 4: POKE 36,40
440 INPUT "": FIL$
450 IF FIL$ < > "" THEN 520
460 POKE 34,4
470 HOME
480 ONERR GOTO 600
490 PRINT D$"CATALOG /RAWDAT"
495 POKE 216,0
500 TEXT
510 GOTO 430
520 ONERR GOTO 650
530 PRINT D$"OPEN "FIL$;"C,D2"
535 PRINT D$"READ "FIL$;"C"
537 INPUT Z
540 PRINT D$"CLOSE"
545 POKE 216,0
550 GOSUB 3000
560 RETURN
600 REM NOT RAWDAT DISK
610 PRINT "Please insert the RAWDAT disk and press any key ...."
620 GET KB$
630 GOSUB 490
640 GOTO 190
650 REM FILE NOT FOUND
655 PRINT D$"CLOSE"
660 VTAB 23
670 PRINT "File not found on drive 2..."
675 PRINT D$"DELETE "FIL$;"C"
680 GOSUB 430
690 GOTO 190
700 REM ****************************
710 REM * SET X,Y PARAMS   *
720 REM ****************************
730 VTAB 5: POKE 36,40
740 INPUT "";SR$
750 IF SR$ < > "Y" AND SR$ < > "N" THEN 730
760 IF SR$ = "N" THEN CR$ = "": GOSUB 3000: GOTO 800
770 VTAB 6: POKE 36,40
780 INPUT "";CR$
790 IF VAL (CR$) < = 0 THEN 770
800 RETURN
850 REM ****************************
860 REM * SET DERIVATIVE PARAMS  *
870 REM ****************************
880 VTAB 7: POKE 36,40
890 INPUT "";M1$
900 IF VAL (M1$) < 3 THEN 880
910 VTAB 8: POKE 36,40
920 INPUT "";S1$
930 IF S1$ < > "Y" AND S1$ < > "N" THEN 910
940 RETURN
1000 REM ****************************
1010 REM * SET X,Z PARAMS  *
1020 REM ****************************
1030 VTAB 9: POKE 36,40
1040 INPUT "";S2$
1050 IF S2$ < > "Y" AND S2$ < > "N" THEN 1030
1060 RETURN
1100 REM ****************************
1110 REM * SET X,VP PARAMS  *
1120 REM ****************************
1130 VTAB 10: POKE 36,40
1140 INPUT "";S3$
1150 IF S3$ < > "Y" AND S3$ < > "N" THEN 1130
1160 RETURN
1200 REM ****************************
1210 REM * SET R,VP PARAMS  *
1220 REM ****************************
1230 VTAB 11: POKE 36,40
1240 INPUT "";K$
1250 IF K$ < > "Y" AND K$ < > "N" THEN 1230
1260 VTAB 12: POKE 36,40
1270 INPUT "";TO$
MAIN MENU

1280  RETURN
1300  REM  ****************************************************************************************************
1310  REM  *  SET R.DVPDR PARAMS  *
1320  REM  ****************************************************************************************************
1330  VTAB 13: POKE 36,40
1340  INPUT "";M2$
1350  IF VAL (M2$) < 3 THEN 1330
1360  RETURN
1362  REM  ****************************************************************************************************
1365  REM  *  SET R.DVPDLR PARAMS  *
1370  REM  ****************************************************************************************************
1375  VTAB 14: POKE 36,40
1380  INPUT "";M3$
1385  IF VAL (M3$) < 3 THEN 1375
1390  RETURN
1400  REM  ****************************************************************************************************
1410  REM  *  RUN CALCULATIONS  *
1420  REM  ****************************************************************************************************
1422  IF FIL$ = "" THEN 190
1424  HOME
1428  PRINT "Performing the calculations..."
1430  REM CALL T.C.TO.X.Y
1440  CR = VAL (CR$)
1450  PRINT D$"CHAIN /CONPROG1/PROGRAMS/T.C.TO.X.Y"
1460  REM CALL DER.X.Y
1470  MA = VAL (M1$):SA = 1
1480  IF S1$ = "Y" THEN SA = 0
1490  PRINT D$"CHAIN /CONPROG1/PROGRAMS/DER.X.Y"
1500  REM CALL INT
1510  SA = 1
1520  IF S2$ = "Y" THEN SA = 0
1530  PRINT D$"CHAIN /CONPROG1/PROGRAMS/INT"
1540  REM CALL X.VP.FROM.X.Z
1550  SA = 1
1560  IF S3$ = "Y" THEN SA = 0
1570  PRINT D$"CHAIN /CONPROG1/PROGRAMS/X.VP.FROM.X.Z"
1580  REM CALL R.VP.FROM.X.VP
1590  PRINT D$"CHAIN /CONPROG1/PROGRAMS/R.VP.FROM.X.VP"
1600  REM 'CALL DER.R.VP
1610  MA = VAL (M2$)
1620  PRINT D$"CHAIN /CONPROG1/PROGRAMS/DER.R.VP"
1625  MA = VAL (M3$)
1630  PRINT D$"CHAIN /CONPROG1/PROGRAMS/DER.LR.VP"
1700  REM  ****************************************************************************************************
1710  REM  *  CALL PLOT  *
1720  REM  ****************************************************************************************************
1730  PRINT D$"RUN /CONPROG1/PROGRAMS/R"
1800  REM  ****************************************************************************************************
MAIN MENU

1810 REM * RUN CONDUCTANCE TEST
1820 REM ***********************************************************************
1830 PRINT D$"RUN COND2,D1"
3000 REM ***********************************************************************
3010 REM * PRINT OUT THE MENU
3020 REM ***********************************************************************
3030 HOME : PRINT
3040 HTAB 32: PRINT "CONDUCTANCE MENU"
3050 PRINT
3060 PRINT "1. Base Filename : ";FIL$ 
3070 PRINT "2. T.C to X.Y Series Resistor : ";SR$
3080 PRINT " Cond of Resistor : ";CR$
3090 PRINT "3. X.Y to X.DYDX Moving Average : ";M1$
3100 PRINT " Save File : ";S1$
3110 PRINT "4. X.DYDX to X.Z Save File : ";S2$
3120 PRINT "5. X.Z to X.VP Save File : ";S3$
3130 PRINT "6. X.VP to R.VP Thin File Out : ";K$
3135 PRINT " Temp of TO : ";TO$
3140 PRINT "7. R.VP to R.DVPDR Moving Average : ";M2$
3150 PRINT "8. R.VP to R.DVPDLR Moving Average : ";M3$
3155 PRINT : PRINT
3160 PRINT " A. Calculate the data"
3170 PRINT " B. Plot data"
3180 PRINT " C. Run Conductance test"
3185 PRINT " D. Exit to system"
3190 RETURN
CONTROLLER

10 REM CONDUCTANCE CONTROLLER FOR ONE SAMPLE
11 REM MODIFIED TO ONE SAMPLE ON 2 OCT 86
12 HOME
15 D$ = CHR$(4)
18 HIMEM: 256 * PEEK(116) + PEEK(115) - 1024
20 PRINT D$"BLOAD CAP.RES.2, A$340, D1"
30 PRINT D$"BLOAD IO.CLOCK.SLOT1, A$9800"
45 POKE 1535, 0
50 POKE 1407, 0
55 POKE 1279, 0
60 CALL -26624
65 POKE 1919, 1:
REM DISPLAYTIME
70 GOTO 2000
100 POKE 824, 0:
CALL 832
110 IF PEEK(822) > 3 THEN 140
120 TV = PEEK(823): IF TV > 255 THEN POKE 823, TV + 1:
GOTO 140
130 POKE 823, 0
140 R = 65536 - (PEEK(823) * 256 + PEEK(822))
150 R = R - 25000: IF R < 0 THEN R = R + 40536
160 RR = RR + R - AR(SR): AR(SR) = R: IF MR > SR THEN SR = SR + 1:
GOTO 180
170 SR = 1
180 TEMP = INT(RR / MR + .5)
182 IF TEMP > P(NMPT) THEN TEMP = P(NMPT)
184 IF TEMP < P(1) THEN TEMP = P(1)
186 IF (TEMP < P(TI)) AND (TI > 1) THEN TI = TI - 1:
GOTO 186
188 IF (TEMP > P(TI + 1)) AND (TI < NMPT - 1) THEN TI = TI + 1:
GOTO 188
190 TEMP = INT(((TEMP - P(TI)) * (T(TI + 1) - T(TI)) / (P(TI + 1) -
P(TI)) + T(TI)) * 1E3 + .5) / 1E3
192 VTAB 6: HTAB 30
194 PRINT " \t; HTAB 30
196 PRINT TEMP;
200 OSEC = PEEK(1279) + 60 * PEEK(1407) + 3600 * PEEK(1535)
210 RETURN
300 REM SWITCH LEADS AND READS CONDUCTANCE
310 PO = (PO - INT(PO / 2) * 2) + INT(PO / 4) * 4
320 POKE C1, PO
340 CX = PEEK(C1): CY = PEEK(B1): CZ = PEEK(A1)
350 CX = (CX - INT(CX / 2) * 2) * 10000
360 CY = (CY - INT(CY / 16) * 6) * 100
370 CZ = CZ - INT(CZ / 16) * 6
380 CND = CX + CY + CZ
390 RETURN
400 REM CALCULATE TEMP CONTROL INFO
410 OT = INT((M1 * S9 + B) + .5)
420 PT = INT((M1 * F9 + B) + .5)
430 TS = 60 * (ABS(F9 - S9) / (RA(TC(CCYCLE)) / 60)) / ABS(OT - PT)
440 SD = SGN(S9 - F9)
450 U6 = OSEC
EXPECTED SIGNIFICANCE OF THE PROJECT

It is expected that the proposed project will lead (1) to understanding the fundamental processes involved in the freezing of pore water in concrete, and on the basis of this, (2) to establishing criteria for assessing the frost susceptibility of concrete and thus to developing a simple and reliable testing method for predicting its performance in the field without resorting to tedious freeze-thaw cycles.


REFERENCES


structure on repeated freezing and thawing will be examined systematically in relation to the magnitude of the characteristic volume change on freezing.

The rate of water uptake of all samples will also be determined when they are immersed at a constant temperature. The time required to bring each sample to the corresponding characteristic (critical or mid-range) saturation will be noted. A frost susceptibility index may then be assigned to each sample, for instance, by dividing the measured characteristic volume change per unit volume of sample by the saturation time determined. Then the discriminating ability of the index will be evaluated.

The research plan also includes collaboration with the Iowa Department of Transportation to take samples from concrete pavements with good performance records, which therefore justifies the assumption that they have not suffered significant structural changes since their placement. These samples will be tested to determine their frost susceptibility index as described above. These numerical results will be compared with similar results previously obtained with the lab-made samples to make a final judgment on how well the proposed index indicates field performance.
pore water freezes in one step irrespective of the degree of saturation and will leave some liquid in these pores.

To achieve Purpose (2), we will determine the characteristic volume change per unit volume of each sample at critical saturation, if any, or else at mid-saturation range (i.e., mean of threshold saturation and 100%) in the case of the existence of a threshold saturation.

In a research project in progress [3], we have recently observed by electrical conductance measurements that a consistent and progressive shift in pore structure of concrete upon freezing and thawing at near-saturation is characteristic for its frost susceptibility. Therefore, the duplicate of each sample will be subjected to freeze-thaw cycles at critical saturation, or at mid-range saturation as the case may be. Then they will be subjected both to Phase Transition Porosimetry [2,4,5,7], developed in this laboratory to establish its pore structure and size distribution, as well as to mercury porosimetry. The former method comprises saturating the sample completely by applying vacuum or by boiling in water under reduced pressure and then measuring the volume changes by a dilatometer as a function of temperature while the sample is gradually frozen and thawed. This method is capable of providing pore-body-size and pore-neck-size distributions. If needed, scanning electron microscopy will also be used. An original triplicate sample will also be analyzed for pore-size distribution by these methods. This sample will serve as a control sample to establish structural changes caused by freeze-thaw cycles. The shifts in pore
intermediate strength but not indicative of the performance of high-
strength concretes as mentioned in the Introduction.

3. PROPOSED WORK

The proposed work has a dual purpose:

(1) To investigate the applicability of the two-stage model put
    forward above for the mechanism of freezing in concrete in
    near-saturated states. We would use dilatometric measurements
    in this investigation.

(2) To investigate the possibility of correlating the measured
    volume increase that accompanies bulk-ice-induced freezing
    in near-saturated states to frost susceptibility of concrete.
    Ultimately we hope to devise a laboratory testing method to
    predict the performance of concrete in the field more reliably
    than do the existing methods and to do so without resorting
    to tedious freeze-thaw cycles.

To achieve Purpose (1), we will prepare plain and air-entrained
mortar samples with various water/cement ratios but with other composi-
tional variables kept the same. These samples will be subjected to
dilatometric measurements during freezing at a specified temperature
and at various levels of saturation. If the plots of volume change
versus saturation are of the type shown in Fig. 5 (signifying critical
saturations), then the model is verified. However, if the plots
indicate a threshold saturation rather than a critical saturation, as
shown in Fig. 5 by the dotted line (a), it will mean that the freezable
that nature), but would not fall strikingly below it. (The line cor-
responding to this is also indicated in Fig. 5 by (a). In other words,
the Powers model based on one-stage freezing cannot explain the observed
abruptness in frost resistance, as does the two-stage freezing model
presently put forward.

The magnitude of volume change upon freezing a unit volume of the
sample at a critical saturation and at a temperature compatible with
the climatic conditions in the field is expected to be indicative of
the frost susceptibility of a sample at this saturation. Another factor
that should determine its performance in the field is the tendency of
concrete to acquire this critical saturation under the prevalent satu-
rating conditions. For instance, the rate with which an air-dried
sample of a standard shape and size takes up water to reach critical
saturation in an immersed state may be used as such a factor. An
appropriate combination of the volume change and the rate of saturation
may characterize the overall frost susceptibility in the field.

In as much as the entrained air spacing factor is important in
protecting concrete from mild internal frost stresses below critical
saturation, air entrainment in general is probably effective in protect-
ing concrete from severe frost stresses at or above critical saturation.
The reason is that incorporating air voids much larger than already
existing capillary voids in concrete may retard its saturation and
thus prevent it from reaching the critical saturation level and from
being exposed to severe frost stresses. This may explain why the
spacing factor is critical for the performance of concretes of
Fig. 5. Influence of saturation of concrete on its resistance to frost (Adapted from Ref. 10).
1. INTRODUCTION

Damage caused to concrete structures by the action of frost is one of the greatest concerns in civil and construction engineering practice in temperate climates. That frost damage to concrete is related to its pore structure is well known. During the past four decades a considerable amount of outstanding research has been done and much progress has been made on elucidating the mechanism of frost action in concrete.

Since the 1940s, air entrainment has been used to affect the pore structure of concrete and to render it nonsusceptible to frost damage. Although using air entrainment has proved effective, it has not prevented frost damage in some cases. The Powers theory [12,13] has been most successful in explaining the role of entrained air. In accordance with this theory, the use of the average spacing between air bubbles has been put forward [1] to characterize frost resistance. In general, the correlation is satisfactory for spacing factors less than 0.008 in. For larger spacing factors, however, the correlation breaks down as in the case of concretes of super low ratios of water to cement [11].

The Powers model of frost damage is valid as long as concrete is far from the state of saturation. In near-saturated states greater stresses, however, are developed within the structure than in the Powers model (see Section 2.2). Therefore, the question is whether air entrainment minimizes the frost damage by reducing the internal frost stresses as in this model or by protecting concrete from severe
The objective of the proposed work is to present a basic understanding of the freezing mechanism of pore water and on the basis of this understanding to establish criteria for assessing the freeze-thaw durability of concrete. Two mechanisms appear to control the freezing of pore water, namely, in situ nucleation and bulk-ice-initiated freezing. The first mechanism operates at low levels of saturation whereas the second controls the freezing process at high levels of saturation. The operation of the two mechanisms are reflected in the volumetric expansion of concrete upon freezing as a function of the degree of saturation. The damage to concrete depends on the internal cyclic stresses developed during freezing and thawing because of flow of water or ice.

The proposed work consists of a systematic study of the shifts in pore structure and expansion of the sample upon freezing as well as the rate of saturation of samples from the laboratory and the field to establish a correlation between these variables and the freeze-thaw durability of concrete.
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APPENDIX D

Frost susceptibility of concrete in near-saturated states

NSF project proposal
CALIBRATE

4050 PRINT "You must have a filename to save data.";
4060 GET KB$
4070 GOSUB 1300
4080 GOSUB 1900
4090 GOTO 530
4200 REM ************************************************************
4210 REM * ESCAPE SO EXIT OR NOT  *
4220 REM ************************************************************
4230 POKE 34,23: POKE 35,24
4240 HOME
4250 PRINT "This will leave the data unchanged. Continue (Y/N Default = N).";
4260 GET KB$
4270 IF KB$ = "Y" THEN 9000
4280 GOSUB 1300
4290 GOSUB 1900
4300 GOTO 530
9000 REM WE GONE BYE BYE
9010 PRINT D$"RUN STARTUP,D1"
CALIBRATE

3080 IF X = 2 THEN Y(N + Y - 5) = VAL (KB$)
3090 GOSUB 1900: REM RESET CURSOR
3100 PRINT VAL (KB$); " ";
3110 IF X = 1 THEN X = 2: GOTO 3140
3120 IF (Y - 5) + N < NMPT THEN Y = Y + 1: X = 1
3130 IF Y > 23 THEN N = N + 1: GOSUB 1700
3140 GOSUB 1900
3150 GOTO 530
3200 REM ****************************
3210 REM * LEFT ARROW *
3220 REM ****************************
3230 IF X = 2 THEN X = 1: GOSUB 1900
3240 GOTO 530
3300 REM ****************************
3310 REM * RIGHT ARROW *
3320 REM ****************************
3330 IF X = 1 THEN X = 2: GOSUB 1900
3340 GOTO 530
3400 REM ****************************
3410 REM * DOWN ARROW *
3420 REM ****************************
3430 IF (Y - 5) + N < NMPT THEN Y = Y + 1
3440 IF Y > 23 THEN N = N + 1: Y = 23: GOSUB 1700
3450 GOSUB 1900
3460 GOTO 530
3500 REM ****************************
3510 REM * UP ARROW *
3520 REM ****************************
3530 IF Y = 5 AND N < 1 THEN N = N - 1: GOSUB 1500: GOTO 3560
3540 IF Y < 5 THEN Y = Y - 1
3550 GOSUB 1900
3560 GOTO 530
3600 REM ****************************
3610 REM * CONTROL-S SAVE DATA *
3620 REM ****************************
3625 IF FIL$ = "" THEN 4000
3630 POKE 34,23: POKE 35,24
3640 HOME
3650 PRINT "Saving "; FIL$; " ...";
3660 GOSUB 2300
3670 POKE 34,0
3680 CLEAR
3690 GOTO 9000
4000 REM ****************************
4010 REM * TRIED TO SAVE WITHOUT A FILE NAME *
4020 REM ****************************
4030 POKE 34,23: POKE 35,24
4040 HOME
CALIBRATE

1950 IF X = 2 THEN POKE 36,45
1960 RETURN
2000 REM *****************************************************************************
2010 REM  * RETRIEVE FILE  *
2020 REM *****************************************************************************
2030 PRINT D$"OPEN "FIL$",D1"
2040 PRINT D$"READ FILE$
2050 INPUT NMPT
2060 DIM X(NMPT),Y(NMPT)
2065 IF CO = 1 THEN 2080
2070 INPUT XA$
2072 IF XA$ = "" THEN INPUT XA$
2075 INPUT YA$
2077 IF YA$ = "" THEN INPUT YA$
2080 FOR I = 1 TO NMPT
2090 INPUT X(I),Y(I)
2100 NEXT I
2110 PRINT D$"CLOSE"
2120 RETURN
2300 REM *****************************************************************************
2310 REM  * SAVE FILE  *
2320 REM *****************************************************************************
2330 PRINT D$"OPEN "FIL$",D1"
2340 PRINT D$"WRITE FIL$
2350 PRINT NMPT
2352 IF CO = 1 THEN 2370
2355 IF XA$ = "" THEN XA$ = "none"
2357 IF YA$ = "" THEN YA$ = "none"
2360 PRINT XA$: PRINT YA$
2370 FOR I = 1 TO NMPT
2380 PRINT X(I): PRINT Y(I)
2390 NEXT I
2400 PRINT D$"CLOSE"
2410 RETURN
3000 REM *****************************************************************************
3010 REM  * ENTER THE DATA INTO ARRAY  *
3020 REM  *****************************************************************************
3025 PRINT KB$;
3030 GET IN$
3040 IF (IN$ > = "0" AND IN$ < = "9") OR IN$ = "," OR IN$ = "-" OR IN$ = "E" THEN KB$ = KB$ + IN$: PRINT IN$: GOTO 3030
3042 IF ASC (IN$) = 8 AND LEN (KB$) = 1 THEN KB$ = ": PRINT CHR$ (8):"
3044 IF ASC (IN$) = 8 AND LEN (KB$) > 1 THEN KB$ = LEFT$ (KB$, LEN (KB$) -1): PRINT CHR$ (8):": PRINT CHR$ (8):
3050 IF ASC (IN$) = 13 THEN 3070
3060 GOTO 3030
3070 IF X = 1 THEN X(N + Y - 5) = VAL (KB$)
CALIBRATE

1020 REM ******************************************************************************
1030 POKE 34,0: REM SET TOP TO LINE 0
1040 POKE 35,4: REM SET BOTTOM TO LINE 3
1050 HOME
1060 PRINT "Filename : "; HTAB 40: PRINT ".# of points : 
1070 PRINT "X-Axis Label : "
1080 PRINT "Y-Axis Label : "
1090 PRINT "Point "; TAB(30);"X";: POKE 36,50: PRINT "Y";
1100 POKE 34,4: POKE 35,23
1110 RETURN
1130 REM ******************************************************************************
1151 REM * PRINTS BOTTOM LINE *
1132 REM ******************************************************************************
1133 POKE 34,23: POKE 35,24
1134 HOME
1135 PRINT "Control-S to Save Control-Q to Exit";
1136 POKE 34,4: POKE 35,23
1137 RETURN
11350 REM ******************************************************************************
11510 REM * DISPLAY A PAGE OF DATA (19 LINES) *
11520 REM * N = THE DATA NUMBER TO START FROM *
11530 REM ******************************************************************************
11540 HOME
11550 FOR I = N TO N + 18
11560 IF I > NMPT THEN 1590
11570 PRINT TAB(3);I; TAB(25);X(I);: POKE 36,45: PRINT Y(I);
11580 IF I < > N + 18 THEN PRINT
11590 NEXT I
11600 X = 1: Y = 5
11610 GOSUB 1900
11620 RETURN
11700 REM ******************************************************************************
11710 REM * SCROLL UP ONE LINE *
11720 REM ******************************************************************************
11725 IF N + 18 > NMPT THEN 1800
11730 VTAB 23: POKE 36,78
11735 PRINT
11740 I = N + 18
11750 IF I > NMPT THEN 1780
11760 PRINT TAB(3);I; TAB(25);X(I);: POKE 36,45: PRINT Y(I);
11780 X = 1: Y = 23
11790 GOSUB 1900
11800 RETURN
11900 REM ******************************************************************************
11910 REM * MOVE CURSOR TO APPROPRIATE X,Y POSITION *
11920 REM ******************************************************************************
11930 VTAB Y
11940 IF X = 1 THEN HTAB 25
CALIBRATE

100 REM ***************************************************************
110 REM * DATA ENTRY PROGRAM  * 
120 REM ***************************************************************
125 D$ = CHR$ (4)
130 CO = 1
140 REM RETRIEVE AND DISPLAY FILE
150 HOME : GOSUB 1000
160 POKE 34,0
170 VTAB 1: HTAB 12
180 FILE$ = "CAL": PRINT "CAL"
190 VTAB 1: HTAB 40: PRINT "# of points : ";
200 GOSUB 2000
205 N = 1
210 VTAB 1: POKE 36,55: PRINT NMPT
220 VTAB 2: HTAB 16: PRINT XA$
230 VTAB 3: HTAB 16: PRINT YA$
240 GOSUB 1300
245 N = 1
250 GOSUB 1500
260 X = 1: Y = 5
270 GOSUB 1900
280 GOTO 500
290 REM INPUT NEW FILE
300 HOME : GOSUB 1000
310 POKE 34,0
320 VTAB 1: POKE 36,55
330 INPUT ""; NMPT
340 DIM X(NMPT), Y(NMPT)
350 POKE 34,4
360 N = 1
370 GOSUB 1500
380 GOSUB 1300
390 X = 1: Y = 5
400 GOSUB 1900
410 REM ***************************************************************
420 REM * MAIN CONTROLLER FOR EDITING AND ENTRY  * 
430 REM ***************************************************************
440 GET KB$
450 IF (KB$ > = "0" AND KB$ < = "9") OR KB$ = "." OR KB$ = "-" THEN 3000
460 IF ASC (KB$) = 8 THEN 3200: REM LEFT ARROW
470 IF ASC (KB$) = 21 OR ASC (KB$) = 32 THEN 3300: REM RIGHT ARROW
480 IF ASC (KB$) = 10 THEN 3400: REM DOWN ARROW
490 IF ASC (KB$) = 11 THEN 3500: REM UP ARROW
500 IF ASC (KB$) = 19 THEN 3600: REM CONTROL S
510 IF ASC (KB$) = 17 THEN 4200: REM CONTROL Q
520 GOTO 530
530 REM ***************************************************************
540 REM * DISPLAY HEADINGS  *
TEMP MEASUREMENT

VARIABLES

C100    BASE ADDRESS FOR I/O CARD
C100    OUTPUT REGISTER B
C101    OUTPUT REGISTER A
C104    TIMER 1, LATCH LOW
C105    TIMER 1, COUNTER HIGH
C108    TIMER 2, LATCH LOW
C109    TIMER 2, COUNTER HIGH
C10B    AUXILIARY CONTROL REGISTER
C10C    PERIPHERAL CONTROL REGISTER
C10D    INTERRUPT FLAG REGISTER

PROGRAM

0340  A2 70  LDX #$70
0342  8E A2 70  STX $70A2  CA1 POSITIVE ACTIVE EDGE
0345  8E 0C C1  STX $C10C  CB1 NEGATIVE ACTIVE EDGE
0348  A0 00  LDY #$00
034A  8C OB C1  STY #C10B  T2 TIMED INTERRUPTS
034D  A9 02  LDA #$02  SWITCHING MASK
034F  AC 38 03  LDY $0338
0352  F0 02  BEQ $0356  IF EQUAL THEN DON'T SWITCH
0354  A9 10  LDA #$10  MASK
0356  A0 FF  LDY #$FF
0358  8C OD C1  STY $C10D  CLEAR INTERRUPT FLAGS
035B  2C OD C1  BIT $C10D  FIRST ACTIVE EDGE?
035E  F0 FB  BEQ $0358  NO, THEN CONTINUE POLLING
0360  8C 08 C1  STY $C108
0363  8C 09 C1  STY $C109  START COUNTING PERIOD
0366  8C OD C1  STY $C10D  CLEAR INTERRUPT FLAGS
0369  2C OD C1  BIT $C10D  SECOND ACTIVE EDGE?
036C  F0 FB  BEQ $0369  NO, THEN CONTINUE POLLING
036E  AC 08 C1  LDY $C108  GET LOW BYTE OF PERIOD
0371  AE 09 C1  LDX $C109  GET MID BYTE OF PERIOD
0374  8C 36 03  STY $0336  STORE PERIOD
0377  8E 37 03  STX $0337  STORE PERIOD
037A  60  RTS  RETURN TO PROGRAM
600 PRINT N1$
610 PRINT N2$
620 PRINT N3$
630 PRINT N4$
640 VTAB 23: HTAB 10
650 PRINT "1. Plot Out to HP"
655 VTAB 23: POKE 36,40
660 PRINT "2. Quit"
670 INPUT "Enter menu choice (1-2) : ";TMP$
680 IF TMP$ > "2" OR TMP$ < "1" THEN 510
700 IF TMP$ = "1" THEN RETURN
710 PRINT "DONE"
720 END
1000 REM *********************************************
1010 REM * PLOT OUT TO PLOTTER *
1020 REM *********************************************
1030 REM INIT HP
1035 C$ = CHR$(3)
1040 PRINT D$"PR#2"
1050 PRINT CHR$(27)."IN;"
1060 PRINT "IN;"
1070 PRINT CHR$(27)."140;0;17;"
1075 PRINT CHR$(27)."N;19;"
1080 PRINT "SP1;SI.4,.6;"
1090 PRINT "DI1,0;VS20;"
1095 PRINT "PA"5150 - LEN (F$) / 2 * 240,"6500;LB";F$;C$
1096 PRINT "SI.2,.3;"
1100 PRINT "PA1000,5650;"
1110 PRINT "LBCycle Type Top Temp Bottom Temp Rate Sample Interval";C$
1120 PRINT "PA1000,5450;PD;PA9280,5450;PU;"
1130 FOR X = 1 TO CT
1140 PRINT "PA1600","5450 - 200 * X;";LB”;X;C$
1150 PRINT "PA3400","5450 - 200 * X;";LB”;TP(X);C$
1160 PRINT "PA5080","5450 - 200 * X;";LB”;BTM(X);C$
1170 PRINT "PA6520","5450 - 200 * X;";LB”;RTE(X);C$
1180 PRINT "PA8440","5450 - 200 * X;";LB”;IT(X);C$
1182 NEXT X
1183 PRINT "PA1000,4250;PD;PA9280,4250;PU;"
1184 PRINT "PA1000,4050;"
1185 PRINT "LBCycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle 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10 REM READ DATA ON SAMPLE AND PLOT OUT
15 DS = CHR$(4)
20 HOME: VTAB 5
30 PRINT "Insert a /RAWDAT disk in drive 2 and hit a key...";
40 GET TMP$
50 PRINT DS"CATALOG",D2"
60 PRINT : INPUT "Enter new file name : ";F$
70 IF F$ = "" THEN 60
80 GOSUB 200: REM READ IN DATA
90 GOSUB 500: REM PRINT TO SCREEN
100 GOSUB 1000: REM PLOT OUT
110 GOTO 90
200 PRINT DS"OPEN ";F$;",D2"
210 PRINT DS"READ ";F$
215 INPUT SCYCLE
220 INPUT CT
230 FOR X = 1 TO CT
240 INPUT TP(X),BTTM(X),RT$(X),IT(X),TD$(X)
245 IF TD$(X) = "N" THEN IT(X) = 0
250 NEXT X
251 INPUT MCYCLE
253 DIM TC(MCYCLE)
254 FOR X = 1 TO MCYCLE
256 INPUT TC(X)
258 NEXT X
260 INPUT N1$,N2$,N3$,N4$
270 PRINT DS"CLOSE ";F$
280 RETURN
500 REM PRINT TO SCREEN
510 HOME: VTAB 2
520 HTAB INT (LEN (F$) / 2)
530 PRINT F$
540 VTAB 4
550 PRINT "Cycle Type": POKE 36,15: PRINT "Top Temp": POKE 36,30:
PRINT "Bottom Temp": POKE 36,45: PRINT "Rate": POKE 36,55:
PRINT "Sample Interval"
560 FOR X = 1 TO CT
570 PRINT TAB(5);X;: POKE 36,20: PRINT TP(X);: POKE 36,34:
PRINT BTTM(X);: POKE 36,46: PRINT RT$(X);: POKE 36,62: PRINT IT(X)
572 NEXT X
574 VTAB 9: PRINT "Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type Cycle Type"
576 FOR Y = 0 TO MCYCLE - 1
578 X = 2 + INT (Y / 8) * 11
580 VTAB 10 + (Y - INT (Y / 8) * 8): POKE 36,X
582 PRINT Y + SCYCLE;: POKE 36,X + 6: PRINT TC(Y + 1)
584 NEXT Y
590 VTAB 18: PRINT "NOTES : "
SURFACE AREA

100 REM  ********************************************************************
110 REM  * PROGRAM TO CALCULATE SURFACE AREA  *
120 REM  ********************************************************************
125 D$ = CHR$ (4)
130 PRINT "Calculating the surface area..."
135 IF DT = 0 THEN GOSUB 2000
140 A = 0
150 FOR L = 2 TO NMPTS(0)
155 IF A(0,L) < = 12 THEN 170
160 A = A + (1 / A(0,L - 1) - 1 / A(0,L)) * (PV * B(0,L - 1)) * - 1E4
170 NEXT L
210 A = INT (A * 2.5 * 1E4) / 1E4
220 PRINT "Surface Area = ";A
230 PRINT : PRINT
260 END
2000 REM  ********************************************************************
2010 REM  * FILE LOADER  *
2020 REM  ********************************************************************
2030 INPUT "Base Filename : ";FILS
2040 IF FILS = "" THEN PRINT D$"CATALOG /CALDAT/R.VP/": GOTO 2000
2050 PRINT D$"OPEN /CALDAT/R.VP/";FILS;",D2"
2060 PRINT D$"READ /CALDAT/R.VP/";FILS
2070 INPUT NMPTS(0)
2080 DIM A(1,NMPTS(0)),B(1,NMPTS(0))
2090 FOR I = 1 TO NMPTS(0)
2100 INPUT A(0,I),B(0,I)
2110 NEXT I
2120 PRINT D$"CLOSE"
2130 INPUT "Pore volume of Sample : ";PV$
2140 PV = VAL (PV$)
2150 RETURN
2160 INPUT DIL$,CO$,DT$
2165 INPUT MA$,N1$,N2$
2170 PRINT D$"CLOSE"
2180 RETURN
DERIVATIVE LVP

820 OT = TS:OV = VS
830 NEXT I
835 NMPTS(K) = NMPTS(K) - 1
850 PRINT D$"OPEN /CALDAT/R.DVPDLR/"FIL$;C$(K)
860 PRINT D$"WRITE /CALDAT/R.DVPDLR/"FIL$;C$(K)
870 PRINT NMPTS(K)
880 FOR L = 1 TO NMPTS(K)
885 A(K,L) = 10 @ A(K,L)
890 PRINT A(K,L): PRINT B(K,L)
900 NEXT L
910 PRINT D$"CLOSE"
920 NEXT K
925 FOR T = 1 TO 5: PRINT CHR$ (7): NEXT T
930 PRINT D$"CHAIN STARTUP,@180,D1"
1000 REM ********************
1010 REM * TO LOG R *
1020 REM ********************
1025 LT = LOG (10)
1030 FOR K = 0 TO 1
1040 FOR L = 1 TO NMPTS(K)
1050 A(K,L) = LOG (A(K,L)) / LT
1060 NEXT L
1070 NEXT K
1080 RETURN
DERIVATIVE LVP

100 REM *****************************************
110 REM * THIS PROGRAM CALCULATES THE DERIVATIVE OF *
120 REM * THE PORE VOLUME W/RESPECT THE LOG OF THE *
130 REM * PORE RADIUS *
140 REM *****************************************
150 GOSUB 1000
160 PRINT "Converting R.VP to R.DVPDLR"
440 FOR K = 0 TO 1
445 FL = 0
446 FOR S = 1 TO MA: T1(S) = 0: V1(S) = 0: NEXT S
450 FOR S = 1 TO MA - 1: T1(S) = A(K,S): V1(S) = B(K,S)
460 NEXT S
465 PO = 0: PI = MA - 1
470 FOR I = INT (MA / 2 + 1) TO MA - 1: T = 0: V = 0
480 FOR J = 1 TO I: T = T + T1(J): V = V + V1(J): NEXT J
490 TS = T / I
500 VS = V / I
510 IF NOT FL THEN FL = 1: GOTO 570
520 DVDT = INT ((VS - OV) / (TS - OT) * 1E5 + .5) / 1E5
530 WT = INT ((TS + OT) / 2 * 1E3 + .5) / 1E3
540 FL = FL + 1
550 PO = PO + 1
560 A(K,PO) = WT: B(K,PO) = DVDT: IF FL = 2 THEN PO = PO + 1: A(K,PO) =
570 OT = TS: OV = VS
580 NEXT I
590 FOR I = 1 TO NMPTS(K) - MA + I
600 PI = PI + 1: TE = A(K,PI): VO = B(K,PI)
610 IF I > NMPTS(K) - 2 * MA + 2 THEN Z = I - NMPTS(K) + 2 * MA - 1: T2(Z) =
620 TE: V2(Z) = VO
630 T = T + TE - T1(S): T1(S) = TE
640 S = S + 1: IF MA < S THEN S = 1
650 TS = T / MA
660 VS = V / MA
680 IF TS = OT THEN DVDT = 00: GOTO 700
690 DVDT = INT ((VS - OV) / (TS - OT) * 1E5 + .5) / 1E5:00 = DVDT
700 WT = INT ((TS + OT) / 2 * 1E3 + .5) / 1E3
710 PO = PO + 1: A(K,PO) = WT: B(K,PO) = DVDT
720 OT = TS: OV = VS
730 NEXT I
740 FOR I = 2 TO INT (MA / 2 + 1): T = 0: V = 0
750 FOR J = I TO MA: T = T + T2(J): V = V + V2(J): NEXT J
760 TS = T / (J - I)
770 VS = V / (J - I)
790 DVDT = INT ((VS - OV) / (TS - OT) * 1E5 + .5) / 1E5
800 WT = INT ((TS + OT) / 2 * 1E3 + .5) / 1E3
810 PO = PO + 1: A(K,PO) = WT: B(K,PO) = DVDT
PRINT DS"CHAIN STARTUP;61630;DI"
920 NEXT I
940 PRINT DS"CLOSE"
830 NEXT I
820 VL = 15.07
810 PRINT VT: PRINT DVT

DERIVATIVE XP
DERIVATIVE VP

100 REM ****************************
110 REM * THIS PROGRAM CALCULATES THE DERIVATIVE OF *
120 REM * OF THE PORE VOLUME WITH RESPECT TO *
130 REM * PORE RADIUS *
140 REM ****************************
160 PRINT "Converting R.VP to R.DVPDR"
360 DIM T1(MA),V1(MA),T2(MA),V2(MA)
440 FOR K = 0 TO 1
442 PRINT $OPEN /CALDAT/R.DVPDR/"FIL$;C$(K)
443 PRINT $WRITE /CALDAT/R.DVPDR/"FIL$;C$(K)
444 PRINT NMPTS(K) - 1
445 FL = 0
446 FOR S = 1 TO MA:T1(S) = 0:V1(S) = 0: NEXT S
450 FOR S = 1 TO MA - 1:T1(S) = A(K,S):V1(S) = B(K,S)
460 NEXT S
465 PI = MA - 1
470 FOR I = INT (MA / 2 + 1) TO MA - 1:T = 0:V = 0
480 FOR J = 1 TO I:T = T + T1(J):V = V + V1(J): NEXT J
490 TS = T / I
500 VS = V / I
510 IF NOT FL THEN FL = 1: GOTO 570
520 DVDT = INT ((VS - OV) / (TS - OT) * 1E5 + .5) / 1E5
530 WT = INT ((TS + OT) / 2 * 1E3 + .5) / 1E3
540 FL = FL + 1
560 PRINT WT: PRINT DVDT: IF FL = 2 THEN PRINT WT: PRINT DVDT
570 OT = TS:OV = VS
580 NEXT I
590 FOR I = 1 TO NMPTS(K) - MA + 1
600 PI = PI + 1:TE = A(K,PI):VO = B(K,PI)
610 IF I > NMPTS(K) - 2 * MA + 2 THEN Z = I - NMPTS(K) + 2 * MA - 1:
   T2(Z) = TE:V2(Z) = VO
620 T = T + TE - T1(S):T1(S) = TE
630 V = V + VO - V1(S):V1(S) = VO
640 S = S + 1: IF MA < S THEN S = 1
650 TS = T / MA
660 VS = V / MA
680 IF TS = OT THEN DVDT = 00: GOTO 700
690 DVDT = INT ((VS - OV) / (TS - OT) * 1E5 + .5) / 1E5:OV = DVDT
700 WT = INT ((TS + OT) / 2 * 1E3 + .5) / 1E3
710 PRINT WT: PRINT DVDT
720 OT = TS:OV = VS
730 NEXT I
740 FOR I = 2 TO INT (MA / 2 + 1):T = 0:V = 0
750 FOR J = I TO MA:T = T + T2(J):V = V + V2(J): NEXT J
760 TS = T / (J - I)
770 VS = V / (J - I)
790 DVDT = INT ((VS - OV) / (TS - OT) * 1E5 + .5) / 1E5
800 WT = INT ((TS + OT) / 2 * 1E3 + .5) / 1E3
CONVERT R

100 REM *********************************************************
110 REM *THIS PROGRAM CONVERTS THE X VS PORE VOLUME FILE *
120 REM * TO RADIUS VS PORE VOLUME.                        *
130 REM *********************************************************
135 TO = VAL (TO$)
140 PRINT "Converting X.VP to R.VP"
320 FOR K = 0 TO 1
325 PO = 0:R1 = 0
330 FOR L = 1 TO NMPTS(K)
422 XO = A(K,L)*1E-4
425 R = (( - 2 * TO * (.25 - (29 * XO) + (.25 * TO * XO))) / 
      ( (.9998 * 3.33539) * (1 + TO * XO) ) ) * 1E8
427 IF R < 0 THEN 490
428 IF ( ABS (R - R1) < 1) AND (K$ = "Y") THEN 490
450 PO = PO + 1:R1 = R
460 A(K,PO) = R:B(K,PO) = B(K,L)
490 NEXT L
500 NMPTS(K) = PO
510 NEXT K
520 FOR K = 0 TO 1
530 PRINT D$"OPEN /CALDAT/R.VP/"FIL$;C$(K)
540 PRINT D$"WRITE /CALDAT/R.VP/"FIL$;C$(K)
550 PRINT NMPTS(K)
560 FOR L = 1 TO NMPTS(K)
570 PRINT A(K,L): PRINT B(K,L)
580 NEXT L
590 PRINT D$"CLOSE"
600 NEXT K
610 PRINT D$"CHAIN STARTUP,@1600,D1"
CONVERT VP

100 REM ************************************************************
110 REM * CONVERTS THE X.Z FILE TO X.VP  *
120 REM * BASES THE LOW POINT ON THE AVERAGE OF  *
130 REM * COOLING DATA FROM -36 TO -36.5  *
140 REM ************************************************************
150 PRINT "Converting X.Z to X.VP"
330 FOR K = 0 TO 1
340 FOR L = 1 TO NMPTS(K)
360 VP = 1 / 10 * B(K,L)
370 B(K,L) = VP
380 NEXT L
390 NEXT K
400 IF (SA) THEN 500
410 FOR K = 0 TO 1
420 PRINT D$"OPEN /CALDAT/X.VP/"FIL$;C$(K)
430 PRINT D$"WRITE /CALDAT/X.VP/"FIL$;C$(K)
440 PRINT NMPTS(K)
450 FOR L = 1 TO NMPTS(K)
460 PRINT A(K,L): PRINT B(K,L)
470 NEXT L
490 NEXT K
500 PRINT D$"CHAIN STARTUP,@1580,D1"
INTEGRATE XDYDX

100 REM *******************************
110 REM * THIS PROGRAM INTEGRATES X, DY/DX DATA *
120 REM * TO CALCULATE THE PARAMETER Z *
130 REM *******************************
150 D$ = CHR$(4): SPEED = 255: PRINT D$"PR#3"
160 PRINT "Converting X.DYDX to X.Z"
260 REM PROCESS DATA
305 I = 1: Z = 0: TS = 0: TN = 0
330 IF A(1, I) < = -36 THEN 370
340 B(1, I) = 0
350 I = I + 1
360 GOTO 330
370 IF A(1, I) < = -36.5 THEN 420
380 TS = TS + B(1, I)
390 TN = TN + 1
400 I = I + 1
405 B(1, I) = 0
410 GOTO 370
420 Y1 = TS / TN: X1 = A(1, I - 1)
440 FOR K = 1 TO NMPTS(1)
450 Z = Z + (X1 - A(1, K)) * (B(1, K) - Y1)
460 B(1, K) = Z
475 X1 = A(1, K)
490 NEXT K
520 Z = 0: X1 = A(0, 1)
540 FOR K = 1 TO NMPTS(0)
550 IF A(0, K) > -36.5 THEN 570
560 Z = Z + (X1 - A(0, K)) * (B(0, K) - Y1)
570 B(0, K) = Z
580 X1 = A(0, K)
590 NEXT K
600 IF (SA) THEN 700
610 FOR K = 0 TO 1
620 PRINT D$"OPEN /CALDAT/X.Z/"FIL$;C$(K)
630 PRINT D$"WRITE /CALDAT/X.Z/"FIL$;C$(K)
640 PRINT NMPTS(K)
650 FOR L = 1 TO NMPTS(K)
660 PRINT A(K, L): PRINT B(K, L)
670 NEXT L
680 PRINT D$"CLOSE"
690 NEXT K
700 PRINT D$"CHAIN STARTUP, @1540,D1"
PRINT $C"CHAIN STARTUP",1900,DI"

NEXT X
PRINT $C"CLOSE"
NEXT I
PRINT XI(t),: PRINT K(X,t)
NEXT I = 1 TO NMR(TS)(K)
PRINT NMR(TS)(K)
PRINT D$"WRITE//CALDAT/X.DDX//"FIL$C$S(K)
PRINT D$"OPEN//CALDAT/X.DDX//"FIL$C$S(K)
IF (SA) THEN 920
IF (SA) THEN 790
835 NMR(TS)(K) = NMR(TS)(K) - 1
NEXT I

DERIVATIVE X
DERIVATIVE XY

100 REM ***************************************************************
110 REM * THIS PROGRAM FINDS THE DERIVATIVE *                   *
120 REM * OF X W/RESPECT TO Y, DY/DX *                       *
140 REM ***************************************************************
160 PRINT "Converting X.Y to X.DYDX"
360 DIM TE(MA),VO(MA),TZ(MA),VZ(MA)
440 FOR K = 0 TO 1
445 FL = 0
446 FOR S = 1 TO MA: TE(S) = 0: VO(S) = 0: NEXT S
450 FOR S = 1 TO MA - 1: TE(S) = A(K,S): VO(S) = B(K,S)
460 NEXT S
465 PO = 0: PI = MA - 1
470 FOR I = INT (MA / 2 + 1) TO MA - 1: T = 0: V = 0
480 FOR J = 1 TO I: T = T + TE(J): V = V + VO(J): NEXT J
490 TS = T / I
500 VS = V / I
510 IF NOT FL THEN FL = 1: GOTO 570
520 DVDT = INT ((VS - OV) / (TS - OT) * 1E5 + .5) / 1E5
530 WT = INT ((TS + OT) / 2 * 1E3 + .5) / 1E3
540 FL = FL + 1
550 PO = PO + 1
560 A(K,PO) = WT: B(K,PO) = DVDT: IF FL = 2 THEN PO = PO + 1:
   A(K,PO) = WT: B(K,PO) = DVDT
570 OT = TS: OV = VS
580 NEXT I
590 FOR I = 1 TO NMPTS(K) - MA + 1
600 PI = PI + 1: TE = A(K,PI): VO = B(K,PI)
610 IF I > NMPTS(K) - 2 * MA + 2 THEN Z = I - NMPTS(K) + 2 * MA - 1:
   TZ(Z) = TE: VZ(Z) = VO
620 T = T + TE - TE(S): TE(S) = TE
630 V = V + VO - VO(S): VO(S) = VO
640 S = S + 1: IF MA < S THEN S = 1
650 TS = T / MA
660 VS = V / MA
680 IF TS = OT THEN DVDT = 0: GOTO 700
690 DVDT = INT ((VS - OV) / (TS - OT) * 1E5 + .5) / 1E5: OT = DVDT
700 WT = INT ((TS + OT) / 2 * 1E3 + .5) / 1E3
710 PO = PO + 1: A(K,PO) = WT: B(K,PO) = DVDT
720 OT = TS: OV = VS
730 NEXT I
740 FOR I = 2 TO INT (MA / 2 + 1): T = 0: V = 0
750 FOR J = I TO MA: T = T + TZ(J): V = V + VZ(J): NEXT J
760 TS = T / (J - I)
770 VS = V / (J - I)
790 DVDT = INT ((VS - OV) / (TS - OT) * 1E5 + .5) / 1E5
800 WT = INT ((TS + OT) / 2 * 1E3 + .5) / 1E3
810 PO = PO + 1: A(K,PO) = WT: B(K,PO) = DVDT
820 OT = TS: OV = VS
CONVERT XY

100 REM **********************
110 REM * THIS PROGRAM CONVERTS RAW DATA OF TEMP AND *
120 REM * CONDUCTANCE INTO X,Y DATA PAIRS *
130 REM **********************
140 SU = 1
142 IF SR$ = "Y" THEN SU = 10
145 DEF FN CN(X) = LOG (X / SU) / LOG (10)
170 PRINT "Converting Raw Data to X,Y"
180 DEF FN CN(X) = LOG ((X * CR / SU) / (CR - X / SU)) / LOG (10)
190 IF SR$ = "N" THEN 240
200 PRINT D$"OPEN "FIL$;C$(0)"",D2"
210 PRINT D$"OPEN "FIL$;C$(1)
220 PRINT D$"READ "FIL$;C$(0)
230 INPUT NMPTS(0)
240 PRINT D$"READ "FIL$;C$(1)
250 INPUT NMPTS(1)
260 N = NMPTS(0)
270 IF NMPTS(1) > NMPTS(0) THEN N = NMPTS(1)
280 DIM A(l,N),B(l,N)
285 PRINT D$"READ "FIL$;C$(0)
287 FOR K = NMPTS(0) TO 1 STEP - 1
290 INPUT A(0,K),B(0,K)
295 NEXT K
300 PRINT D$"READ "FIL$;C$(1)
305 FOR K = 1 TO NMPTS(1)
307 INPUT A(1,K),B(1,K)
310 NEXT K
320 PRINT D$"CLOSE"
325 INPUT "Please insert the CALDAT disk in drive 2 and press RETURN...";KB$
327 IF KB$ < > "" THEN 325
328 ONERR GOTO 1000
329 FOR L = 0 TO 1
330 PRINT D$"OPEN/CALDAT/X.Y/"FIL$;C$(L)
340 PRINT D$"WRITE/CALDAT/X.Y/"FIL$;C$(L)
344 PRINT NMPTS(L)
350 FOR K = 1 TO NMPTS(L)
360 A(L,K) = - 1 / (A(L,K) + 273.6) * 1E4
370 B(L,K) = FN CN(B(L,K))
380 PRINT A(L,K): PRINT B(L,K)
390 NEXT K
400 PRINT D$"CLOSE /CALDAT/X.Y/"FIL$;C$(L)
410 NEXT L
495 POKE 216,0
500 PRINT D$"CHAIN STARTUP,@1460,D1"
1000 PRINT "Check disk in drive 2"
1010 GOTO 325
CONPROC/PROCGRAMS/P'8390'D1

5200 PRINT $"PE#3"; PRINT $"CHAIN"
5130 PRINT $"SP0";
5120 NEXT X

HP PLTTER
HP PLOTTER

4095 IF YP > YB THEN YP = YB
4100 IF (YP < YA) THEN YP = YA
4120 PRINT "PA"; XP; "YP"; PD; "PA"
4130 FOR I = 2 TO NMPTS
4135 INPUT X, Y
4140 XP = FN XL(X)
4150 YP = FN YL(Y)
4160 IF XP > XB THEN W = XB
4170 IF (XP < XA) THEN XP = XA
4180 IF YP > YB THEN 4210
4190 IF (YP < YA) THEN 4210
4200 PRINT XP, YP;
4210 NEXT I
4215 PRINT D$ "CLOSE"
4220 PRINT XP, YP; PU;
4225 NEXT K
4230 RETURN
4500 REM ****************************
4510 REM * PLOT AXIS LABELS  *
4520 REM ****************************
4530 PRINT "SP1; SI.24, -38;"
4540 XP = (XB + XA) / 2 - LEN (BT$) / 2 * 150
4560 YP = YA - 600
4570 PRINT "PA"; XP, "YP"; LB "BT$"; C$
4575 IF A > 4 THEN 4580
4577 PRINT "SI.1,12;PA"; (XB + XA) / 2 - 50 + LEN (BT$) / 2 * 150", "YA - 500"; LB - 1" C$
4580 PRINT "SI.24, -38;"
4580 YP = (YB + YA) / 2 - LEN (EL$) / 2 * 150
4590 PRINT "DI0,1;PA"; XA - 700", "YP"; LB "EL$"; C$
4595 PRINT "DI1,0;";
4600 RETURN
5000 REM ****************************
5010 REM * TITLES  *
5020 REM ****************************
5025 PRINT "SI.30, -50;"
5030 XP = (XB + XA) / 2 - LEN (TI$) / 2 * 160
5040 YP = YB + 700
5050 PRINT "PA"; XP, "YP"; LB "TI$"; C$
5055 FOR K = 1 TO 2
5057 IF F$(K) = "" THEN 5120
5060 LIN = L(K)
5070 IF LIN = 0 THEN LIN = 2
5080 PRINT "SI.22,.30;LT" LIN",2;"
5085 IF LIN = 7 THEN PRINT "LT;"
5090 PRINT "PA"; XA + 600", "YB + 170"; PD; "PA"; XA + 1275", "YB + 170"; PU;
5100 PRINT "PA"; XA + 1475", "YB + 170"; LB "L$(K); C$
5110 XA = (XA + XB) / 2
HP PLOTTER

2590 FOR YS = Y1 TO Y2 STEP YIN
2600 YN = FN YL(YS)
2610 PRINT "PA""XB","YN";PD;PA""XB - 25","YN";PU;
2620 NEXT YS
2630 RETURN

3000 REM *******************************************
3010 REM * X LABELS *
3020 REM ...........................................
3030 RF = 0
3040 IF XIN < > 0 THEN RF = - INT ( LOG ( ABS (XIN)) / LT)
3050 XS = INT (XS * 10 ® RF + .5) / 10 ® RF
3060 IF XS = 0 OR ABS (XS) > = .01 THEN XS$ = LEFT$(BL$7 - LEN (STR$(XS)))+ STR$(XS): GOTO 3100
3065 XS$ = STR$( INT ( ABS (XS) * 10 ® RF + .5))
3070 IF XS < 0 THEN XS$ = MID$(SN$,1 + RF,7 - LEN (XS$)) + XS$: GOTO 3100
3080 XS$ = MID$(SP$,1 + RF,7 - LEN (XS$)) + XS$
3090 XS$ = RIGHT$(XS$, LEN (XS$) - 1)
3100 RETURN

3200 REM *******************************************
3210 REM * Y LABELS *
3220 REM ...........................................
3230 RF = 0
3240 IF YIN < > 0 THEN RF = - INT ( LOG (YIN) / LT)
3250 YS = INT (YS * 10 ® RF + .5) / 10 ® RF
3260 IF YS = 0 OR ABS (YS) > = .01 THEN YS$ = LEFT$(BL$7 - LEN (STR$(YS)))+ STR$(YS): GOTO 3300
3265 YS$ = STR$( INT ( ABS (YS) * 10 ® RF + .5))
3270 IF YS < 0 THEN YS$ = MID$(SN$,1 + RF,7 - LEN (YS$)) + YS$: GOTO 3300
3280 YS$ = MID$(SP$,1 + RF,7 - LEN (YS$)) + YS$
3290 YS$ = RIGHT$(YS$, LEN (YS$) - 1)
3300 RETURN

4000 REM *******************************************
4010 REM * PLOT FUNCTION *
4020 REM *******************************************
4040 FOR K = 1 TO 2
4041 IF F$(K) = "" THEN 4225
4042 PRINT "SP1;LT"L(K)";25"
4045 PRINT D$"OPEN /"DR$/"FIL$"/F$(K)
4047 PRINT D$"READ /"DR$/"FIL$"/F$(K)
4048 INPUT NMPTS
4050 I = 1
4055 INPUT X,Y
4060 XP = FN XL(X)
4070 YP = FN YL(Y)
4080 IF XP > XB THEN XP = XB
4090 IF (XP < XA) THEN XP = XA
2060 GOSUB 2500: REM LINEAR Y
2070 RETURN
2100 REM ************************************************************
2110 REM * LINEAR X PLOT
2120 REM ************************************************************
2130 FOR XS = X1 TO X2 STEP XIN
2140 XN = FN XL(XS)
2150 GOSUB 3000: REM X LABEL
2160 PRINT "PA"XN - 550","YA - 200";LB"XS$;C$
2170 PRINT "PA"XN","YA";PD; PA"XN","YA + 50";PU;"
2180 NEXT XS
2190 FOR XS = X1 TO X2 STEP XIN
2200 XN = FN XL(XS)
2210 PRINT "PA"XN","YB";PD;PA"XN","YB - 25";PU;"
2220 NEXT XS
2230 RETURN
2300 REM ************************************************************
2310 REM * LOG X PLOT
2320 REM ************************************************************
2330 FOR K = LOG (ABS (X1)) / LT TO LOG (ABS (X2)) / LT - 1
2340 FOR K1 = 1 TO 10
2345 XS = K1 * 10 @ K
2350 XN = ( LOG (XS) / LT - XT) / HARSCAL + XA
2360 PRINT "PA"XN","YA";PD;PA"XN","YA + 50";PU;"
2370 IF (K1 < > 1) AND (K1 < > 5) AND ((K1 < > 10) OR
(K < > ( LOG (ABS (X2)) / LT - 1))) THEN 2400
2375 XIN = 10 @ K
2380 GOSUB 3000: REM X LABEL
2390 PRINT "PA"XN - 550","YA - 200";LB"XS$;C$
2400 NEXT K1
2410 NEXT K
2420 FOR K = LOG (ABS (X1)) / LT TO LOG (ABS (X2)) / LT - 1
2430 FOR K1 = 1 TO 10
2435 XS = K1 * 10 @ K
2440 XN = FN XL(XS)
2450 PRINT "PA"XN","YB";PD;PA"XN","YB - 25";PU;"
2460 NEXT K1
2470 NEXT K
2480 RETURN
2500 REM ************************************************************
2510 REM * LINEAR Y PLOT
2520 REM ************************************************************
2530 FOR YS = Y1 TO Y2 STEP YIN
2540 YN = FN YL(YS)
2550 GOSUB 3200: REM Y LABEL
2560 PRINT "PA"XA - 640","YN";LB"YS$;C$
2570 PRINT "PA"XA","YN";PD;PA"XA + 50","YN";PU;"
2580 NEXT YS
```plaintext
REM 2300: REM LOG X
2040 IF A > 5 THEN GOSUB 2100: GOTO 2060
* PLots Scale
**---------------------------------------------------------------------------------------
2020 REM 2010 REM 2000 REM
1410 RETURN
1400 DEF FN X(R) = (LOG ) ABS (R) = (LOG ) ABS (X(R) = (LOG ) ABS (X(R) = (LOG ) ABS (X(R) =
1390 DEF VERSCAL = (X(R) = (LOG ) ABS (X(R) = (LOG ) ABS (X(R) = (LOG ) ABS (X(R) =
1380 REM LINEAR FUNCTION
1370 REM LINEAR FUNCTION
1360 DEF HARSICAL = (LOG ) ABS (X(R) = (LOG ) ABS (X(R) = (LOG ) ABS (X(R) = (LOG ) ABS (X(R) =
1350 REM LINEAR FUNCTION
1340 REM LINEAR FUNCTION
1330 IF A > 5 THEN GOTO 1290
1320 IF A > 5 THEN GOTO 1290
1220 REM * DEFINE FUNCTIONS
1210 REM * DEFINE FUNCTIONS
1200 REM * DEFINE FUNCTIONS
1190 REM * DEFINE FUNCTIONS
1180 REM * DEFINE FUNCTIONS
1170 REM * DEFINE FUNCTIONS
1160 REM * DEFINE FUNCTIONS
1150 REM * DEFINE FUNCTIONS
1140 REM * DEFINE FUNCTIONS
1130 REM * DEFINE FUNCTIONS
1120 REM * DEFINE FUNCTIONS
1110 REM
1090 IF P.L = 14 THEN XA = 900: XB = 900: YA = 900: YB = 6400: GOTO 1110
1080 PRINT "D1","V1.0420:"
1070 PRINT "SPLF'S KNOWN":"KNOW"
1060 PRINT CHR$(27)"@","","","","","
1050 PRINT "IN":"","","","","
1040 PRINT CHR$(27)"","
1030 PRINT "#S",#S,"","
1020 REM * INIT FOR THE HP
1010 REM * INIT FOR THE HP
1000 REM * INIT FOR THE HP
990 REM * INIT FOR THE HP
980 REM * INIT FOR THE HP
970 REM * INIT FOR THE HP
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130 REM * INIT FOR THE HP
120 REM * INIT FOR THE HP
110 REM * INIT FOR THE HP
100 REM * INIT FOR THE HP

HP PL OTTER
```
PLOTTER

3130 GOTO 3060
3150 REM LABEL
3160 VTAB 5: HTAB 40
3170 INPUT ""; L$(1)
3180 GOTO 520
3200 REM LINETYPE
3210 VTAB 6: HTAB 40
3220 INPUT ""; L(1)
3230 GOTO 520
3250 REM FILENAME 2
3260 VTAB 7: HTAB 40
3270 INPUT ""; F$(2)
3280 IF F$(2) < > "" THEN 390
3290 POKE 34, 9
3300 HOME
3310 PRINT D$"CATALOG /"DR$"/"FIL$
3320 TEXT
3330 GOTO 3260
3350 REM LABEL
3360 VTAB 8: HTAB 40
3370 INPUT ""; L$(2)
3380 GOTO 520
3400 REM LINETYPE
3410 VTAB 9: HTAB 40
3420 INPUT ""; L(2)
3430 GOTO 520
3450 REM MIN X
3460 VTAB 10: HTAB 40
3470 INPUT ""; X1
3475 IF X1 = 0 AND KB$ = "Y" THEN X1 = 1
3477 VTAB 10: HTAB 40: PRINT X1
3480 GOTO 520
3500 REM MAX X
3510 VTAB 11: HTAB 40
3520 INPUT ""; X2
3530 GOTO 520
3550 REM X INT
3560 VTAB 12: HTAB 40
3570 INPUT ""; XIN
3580 GOTO 520
3600 REM MIN Y
3610 VTAB 13: HTAB 40
3620 INPUT ""; Y1
3630 GOTO 520
3650 REM MAX Y
3660 VTAB 14: HTAB 40
3670 INPUT ""; Y2
3680 GOTO 520
1480 REM * CHECKING THE DISK IN DRIVE 2 FOR*
1490 REM * THE PREFIX OF /CALDAT. *
1500 REM *************************************************************************************************************************
1510 PRINT "THE DISK IN DRIVE 2 IS NOT CALDAT. PLEASE REPLACE THE DISK IN DRIVE 2 WITH CALDAT."
1520 INPUT "AND PRESS RETURN TO CONTINUE.";X$
1530 POKE 216,0: GOTO 100
2000 PRINT CHR$(17): POKE -16304,0: POKE -16302.0: POKE -16299,0: POKE -16297,0
2001 GET A$
2010 POKE -16303,O:POKE -16300,O
2020 PRINT D$"PR#3": PRINT: GOTO 390
2100 REM SETS UP X AXIS ON A LOG SCALE
2105 IF X1 = 0 THEN X1 = 1
2110 FOR K = LOG (X1) / LOG (10) TO LOG (X2) / LOG (10) - 1
2120 FOR K1 = 1 TO 10
2130 XP = FN CN(K1 * 10 © K)
2135 IF XP = 280 THEN 2150
2140 HPLot XP,159 TO XP,154
2150 NEXT K1
2160 NEXT K
2180 GOTO 862
2300 REM ROUNDS DOWN TO THE NEXT CYCLE
2310 VTAB (L): HTAB (MM)
2320 INPUT "";X1
2330 X1 = 10 © ( INT ( LOG (X1) / LOG (10))))
2340 VTAB (L): HTAB (MM)
2350 PRINT X1;" "
2360 GOTO 520
2400 REM ROUNDS TO NEAREST CYCLE
2410 VTAB (L + 1): HTAB (MM)
2420 INPUT "";X2
2430 X2 = 10 © ( INT ( LOG (X2) / LOG (10) + .5))
2440 VTAB (L + 1): HTAB (MM)
2450 PRINT X2;" "
2460 GOTO 520
3000 REM TITLE
3010 VTAB 3: HTAB 40
3020 INPUT "";TI$
3030 GOTO 520
3050 REM FILENAME
3060 VTAB 4: HTAB 40
3070 INPUT "";F$(1)
3080 IF F$(1) < > "" THEN 390
3090 POKE 34,9
3100 HOME
3110 PRINT D$"CATALOG /"DRS$"/"FIL$
3120 TEXT
PLOTTER

1260 RETURN
1270 LAB$ = "":PL = 8.5:LIN = 7:PEN = 1:X1 = -41:X2 = -36:Y1 = 0:
        Y2 = 1:YIN = .1:XNUM = .15:YNUM = .185:XINC = 1
1280 EL$ = "Relative Conducting Pore Volume":BT$ = "(-1/T), K x 10":
        FIL$ = "X.VP"
1290 DEF FN MOH(T) = 159 - (T) * YA / (Y2 - Y1)
1300 DEF FN CN(R) = ((R - X1) * XB / (X2 - X1)) + 1:
        A = 6:X1 = 0:XINC = 1000
1310 RETURN
1320 LAB$ = "":PL = 8.5:X1 = 10:X2 = 10000:Y1 = 0:Y2 = 1.1:YIN = .1:
        XNUM = .15:YNUM = .185:XINC = 10:BT$ = "Radius, Angstroms":
        EL$ = "Relative Conducting Pore Volume":FIL$ = "R.VP"
1321 DEF FN MOH(T) = 159 - (T - Y1) * (YA - YB) / (Y2 - Y1)
1322 DEF FN CN(R) = (LOG (R) / LOG (10) - LOG (X1) / LOG (10)) /
        (LOG (X2) / LOG (10) - LOG (X1) / LOG (10)) * XB + 1
1324 IF KB$ = "N" THEN DEF FN CN(R) = ((R - X1) * XB / (X2 - X1)) + 1:
        A = 6:X1 = 0:XINC = 1000
1325 PEN = 1:LIN = 7
1326 RETURN
1330 LAB$ = "":PL = 8.5:YIN = 1:XIN = 1:X1 = -41:X2 = -36:Y1 = 0:
        Y2 = 5:PEN = 1:LIN = 2:XNUM = .15:YNUM = .185:BT$ = "(-1/T) K x 10":
        EL$ = "Radius, Angstroms"
1333 PEN = 1:LIN = 7:FIL$ = "X.Z"
1340 DEF FN MOH(T) = 159 - (T - Y1) * (YA - YB) / (Y2 - Y1)
1350 DEF FN CN(R) = ((R - X1) * XB / (X2 - X1)) + 1
1360 RETURN
1361 LAB$ = "":PL = 8.5:X1 = 10:X2 = 10000:Y1 = 0:Y2 = 2:YIN = .2:
        XNUM = .15:YNUM = .185:XINC = 10:BT$ = "Radius, Angstroms"
1362 EL$ = "d(Pore Volume)/d(log Radius)":PEN = 1:LIN = 7:
        FIL$ = "R.DVPDLR"
1363 IF A = 6 THEN EL$ = "d(Pore Volume)/d(Radius)":FIL$ = "R.DVPDR"
        Y2 = .1:YIN = .01
1364 IF KB$ = "N" THEN X1 = 0:XINC = 1000
1365 DEF FN MOH(T) = 159 - (T - Y1) * (YA - YB) / (Y2 - Y1)
1366 IF KB$ = "Y" THEN DEF FN CN(R) = (LOG (R) / LOG (10) - LOG (X1)
        / LOG (10)) / (LOG (X2) / LOG (10) - LOG (X1) / LOG (10)) * XB + 1:
        A = 5:GOTO 1368
1367 DEF FN CN(R) = ((R - X1) * XB / (X2 - X1)) + 1
1368 RETURN
1370 HOME
1380 PRINT D$"CATALOG /"DR$"/"FIL$;
1390 INPUT "ENTER NEW FILE NAME       ";SUB$
1400 IF SUB$ = "" THEN GOTO 1370
1410 RETURN
1420 ONERR GOTO 1510
1430 PRINT D$"OPEN /CALDAT, TDIR"
1440 PRINT D$"CLOSE /CALDAT"
1450 POKE 216,0: GOTO 240
1470 REM ********************************************
PLOTTER

865 IF FS(I) = "" THEN 1021
870 PRINT CHR$(4)"OPEN /"DR$"/FIL$"/FS(I)
880 ON ERR GOTO 1090
890 PRINT CHR$(4)"READ /"DR$"/FIL$"/FS(I)
900 INPUT NMPTS
920 POKE 216,0
930 FOR T = 1 TO NMPTS
935 IF Peek (-16384) = 27 THEN T = NMPTS: GOTO 1010
936 POKE -16368,0
940 INPUT X,Y
950 IF (X < X2) AND (X > X1) THEN J = FN CN(X)
960 IF (Y < Y2) AND (Y > Y1) THEN K = FN MOH(Y)
970 IF (X > X2) OR (X < X1) THEN J = 0
980 IF (Y > Y2) OR (Y < Y1) THEN K = 1
990 IF (J = 0) OR (K = 1) THEN J = 0: K = 1
1000 HPLOT J,K
1010 NEXT T
1020 PRINT CHR$(4)"CLOSE /"DR$"/FIL$"/FS(I)
1021 NEXT I
1030 GET A$: PRINT CHR$(18): TEXT:
1040 PRINT D$"PR#3": K = 10: HOME: GOTO 390
1050 PRINT CHR$(4)"RUN STARTUP, D1"
1060 REM *THIS IS AN ERROR HANDLING ROUTINE WRITTEN TO CLEAR*
1070 REM *ERRORS IN INPUTING FILE NAMES.*
1080 REM *ERRORS IN INPUTING FILE NAMES.*
1090 TEXT: PRINT CHR$(4)"CLOSE /"DR$"/FIL$"/SUB$
1100 PRINT CHR$(4)"DELETE /"DR$"/FIL$"/SUB$: POKE 216,0
1110 GET A$: PRINT D$"PR#3": GOTO 150
1120 END
1130 REM * THIS IS A LOOKUP TABLE FOR VARIABLE DEFAULTS AND *
1140 REM *EQUATIONS.*
1150 REM * THIS IS A LOOKUP TABLE FOR VARIABLE DEFAULTS AND *
1160 REM *EQUATIONS.*
1170 REM * THIS IS A LOOKUP TABLE FOR VARIABLE DEFAULTS AND *
1180 LAB$ = "Degrees Celcius": PL = 8.5: X1 = -41: X2 = -36: Y1 = -1:
1190 Y2 = 4: XNUM = .15: YNUM = .185: EL$ = "Log (Conductance in micro Mho)"
1200 BT$ = "(-1/T), K x 10"
1210 SL = 2: XIN = 1: YIN = .5: LIN = 7: PEN = 1: FIL$ = "X.Y"
1220 DEF FN MOH(T) = 159 - (T - Y1) * (YA - YB) / (Y2 - Y1)
1230 DEF FN CN(R) = ((R - X1) * XB / (X2 - X1)) + 1
1240 RETURN
1250 DEF FN MOH(T) = 159 - (T - Y1) * (YA - YB) / (Y2 - Y1)
1260 DEF FN CN(R) = ((R - X1) * XB / (X2 - X1)) + 1
PLOTTER

407 HTAB (K): PRINT "7. LINETYPE ....................... "L(2)
410 HTAB (K): PRINT "8. MINIMUM X ....................... "X1
420 HTAB (K): PRINT "9. MAXIMUM X ....................... "X2
430 HTAB (K): PRINT "10. X-INTERVAL SIZE .................. "XINC
440 HTAB (K): PRINT "11. MINIMUM Y ....................... "Y1
450 HTAB (K): PRINT "12. MAXIMUM Y ....................... "Y2
480 HTAB (K): PRINT "14. PAPER LENGTH ................... "PL
495 PRINT "";HTAB (K)
500 PRINT "A-ONSCREEN PLOTTING";: HTAB 30: PRINT "D-CLEAR GRAPHICS SCREEN";CS$(CS)
502 PRINT "B-HP722 PLOTTING ";: HTAB 30: PRINT "E-EXIT PROGRAM"
504 PRINT "C-VIEW GRAPHICS SCREEN";: HTAB 30: PRINT "F-FIND NEW DATA POINTS"
510 PRINT
520 VTAB (23): INPUT "ENTER YOUR CHOICE AND PRESS RETURN.";SE$
525 IF SE$ = "" THEN 520
530 IF (VAL (SE$) < 1 OR VAL (SE$) > 13) AND (SE$ < "A" OR SE$ > "F") THEN 520
540 M = VAL (SE$)
550 ON M GOTO 3000,3050,3150,3200,3250,3350,3400,3450,3500,3550,3600,3650,3700,3750
560 IF ASC (LEFT$(SE$,1)) = 65 THEN 720: REM A
570 IF ASC (LEFT$(SE$,1)) = 66 THEN PRINT D$"CHAIN /CONPROG/PROGRAMS/PLOT": REM B
580 IF ASC (LEFT$(SE$,1)) = 67 THEN GOTO 1200: REM C
590 IF ASC (LEFT$(SE$,1)) = 68 THEN CS = NOT CS: GOTO 390: REM D
600 IF ASC (LEFT$(SE$,1)) = 69 THEN PRINT D$"RUN STARTUP,D1": REM E
610 IF ASC (LEFT$(SE$,1)) = 70 THEN 160: REM F
720 PRINT CHR$(17)
730 IF NOT CS THEN POKE -16304,0: POKE -16302,0: POKE -16299,0:
740 HGR2
750 POKE -16368,0
755 YA = 159:YB = 0:XA = 1:XB = 279
760 HCOLOR= 3: IF NOT CS THEN GOTO 862
770 HPLOT 0,0 TO 279,0 TO 279,159 TO 1,159 TO 1,0
790 VARSCAL = (YA - YB) * YINC / (Y2 - Y1)
800 FOR K = 1 + VARSCAL TO YA STEP VARSCAL
810 HPLOT 1,K TO 5,K: HPLOT 279,K TO 274,K: NEXT K
815 IF A = 5 THEN 2100: REM PLOT X ON LOG SCALE
820 HARSCAL = (XB - XA) * XINC / (X2 - X1)
825 IF HARSCAL < 1 THEN HARSCAL = 1
830 FOR K = 1 TO XB - HARSCAL STEP HARSCAL
840 HPLOT K,159 TO K,154
850 K = INT (K)
860 NEXT K
862 FOR I = 1 TO 2
PLOTTER

100 REM ********************************************************************************
110 REM * THIS PROGRAM PLOTS ONSCREEN PLOTS OR SAVES THE* 
120 REM * VARIABLES IN A VARIABLE FILE AND PLOTS ON THE * 
130 REM * HP7220 PLOTTER. 
140 REM ********************************************************************************
150 TEXT:CS$(1) = "TRUE":CS$(0) = "FALSE"
155 DIM AS%(30)
160 HOME :D$ = CHR$(4)
170 DR$ = "CALDAT"
180 ~(1) = 7:
190 CS = 1
235 REM ********************************************************************************
235 REM * CHECKING TO SEE IF DISK IN DRIVE TWO IS * 
236 REM * CALDAT OR NOT. * 
238 REM ********************************************************************************
240 K = 10: PRINT "MENU OF SUBDIRECTORIES"
250 PRINT : PRINT
260 HTAB (K): PRINT "1. X.Y"
270 HTAB (K): PRINT "2. X.DYDX"
275 HTAB (K): PRINT "3. X.Z"
280 HTAB (K): PRINT "4. X.VP"
290 HTAB (K): PRINT "5. R.VP"
300 HTAB (K): PRINT "6. R.DVPDR"
302 HTAB (K): PRINT "7. R.DVPDLR"
305 HTAB (K): PRINT "8. EXIT TO MAIN MENU"
310 INPUT "ENTER NUMBER OF YOUR CHOICE " ;A$
320 IF (A$ < "1") AND (A$ > "8") THEN GOTO 240
330 A = VAL (A$)
332 IF A$ = "8" THEN 1040
333 IF A > = 2 AND A < = 4 THEN PRINT : INPUT "DO YOU WISH PORE RADIUS MARKS ON TOP (Y/N DEFAULT = N) ";PZ$
334 K1$ = "Y" : IF A$ = "6" THEN K1$ = "N"
335 IF A$ < > "6" AND A$ < > "7" AND A$ < > "5" THEN 338
336 PRINT : PRINT "DO YOU WISH TO PLOT THE RADIUS ON A LOG SCALE (Y/N DEFAULT = ";K1$;") ": INPUT TEMPS
337 KB$ = TEMPS: IF TEMPS = "" THEN KB$ = K1$
338 IF A$ < "5" THEN L$(1) = "WARMING":L$(2) = "COOLING": GOTO 340
339 L$(2) = "NECK SIZES":L$(1) = "BODY SIZES"
340 ON A GOSUB 1180,1230,1330,1270,1320,1361,1361
340 HOME : PRINT "ENTER THE LETTER OF ANY VALUE THAT YOU WISH TO CHANGE."
391 L = 3:K = 2
400 PRINT "AND PRESS RETURN"
401 HTAB (K): PRINT "1. TITLE .......................... "TIS"
402 HTAB (K): PRINT "2. FILENAME ........................ "F$(1)
403 HTAB (K): PRINT "3. LABEL ........................ "L$(1)
404 HTAB (K): PRINT "4. LINETYPE ........................ "L(1)
405 HTAB (K): PRINT "5. FILENAME ........................ "F$(2)
406 HTAB (K): PRINT "6. LABEL ........................ "L$(2)
6340 RETURN
6500 REM DISPLAY ITEMS
6510 VTAB 18: HTAB 4
6520 PRINT "Maximum Temp : ";TP(TC(CCYCLE));" ";
6530 HTAB 30
6540 PRINT "Minimum Temp : ";BTM(TC(CCYCLE));" ";
6550 POKE 36,58
6560 PRINT "Temp Rate : ";RA(TC(CCYCLE));" ";
6570 VTAB 20: HTAB 10
6580 PRINT "Temp Interval between readings : ";
6590 IF TD$(TC(CCYCLE)) = "N" THEN PRINT "0": GOTO 6610
6600 PRINT INVL(TC(CCYCLE))
6610 RETURN
7000 REM SAVE OFF CYCLE TYPE DESCRIPTIONS ON DISK
7010 D$ = CHR$ (4)
7030 PRINT D$;"OPEN ";DIS$;".";SCYCLE;".CT,D2"
7040 PRINT D$;"WRITE ";DIS$;".";SCYCLE;".CT"
7045 PRINT SCYCLE
7050 PRINT CT
7060 FOR N = 1 TO CT
7070 PRINT TP(N)
7072 PRINT BTM(N)
7074 PRINT RA(N)
7076 PRINT INVL(N)
7078 PRINT TD$(N)
7080 NEXT N
7081 PRINT MCYCLE
7082 FOR N = 1 TO MCYCLE
7083 PRINT TC(N)
7084 NEXT N
7085 PRINT N1$; PRINT N2$; PRINT N3$; PRINT N4$ 
7090 PRINT D$;"CLOSE ";DIS$;".";SCYCLE;".CT"
7110 RETURN
9999 POKE -15986,64: HIMEM: 38400: END
CONTROLLER

3500 REM NOTES ON SAMPLE
3510 HOME : VTAB 3: HTAB 29
3520 PRINT "Conductance Controller"
3530 VTAB 8: PRINT "Notes on Sample (press 'Return' at end of line) :
3540 INPUT "">";N1$
3550 INPUT "">";N2$
3560 INPUT "">";N3$
3570 INPUT "">";N4$
3580 RETURN
4000 PRINT D$"OPEN CAL, D1"
4005 PRINT D$"READ CAL"
4010 INPUT NMPT
4020 DIM P(NMPT), T(NMPT)
4025 FOR TI = 1 TO NMPT
4030 INPUT P(TI), T(TI)
4040 NEXT TI
4042 TI = 1
4045 PRINT D$"CLOSE"
4050 RETURN
6000 REM NOW SPECIFY EACH CYCLE
6010 HOME : VTAB 16: HTAB 10
6020 PRINT "Number of Cycles : ";
6030 GOSUB 1900
6040 IF TMP = > 1 THEN 6070
6050 HTAB 29: PRINT " ";: HTAB 29
6060 GOTO 6030
6070 MCYCLE = INT (TMP)
6075 DIM TC(MCYCLE)
6080 FOR CCYCLE = 1 TO MCYCLE
6090 HOME : VTAB 16: HTAB 10
6100 PRINT "Cycle Number : ";CCYCLE;
6110 POKE 36, 40
6120 PRINT "Cycle Type : ";
6130 GOSUB 1900
6140 IF TMP = > 1 AND TMP < = CT THEN 6160
6150 POKE 36, 53: PRINT ";; POKE 36, 53
6155 GOTO 6130
6160 TC(CCYCLE) = INT (TMP)
6170 GOSUB 6500: REM PRINT OUT PARAMETERS
6180 VTAB 24: HTAB 5
6190 PRINT "Is this the correct cycle type ?"
6200 GET TMP$
6210 IF TMP$ = "Y" OR TMP$ = "y" THEN 6250
6220 IF TMP$ = "N" OR TMP$ = "n" THEN 6090
6230 GOTO 6200
6250 VTAB 24: HTAB 1: CALL - 868
6255 NEXT CCYCLE
6330 VTAB 16: HTAB 1: CALL - 868
CONTROLLER

2635 CALL - 868: INVERSE : PRINT " Press 'C' to not halt ": NORMAL
2636 GOTO 2639
2637 FSTP = 0: VTAB 3: POKE 36,50
2638 PRINT "Press F to stop at cycle"
2639 POKE - 16368,0
2640 IF COOL AND TEMP < = RTEMP OR NOT COOL AND TEMP > = RTEMP THEN
2650 GOTO 2635: REM NEXT TEMP
2655 IF TD$(TC(CCYCLE)) = "N" THEN 2730
2660 GOSUB 300: REM TAKE CND READING
2670 SDT(PNT,0) = TEMP
2680 SDT(PNT,1) = CND
2690 HTAB 40: PRINT " ";
2700 HTAB 40: PRINT CND;
2710 POKE 36,51: PRINT "I*"
2720 POKE 36,51: PRINT PNT
2730 IF RTEMP < = BTTM(TC(CCYCLE)) AND COOL OR RTEMP > > TP(TC(CCYCLE))
AND NOT COOL THEN 3000: REM AT END OF CYCLE FOR SAMPLE
2740 RTEMP = INT ((RTEMP + INVL(TC(CCYCLE))) * 100) / 100
2750 PNT = PNT + 1
2760 GOTO 2630
2770 GOSUB 1000: REM SAVE TO TEMPORARY DISK
2780 IF NOT FSTP OR COOL AND FSTP THEN 3130
2790 IF COOL THEN
2800 GOSUB 600: GOTO 3200: REM TURN ON HEATER
2810 GOSUB 550: REM TURN ON COMPRESSOR
2820 GOTO 2610: REM START NEXT CYCLE
2830 GOSUB 500: REM TURN OFF HEATER AND QUIT
2840 VTAB 15: HTAB 5
2850 IF (CCYCLE - LCYCLE = NCYCLE OR CCYCLE = MCYCLE) AND NOT COOL THEN
2860 LCYCLE = CCYCLE
2870 IF (CCYCLE = MCYCLE) OR FSTP THEN 3210
2880 IF COOL THEN GOSUB 600: GOTO 3200: REM TURN ON HEATER
2890 GOSUB 550: REM TURN ON COMPRESSOR
2900 GOTO 2610: REM START NEXT CYCLE
2910 GOSUB 500: REM TURN OFF HEATER AND QUIT
2920 VTAB 24: HTAB 5
2930 PRINT "Program finished ";
2940 PRINT D$"RUN STARTUP,D1"
CONTROLLER

2174 POKE 36,70: PRINT " "; POKE 36,70
2175 GOTO 2172
2178 RA(X) = TMP
2250 VTAB 20: HTAB 10
2260 PRINT "Temp Interval Between Readings : ";
2270 GOSUB 1900
2280 IF TMP < = (TP(X) - BTM(X)) AND TMP > = 0 THEN 2302
2290 POKE 36,42: PRINT " ";: POKE 36,42
2300 GOTO 2270
2302 IF TMP = 0 THEN TD$(X) = "N": INVL(X) = .1: GOTO 2440
2304 TD$(X) = "Y"
2305 INVL(X) = TMP
2440 VTAB 24: HTAB 5
2450 PRINT "Is all information correct?";
2460 GET TMP$
2470 IF TMP$ = "Y" OR TMP$ = "y" THEN HTAB 5: CALL - 868: GOTO 2492
2480 IF TMP$ = "N" OR TMP$ = "n" THEN 2080
2490 GOTO 2460
2492 NEXT X
2493 GOSUB 6000: HOME
2496 CCYCLE = 0
2500 POKE 35,15: HOME : TEXT : VTAB 5: HTAB 30
2510 PRINT "Sample Description Starting Cycle"
2515 VTAB 6: HTAB 18: CALL - 868: PRINT "Sample 1":: INPUT DIS$
2516 VTAB 6: POKE 36,55: GOSUB 1900: SCYCLE = TMP
2520 VTAB 15: HTAB 5: PRINT "Is This name correct? ";: GET TMP$
2522 IF TMP$ = "Y" OR TMP$ = "y" THEN 2528
2525 IF TMP$ = "N" OR TMP$ = "n" THEN 2500
2527 GOTO 2520
2528 POKE 35,15: HOME : TEXT : GOSUB 7000
2530 VTAB 5: HTAB 30
2532 PRINT "Temp (C) Cond (uS) Point"
2534 VTAB 6: HTAB 5: PRINT LEFT$(DIS$,1)
2535 VTAB 6: HTAB 18: CALL - 868: PRINT "Sample 1"
2545 VTAB 3: POKE 36,50: PRINT "Press F to stop at cycle"
2550 DIM SDT(400,1)
2562 MR = 30
2565 DIM AR(MR)
2580 RTEMP = TP(TC(1))
2600 GOSUB 550: REM START COMPRESSOR
2610 GOSUB 6500
2620 GOSUB 700: REM INITIALIZE
2630 GOSUB 100: REM READ TEMP
2631 IF ABS (OSEC - U6) > = TS THEN U6 = OSEC: OT = OT + SD: IF OT > = 0
2632 AND OT < = 255 THEN POKE D1, OT
2633 IF PEEK ( - 16384) = 195 THEN 2637
2634 IF PEEK ( - 16384) < > 198 THEN 2639
2634 FSTP = 1: VTAB 3: POKE 36,50
CONTROLLER

1950 IF ASC (K$) = 8 AND LEN (TMP$) = 1 THEN TMP$ = "": PRINT CHR$ (8); " "; CHR$ (8);
1952 IF ASC (K$) = 8 AND LEN (TMP$) > 1 THEN TMP$ = LEFT$ (TMP$, LEN (TMP$) - 1): PRINT CHR$ (8); " "; CHR$ (8);
1955 GOTO 1920
1960 TMP$ = TMP$ + K$
1965 PRINT K$;
1970 GOTO 1920
1980 TMP = VAL (TMP$)
1990 RETURN
2000 REM PRE MAIN PROGRAM
2005 GOSUB 4000
2020 PSLOT = 4:ISLOT = 1:COOL = 0:LCYCLE = 0:D$ = CHR$ (4):INVL = 0
2030 FSTP = 0:CCYCLE = 0
2035 M1 = 255 / ( - 35 - 7):B = 7 * M1:D1 = - 16384 + ISLOT * 256 + 1: OKE D1 + 2,255
2040 A1 = - 16384 + PSLOT * 256 + 1:B1 = - 16384 + PSLOT * 256
2050 A3 = A1 + 2:B3 = B1 + 2
2057 C1 = - 16256 + PSLOT * 256 + 1:C3 = C1 + 2
2058 POKE A3,0: POKE B3,0: POKE C3,254
2059 GOSUB 3500: REM GET NOTES
2060 HOME
2062 VTAB 16: HTAB 2: PRINT "# of Cycle Types : ";
2064 GOSUB 1900
2066 IF TMP > 1 THEN 2072
2068 HTAB 21: PRINT " "; HTAB 21
2070 GOTO 2064
2072 CT = INT (TMP)
2074 DIM TP(CT),BTM(CT),INVL(CT),RA(CT),TD$(CT)
2076 FOR X = 1 TO CT
2080 HOME : VTAB 16: HTAB 2: PRINT "Cycle Type : ";X
2085 VTAB 18: HTAB 4
2087 PRINT "Maximum Temp : ";
2090 GOSUB 1900
2092 IF TMP < 7 THEN 2100
2094 POKE 36,18: PRINT " "; POKE 36,18
2096 GOTO 2090
2100 TP(X) = TMP
2110 HTAB 30
2120 PRINT "Minimum Temp : ";
2130 GOSUB 1900
2140 IF TMP < TP(X) THEN 2170
2150 POKE 36,44: PRINT " "; POKE 36,44
2160 GOTO 2130
2170 BTM(X) = TMP
2171 VTAB 18: POKE 36,58: PRINT "Temp Rate : ";
2172 GOSUB 1900
2173 IF TMP > 0 AND TMP < 30 THEN 2178