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Effectiveness of Rubberized Asphalt Chip Seals on Bridges

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Final Report

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16. Abstract

Chloride ions, which are derived from the salts used for winter highway maintenance, penetrate into the concrete of pavements and bridge decks. This results in corrosion of the rebar and ultimately in damage to the concrete. The subject of this report is a research project in which we attempted to determine the extent to which the presence of humidity, in conjunction with the diurnal cycle, influences the migration of these chloride ions, and whether the application of a rubberized asphalt chip seal to the upper concrete surface mitigates or enhances this migration.

The state of dissociation of NaCl within concrete was found to be uncertain, and the monitoring of chloride ions was found to be difficult. Use of built-in cells has been found to be effective. Thermistors inside a protective sleeve are effective thermometers with good stability and sensitivity. Two-wire sensors with ac excitation can be used to monitor moisture levels. It was, however, determined that the ambient moisture distribution and the effects of radiative cooling cannot be simulated in a closed container. The movement of moisture and differential potentials between layers of rebar in actual bridges appears to have been observed in the laboratory. It is recommended that further laboratory studies with well-defined objectives and a field study to compare sealed and unsealed bridge decks, and which includes careful meteorological monitoring, should be carried out.

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EXECUTIVE SUMMARY

The deterioration of concrete bridges is a very serious problem, both for South Dakota and nation-wide. Many bridge decks have a construction which involves a slab of concrete 8" thick which contains two layers of rebar. Initially, chloride ions are present only in the top surface of the concrete. To help prevent the further infiltration of chloride ions into the concrete and provide a surface with good skid-resistance characteristics, rubberized asphalt chip seals (RACS) have been used on bridge decks.

The questions which we attempted to address in the research project were:

a) In what manner do ambient conditions, particularly the presence of humidity and the diurnal cycle, influence the migration of the chloride ions into the concrete?

b) In what manner does the use of a rubberized asphalt chip seal affect these processes, both for newer bridges and for older bridges which already have the upper portions of the concrete deck strongly impregnated with chloride ions?

c) Does moisture in the form of liquid water collect at the seal-concrete interface as a result of thermal cycling? If so, does freeze-thaw cycling of the interface lead to disbonding of the chip seal from the concrete and/or deterioration of the concrete itself? Does the migration of this water downward lead to further damage of the rebar (particularly the lower layer of rebar) as a result of enhanced chloride migration?

When the answers to these questions are available, one will be in a position to examine the potential of RACS for increasing or decreasing the damage to both newer and older structures, and hence for developing a policy on sealing bridge new and old bridge decks with RACS.

The mechanism by which chloride ions migrate through a concrete matrix is not well understood. There is concern that, in concrete structures such as bridges, the mechanism is related to the presence of water vapor in the surrounding atmosphere coupled with thermal cycling. Very little research seems to have been carried out on this problem.

Detection of the presence and number of ions in the concrete matrix is also complex. For this reason, the experimental design used was a differential or comparative study in which some reference specimens are exposed to conditions identical to those of the test specimens containing chloride ions. Thus, any detected difference between specimens can then be attributed to the presence and movement of the chloride ions. The alternative was to complete an exhaustive study of the behavior of water, chloride, oxygen, hydroxyl, and a large number of other ions in a concrete matrix and their interactions (which would take several years) and then to perform the simulation of the problem of interest. Clearly, since answers were required as quickly as possible, there was no choice of methodology. The differential study was not expected to result in nearly as complete an understanding of the mechanism as would the much larger and more costly study, but this was a necessary compromise.

The following conclusion can be drawn from the data collected and the observations made whilst performing the work described in the preceding sections:

The comparative experiment in its original form was feasible, and would probably have given useful information regarding the problem. However, it would certainly have fallen well short of being able to define the mechanisms involved, and it would not have answered all the questions regarding the possible benefits/detriments of chip seals.

It is very difficult to accurately simulate natural environmental diurnal temperature cycles within the laboratory. It is made even more difficult if the space available is severely limited. It is not possible to simulate the effects of natural radiative cooling in a closed chamber. Further, we do not believe that the natural environment can be accurately simulated by a forced air system.

The incorporation of moisture into RAC-sealed bridge decks could be a two-stage process. Moisture has to enter at the underside of the deck, since the upper surface is sealed. The critical issue is whether there is a monotonic temperature change throughout the thickness of the deck; that is, the temperature is lowest at the top surface and steadily increases down to the bottom surface. Such a temperature profile will result in a vapor pressure within the lower portion of the deck being higher than that in the upper portion of the deck. Under these conditions, if the lower surface is somewhat cooler than the surrounding air and the air is at saturation, then moisture will condense on the lower surface and the vapor pressure gradient will tend to drive the moisture directly to the upper surface. Alternatively, if a monotonic temperature change does not exist, even when the underside of a bridge deck is somewhat colder than the surrounding air and the air is at saturation, moisture will remain in the lower section of the deck. Then, when the upper portion of the deck is colder than the middle portion, the moisture will migrate to the underside of the RACS by this two-stage process. Further work should be performed on an actual bridge deck to determine which of these hypotheses is correct.

For monitoring specimens, some of which have simulated RACS, the use of a $CuSO_4$ half-cell is both inconvenient and does not have good reproducibility. The differential potentials between layers of rebar and relative potentials between iron rebar or wires and a built-in reference electrode give much more consistent values than a half-cell. These potentials are useful and reliable for the monitoring. Victory Engineering thermistors mounted in a protective sleeve of heat shrink tube have worked very effectively as temperature sensors. They are very sensitive and stable. The two wire sensors with ac excitation work well as a sensor of moisture in concrete. Measurements made with a high frequency signal (near 1 MHz) are the most sensitive. Resonant modes for water molecules are in this frequency range. However, a signal in the 3 kHz to 30 kHz produces the smoothest calibration curve. Thus, we were able to see the migration of moisture in the concrete, but not the migration of NaCl or its ions. Impedance measurements made with dc excitation have little sensitivity to moisture. It is believed that the crack simulation was effective.

Overall, the instrumentation developed during the course of this research can be used to monitor temperature (using thermistors), moisture migration (using two-wire sensors), and chloride ion migration (using built-in cells) in actual bridge decks either with or without rubberized chip seals.

Our observation that the data obtained from the two-wire sensors under ac excitation does not follow the expectations from both theory and a number of measurements of the dielectric properties of concrete is interesting. An equivalent sensor also operated with ac excitation shows a strong and reproducible effect when used in saline solutions. This would seem to indicate that NaCl does not fully dissociate in water, and the sensor is then responding to the dipole moment of the remaining molecules. It seems that, in concrete, any NaCl present is either fully dissociated, or the remaining molecules are somehow bound to the matrix in such a manner that they cannot be rotated by an electric field of the strength we have been using. Monitoring the specimens while they were in a "humidity soak" chamber has produced useful results. It seems that the effects observed are reproducing the effects which are seen in bridge decks in the field. This includes both the behavior of rebar potentials as bridge decks dry and become wet again, and the effect of the presence of cracks upon the potentials during drying and wetting. It was of substantial benefit that this test was carried out; significant information about the influence of the simulated RACS and simulated cracks has been obtained.

In conducting this research, we have so far developed a great deal of useful information, but we are not presently in a position to answer all of the specific questions which were the objectives of the proposal. This has been the result of the difficulty of the project, the delays in the acquisition of materials, and the mid-project changes which were made.

Generally, our most important recommendation is that one or more further research projects should be initiated on this problem. Rather than attempt additional laboratory simulation of bridge decks both with and without simulated RACS, laboratory experiments should be designed to investigate specific mechanisms and effects within the concrete. Comparative experiments between RACS and non-RACS cases should be done in the field on actual bridge decks; meteorological data for the sites should be taken as part of the study. Fairly large slab mock-ups of bridge decks could perhaps be substituted for actual bridge decks. Findings from the project reported here should be used to guide the design of both the laboratory and field experiments.

The following specific recommendations are made:

1) Further attempts to study model bridge decks in a laboratory simulation of the natural environment should not be made. Simulation of the radiative cooling of the specimens simply cannot be accurately made in an enclosed chamber. Thus, the humidity profile around the specimens cannot be simulated.

2) In order to make the best progress on this problem, additional laboratory studies should first be made. These should include experiments such as monitoring specimens as they adsorb and lose moisture in a simple humidity soak environment and a very dry environment, and simple comparative tests to further investigate the movement of moisture in concrete and to gain a much better understanding of the state of dissociation of NaCl within concrete and the migration of the molecules and/or ions.

3) Our procedures for achieving controlled impregnation and its monitoring appear to work. They should be checked and, if necessary, refined.

4) Further studies of moisture and ion migration in concrete under a temperature gradient should be performed in the laboratory. However, it would likely be simpler and more profitable to use internal heating and cooling within the specimens rather than simulation of the natural environment.

5) A question which should be asked is "Do RACS really seal against the infiltration of ponded moisture, or is the interfacial moisture being introduced through the seal?" Careful laboratory tests need to be carried out to determine the answer to this question if such tests have not been performed previously.

6) It would be appropriate to instrument one or more bridge decks to determine the actual temperature variations with time. Dry and wet bulb temperatures should be monitored close to both the top and bottom surfaces of the decks. Also, other meteorological data such as wind data and precipitation should be recorded at the site(s). Such measurements would have the greatest possibility for determining whether the incorporation of moisture into RAC-sealed bridge decks is a single or a two-stage process.

7) It is recommended that a significant field experiment be performed. The experimental design could use either actual bridge decks or fairly large slabs constructed to the same specifications as a bridge deck. These experiments should be located at least in regions of both high and low humidity, and should represent both RACS and non-RACS decks. The decks should be fully instrumented with thermistors for temperature monitoring, single stovepipe (or equivalent) wire sensors with a reference electrode to monitor the presence of chloride ions, and two wire sensors to monitor moisture levels. Monitoring of the environmental conditions should be a required part of the project.

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I. STATEMENT OF PROBLEM

The deterioration of concrete bridges is a very serious problem, both for South Dakota and nation-wide. One of the main causes of this deterioration is the interaction of chloride ions, derived from the salt used for winter highway maintenance, with the steel rebar in the concrete. As the surface of the steel rebar reacts with the chloride ions to form corrosion products, there is a significant increase in volume. This results in a large build-up of pressure, and ultimately in the breaking of the concrete. To help prevent the further infiltration of chloride ions into the concrete and provide a surface with good skid-resistance characteristics, rubberized asphalt chip seals (RACS) have been used on bridge decks.

Many bridge decks have a construction which involves a slab of concrete 8" thick which contains two layers of rebar, the upper about 1.5" below the top surface and the other about 1.5" above the lower surface. Initially, chloride ions are present only in the top surface of the concrete. The questions which we attempted to address in the proposed research were:

a) In what manner do ambient conditions, particularly the presence of humidity and the diurnal cycle, influence the migration of the chloride ions into the concrete?

b) In what manner does the use of a rubberized asphalt chip seal affect these processes, both for newer bridges and for older bridges which already have the upper portions of the concrete deck strongly impregnated with chloride ions?

c) Does moisture in the form of liquid water collect at the seal-concrete interface as a result of thermal cycling? If so, does freeze-thaw cycling of the interface lead to disbonding of the chip seal from the concrete and/or deterioration of the concrete itself? Does the migration of this water downward lead to further damage of the rebar (particularly the lower layer of rebar) as a result of enhanced chloride migration?

When the answers to these questions are available, one will be in a position to examine the potential of RACS for increasing or decreasing the damage to both newer and older structures, and hence for developing a policy on sealing bridge decks with RACS.

II. BACKGROUND SUMMARY

The mechanism by which chloride ions migrate through a concrete matrix is not well understood. There is concern that, in concrete structures such as bridges, the mechanism is related to the presence of water vapor in the surrounding atmosphere coupled with thermal cycling. Very little research seems to have been carried out on this problem.

Water in concrete also creates a very complex situation [1,2,3]. It is always present in the form of hydrate products which form during the curing process; the strength of these crystals and their bonding to the other components of the matrix are largely responsible for the strength of concrete. Remove this water and the material will fall apart. Additional water, which may be present in either liquid or vapor form, has a multitude of sites on which to attach. The movement of individual molecules through the matrix can take place either by direct movement (a ballistic trajectory of a single molecule or a cluster of a few molecules), between collisions with the matrix, or by surface migration in which a molecule experiences interactions with adjacent sites. Liquid water can move, to some extent, in a hydrodynamic mode. However, the molecules near a surface are in strong interaction with the surrounding material and must therefore move in much the same manner as an individual molecule undergoing surface migration. The fraction of the liquid water which can move under hydrodynamic flow depends upon the range of the surface interaction forces, the size of the pores and cavities in the matrix, and the fraction of the cavities and pores which are seriously constricted or sealed.

The presence of other ions adds further complications. This is the case in concrete since there will always be free anions and cations in the material. Such ions can move by surface migration. Depending on the strength of the interactive forces (bonding forces) and the spatial distribution of appropriate sites, such movement can have widely different rates. Since ions can often interact with water molecules, the presence of water can influence the migratory process by modifying bonding sites, and by providing a mechanism for the ions to be carried along in a hydrodynamic flow.

Detection of the presence and number of ions in the concrete matrix is also complex. For this reason, the experimental design used was a differential or comparative study in which some reference specimens are exposed to conditions identical to those of the test specimens containing chloride ions. Thus, any detected difference between specimens can then be attributed to the presence and movement of the chloride ions. The alternative was to complete an exhaustive study of the behavior of water, chloride, oxygen, hydroxyl, and a large number of other ions in a concrete matrix and their interactions (which would take several years) and then to perform the simulation of the problem of interest. Clearly, since answers were required as quickly as possible, there was no choice of methodology. The differential study was not expected to result in nearly as complete an understanding of the mechanism as would the much larger and more costly study, but this was a necessary compromise.

III. OBJECTIVES OF THIS RESEARCH

The objectives of the project were to obtain further understanding of the mechanism of chloride migration in concrete, and to determine the role which ambient water vapor, thermal cycles, and the presence of a moisture-impervious layer on the upper surface of the concrete have on the process. Liquid water collection at the interface between the upper concrete surface and the sealant was also to be investigated. With this information, it would be possible to determine strategies for the use of rubberized asphalt chip seals on new and old bridge decks.

Personnel at the SD DOT are concerned that the use of rubberized asphalt chip seals may have differing levels of benefit, possibly including adverse consequences, under various conditions. The research attempted to provide the base information necessary to determine the conditions under which RACS produce favorable results, and those under which they are ineffective or counter-productive. This would allow optimization of the management of bridge decks to slow deterioration and to obtain increased useful (safe) lifetimes.

The products of the work were expected to be:

1. An improved understanding of the role of water and thermal cycling in the enhancement of the migration of chloride ions in concrete.

2. A determination of whether liquid water accumulates at the interface between the upper concrete surface and a waterproof seal applied to it, and whether freeze/thaw cycles lead to damage.

3. From this information, recommendations could be given regarding the use of rubberized asphalt chip seals on bridge decks with varying degrees of existing damage and chloride ion impregnation.

4. A laboratory procedure for studying chloride ion migration.

Using this information, we hoped to assist SD DOT personnel in formulating policies for the use of rubberized asphalt chip seals.

During the period of the project, little involvement by SD DOT was anticipated in terms of manpower. However, the close involvement of the project manager to provide advice in the areas of chemistry and highway engineering practice were be required. We also wanted the project manager to be involved in the required decisions regarding the design of the experiment and specimen instrumentation. Since an ultrasonic tester was not available in the SDSM&T Physics Department, it was intended that the SD DOT tester would be used to determine whether any damage had been sustained at the seal-concrete interface; this had been discussed with Mr. Johnston. Unfortunately, the project did not reach the stage were such testing was needed.

IV. RESEARCH PLAN

Work to be undertaken was divided into four components. Task 1 involved acquiring information. Task 2 was the design and fabrication of the systems for sensing, for monitoring, and for data acquisition. Design and fabrication of the environmental chamber, and formulation of the experimental design (this latter item was done in consultation with SD DOT staff) were also included in Task 2. The third task, Task 3, was to perform the specified experiments, and the final task, Task 4, was to form the conclusions and recommendations, and prepare the final report with indications on the impact of the current practice of using RACS.

Task 1 had three parts:

1A. Observation of existing RACS on bridge decks to become familiar with their form and the existing and potential problems, and observing the application of a RACS. The observations were to be made with the guidance of SD DOT staff in order to become familiar with DOT practices.

1B. An in-depth survey of the literature in order to have as much information as possible on relevant work which has already been performed.

1C. Collection of information about the materials needed for the sample fabrication.

Task 2 was the major part of the project; it included seven main components:

2A. Design of the experiment which is to be performed.

2B. Design and testing of the sensors which are to be embedded into the specimens .

2C. Testing of a system and the materials needed for simulation of cracks (added to the project after it was started).

2D. Determination and testing of methods for the introduction of sodium and chloride ions into the specimens.

2E. Fabrication of the test specimens in accordance with the design developed and approved.

2F. Design of the data acquisition system which was to be used to collect the data.

2G. Design and construction of the environmental testing chamber, and its control and monitoring systems (simulation of solar heating was added to the project after it was started).

Task 3 was to include measurements on two groups of specimens:

3A. Measurements of impedance and temperature of limestone aggregate concrete.

3B. Measurements of impedance and temperature of quartzite aggregate concrete.

Task 4 involved two main components:

4A. Analyzing the data obtained and developing a model for the behavior.

4B. Forming recommendations regarding the influence of RACS and whether they can be used effectively.

Although these components of the tasks can be listed as above, many of the items are interrelated. For example, the design of the experiment was limited by the maximum size of the environmental chamber, which, in turn, was limited by the size of the freezer available. Work could not proceed on the design of the experiment and the environmental chamber, or on fabrication of the specimens and the chamber until a number of decisions had been made. First, the type of sensor to be used had to be chosen, partly based on the results of the literature search; then its ability to detect ions had been proven. Next, the size of and configuration of the sensor which could be squeezed into the size of concrete block had to be chosen. Also, the designed sensor had to be able to survive both the pouring and the environment within the concrete. As far as possible, these factors were 'decoupled' by defining discrete experiments to test or investigate a single factor. But it was then necessary, on several occasions, to go back and modify other decisions and designs based on the outcome of a given test.

The configuration for the environmental chamber and the concrete specimens which was indicated in the proposal for this work, which are shown in Figures 1 and 2, were the basis from which the work began. The chamber had to be designed to allow an adequate heat transfer away from the blocks to achieve cooling at an appropriate rate, but the heat loss rate had to be limited in order to prevent the cooling system of the freezer from being overloaded. Thus, from the beginning of the design, we were aware that the design would have to be a compromise between conflicting requirements. Also, based on previous experience, it was known that the chamber would have to be very tightly sealed in order to prevent loss of moisture to the cold walls of the freezer since a surface at -15°F provides a strong vapor pressure gradient from regions at temperatures above 0°F; an integrated design was envisaged in which the outer surface was a complete and sealed envelope.

Features which had to be incorporated into the design of the environmental chamber were determined by the size and number of specimens which need to be monitored simultaneously, the temperature and humidity ranges which are needed, the period of the thermal cycles, the accuracy of control required, and the degree of uniformity required within the chamber, etc.

Thus, the first decision to be made was the design of the experiment itself. In particular, the number of specimens which needed to be monitored simultaneously was of primary concern. This, in turn, was determined by the number of parameters which could be compared. Originally, the specification of possible specimen parameters included the presence of epoxy seal, the presence of rubberized asphalt layer, the presence of damaged rubberized asphalt layer, the initial impregnation of upper 10 to 25% of specimen with chloride ions, and the impregnation of upper surface with aqueous solution of chloride salt. Clearly, to consider all combinations of a set of parameters required either 2, 4, 8, or 16 specimens for 1, 2, 3 and 4 parameters. Considerations of the size of the freezer limited the experiment to considering at most three parameters which required eight specimens. Final selection of the parameters could be made later.

The next step in the design was to determine the size of the specimens. This again involved a compromise between the size of the space available within the freezer and the number and type of sensors to be embedded within each specimen, their optimum locations and spacing. A size of 8"x8"x4" was decided upon in consultation with Mr. Dan Johnston of SD DOT. Essentially, this is a half scale modeling of a bridge deck of 8" thickness; scaled rebar was also incorporated into the specimens. This would allow the specimens (just!) to be housed within a chamber placed in a large freezer. Had it been determined that larger samples were required, the work definitely could not have proceeded without the construction of a large walk-in cold-room.

The specimen fabrication used Bridge Class A Concrete Mix Design with reduced maximum aggregate size (0.375 inches). The normal 28-day curing procedure was to be followed. In past work, fabrication of concrete specimens had been achieved by hiring one or more of Dr. V. Ramakrishnan's graduate students in the Civil Engineering Department; they have been responsible, under Dr. Ramakrishnan's supervision, for producing material of the specified design mix. This scheme was again followed for the preparation of the specimens for this work.

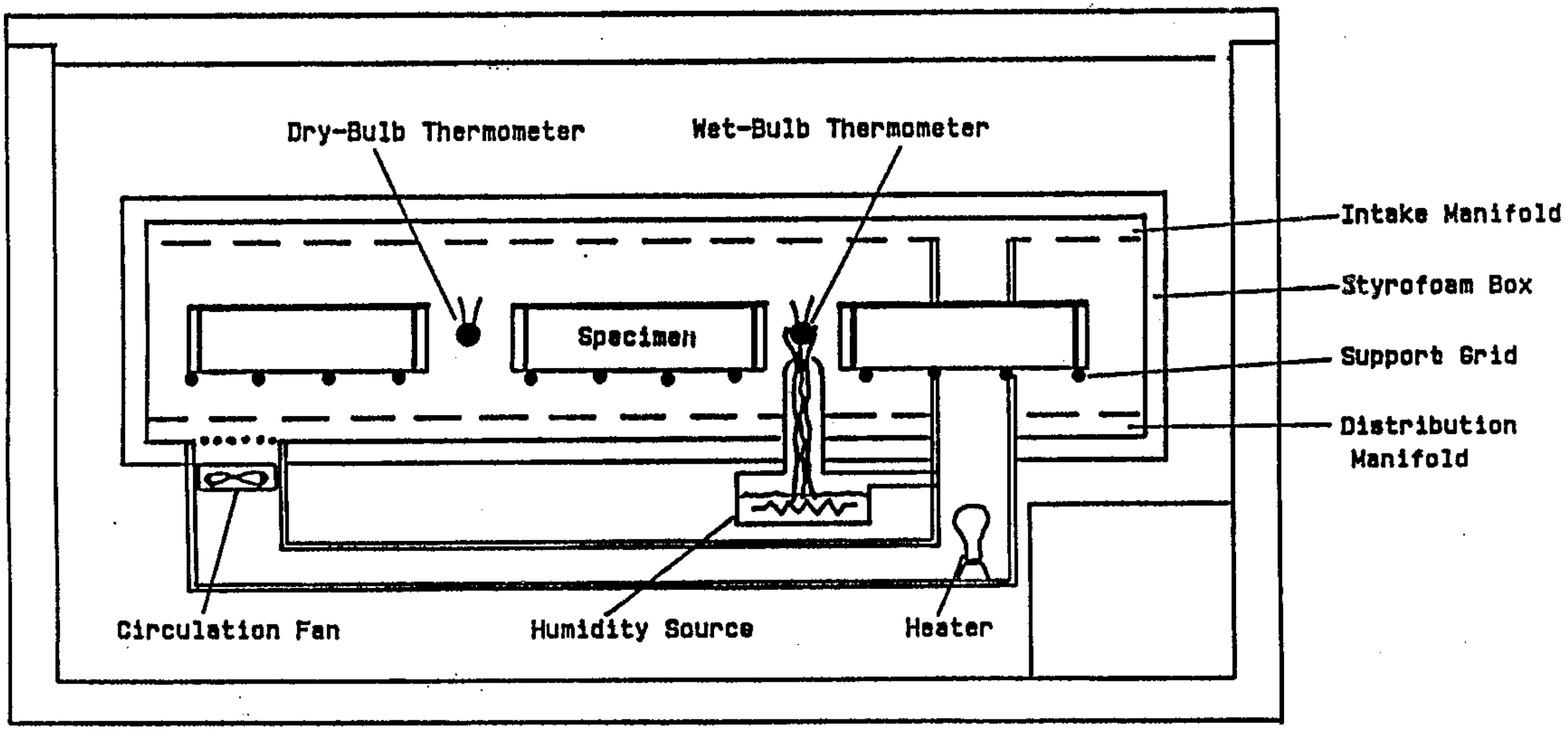


Figure 1. Schematic of Environmental Test Chamber

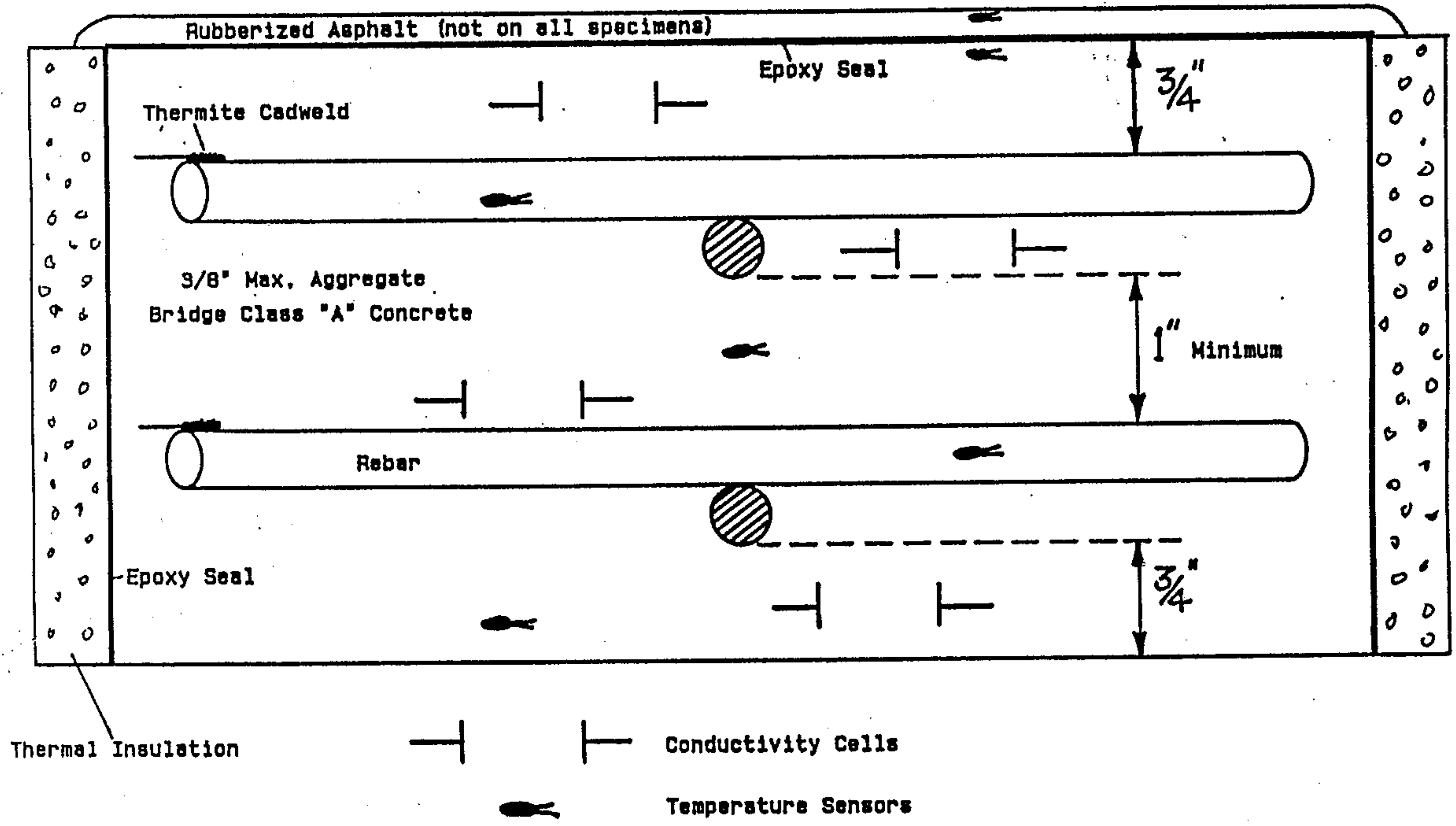


Figure 2. Illustration of Sample Configuration

Final decisions regarding the number and type of sensors to be placed within the specimens were not made until the literature survey had been completed and some initial testing of the proposed sensors had been made. However, we had determined that the temperature and water content of the specimens should be determined if possible, as well as the ion concentration.

With these half-scale specimens, the thermal cycling period would also be scaled. Since the time constant in transient thermal processes involves the square of the primary linear dimension of a solid, equivalent thermal penetration of cyclic or transient temperature variations are obtained if the time-scale of the temperature changes are reduced by a factor of four (4). This has the advantage that a 24-hour diurnal cycle can be simulated by a 6 hour temperature cycle. Since all truly diffusional processes have similar characteristics, the use of a 24-hour cycle for a half-scale specimen would produce erroneous results. Thus, not only was the reduction of the cycle period convenient, it was also necessary. With this in mind, the temperature of the specimens needed to be increased or decreased by about 40^{o}F in about 3 hours. Estimates of the required heat supply/removal rates were around 100 watts, which appeared to be achievable.

The temperature range to be covered was to be 0^{o}F to 100^{o}F. Typically, a freezer can achieve about -15^{o}F, which was expected to have allowed temperatures of 0^{o}F to be attained within the chamber without undue difficulty. Normal atmospheric humidities cover the range 10% to close to 100%. In a large experimental chamber, it is very difficult to achieve higher than 95% during thermal cycling even with the chamber carefully sealed, so that a humidity outside the range of 10% to 90% could not be guaranteed. We did envision that it should be possible to simulate a drizzle falling on the upper surface of the specimen if necessary, but this was not included in the experimental design; later it became evident that water spraying onto electrical fittings and hot light bulbs was not desirable. The accuracy of control and monitoring can be made very precise with a lot of effort. However, for the purposes of this study, temperature control, monitoring, and homogeneity to within 1^{o}F and humidity control, monitoring, and homogeneity to within 5% would be satisfactory. It was intended that three cycles be designed to simulate summer, spring/fall, and winter, with diurnal temperature cycles involving about 40^{o}F. The summer cycle would involve temperature excursions up to 100^{o}F, the spring/fall cycle would involve temperatures falling a little below freezing, with the winter cycle involving temperatures down to 0^{o}F.

Basically, this was the state of the experimental and system design prior to beginning the work itself. Until tests to determine the type and configuration of sensing elements had been completed, the experimental design could not be finalized. However, it was determined that the investigation should include tests on at least one set of specimens fabricated from limestone aggregate concrete and at least one set fabricated from quartzite aggregate. Also, the specimens should be designed so that the presence of liquid water immediately below the top seal could be detected. Upon completion of the thermal cycling tests, the specimens were to be subjected to ultrasonic testing to determine whether damage has occurred to the bond and/or the concrete immediately below it.

In addition to the main experiment, we also intended to perform additional tests. These were to include measurement of the thermal conductivity as a function of moisture content of the concrete from which the specimens were fabricated. This data was then to be used with a finite element code which was available to model the variations of the temperature within the specimens as ambient conditions are cycled. Such a study would add confidence that the experimental system was functioning well, and it was thought that there may be the possibility of determining whether significant thermal effects due to the movement of the moisture were present. It also had become clear that a means of reliably impregnating the concrete specimens with NaCl would have to be found.

V. IMPLEMENTATION OF RESEARCH PLAN

An outline of the work actually performed, including a chronological listing of the tasks performed and the data collected is given in Appendix A and B. Below, a description is given, by research periods, of the work performed and the rationale for some of the decisions made.

a) First Period 15AUG90 - 15DEC90.

During the first period of the work, most of the effort was put into Task 1.

A field trip was made with Mr. Daniel Johnston to inspect bridges on which Rubberized Asphalt Chip Seals (RACS) had been installed. Examples exhibiting both good and poor wear characteristics were inspected; one bridge on I-90 just to the north of Spearfish showed problems of deterioration of the seal itself and area underneath where discoloration and some scaling were evident; another smaller bridge over I-90 between Rapid City and Sturgis showed no deterioration. From this inspection we gained very useful information regarding the construction of chip seals on bridge decks and the problems which can arise -- such as the appearance of liquid water beneath the seal, the staining shown around cracks open to the bottom of the bridge deck, and spalling and scaling of the concrete. This information was valuable for the formulation of the experimental design (so that actual practice can be modeled as closely as possible and the actual practical problems be addressed as directly as possible), and would also be helpful in the formulation of conclusions and recommendations for guidelines for practice.

Some important recent references were found concerning the complex impedance of concrete [1 - 8]. Copies of these papers were made and studied. They indicated that the system we were considering for the monitoring of moisture and other ions in the concrete matrix (measurement of ac impedance) was feasible. Papers describing the ASTM specifications for Cu-$CuSO_4$ half-cells [9] were also copied and studied. Citations and abstracts of some of the more important references found are given in Appendix C.

Work was begun on Task 2. A mock-up of the air circulation/temperature control system was made and it worked well. Further design work was accomplished on the data collection system. Our provisional design required some minor modifications, but was basically correct. A requisition was submitted for the Keithley Model 706 scanner and switching cards. Ordering of other items for the data system was left until further tests had been completed and the exact needs ascertained.

Considerable effort was put into the design of the test specimens and obtaining information about materials which may be used during this period. It was far from trivial to squeeze into the design all the sensors and to try to ensure that they would remain in position and undamaged during the pouring of the concrete. Problems associated with preventing large air cavities in the sensing volume were given consideration.

Design of the sensor system to be used (Task 2B) involved not only a determination of the type and physical configuration of the sensors, but it was also necessary to find a sensor which could monitor ion concentrations and water content. From the literature search, we had determined that a probe capable of measuring the dielectric constant of the concrete through a wide range of dissipation (due to a wide range of free water contents) had the potential to do this, but its efficacy had still to be demonstrated. Past experience suggested that ac measurements would be significantly better than dc measurements, since the latter produce polarization effects in ionic materials. An appropriate electrode size and configuration needed to be determined, along with the optimum frequency of the ac excitation signal. In a previous study on the determination of concrete pavement thickness, a frequency of 100 Hertz was used successfully [10], but for the present problem the use of some other frequencies was expected to be advantageous [1,3,6,7,8]. It was hoped that the use of more than one frequency would allow determination of ionic species; this remained to be demonstrated.

Initially, the use of titanium oxide electrodes was considered desirable. To this end, information on the Elgard Corporation titanium oxide anode rods was obtained, and the company provided some samples of this material. It was found that, although the material would have been ideal, the cost would have been prohibitive. Several other materials including copper, stainless steel, and nichrome were considered. Later, tests would be carried out to determine the level of corrosion to be expected on these materials.

It was always envisioned that temperatures would be measured using thermistors. We had found that greater sensitivity can be obtained using these devices than can be obtained with thermocouples, and we have used a brand and model of thermistor for several years which is small in size and extremely stable. Methods for protecting the sensors from corrosion and leakage conduction had to be found.

The state of corrosion of the rebar was to be monitored by the standard half-cell technique [9]. Wires were to be attached to the rebar using the Thermite Cadweld procedure, and the area of attachment then covered with a non-conducting epoxy coating, or using silver-soldering. A copper-copper sulfate half-cell would be used to determine the rebar potential; measurements of this parameter would be taken according to a schedule which was to be determined as the experiment progressed.

By the end of the period, we had completed a design for the sample mold and were preparing a test mold.

b) Second Period 16DEC90-15MAR91.

During the second period of the project, substantial progress was made, but some delays were experienced in acquiring materials and components.

On 04 February 1991 the research team met with Dan Johnston to discuss the experiment design and other details of the project. In this meeting, Mr. Johnston conveyed an increased perception of the importance of crack simulation and the experiment design was accordingly modified. The design decided upon was as shown in Table 1. For each type of concrete (limestone-based and quartz-based aggregates), 8 specimens would be made and monitored in the environmental chamber. The parameters chosen for inclusion in the study were the

Table 1. Specification of Concrete Specimens

	Specimen Identification							
Parameter	#7A	#7D	#7C	#7F	#7B	#7I	#7H	#7G
I	X	X	X	X	X	X	X	X
II	X	X	X	X				
III	X	X			X	X		
IV	X		X		X		X	

I -- Epoxy seal and thermal insulation on the sides.
II -- Top treated with waterproofing (simulated RACS).
III -- Sodium chloride treatment in top third of specimen.
IV -- Simulated crack (felt) in bottom half of specimen.

simulation of the chip seal, impregnation into the upper one-third of the sample of NaCl, and, per Mr. Johnston's request, the simulation of a crack in the lower one-half of the specimens. The inclusion of this latter parameter represented a modification to the project as stipulated in the contract; Mr. Johnston was informed that the testing needed for this change would not be difficult, but it could cause some delay in the project.

Although the experiment designed was a comparative one, we believed that a better understanding of what was occurring would be of great value in interpreting the results of the comparative experiment. To this end, we then prepared a specimen (#2) which could be dried, and then different regions could be soaked with salt solutions of different concentrations. Also, we made a specimen (#3) with several configurations (different wire thicknesses and different wire separations) of stainless steel wire sensors. These tests were to be run during the next quarter in parallel with the work on the design of the environmental chamber.

Other details of the specimen configuration and instrumentation were discussed. No significant changes were made other than the addition of the simulated crack. Based on the data presented below and construction considerations, the "ion" sensors are to have the configuration of two parallel wires rather than two parallel plates.

Early in the period, a test specimen (#1) was prepared, and for several weeks it was monitored. The specimen was an 8"x8"x4" block of concrete (Redimix) within a plywood frame. Four sensors were embedded for the purpose of determining effective sensor design. A pair of parallel stainless steel wires separated by 0.25" formed one sensor. The other sensors were three pairs of parallel plates, each 0.5"x0.5" separated by 0.25", with copper wires welded to each plate for electrical connection; one pair of plates were of copper, one pair of stainless steel, and one pair of titanium oxide (Elgard ribbon). All four sensors were 2" below the upper surface of the concrete. Throughout the tests, the specimen was kept at laboratory temperature (25 ± 2°C).

The results obtained are shown in Figures 3A, 3B, 3C, and 3D; Figures 3E and 3F show the data of Figures 3A and 3C on a different scale. After the specimen had been allowed to cure for a few days with wet material (paper towel) on the upper surface, the curing was continued and monitored in ambient laboratory conditions for approximately 45 days form the time of mixing. Impedance was measured at 6 frequencies (50 Hz through 1 MHz) by placing (sequentially) a 1000 ohm pure resistor in series with a voltage source (sine wave form) and each sensor; the amplitude of the voltage across the resistor and connected sensor was measured to determine the magnitude of the impedance of the concrete between the wires or the plates; in this test specimen, no attempt was made to measure phase. After 45 days, a moat was placed on top of the specimen and it was filled with pure water; at 55 days NaCl was added to the water to create a saturated solution; at 87 days the top of the specimen was washed clean and dried.

The results shown in Figure 3 indicate that there are no major differences between the performance of the plate and wire sensors; since wire sensors made measurements on a much larger volume of sample material, were easier to construct and locate accurately, and were less susceptible to damage, this configuration was chosen. Data from each sensor have essentially the same characteristics, but there are some small differences. In all cases, there was a steady increase in impedance as the curing progressed, and, in all cases, there was some frequency dependence. As the frequency increased from 50 Hz, the impedance decreased to a minimum in the 1 kHz to 10 kHz range, and then increased again at higher frequencies. Data taken at 1 MHz show more sensitivity than those taken at the lower frequencies. Also, it was noticed that the scatter in the 1 MHz data during the 45 to 55 day period was considerably smaller for the wire sensor than for the plate sensor (see Figures 3E and 3F). This is probably due to the much smaller volume sampled by the plate sensor.

At approximately 45 days, when a modeling clay moat had been placed around the top of the specimen/frame unit, and standing water (approximately 0.25" thick) was maintained on the upper concrete surface. There was a significant response to this addition of water within a few hours.

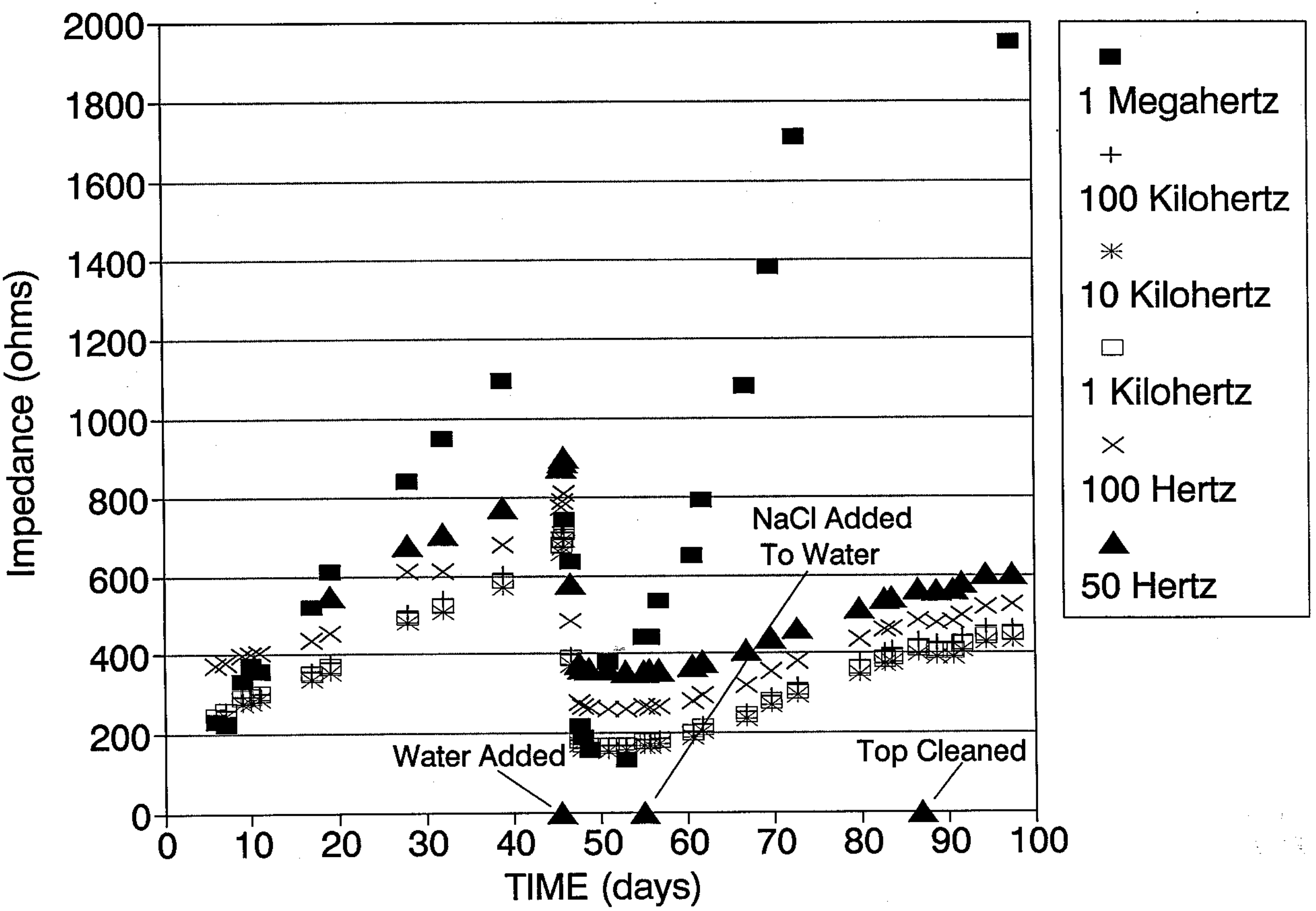


Figure 3A. SPECIMEN #1 - Stainless Steel Wires

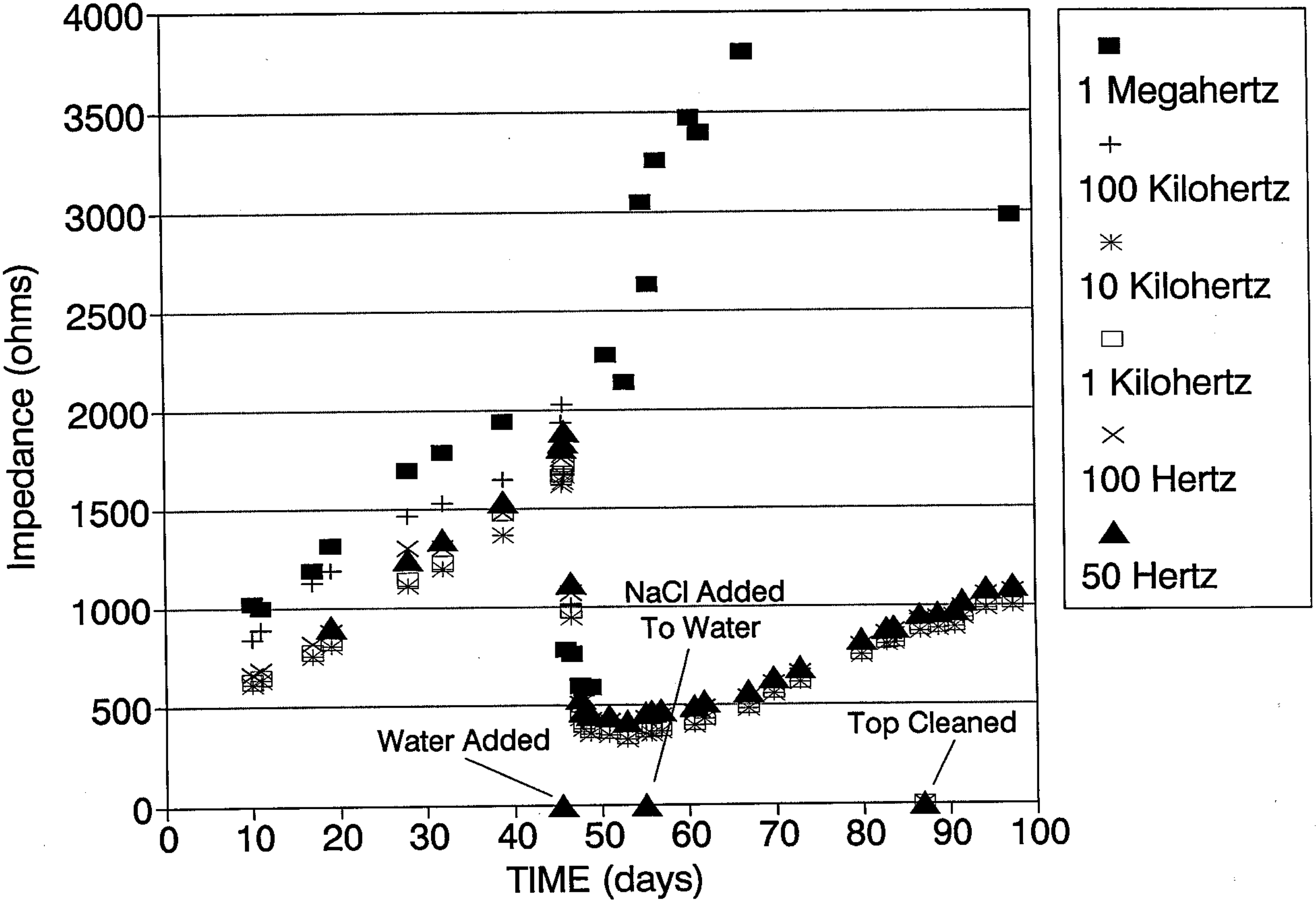


Figure 3B. SPECIMEN #1 - Copper Plates

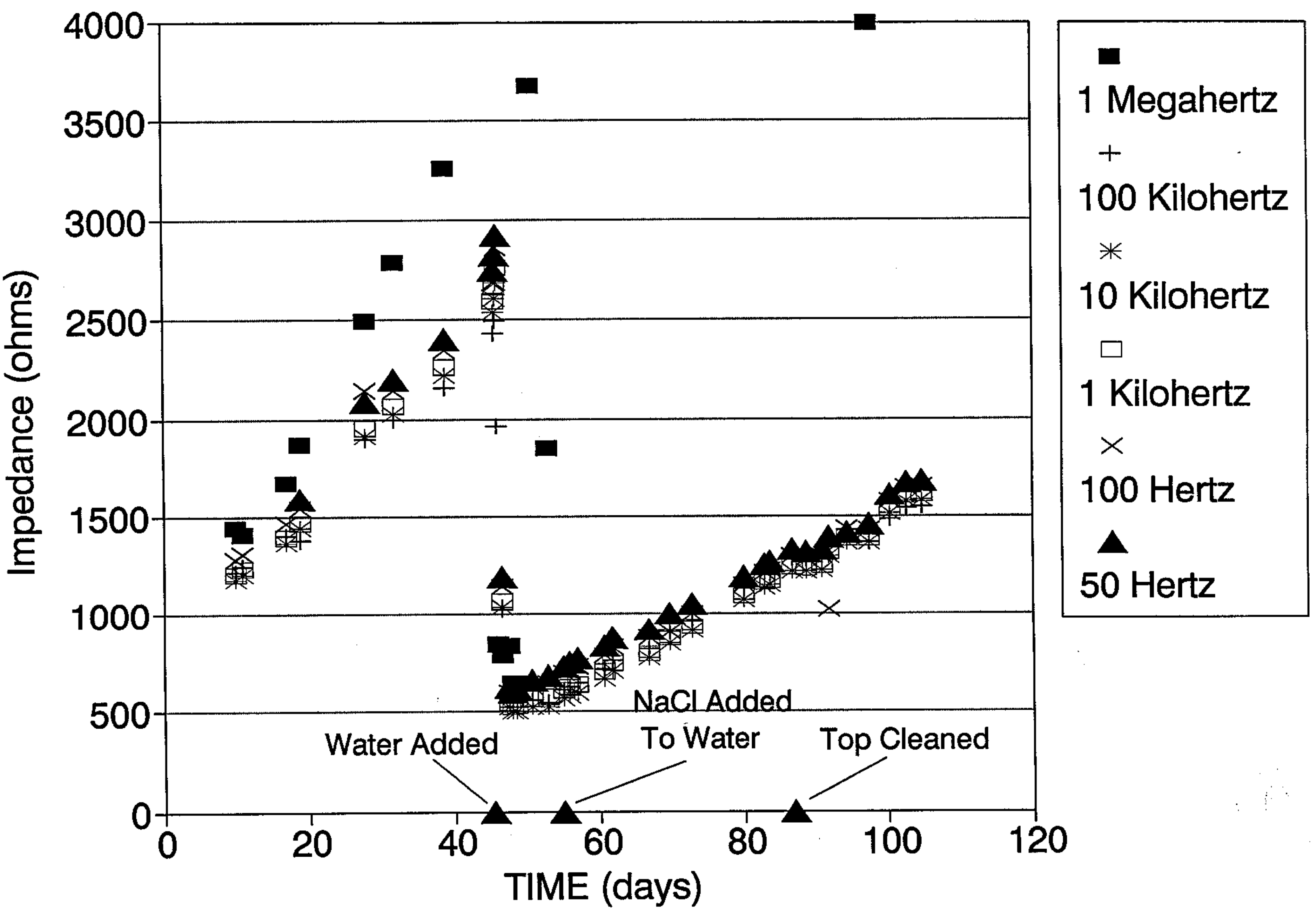


Figure 3C. SPECIMEN #1 - Stainless Steel Plates

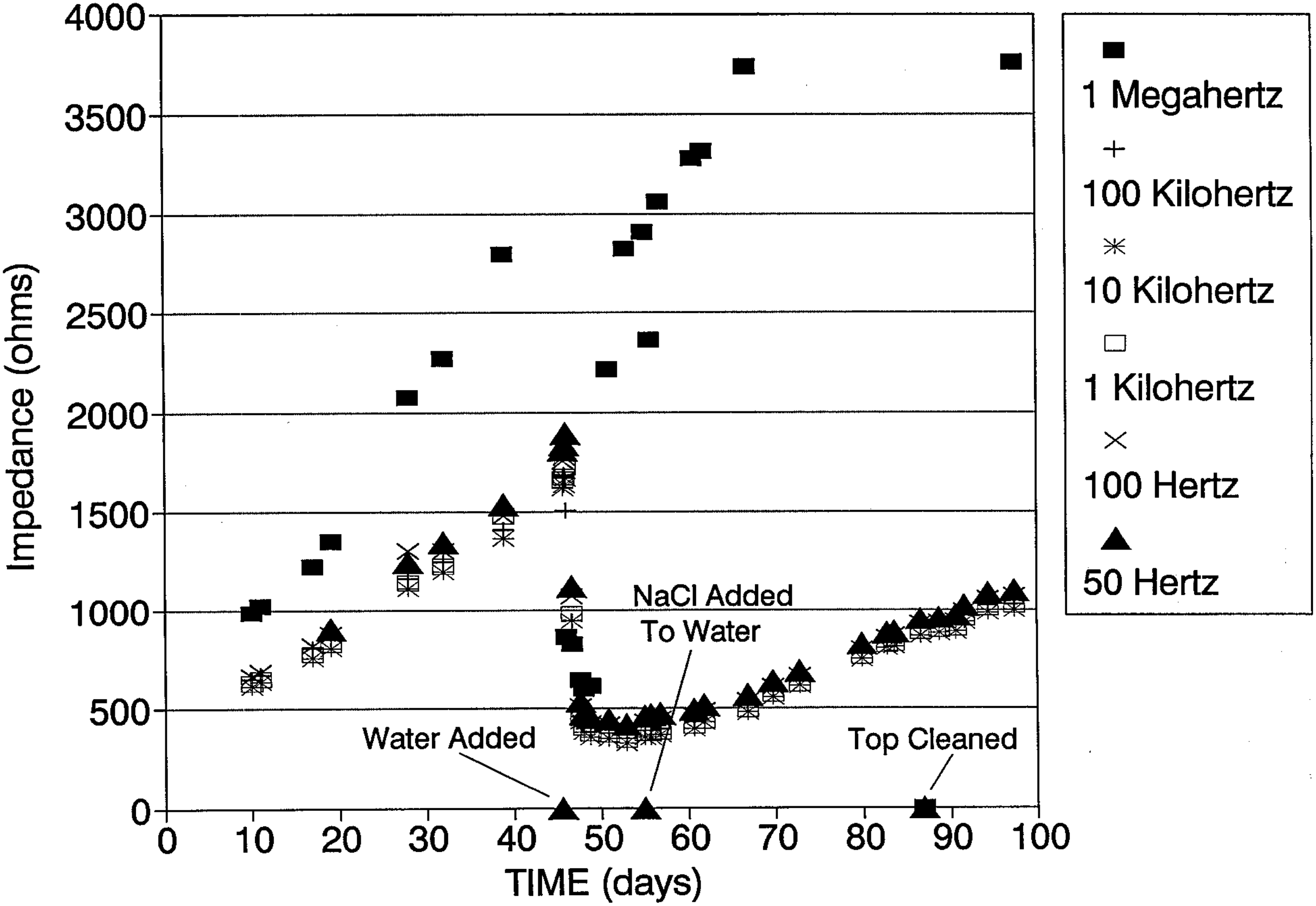


Figure 3D. SPECIMEN #1 - Titanium Oxide Plates

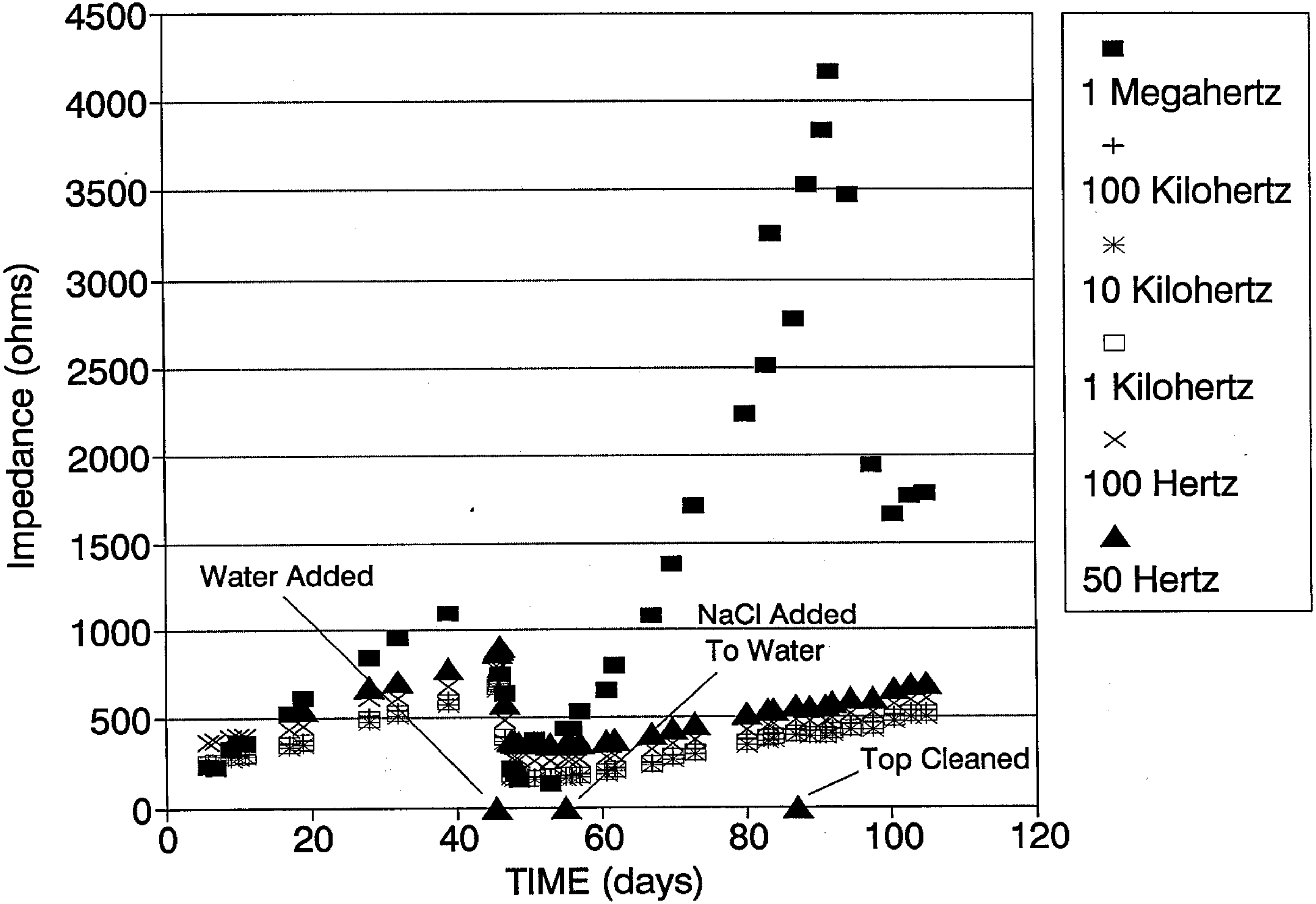


Figure 3E. SPECIMEN #1 - Stainless Steel Wires

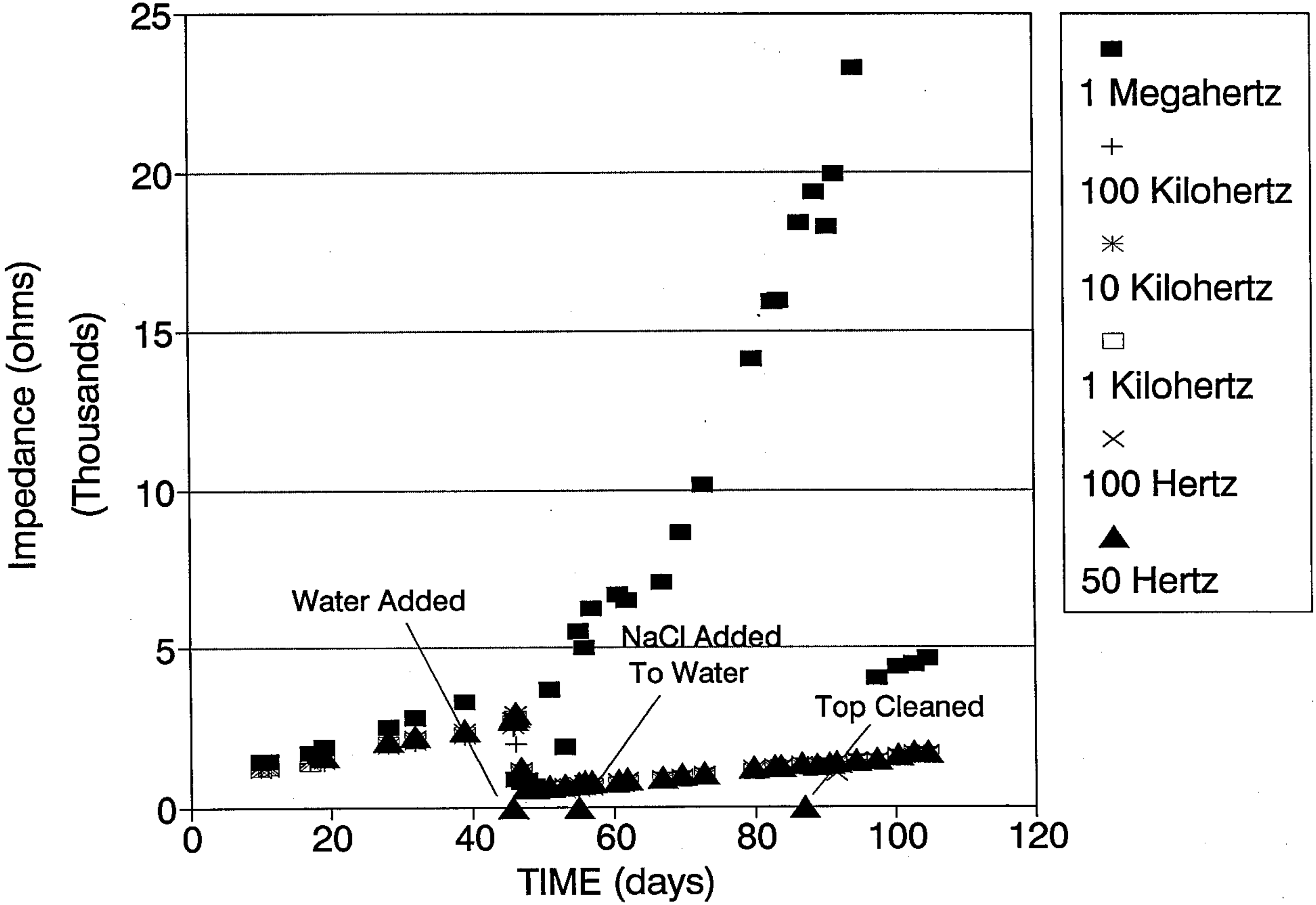


Figure 3F. SPECIMEN #1 - Stainless Steel Plates

A state of minimum resistance was achieved in about 5 days. At 55 days when sodium chloride was added to the water to form a saturated solution, it was expected that there would further decreases in the impedance, but, as can be seen, the opposite occurred; for all the lower frequencies there was a gradual increase in impedance, but the data taken at 1 MHz showed a much stronger increase (see Figures 3E and 3F) which continued until the surface was washed and dried. Clearly, the overall behavior was very complex, and is far from being understood.

Late in the period, test specimens were made for evaluating wicking materials with which to simulate cracks in the concrete slabs; data from these tests were needed before the main specimens could be prepared. In parallel with these tests, we were simultaneously evaluating methods of mounting the thermistors in order to prevent corrosion and shorting of the sensor, by moisture or other ionic species, which would lead to false temperature measurements. A scheme was envisioned of placing the thermistors inside thin-walled tubing which could be continued to the outside of the specimens. During specimen fabrication and impregnation, the tubing would be left long enough for its ends to be kept above the curing solution and impregnation solutions. When these procedures were complete, the tubing could be cut back and incorporated underneath the thermal insulation. Several tests were needed to perfect the technique, but it was shown to be effective.

Task 2 contained the bulk of the work of the project, and it was in this task that we encountered some delays during this period. One problem was simply obtaining materials. Nowadays, manufacturers do not carry an inventory in many cases. As a result, we had a delay of a few months getting the thermistors from Victory Engineering. Thermistors are available from several sources. However, use of another manufacturer was impractical, since the cost would have at least doubled, as would the delivery time; Victory Engineering provided enough thermistors for the initial tests, but the bulk of the sensors were not expected until early April. They did supply the main batch within the delivery time they quoted! We had waited several months before receiving the titanium oxide ribbon samples. Acquisition of components and construction of the environmental testing chamber was under way simultaneously with the work described above.

As indicated, we had some concerns regarding the interpretation of the data from our test specimen. The additional tests which we added to the project involving soaking in salt solutions, and were designed to determine whether there was a problem in sensing chloride ions or whether the data from test specimen #1 are indicative of very interesting mechanisms in which water saturation could be used to control infiltration. These tests on specimens #2 and #3 are described in the next period.

c) Third Period 16MAR91 - 15JUN91.

The main focus of the effort in the third period was to obtain data pertinent to the design of the main experiment and to design the experimental systems. Task 1, as delineated in the contract, was completed during this quarter, but we continued to look for additional material in the current literature and elsewhere which may be of value in the interpretation of the experiments. To this end, we studied textbooks on concrete chemistry and electrochemistry [11,12].

Task 2 turned out to be a significantly bigger job than expected, but it was close to completion by the end of the period. The unexpected results obtained on specimen #1 complicated the design of the proposed specific tests. Contrary to expectations based on the influence of salts on the conductivity of aqueous solutions, the presence of chloride ions in the concrete was either much more difficult to detect, or the ions were not penetrating into the specimen. To try to learn more about this, and to determine an effective method of getting the chloride ions into the top one-third of the specimens, during the second period, as noted, we fabricated specimens #2 and #3; during the third quarter, we fabricated specimen series #4 and #5 for the same purpose. Experiments were carried out to explore ways to simulate cracks in the concrete.

In particular, we needed:

a) To determine what was the best configuration for the parallel wire sensors.

b) To determine what methods of introducing NaCl into the concrete were valid.

c) To determine whether chloride ions could be detected in the concrete by the measurements of impedance.

d) To fabricate and learn to use a copper sulfate half cell to measure potentials within the concrete.

e) To determine whether the proposed crack simulation in the concrete would be effective.

For specimen #2, a plastic container was used as the mold. It produced an approximately 8"x8"x2" block of concrete (Redimix) which had 4 stainless steel parallel wire sensors each located in a quarter-width strip of the specimen. A wooden frame was placed inside the container so that its lid was supported when the interior was evacuated. On top of the specimen, moats were built which allowed the four regions which contained the sensors to be soaked; the fluids used were pure water, 0.01%, 1%, and fully saturated NaCl solution over the regions containing sensors A, B, C, and D respectively. At the beginning of day 18, vacuum drying of the specimen began. It continued for 1.2 days, and then the solutions were placed in the moats and after about one hour air was admitted into the container returning it to atmospheric pressure.

The results are shown in Figure 4. In Figures 4A through 4D it can be seen that impedances increased generally during the vacuum drying, especially those measured at 1 MHz; in 4D these values went off the graph. When the solutions were introduced, all of the impedances dropped dramatically and then, over a further period of 30 days (the solutions were kept on the upper surface), they all rose significantly. It is not easy to see the specific trends on these graphs, so Figures 4E, 4F, and 4G were produced to show the relative effects of the different solutions. Immediately after soaking (Figure 4E) there are no clear differences, except that there is a stronger effect at high frequencies. After 1.75 days (Figure 4F), the difference between the effect of pure water and the saline solutions begins to show in the 30 Hz values. Thirty days after soaking (Figure 4G), a surprising result is clear. The region soaked with pure water has an impedance which is only 40% those of the other regions, and only at 1 MHz is the impedance relationship clearly a systematic function of the strength of the solution used for saturation. Apparently, the presence of the NaCl counteracts the reduction of the impedance caused by the presence of water molecules. The mechanism of this effect is not understood, and we were concerned that we could not detect the presence of chloride ions immediately after the impregnation process.

Specimen #3 was used to determine the effect of the spacing of parallel-wire sensors and whether any advantage could be gained from making simultaneous ac and dc measurements. To accomplish this, a dc source (a 1.5 volt battery) was put in series with an ac source (an oscillator with floating output). Nine stainless steel sensors were placed in the specimen, three of them with 3/4" separation, three with 1/2" separation, and three with 1/4" separation. Both the dc and ac components of the voltages across the sensors and the standard resistor were measured. Data obtained are shown in Figure 5B.

The solution of the problem of parallel conductors in a dielectric material is given in most standard electricity and magnetism textbooks. For example, Jackson [13] gives the result that the impedance between two long, parallel, cylindrical conductors of radii a_1 and a_2 which are separated by a distance d which is large compared to either radius is proportional to $\log_e(d/a)$ where a is the geometric mean of the two radii (see Figure 5A). As can be seen in Figure 5B, the impedance increases as the separation between the wires increases, but it is not highly sensitive to the separation. Thus, parallel wire sensors, of stainless steel or a similar material which resists corrosion are ideal for monitoring the conductance of the concrete; small deviations from true parallelism due to pieces of aggregate displacing the wire slightly will not cause problems. We also worked on a scheme whereby both amplitude and phase could be determined from measurement of voltages across reference, sample, and reference+sample. The method was shown to be valid, but care would have to be taken to prevent losses in the cables at high frequency.

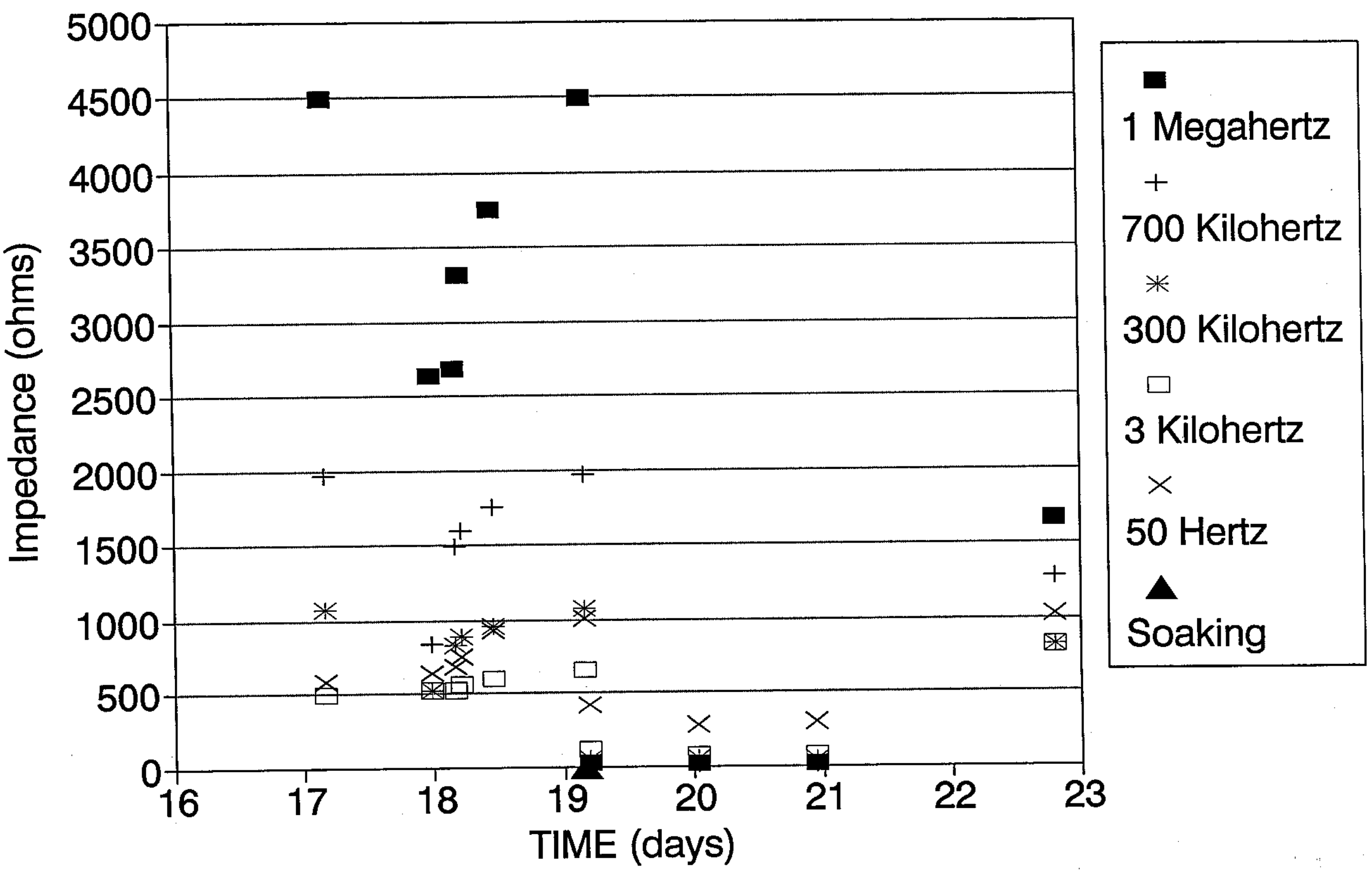


Figure 4A. SPECIMEN #2 - St. St. Wires, Set A
Saturated with Pure Water

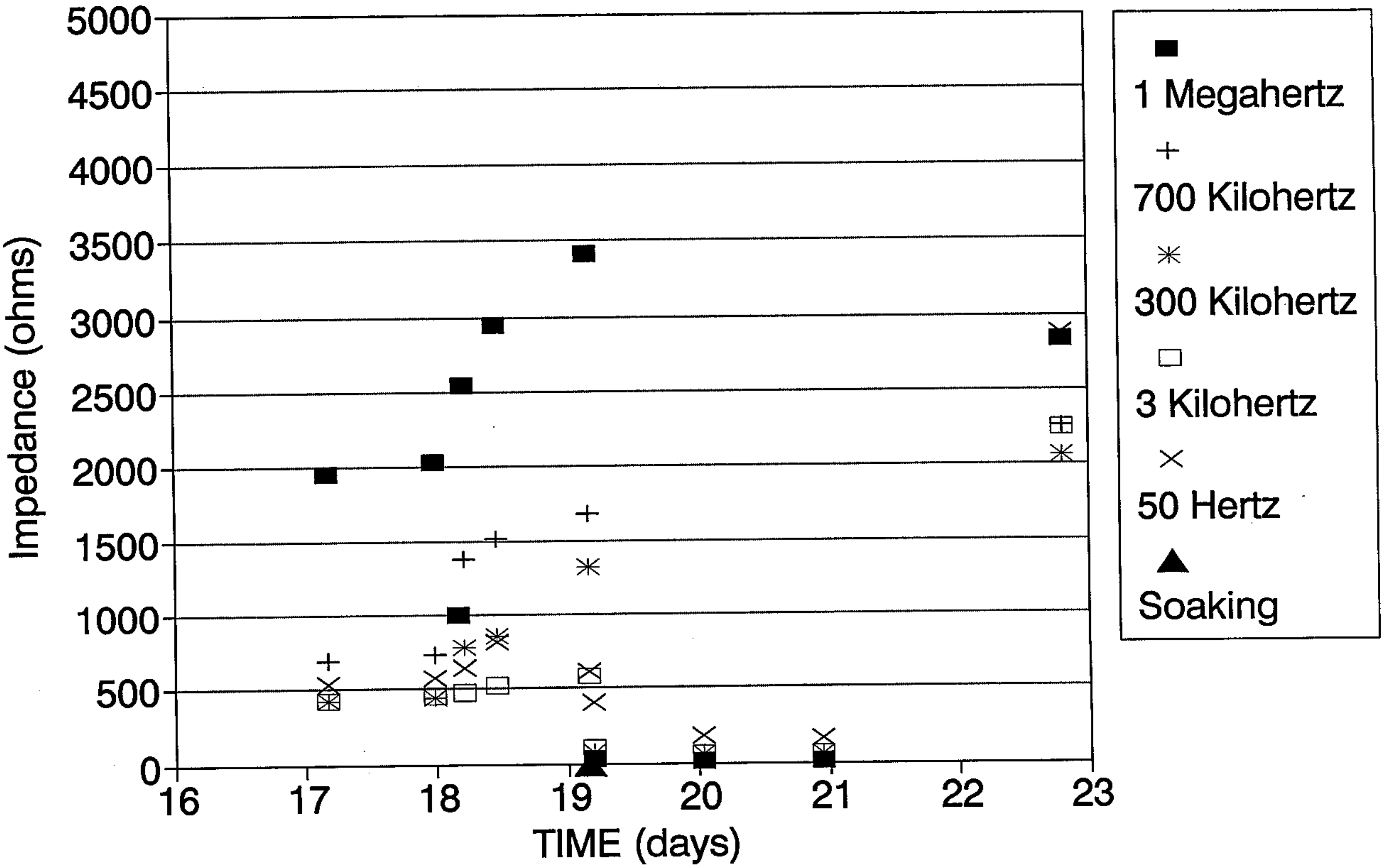


Figure 4B. SPECIMEN #2 - St. St. Wires, Set B
Saturated with 0.01% NaCl Solution

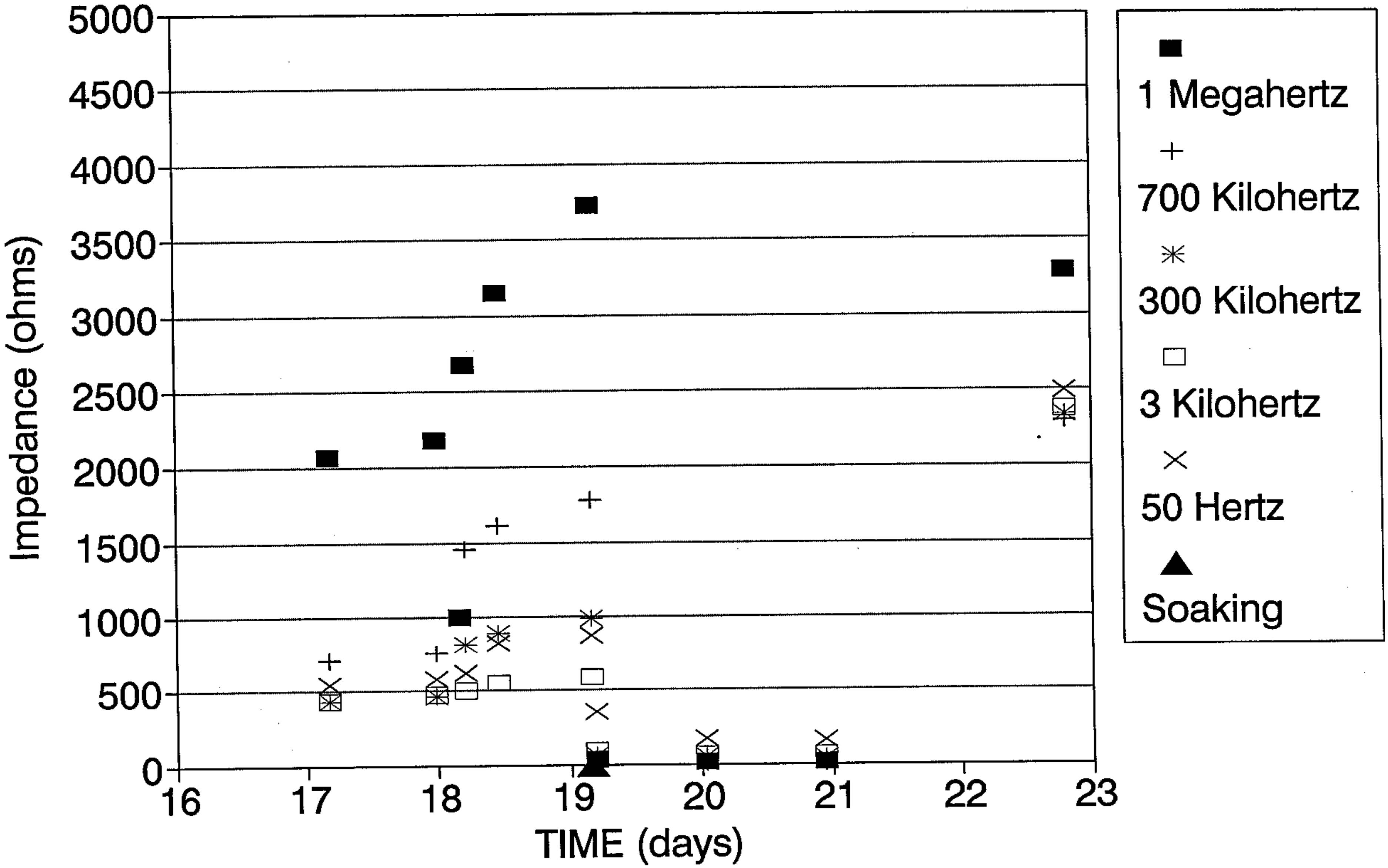


Figure 4C. SPECIMEN #2 - St. St. Wires, Set C
Saturated with 1% NaCl Solution

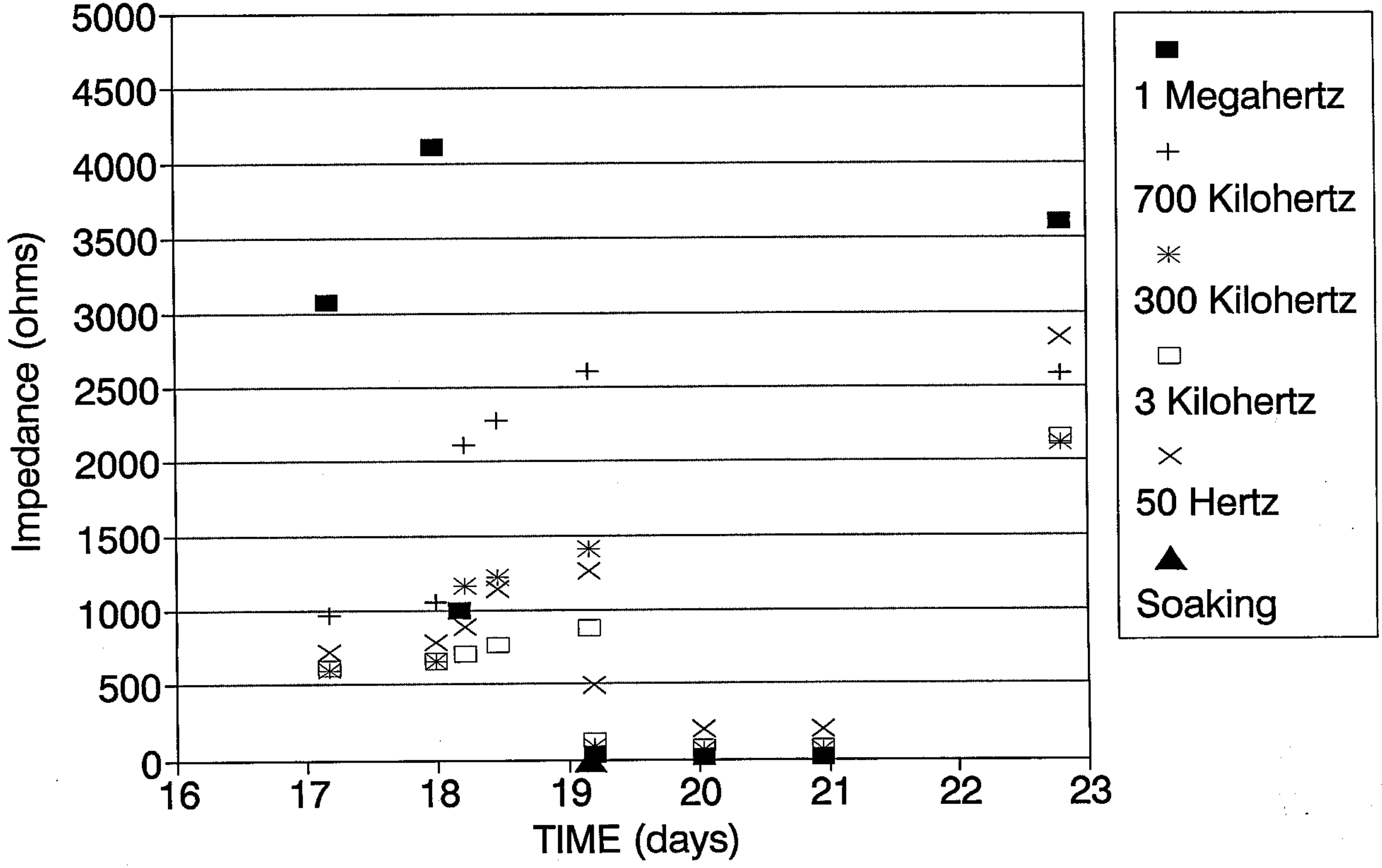


Figure 4D. SPECIMEN #2 - St. St. Wires, Set D
Saturated with 100% NaCl Solution

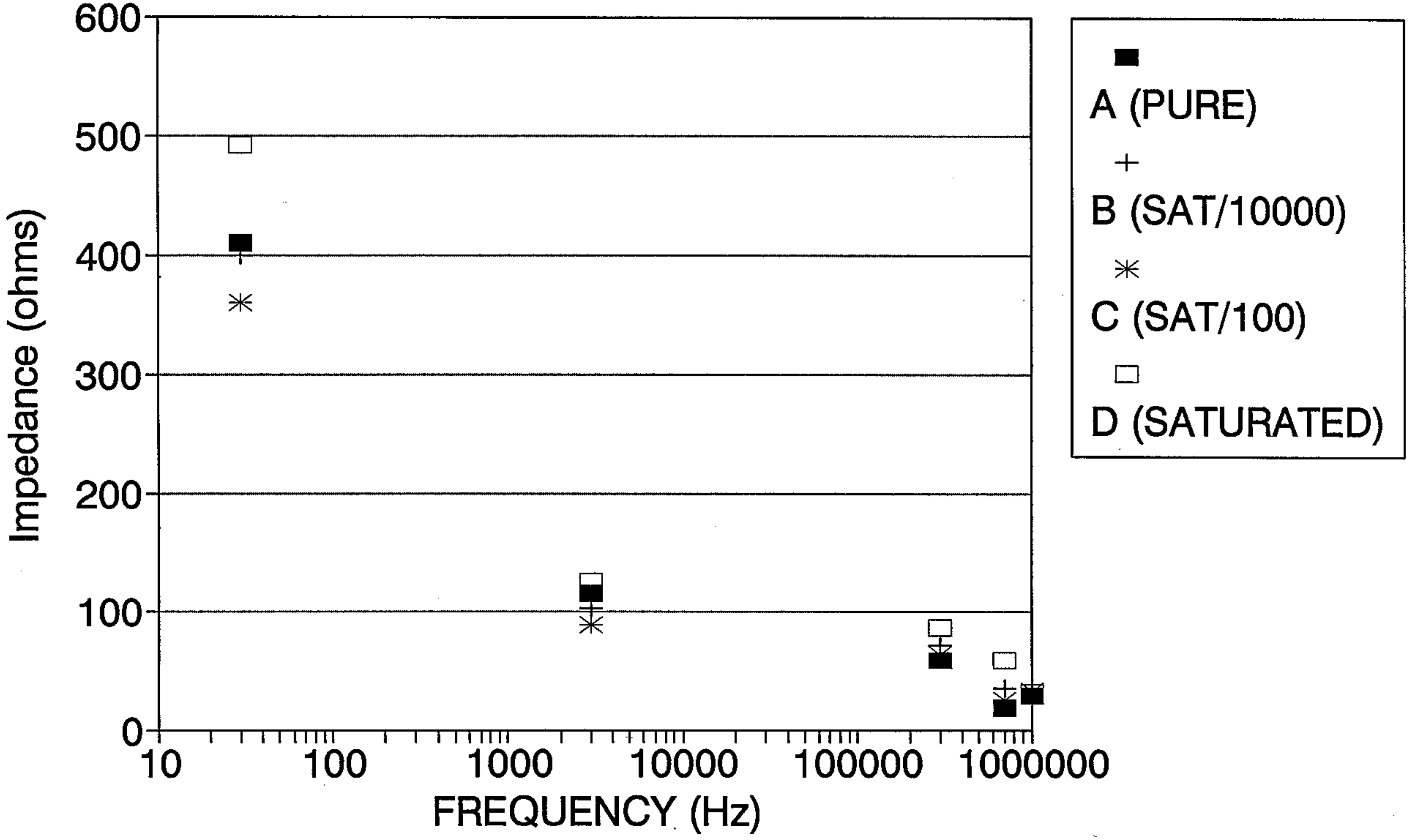


Figure 4E. IMPEDANCE V FREQUENCY
Specimen #2: Immediately After Soaking

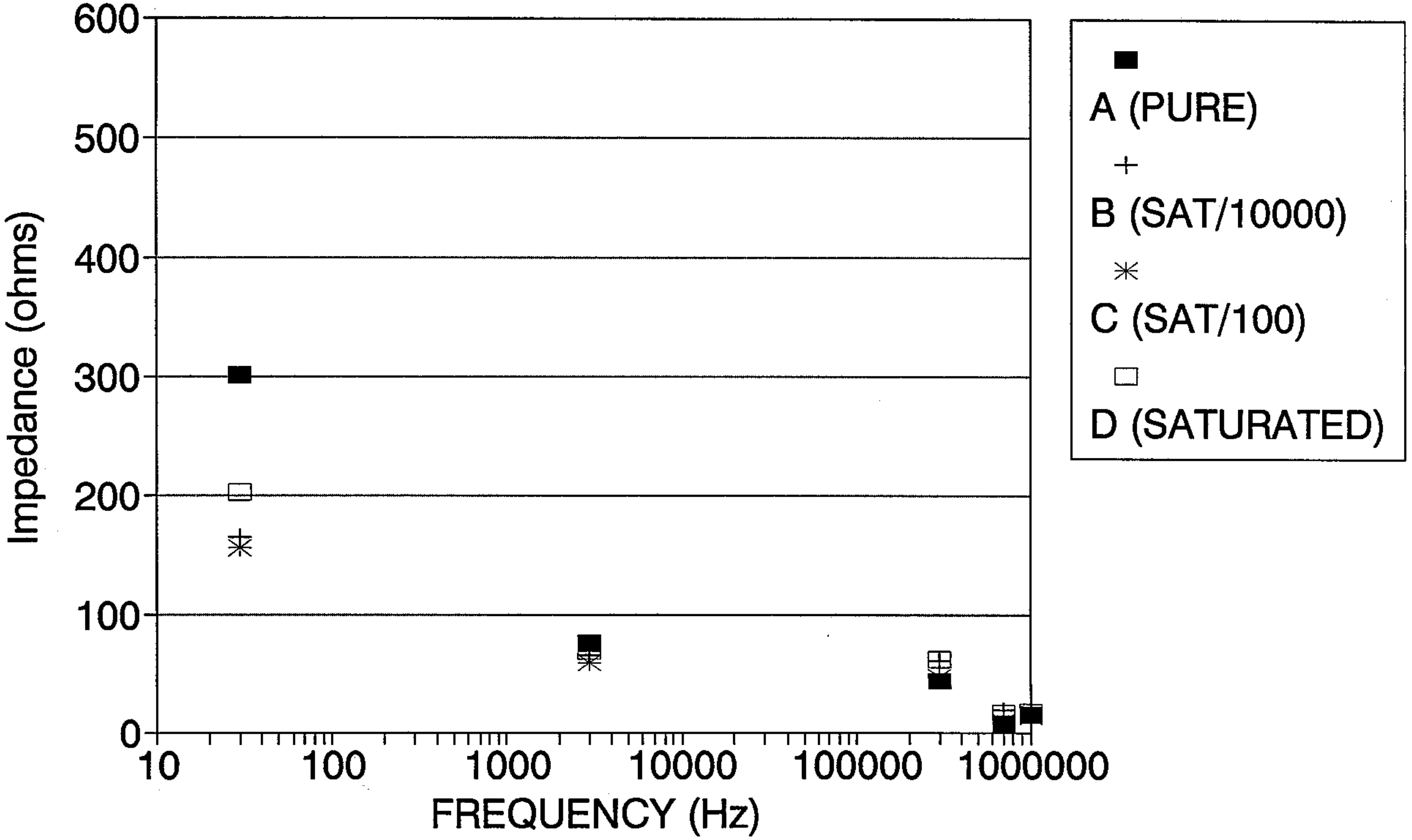


Figure 4F. IMPEDANCE V FREQUENCY
Specimen #2: 1.75 Days After Soaking

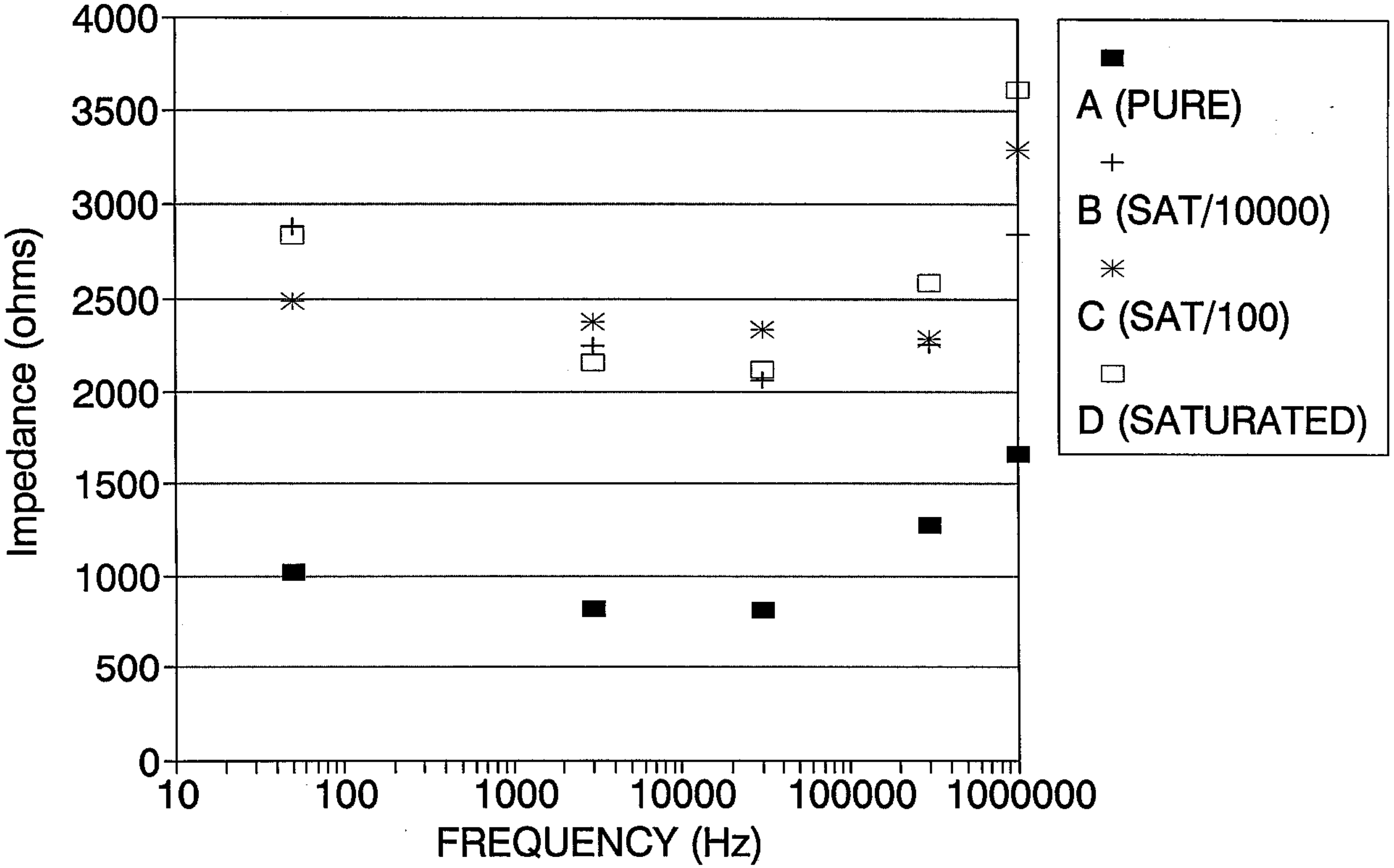
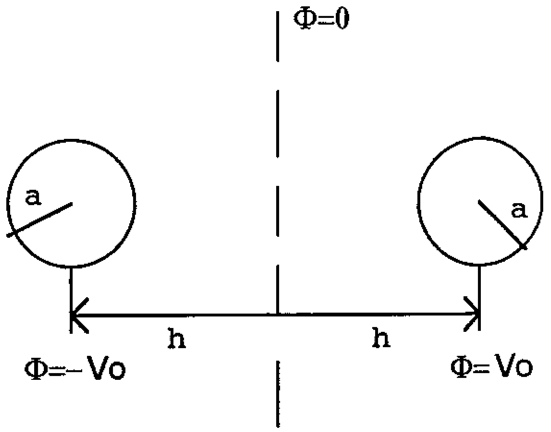


Figure 4G. IMPEDANCE V FREQUENCY
Specimen #2: 30 Days After Soaking



Two conductors separated by distance 2h. Potential is zero at the neutral plane.

$$C = \frac{Q}{V} = \frac{\pi\varepsilon}{COSH^{-1}(h/a)} \text{ (Farads/meter)}$$

$$COSH^{-1}(h/a) \approx \ln(2h/a)$$

$$\text{Let } d = 2h \Rightarrow C = \frac{\pi\varepsilon}{\ln(d/a)} \text{ (Farads/m)}$$

$$\text{Let } C_T = C \times L \Rightarrow C_T = \frac{\pi\varepsilon L}{\ln(d/a)} \text{ (F)}$$

$$\text{Total Conductance, } G = \frac{\pi\sigma L}{\ln(d/a)} \text{ (mho)}$$

$$\text{Total Resistance, } R = \frac{\ln(d/a)}{\pi L\sigma} \text{ (ohm)}$$

$$\rho = 1/\sigma$$

$$\rho = \frac{\pi LR}{\ln(d/a)}$$

Figure 5A. Analysis of a Two Parallel, Circular-Wire Sensor.

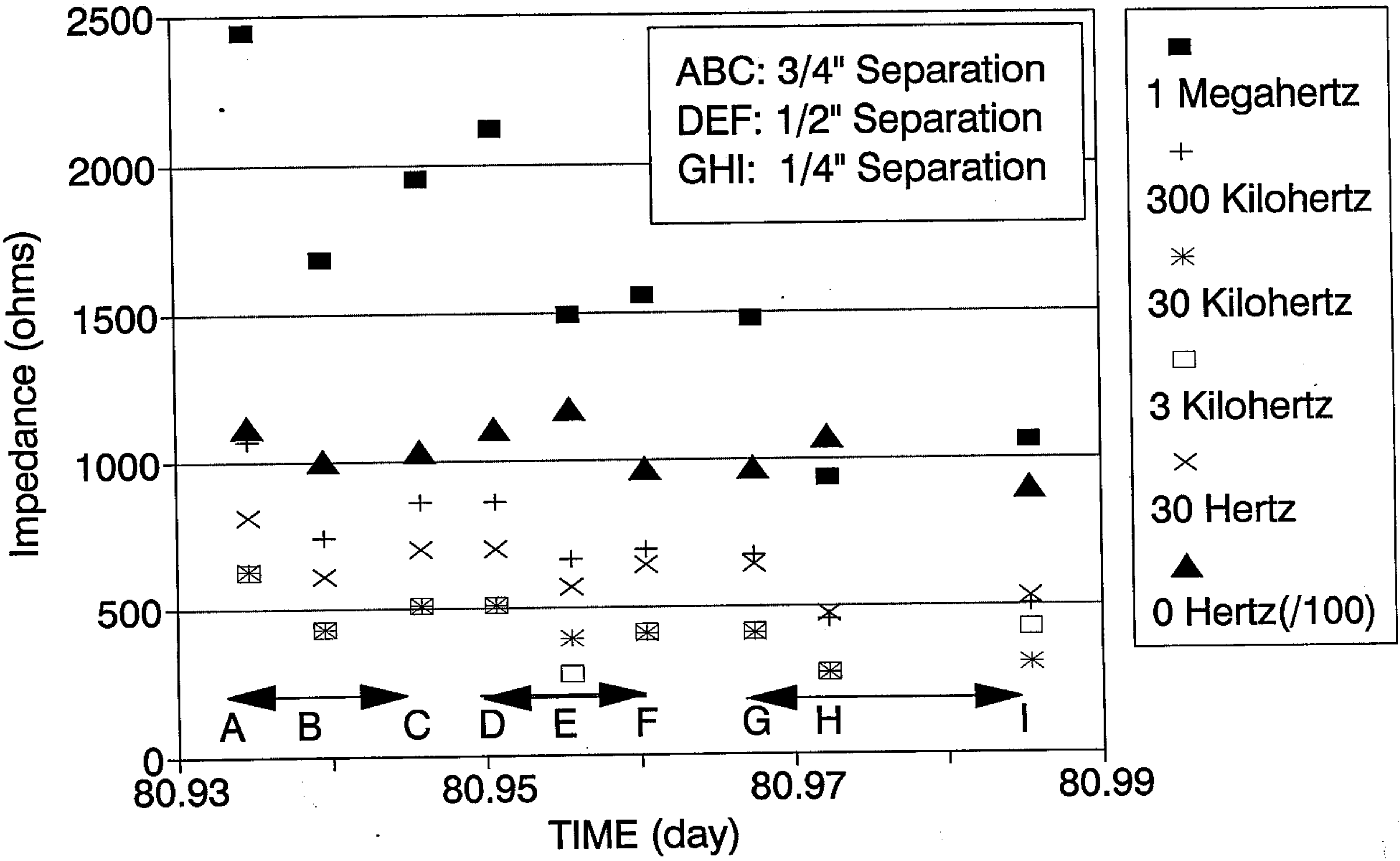


Figure 5B. SECIMEN #3 - St. St. Wires
AC and DC in series, 3 separations

Based on the results on specimens #1 and #2, further investigation of the impregnation process were needed. Hence on 29MAR91, two more sets of specimens (#4 & #5) were fabricated.

Three concrete specimens were prepared in order to test two methods of introducing NaCl into the concrete; these were designated specimens #4A, #4B, and #4C. Each specimen was approximately 4" x 4" x 1" and contained a pair of wires for impedance measurement, each 1/2" above the base of the specimens. All three specimens were made from ready-mix concrete. Specimen #4A was mixed with pure water. Specimen #4B was also mixed with pure water; the form was filled with concrete up to the level of the sensors and a layer of crystalline NaCl was sprinkled onto the surface before adding the remainder of the concrete. Specimen #4C was mixed with saline solution (10% of saturation) rather than water. All specimens were saturated with water for the first 14 days of curing, and they were then allowed to dry.

Impedance measurements were taken from 24 to 37 days after fabrication. Based on the first data taken, it appeared that there were no significant differences (that is, differences which could be used to discriminate the presence of chloride ions and quantify the number) between the three specimens. The upper surfaces were flooded with water at 32 days to see whether the presence of additional water in the concrete would have an effect. Again, there do not appear to be any significant differences. Data obtained are shown in Figures 6A, 6B, 6C, 6D, 6E, & 6F. We were coming to the opinion that either chloride ions introduced into the uncured concrete in solution must largely be bound to some element of the concrete structure under normal circumstances, and that crystalline NaCl put into the wet concrete was being incorporated into the structure without producing separate ions; this point needed to be investigated further.

Our next attempt to introduce chloride ions involved a more careful vacuum soaking of specimens with various solutions of NaCl. An apparatus had to be constructed which would allow good evacuation (down to less than 1 Torr), which would allow introduction of solutions without releasing the vacuum, and which would allow monitoring of the specimens inside the vacuum enclosure. Four concrete specimens were fabricated, each approximately 1" x 3" x 8", with a pair of sensing wires along their length; they were designated as specimens #5A, #5B, #5C, and #5D. All were made using ready-mix concrete and pure water. This was the largest size which could be accommodated by the bell jar which we then had available.

Data obtained from these specimens are shown as plots of impedance versus time in Figures 7A, 7B, 7C, & 7D. As indicated on the graphs, data was first collected with the specimens at ambient pressure. Monitoring then continued as evacuation progressed down to 0.5 Torr or slightly better in all cases. When the designated pressure had been maintained for some time, the solutions were introduced onto the top of the specimens (they were still in the plastic containers used as forms, but the concrete was not bonded to the container walls so that solution could penetrate down to the bottom of the specimen). About ten minutes after the introduction of the solutions, air was readmitted into the bell jar. Data was collected throughout the soaking process.

Specimen #5A was used first to get the details of the method worked out. It was impregnated with distilled water. The effect of the introduction of the water was clearly seen, but the water valve leaked and the data set was not as well defined as we wished. The next test used specimen #5D and it was soaked with saturated NaCl solution; this and subsequent tests went exactly according to plan. Specimen #5B was used for a repeat of the soaking with distilled water, specimen #5C was used for soaking with 1% saturated NaCl solution, and specimen #5A, which had been allowed to dry under ambient conditions, was reused for soaking at 10% saturated NaCl solution.

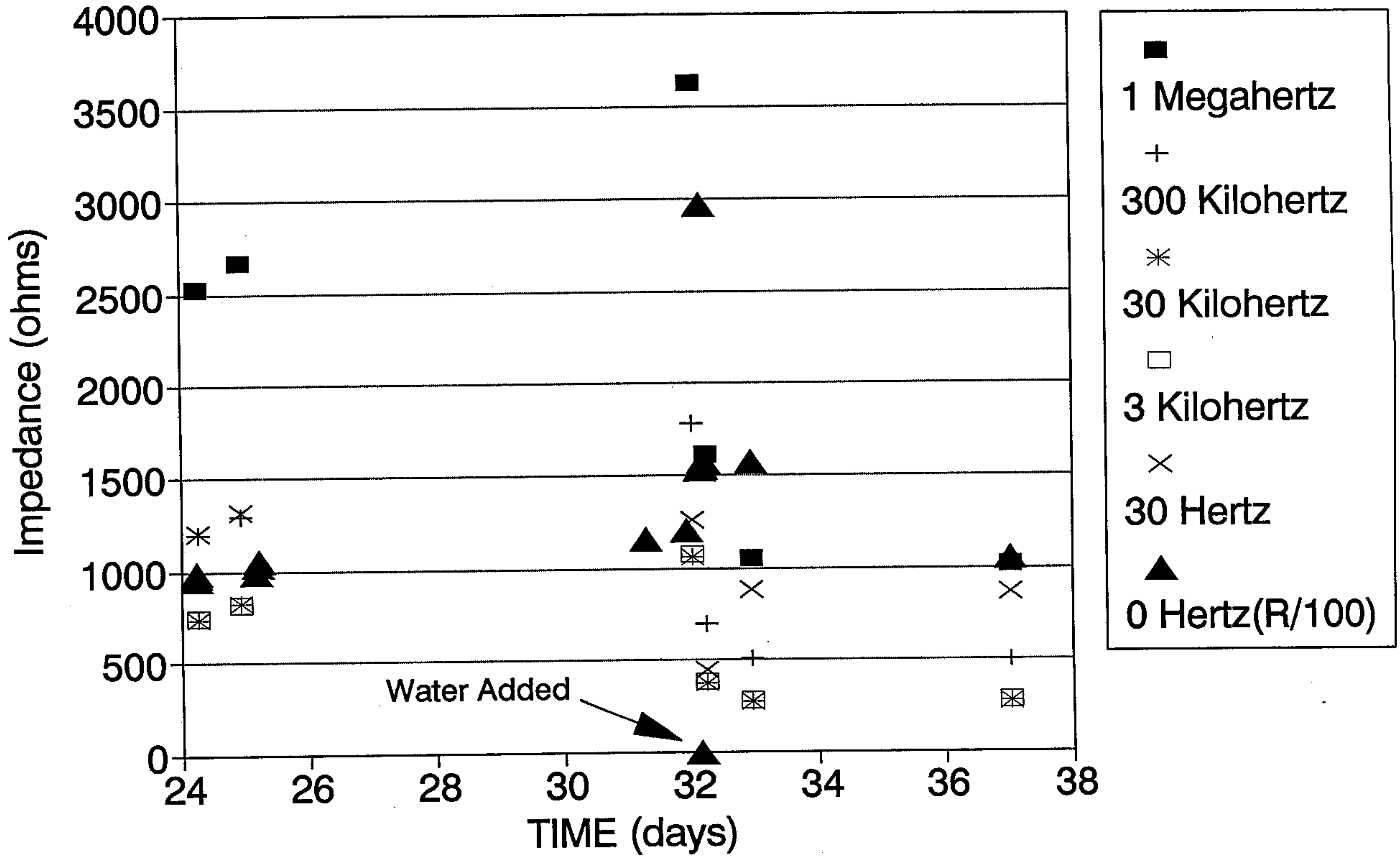


Figure 6A. SPECIMEN #4A - St. St. Wires
Mixed with Pure Water

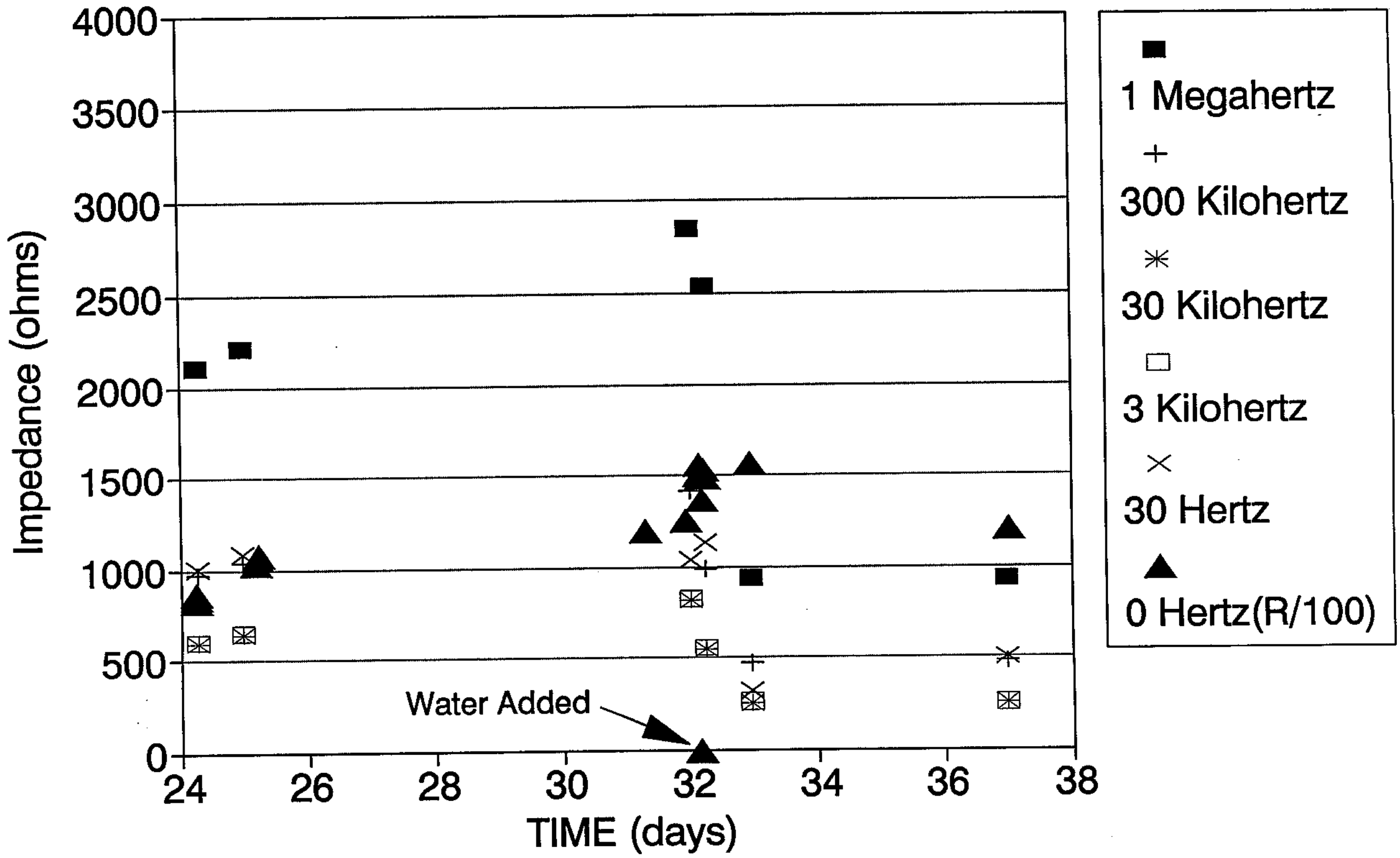


Figure 6B. SPECIMEN #4B - St. St. Wires
Layer of Crystalline NaCl

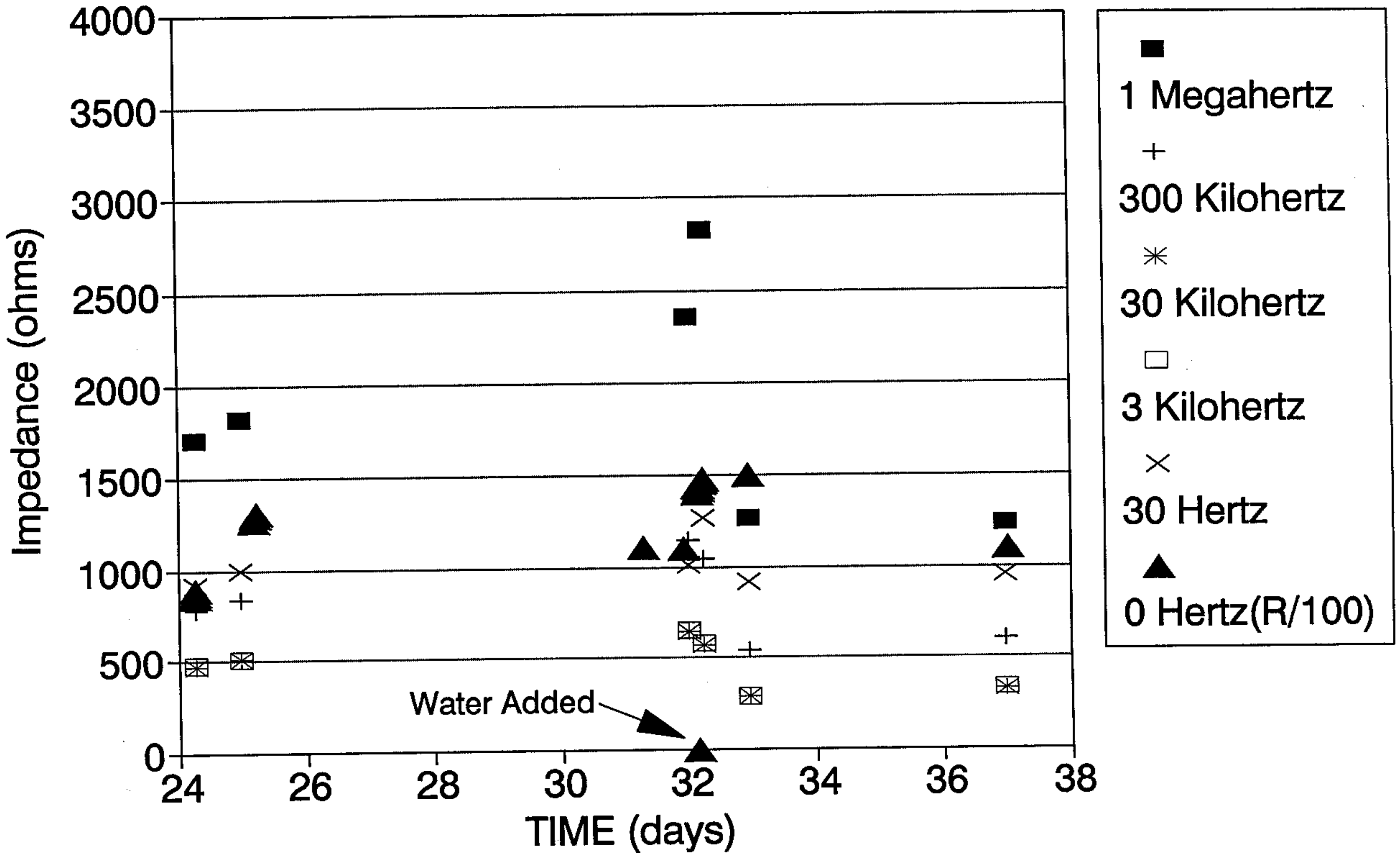


Figure 6C. SPECIMEN #4C - St. St. Wires
Mixed with 10% NaCl Solution

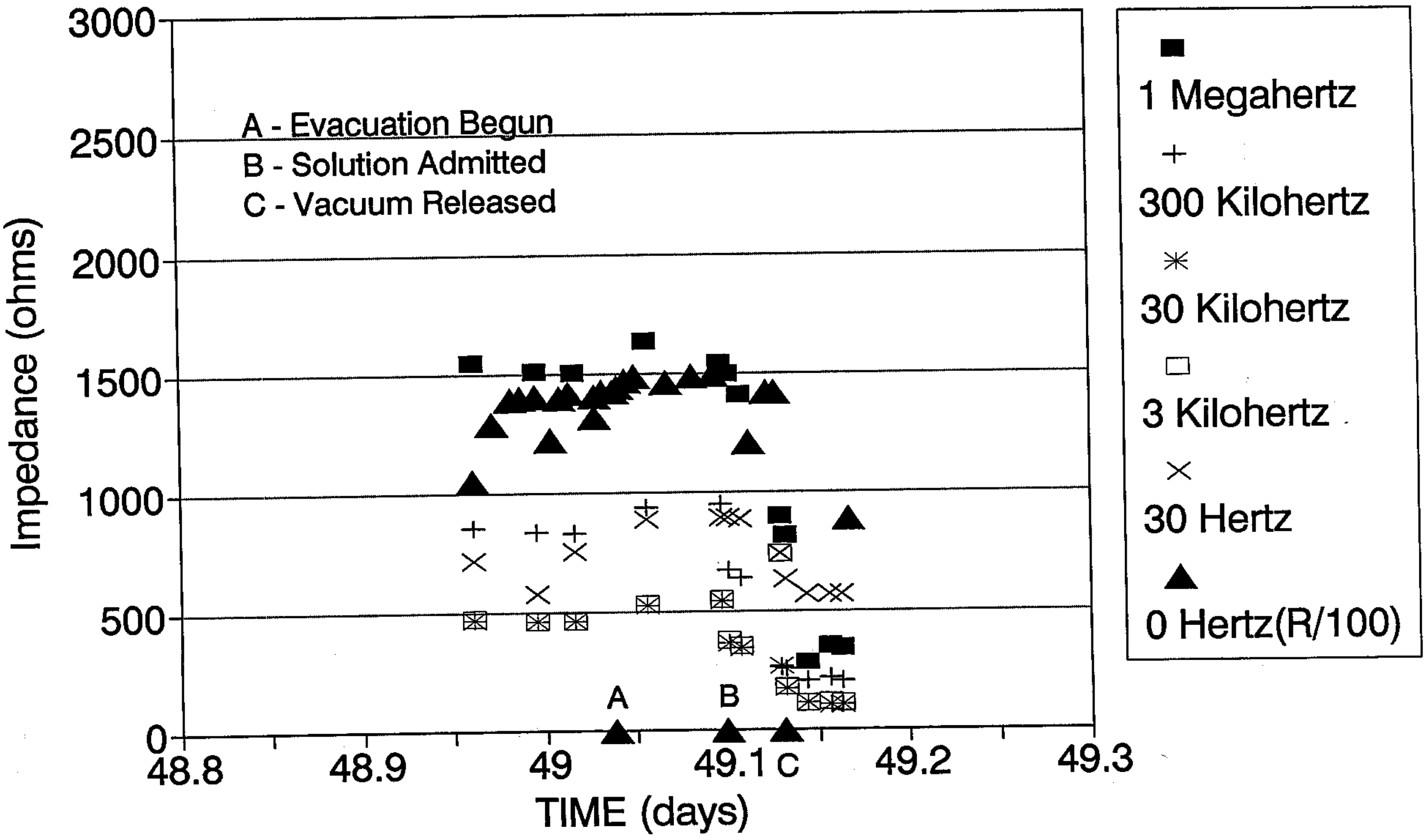


Figure 7A. SPECIMEN #5A - St. St. Wires
Vacuum soaked with 10% NaCl Solution

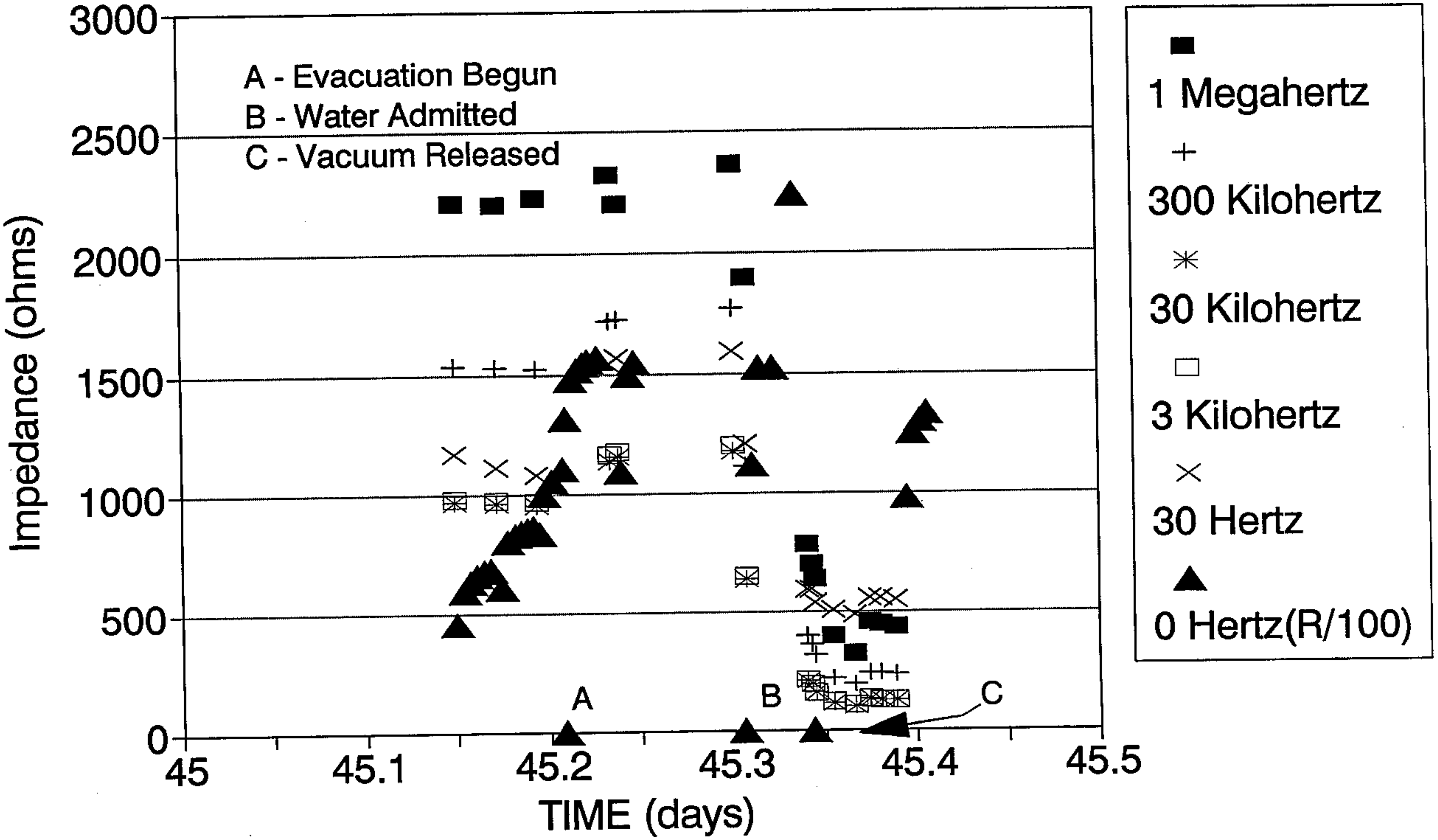


Figure 7B. SPECIMEN #5B - St. St. Wires
Vacuum soaked with distilled water

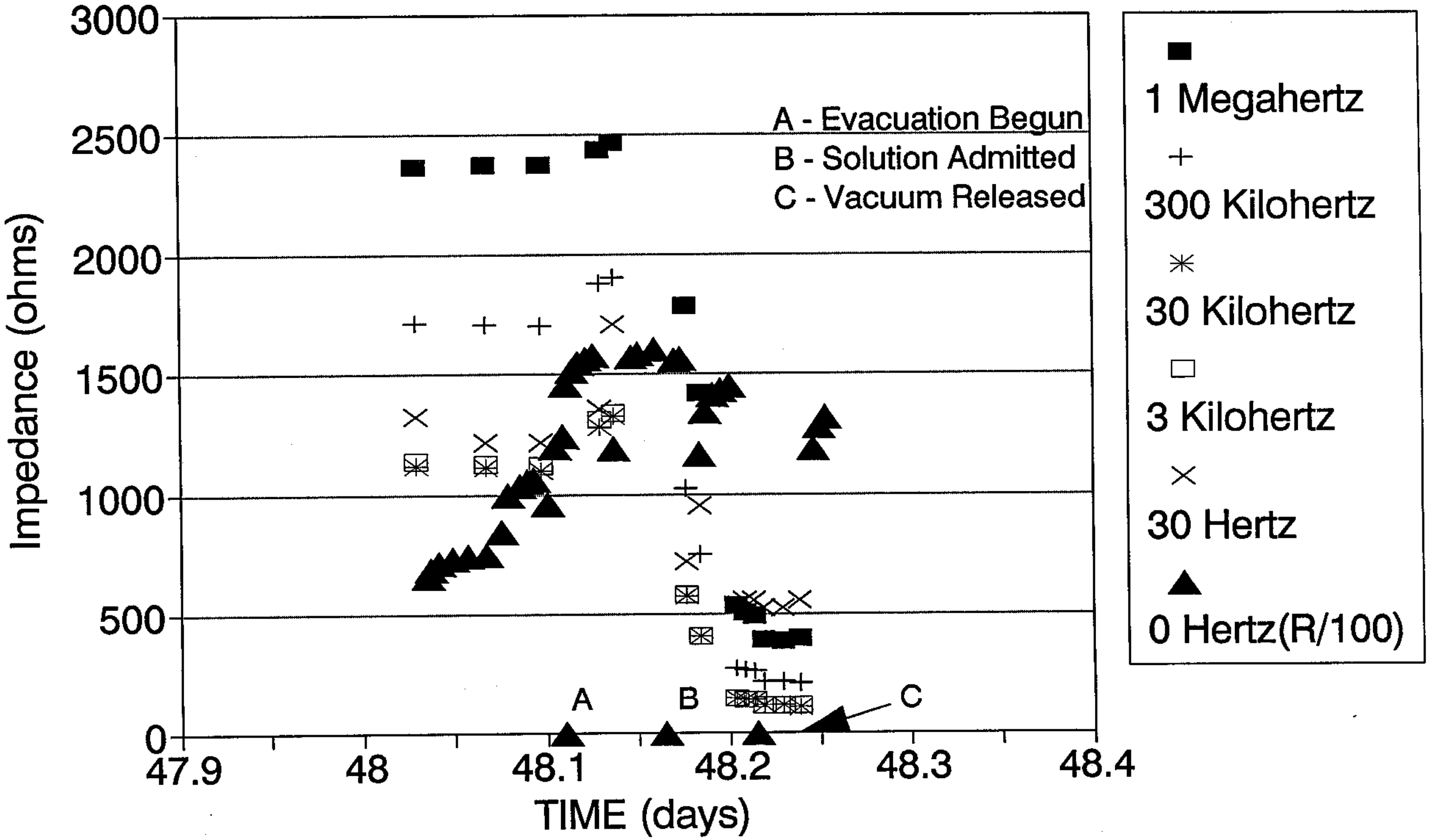


Figure 7C. SPECIMEN #5C - St. St. Wires
Vacuum soaked with 1% NaCl Solution

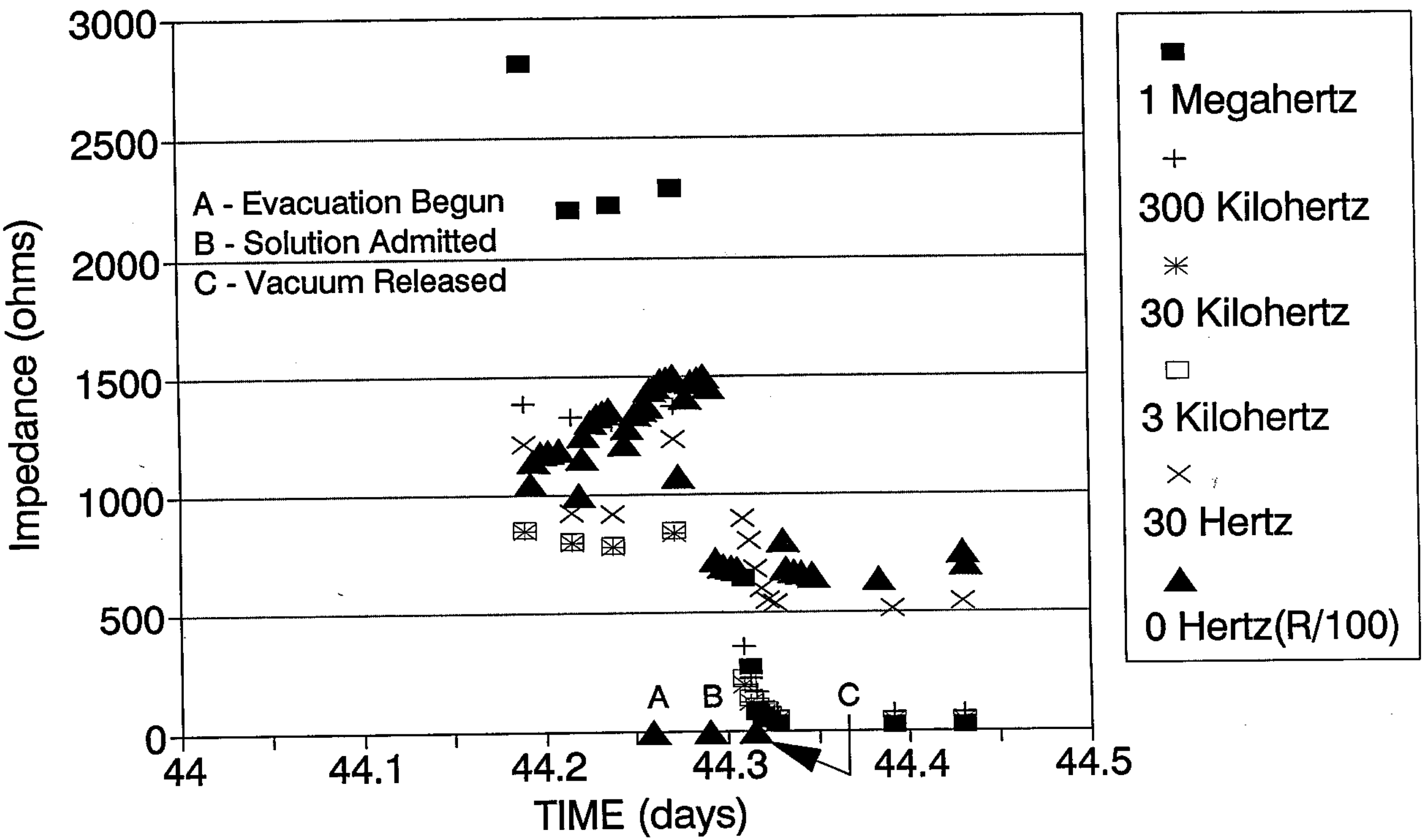
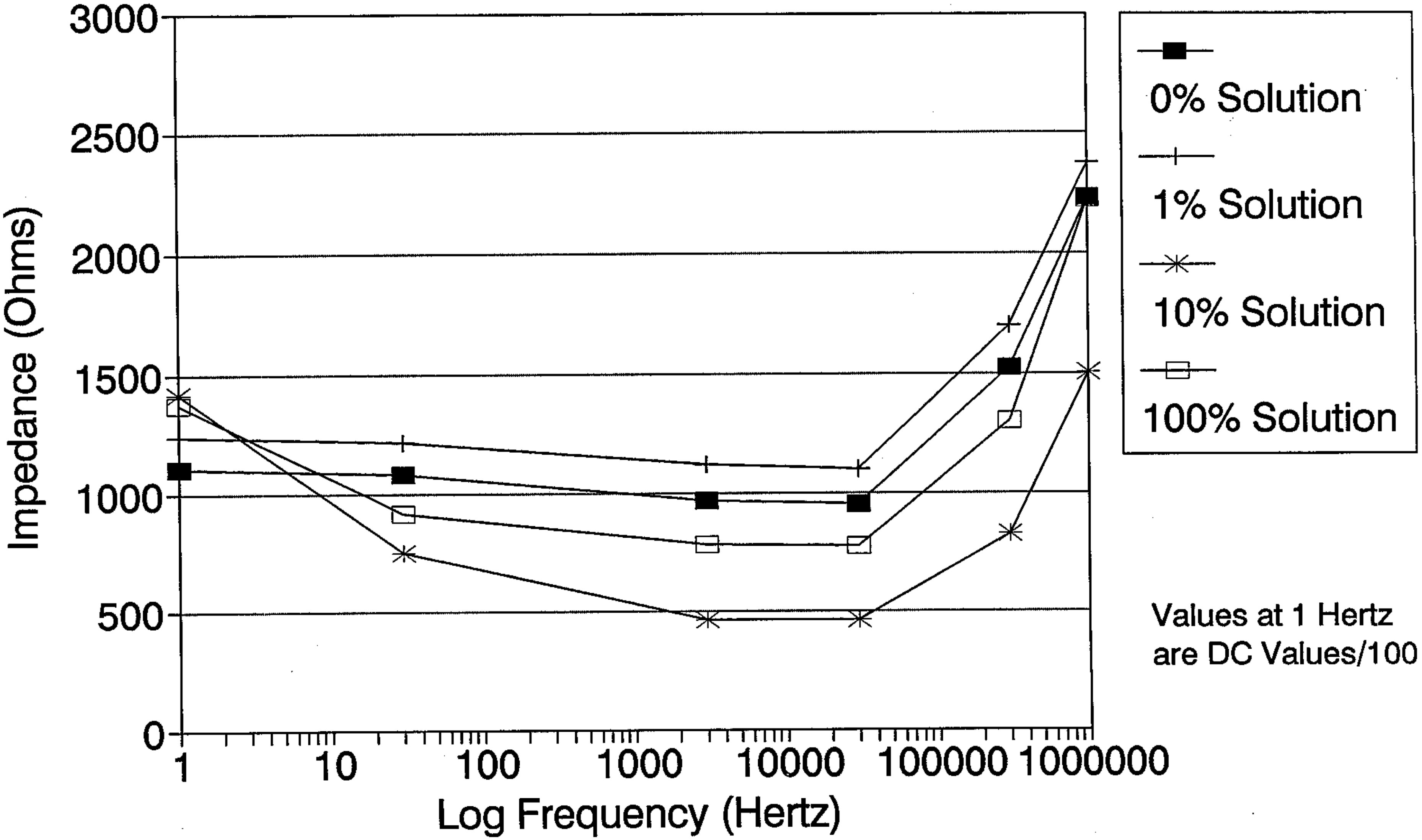
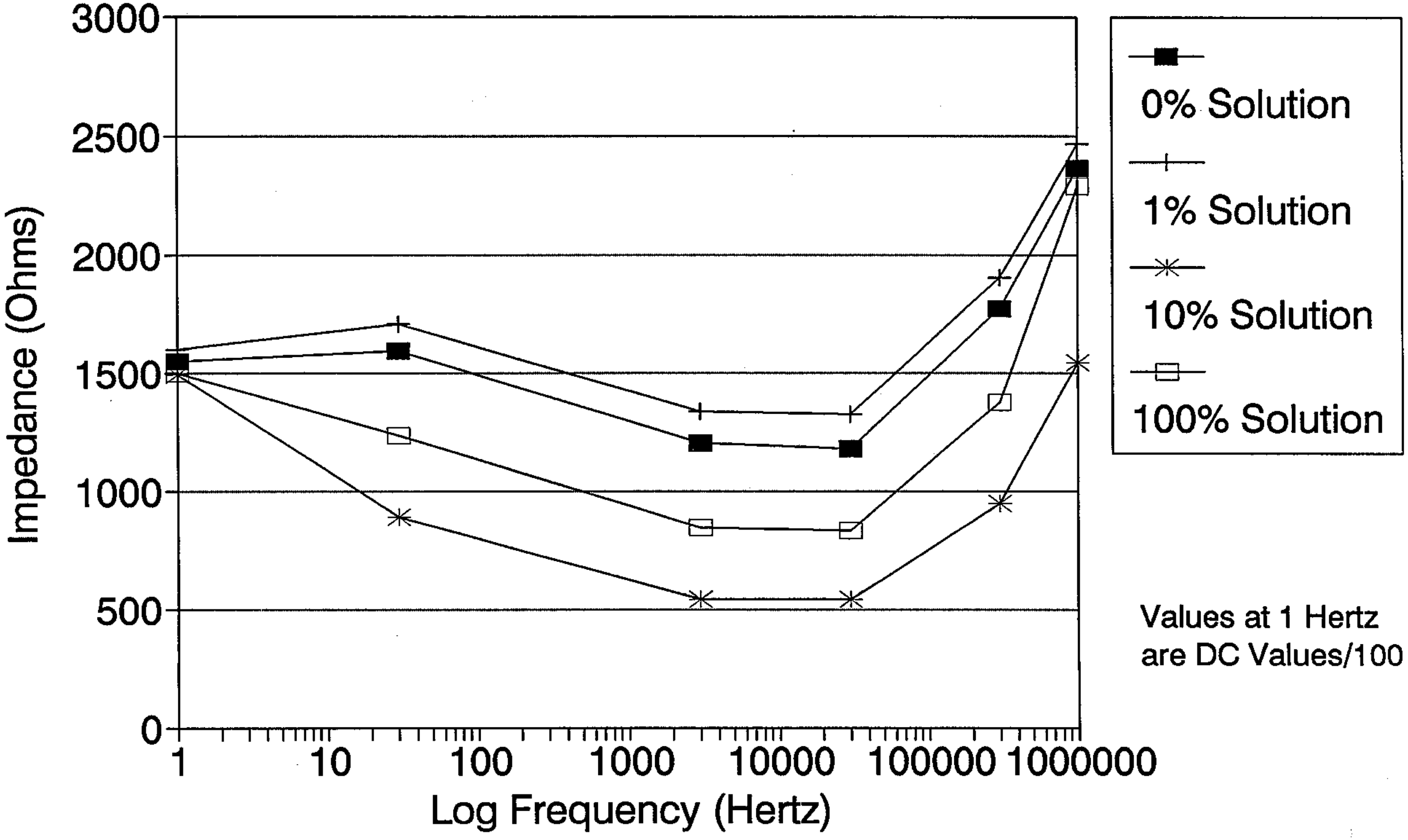


Figure 7D. SPECIMEN #5D - St. St. Wires
Vacuum soaked with saturated NaCl Solution



Values at 1 Hertz are DC Values/100

Figure 7E. IMPEDANCE v FREQUENCY Specimens 5A,B,C&D Prior to Evacuating



Values at 1 Hertz
are DC Values/100

Figure 7F. IMPEDANCE v FREQUENCY
5A,B,C&D Under Vacuum prior to Soaking

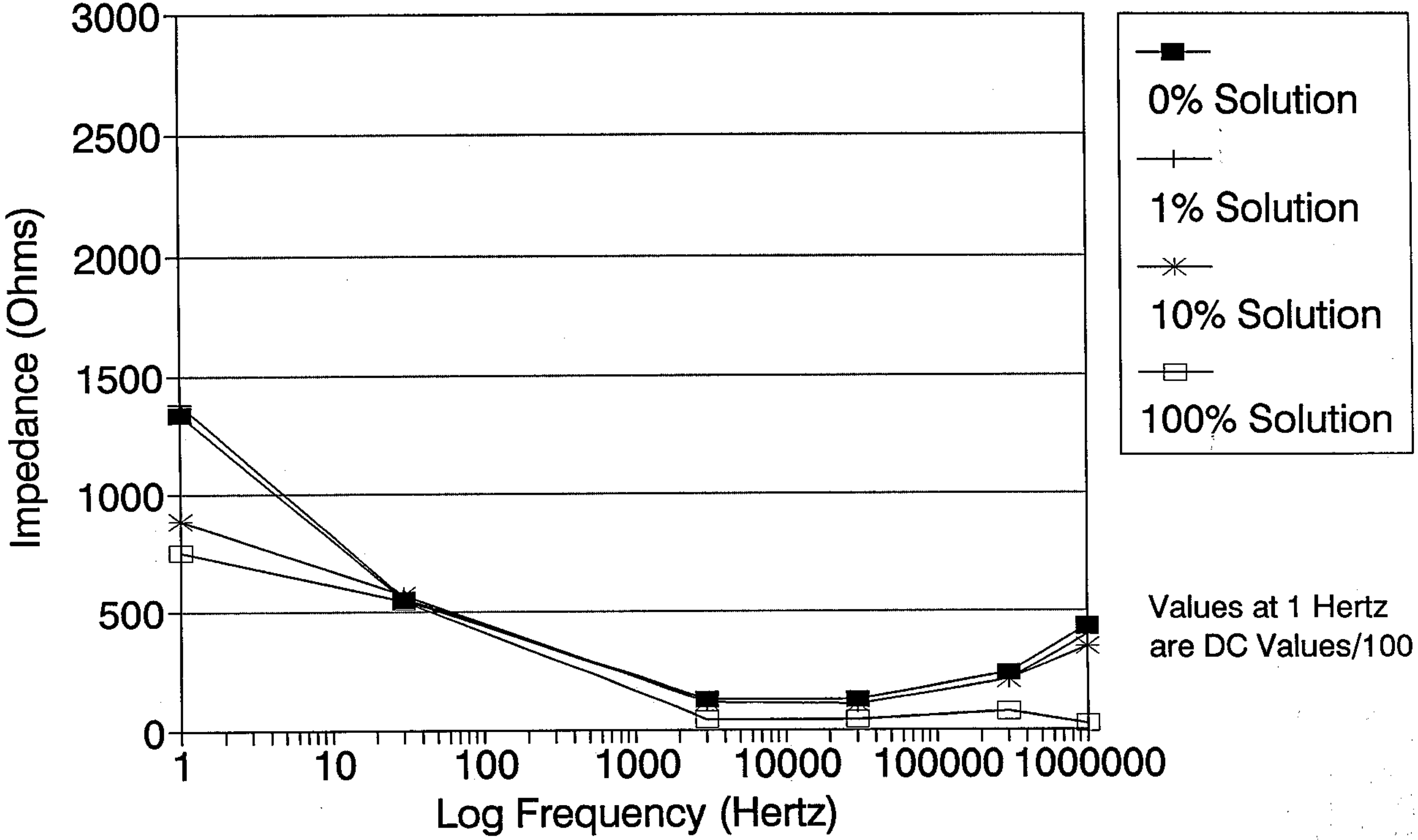
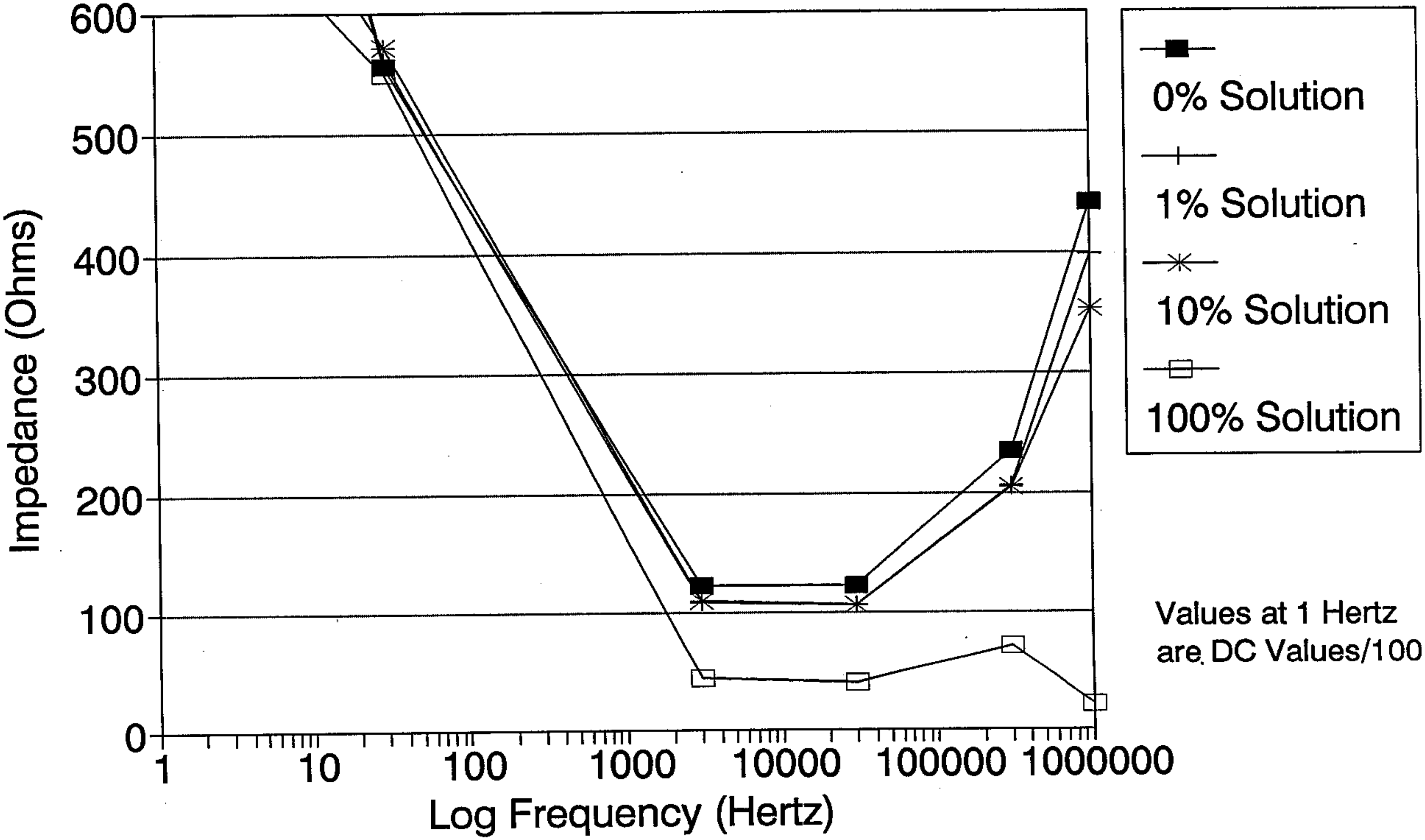


Figure 7G. IMPEDANCE v FREQUENCY
Specimens 5A,B,C&D After Vacuum Soaking



Values at 1 Hertz are DC Values/100

Figure 7H. IMPEDANCE v FREQUENCY
Specimens 5A,B,C&D After Vacuum Soaking

From Figures 7A, 7B, 7C, & 7D it is hard to compare the effects of the water and three solutions. However, when the data is replotted as a function of frequency (dc impedances, after division by 100, were entered at a frequency of 1 Hertz so that they could be presented on the same graphs as the ac impedances) for the periods "Prior to Evacuating" (Figure 7E), "Under Vacuum prior to Soaking" (Figure 7F), and "After Vacuum Soaking" (Figures 7G & 7H), some interesting differences are seen. The differences between specimens before soaking are simply due to the differences in time at which the tests were conducted, and hence the progression of the curing process. Consistency of the dc values under vacuum is noteworthy! Generally, the impedance reduces with increasing frequency up to about 10 kHz, and then it begins to increase again up to the maximum frequency used (1 MHz). After soaking, there is a well defined difference between the values for pure water or 1% solution and the stronger solutions. These results indicated that NaCl solution did penetrate into the concrete, and that saturated solution could be detected by impedance measurements at 1 MHz.

However, it was considered beneficial to also try to monitor the concentration of chloride ions in the concrete by measuring the corrosion potential at the layers of rebar which were to be placed in the specimens. To this end, we learned how to make a simple copper sulfate cell and to use it to make half-cell potential measurements. However, the device is not fully reliable in terms of leakage, and we decided to purchase a commercial cell (Tinker and Rasor, Model 3A) since they were not very expensive. Potentials measured on uncontaminated concrete were consistent with standard values. Measurements on contaminated concrete were under way.

In order to determine whether cracks in concrete could be effectively simulated in our testing environment, we fabricated two cylindrical specimens each 4" in diameter and 4" in length. One of two different felt materials (a fine green felt and a coarse gray felt provided by Mr. Johnston) were placed lengthwise down the center of the specimens. It was hoped that these "wicks" would simulate a crack. A third specimen, which was used as a control, was fabricated which contained no wick. After curing, water was ponded on top of the specimens. The water efflux rate at the lower surface was determined simply by collecting and measuring the water for a given period of time. The test apparatus is shown schematically in Figure 8. It was found that the specimen containing a green felt (baize felt) passed water at the rate of 0.00005 litres/(m-s), and the specimen containing a gray felt passed water at the rate of 0.015 litres/(m-s); the specimen without a wick allowed water to permeate at a rate of less than 10^{-9} litres/(m-s). While the gray felt is more porous than the green felt, it should be noted that the much higher rate of water diffusion through the gray felt specimen was partly due to a poor bond between the gray felt and the concrete, which allowed water seepage along a defect. Since both materials allowed water to pass through them at a much greater rate than through concrete, either would be effective in simulating the effect of a crack; the gray felt was chosen for the specimens.

All the components for the data acquisition system were received during this quarter, and we started to learn how to control the system with programming via the IEEE-488 interface. Construction of the test chamber was in progress.

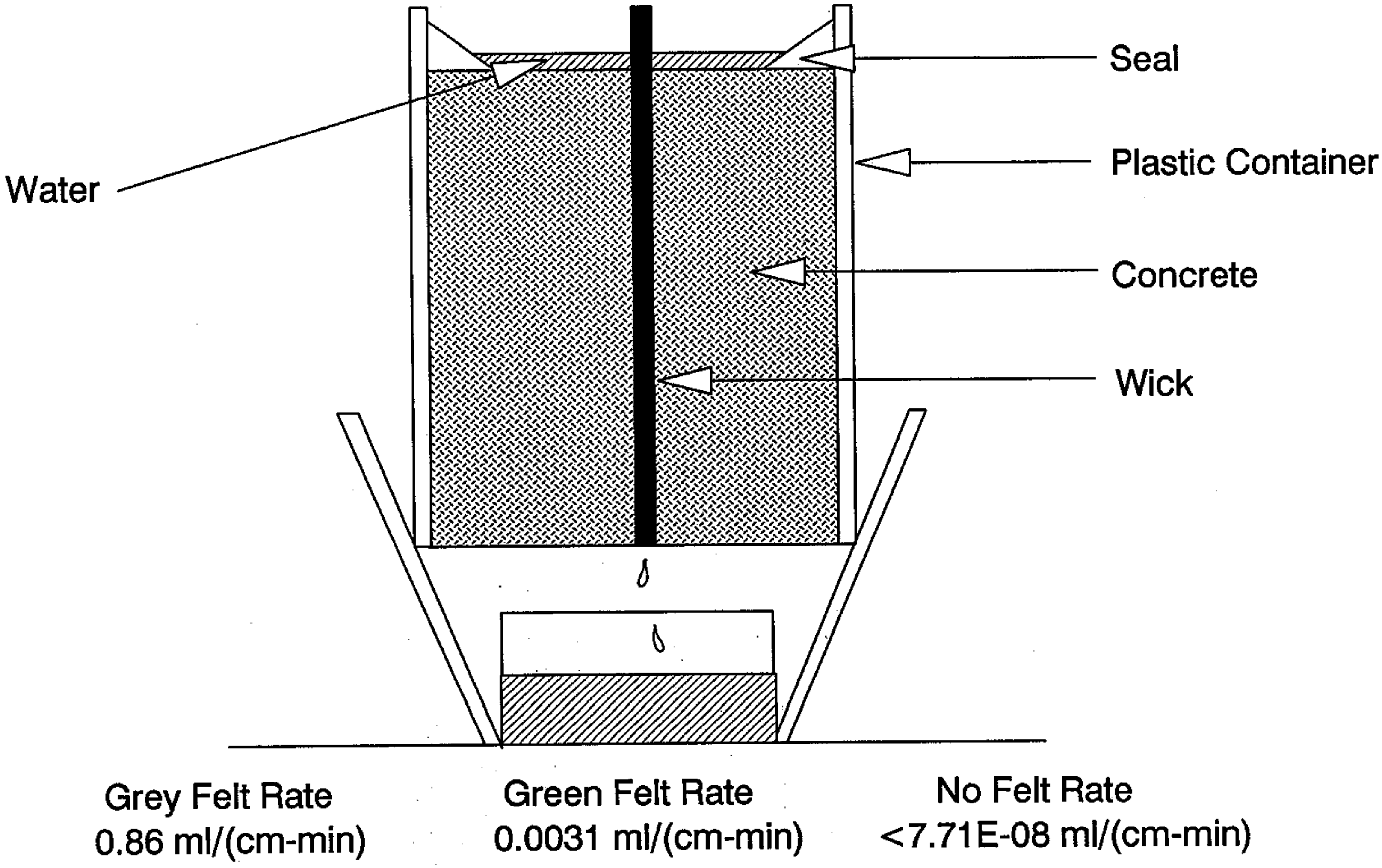


Figure 8. Test of Crack Simulation

d) Fourth Period 16JUN91 - 15SEP91.

The main focus of the effort in this period was to finalize the details of the specimen design, including simulating cracks in the concrete, and to fabricate the limestone aggregate specimens.

To complement the information obtained as part of Task 2 and presented previously, the data shown in Figures 9, 10, and 11 was obtained. Figure 9 shows the results of impedance measurements as a direct function of moisture content of concrete. Specimen #5B, which had previously been used for vacuum impregnation with distilled water, was used. The specimen was first dried by placing it in an oven at 104^{o}C for 9 hours; the specimen then had a mass of 839.1 grams. This was followed by vacuum soaking with distilled water; the mass had increased to 892.1 grams when all the external water had been removed. As shown in the Figure 9, the dc impedance did not change significantly as the mass percent of water decreased from 6.3 down to 3.2, but the ac impedance increased systematically and steadily.

After the above test had been completed, specimen #5B was used make trial measurements with a copper sulfate half-cell. The potentials were roughly the same using each wire initially, but after the sensor had been used for a dc impedance measurement, the potentials were significantly different. Also there was a residual potential between the two wires of the sensor. These data are shown in Figure 10.

A test was carried out to access the amount of corrosion which would occur on various types of wire used for the electrodes in the concrete. The results of this test are shown in Figure 11. It was apparent that none of the wires were corroding in the strong solution very quickly. Therefore, providing that fairly thick wire was used, there should be no corrosion problems. Our decision was to use nichrome wire for the primary sensors with some additional copper wire sensors. This decision was based both upon the results of the corrosion test and the cost and availability of the types of wire.

The final design for the half-scale specimens is illustrated in Figures 12 and 13. This design was approved by Mr. Johnston in July, 1991, and work was begun on the final design of the forms. After conducting a test on one form (which produced test specimen #6), the final forms were fabricated, the rebar cut and silver-soldered, the thermistors mounted, and the nichrome wire sensors installed. The final part of this task was devising a scheme to tension the wires; this was accomplished by inserting Plexiglas spacers on the wires after they emerged from the forms, and then using small wedges. We were ready to proceed with the concrete mix at the end of August, but ran into problems of availability and other commitments of personnel in the Civil Engineering Department. All the ingredients were obtained and the mix performed on 12 September, 1991. The specimens were unmolded on the 13 September, 1991 and placed in a lime cure bath. The concrete was mixed to a bridge pavement class A design with 6.0% air-entrainment. Limestone aggregate of 3/8" maximum size (Pete Lien & Sons quarry) and Wasta S.D. sand were used (Mix No. 162-45-83). These specimens were designated as #7A through #7I.

e) Fifth Period 16SEP91 - 15DEC91.

The main focus of the effort in this period was to complete the sample chamber and to get the limestone aggregate specimens ready for installation. Unfortunately, we ran into equipment problems. Both the monitor and the hard drive on the computer which was to be used to monitor and control the environmental chamber went out. Also, the IEEE-488 multimeter which was interfaced with this computer was needed for other work as well. To avoid having to share this instrument, it was decided to replace the computer-based system with a dedicated programmable temperature controller. In October, it was found that Omega Engineering produced a suitable controller at a surprisingly low price. It had the capability for "ramp and soak" programming and PID control.

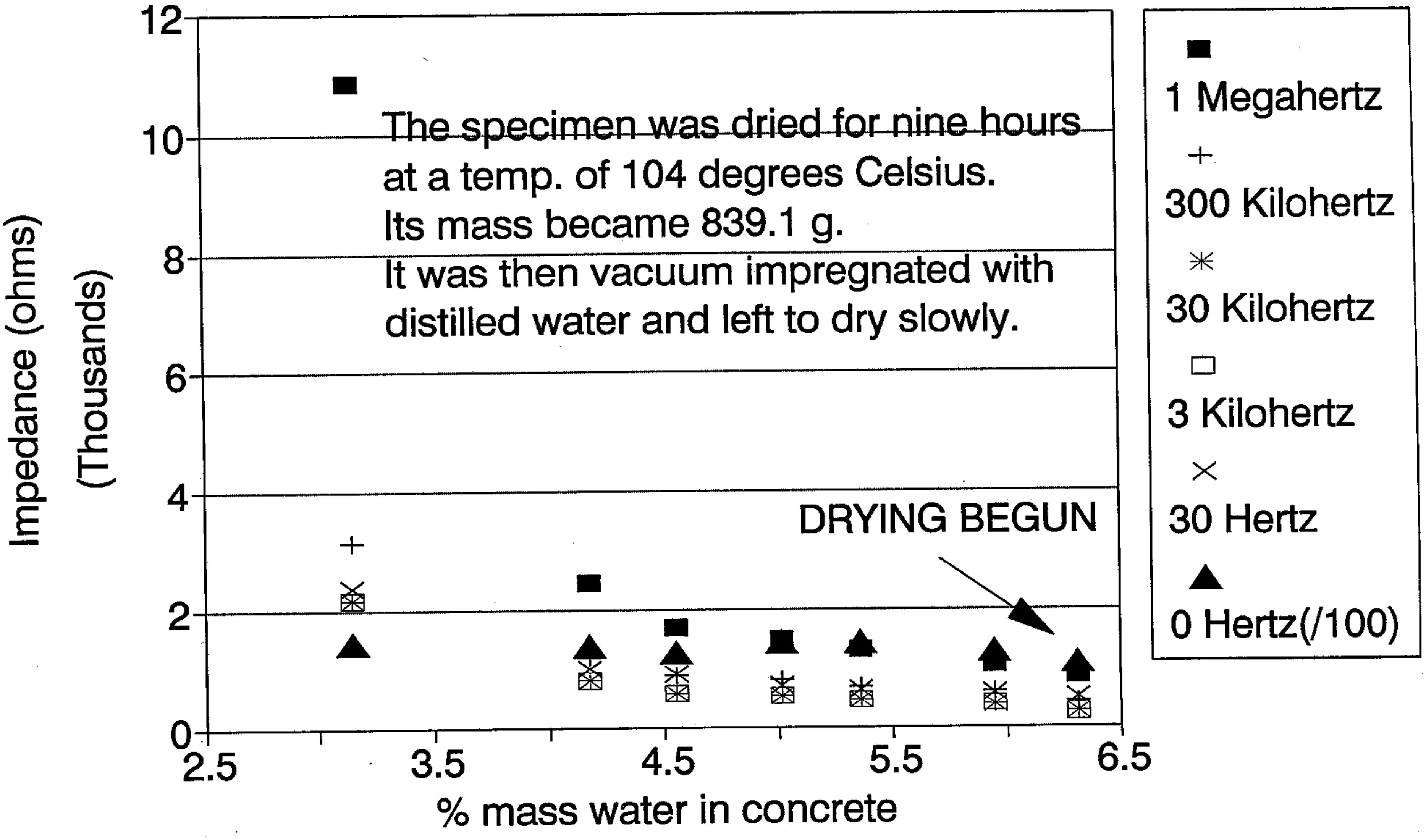
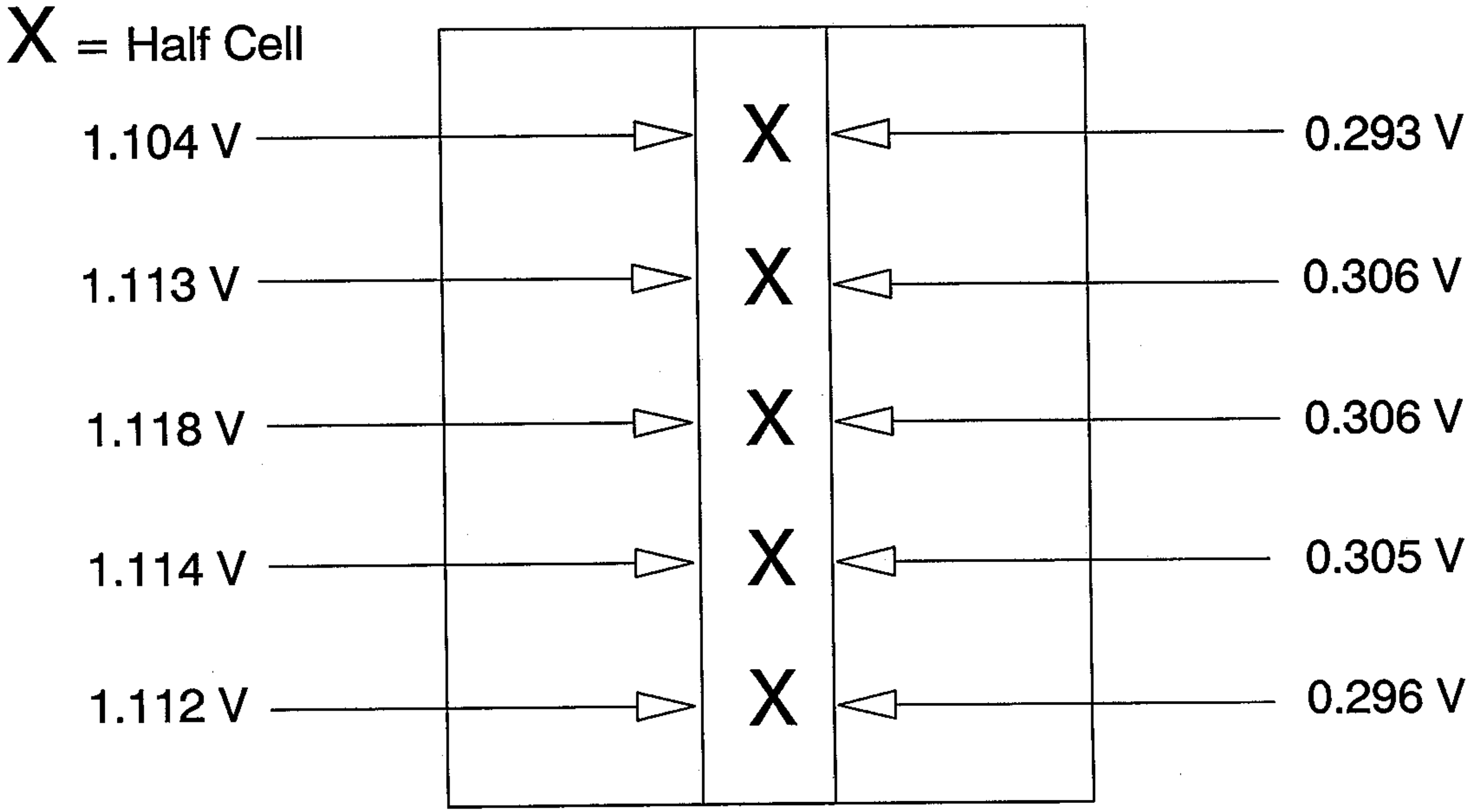


Figure 9. SPECIMEN #5B - St. St. Wires
Impedance vs % Internal Moisture



Residual potential between the wires varied in the range 1.0 V to 1.3 V.

Figure 10. Half Cell and Residual Potentials for Specimen #5B

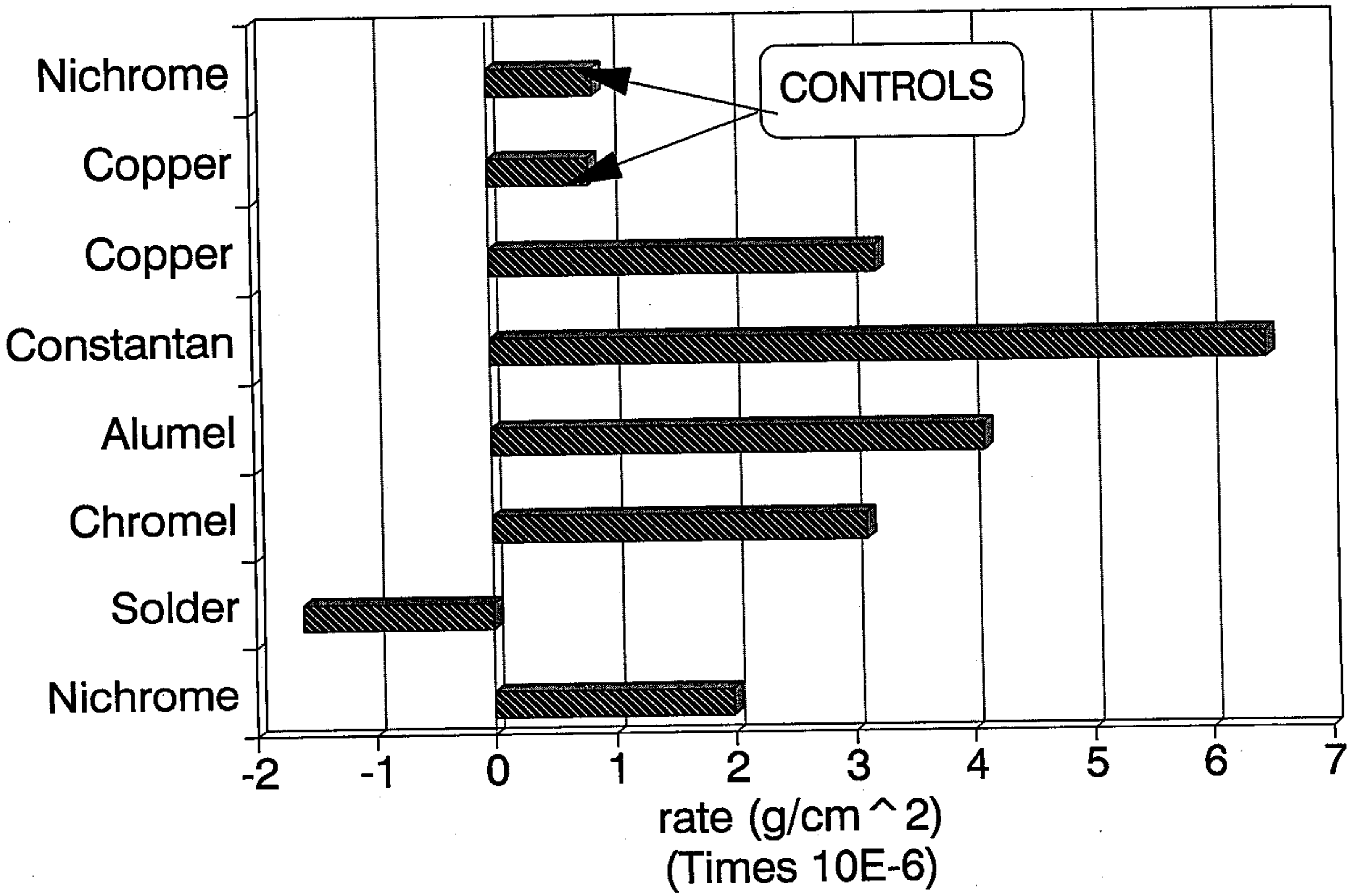


Figure 11. CHANGE OF MASS FOR WIRES

Wires in a saturated CaOH plus 3% NaCl solution for 5 days.

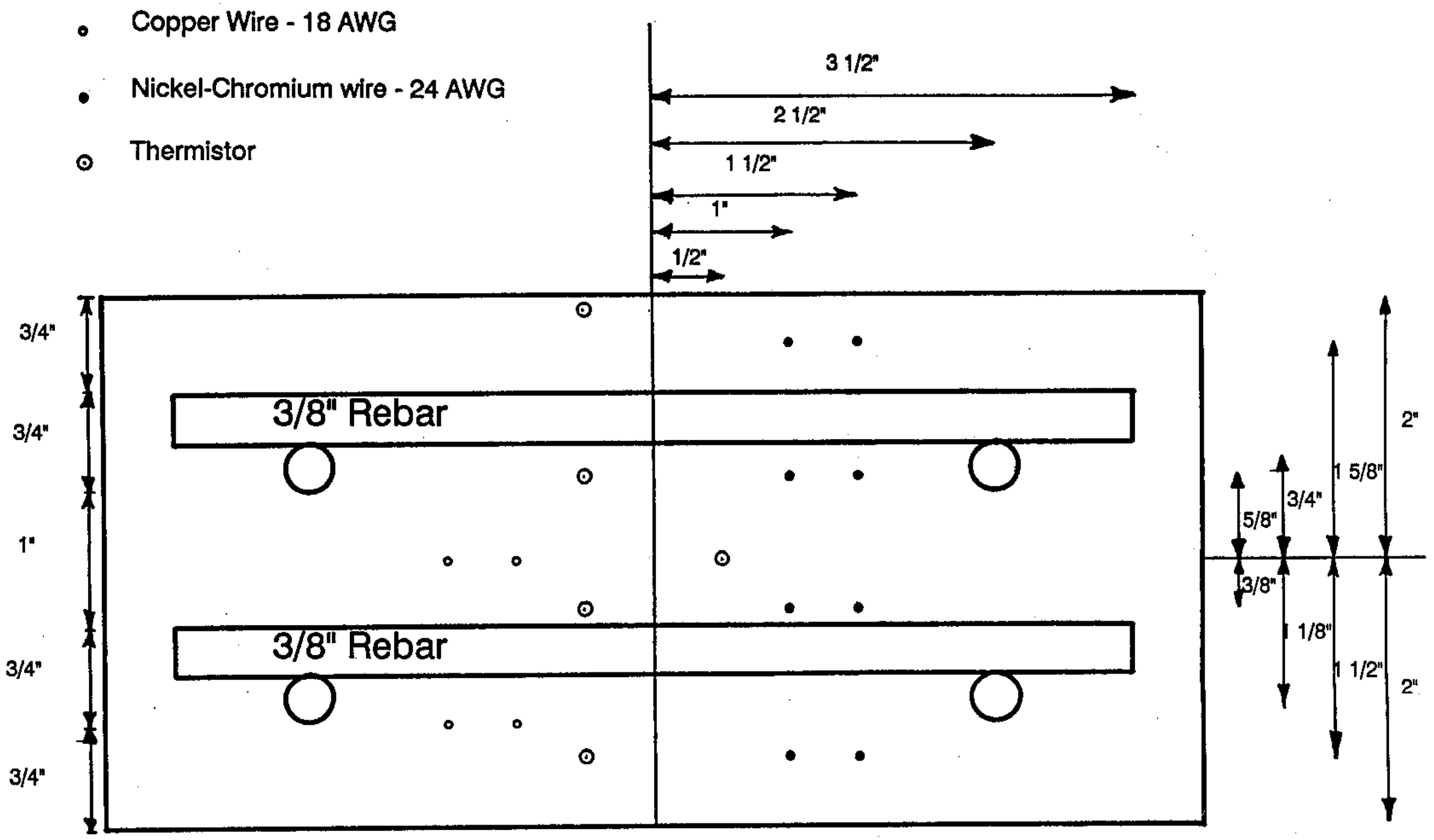


Figure 12. Concrete Sample - Side View

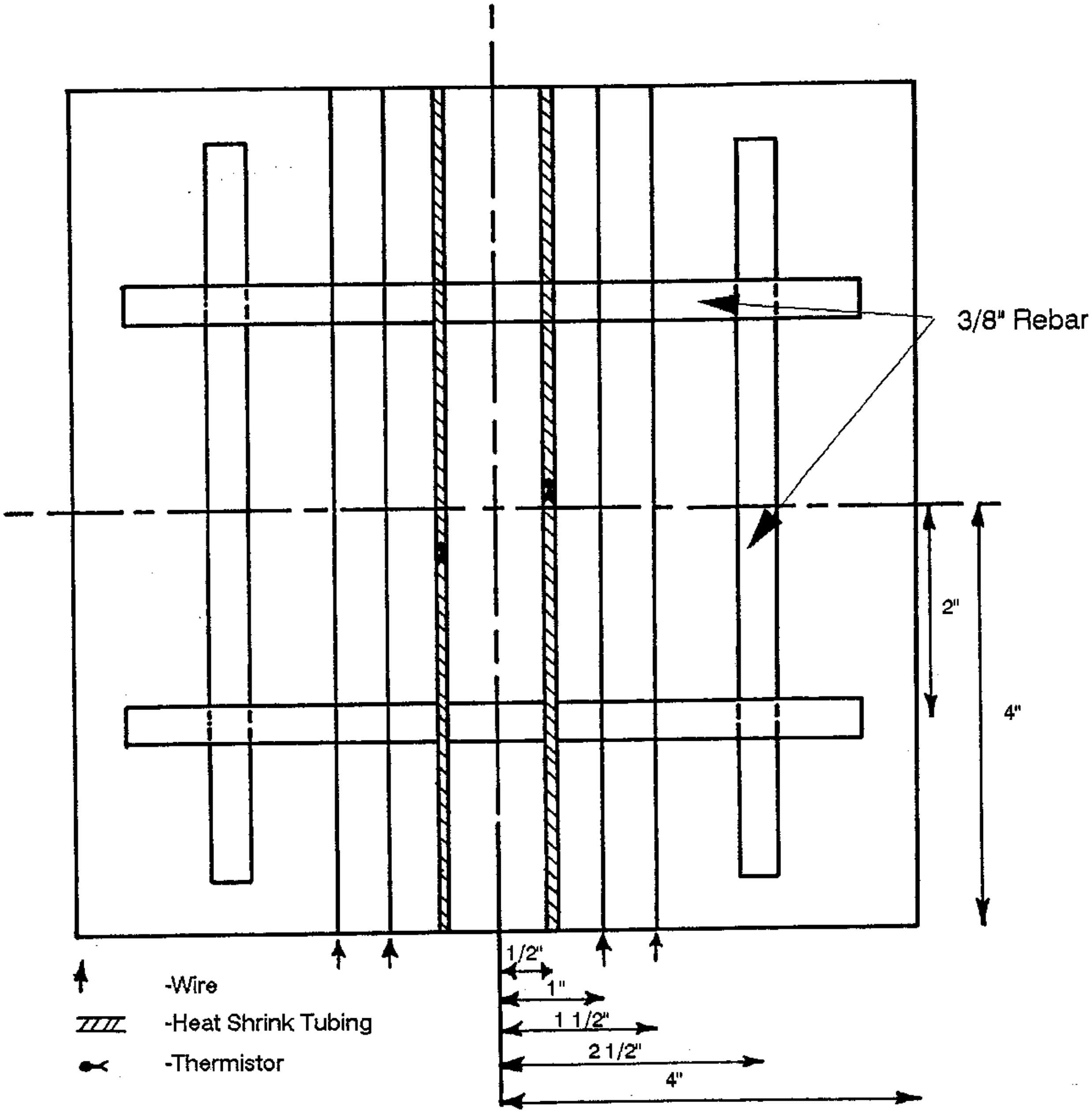


Figure 13. Concrete Sample - Top View

This device was ordered from other funds. The controller was expected to be an off-the-shelf device, but after the order was placed we were informed that there would be a delay in shipment. The controller arrived shortly after the end of the quarter.

Per the design of the experiment, half of the limestone aggregate specimens had to be impregnated with sodium chloride. During the previous period as a result of discussions with Mr. Johnston, it was decided that it would be better to treat all specimens as equally as possible. We proposed following exactly the same procedure with the other four specimens but using only pure water; Mr. Johnston recommended the better procedure of using saturated CaOH solution for half the specimens and saturated CaOH + 3% NaCl by weight for the other half; this recommendation was adopted. Our previous tests indicated that in order to accomplish this impregnation, vacuum soaking was necessary. The facility used for earlier tests was not big enough to accommodate the 4"x 8"x 8" specimens. Consequently, during the previous period, we determined that a bigger facility had to be fabricated, and had located a large glass tube with ports. During the fifth period, we modified this old system for the vacuum saturation. The modifications were almost complete by the end of the period.

Figures 14, 15, and 16 show the plan, end, and side views of the chamber respectively. It can be seen from these drawings how little room was available in all three directions. The integrated design was achieved by placing the fans, heaters, etc. in a plenum at one end of the box which connects the upper supply plenum and the lower removal plenum. Besides the platinum resistance thermometer used for temperature control in the plenum (process temperature), two thermistors (dry and wet bulb temperatures) are located in the main section of the box near the concrete specimens. In this design, the humidity source was also in the side plenum.

f) Sixth Period 16DEC91 - 15DEC92.

Up to the beginning of the time period covered by the report for this period, the project had encountered some difficulties, mainly having to determine how to do things, all of which took quite a bit of time, but, in general, the project had been going smoothly. Subsequently, many problems were encountered, some very significant ones being due to a change in the specification of the project. This modification led to a lot of extra work, and more importantly, to problems with the environmental chamber operation. These problems were in large measure due to having to work within the confines of a freezer rather than having a cold room available. The careful design of the chamber to prevent problems we were aware of, which were mentioned in the proposal, was compromised by the required modifications to the project. The original design of the experiment and the chamber, as proposed, were made taking into account the limitations of the space available in a freezer and the difficulty of attaining high humidity in a chamber with colder ambient conditions. Attempts to make the requested change resulted in a cascade of problems. Eventually, the problems were basically overcome. Throughout, we were in communication with the project monitor, who provided valuable guidance and helpful suggestions in our attempts to solve these problems. Before describing the progress made, some details of the problems encountered are presented.

In the original design of the environmental chamber, we were careful to develop an "integrated" construction. Based on previous experience, it was known that, in order to maintain high humidity inside a chamber located within a freezer maintained at about -15°F, the chamber must be very tightly sealed. Therefore, the schematic design shown in the proposal (Figure 2) was incorporated into an actual design which included a simple, continuous external envelope except for the joint between base and lid which could be sealed carefully. To accomplish this, the circulation fan, heater, and humidity source were placed inside a plenum at the side of the chamber which was directly connected to the intake and distribution manifolds. Thus, all of the chamber's envelope other than the top, was an integral, sealed unit. This concern for the difficulty of achieving high humidity was indicated in the proposal for this project.

At the end of the previous period, Mr. Johnston had communicated a request to add the simulation of direct radiative heating (sunlight) on the top of the specimens. In order to

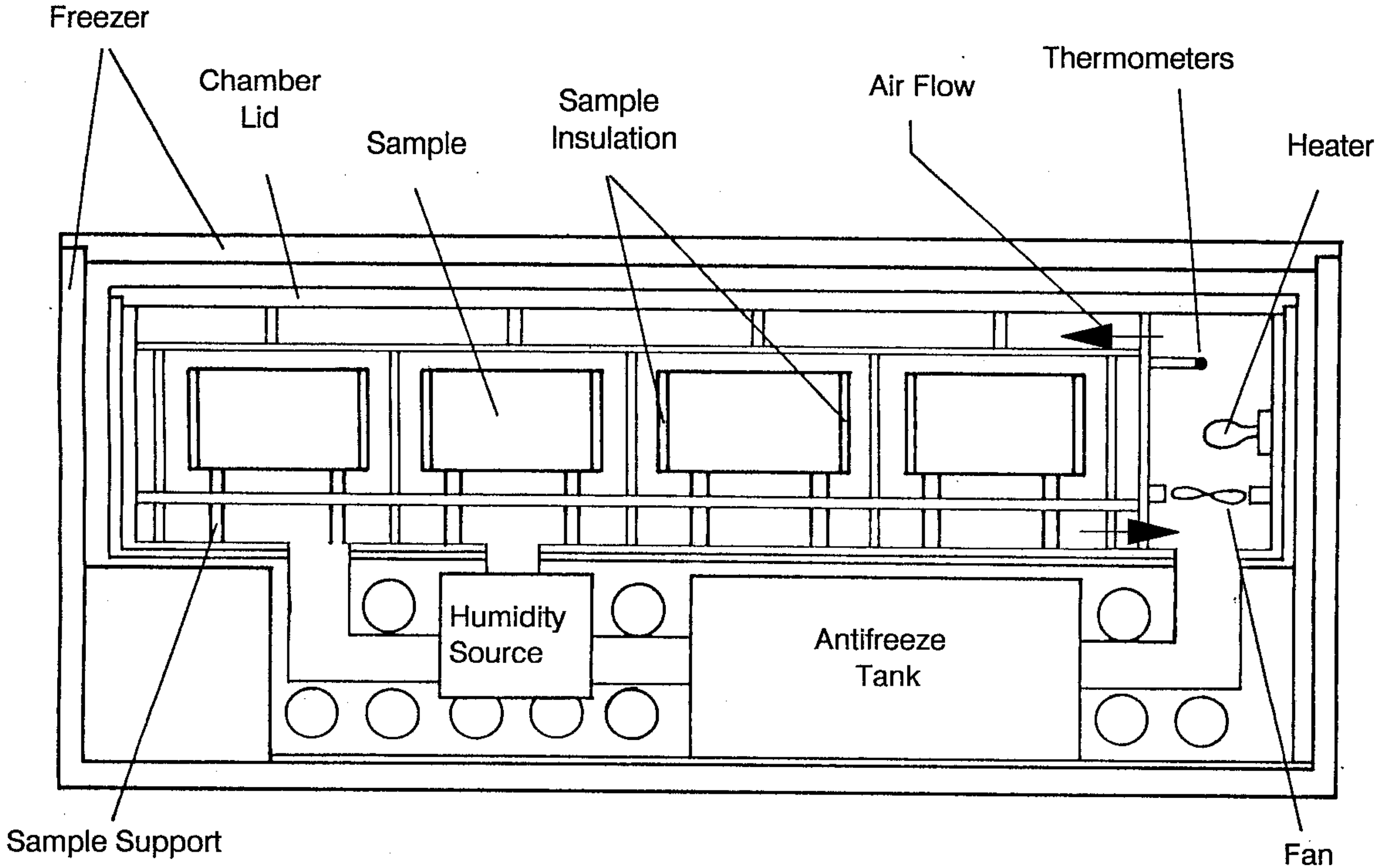


Figure 14. Environmental Chamber - Side View

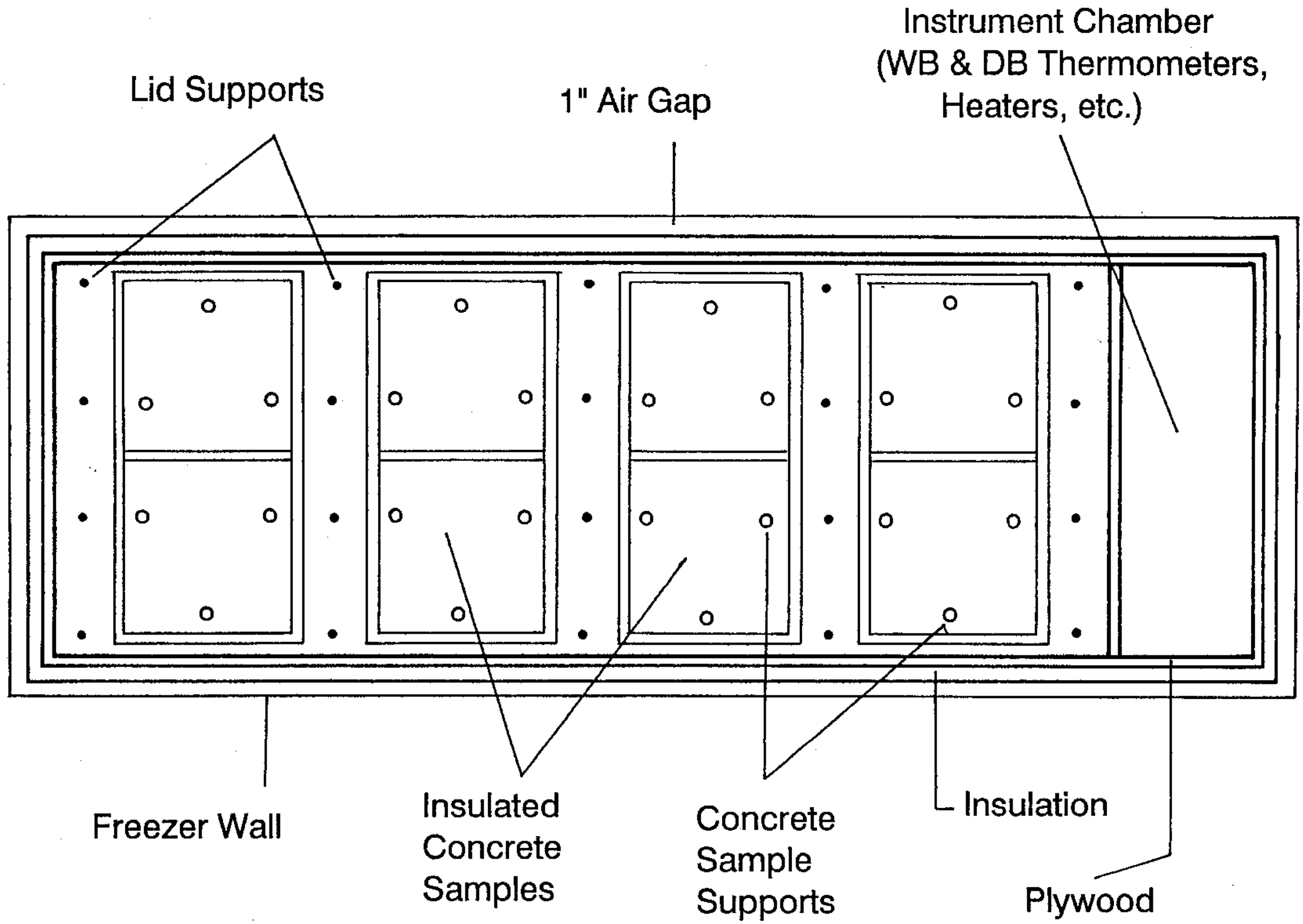


Figure 15. Environmental Chamber - Plan View

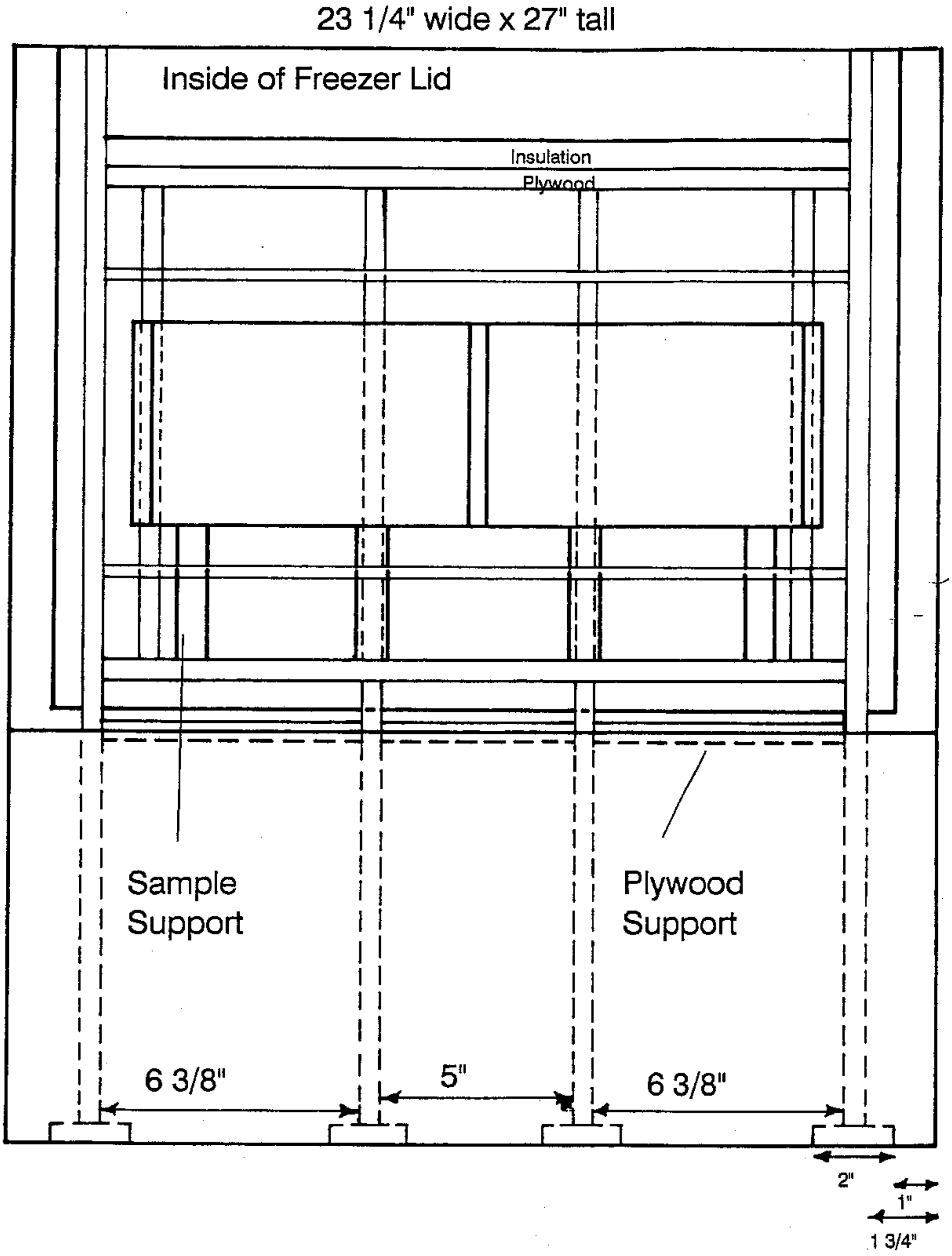


Figure 16. Environmental Chamber - End View

accommodate this request, the height of the chamber had to be increased substantially. Consequently, the space between the chamber top and the freezer lid was greatly depleted, with the unfortunate consequence that the circulation of air around the chamber was essentially stopped. We were only able to see this problem after the changes had been made. This, in turn, resulted in inadequate cooling of the interior of the chamber when the heaters were turned off, and the need for the addition of a metal duct into the bottom of the freezer in an attempt to regain adequate cooling. This compromised the vapor-tightness of the envelope and there was a subsequent loss of humidity. A bigger moisture source, better sealing, and raising the box in the freezer were incorporated to overcome the problem. They were significantly successful, and eventually we were able to get the humidity approaching the levels attainable in the original design with some sacrifice of temperature excursion in the cycles. However, this work took nine months, and in the process the concrete specimens were accidentally dehydrated. In late December, 1992 they were housed in a high humidity container in an attempt to get them back to a normal moisture content.

Our attempt to accommodate the change in the chamber design caused three major problems:

1) The time involved in attempting to overcome the difficulties has involved effort far exceeding that provided in the budget, and a great deal of delay in performing the main experiments. In particular, much of the work was simply trying to determine how to overcome the problems, and this had to be done by the principal investigator. As a result, he has expended hundreds of hours to the project which the budget would not accommodate.

2) The inability to achieve high humidity has caused problems with the experiment. During the time that we were attempting to solve the problems, the concrete specimens were essentially freeze-dried. It was not possible to leave them out of the chamber since their thermal mass and ability to adsorb moisture were necessary in order to determine whether any progress was being made with the chamber.

3) Because of the delays and low moisture content of the specimens, we were not able during the period of the contract to fully address the specific questions which were the objectives of the work proposed.

At the beginning of the period, it was found that the large vacuum chamber would not pump down to the required pressure. It was found that a crack had developed in one of the ports. This had to be repaired very carefully to both seal the crack and prevent its further propagation. This was successfully achieved, and the chamber was able to be pumped down to 50 mTorr. While this repair was being made, we also conducted measurements on a test block (specimen #6) to determine the quantity of solution needed to saturate the concrete specimens. Also, the temperature controller was installed and its operation checked out, and we were working on the redesign of the environmental chamber.

The next four months (January through April, 1992) were spent mostly on reconstructing the chamber and attempting to overcome the initial problems which arose. During this period, several sets of data of the chamber's performance were taken; a listing of the data files generated is given in Appendix B.

Figure 17 shows a temperature-time profile (#4 taken on 04FEB92) achieved inside the environmental chamber, containing the eight concrete specimens, as it was originally designed and constructed. Notice that a temperature of 28°F was achieved. Following this test, containers filled with alcohol were placed in the bottom of the freezer to provide greater thermal mass and cooling ability; with this simple addition, temperatures down to 23°F were reached.

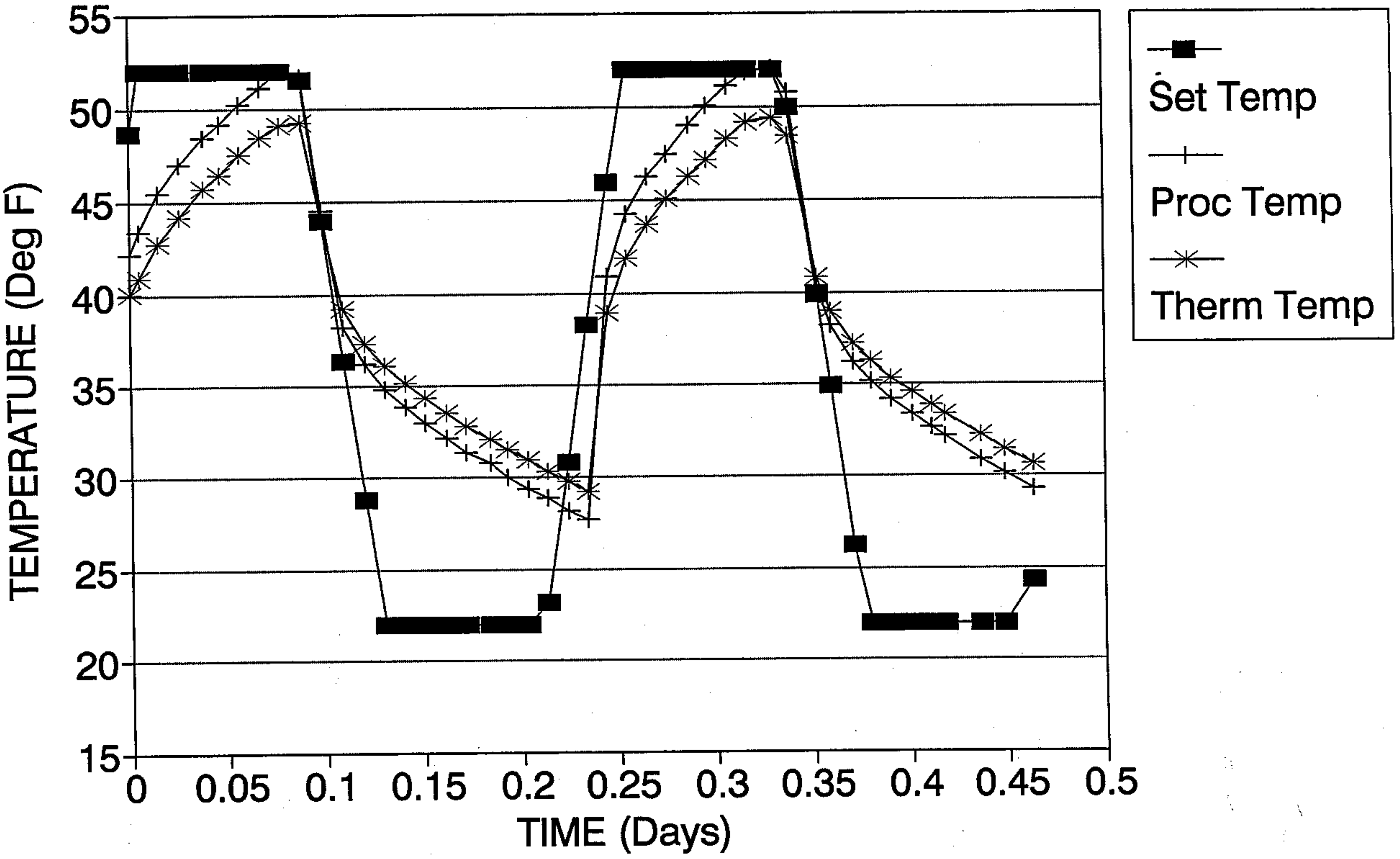


Figure 17. ENVIRONMENTAL CHAMBER TEST #4

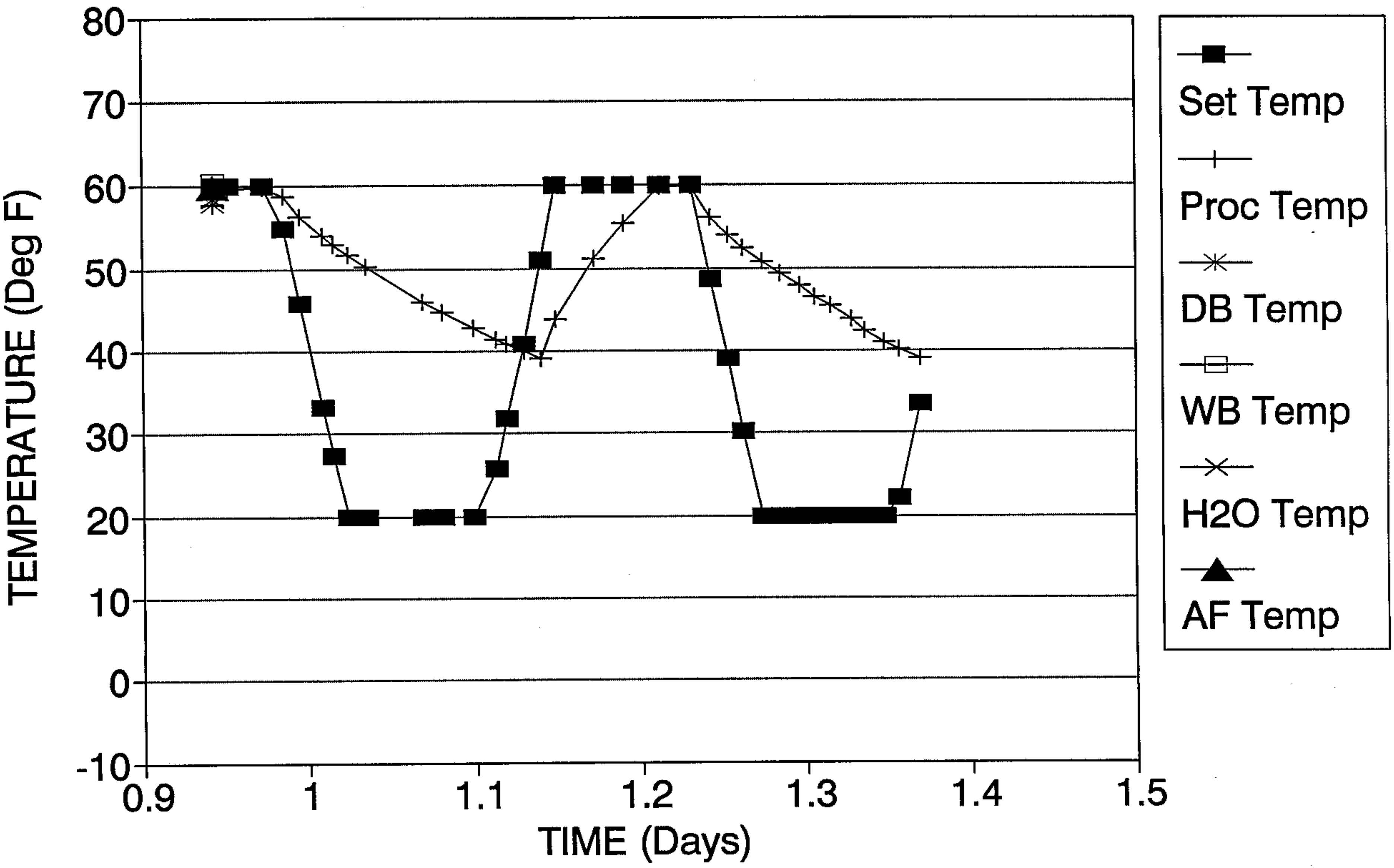


Figure 18. ENVIRONMENTAL CHAMBER TEST #6

This should be compared with the temperature-time profile #6 (Figure 18) which was taken with the same conditions on 30MAR92 but after the height of the chamber had been increase to allow simulation of solar radiation. As can be seen, the lowest temperature which could now be achieved was 40°F because the air circulation around the chamber had been severely restricted by the small space remaining between the chamber and freezer lids. Between the end of March and the middle of June, modifications to regain the ability to get down to temperatures well below freezing were made. These included the addition of ducts into the lower part of the freezer, a large bath of antifreeze in close proximity to the ducts, baffles in the ducts to improve heat exchange, a flap mechanism within the chamber to control the air flow in the ducts, and a large, insulated source of water vapor also in the bottom of the freezer. Figures 19A and 19B compare the effects of not having (flap not opened) and having (flap opened) air flow in the ducts during cooling. Both curves are for a 20-50°F temperature cycle. Without air flow in the duct, the lowest temperature attained in the main chamber was only slightly below 30°F, whereas with air flow in the ducts, temperatures down to 23°F were attained. The efficacy of the temperature controller's ramp and soak ability is clearly shown. The temperature cycle has a period of 6 hours; the extremities of temperature are held for 2 hours with 1 hour for the ramp between them.

Also during the modifications, heaters were placed over the specimens to give direct radiation onto their upper surfaces (sample heaters) in addition to the heater in the side plenum (main heater). Figures 20A, 20B, and 20C show the results of tests #14, #15, and #16 which had heating with the specimen heater only, the main heater only, and with both heaters respectively. All are for a 60-90°F temperature cycle. Notice that with the sample heater only, the temperature within the specimen portion of the chamber ranged between 65°F and over 100°F giving an excursion of over 35°F, with only the main heater the temperature ranged from 55°F to 83°F, and with both heaters supplied with 115 volts the range is from 63°F to 92°F giving an excursion of 29°F. Both heaters were supplied via Variacs, so the ratio of power to each could be varied continuously.

After getting the heater system installed, as indicated elsewhere, we had a lot of problems maintaining the humidity inside the chamber. Figures 21A, 21B, and 21C show some of the short sequences of measurements taken as we were working on the problem. Figures 21A and 21B show data taken after a great deal of improvement had been achieved, but the humidity still was not high enough. Figure 21C, however, shows a short set of temperature and humidity data after further work; it shows that eventually we were able to regain over 90% humidity during the 60°F part of a 60-90°F cycle.

In parallel with the work on the chamber, measurements of the half-cell potentials of the rebar in specimens #6 and #7 were begun (Data File DOT3-D07). The system thermistors were calibrated against a standard platinum thermometer (Data File DOT3-D08), and measurements were made of the temperature of a concrete highway surface as a function of weather conditions and time of day (Data File DOT3-D10).

Highway surface temperatures are shown in Table 2. On the 30 March 1992, the weather was sunny all day; in the mid afternoon, the concrete temperature was 9°F above the air temperature. On 31 March 1992, the difference was 21°F; on this day the surface was heated by sunshine all morning, and then a cold wind came up and abruptly lowered the air temperature. This same pattern and a 21°F temperature difference was again observed on 8 April 1992. On days when the sun shone all morning and afternoon and the air temperature stayed essentially constant during the afternoon, temperature differences reach the 15 to 20°F range. Without full sun all afternoon, temperature differences were considerably smaller.

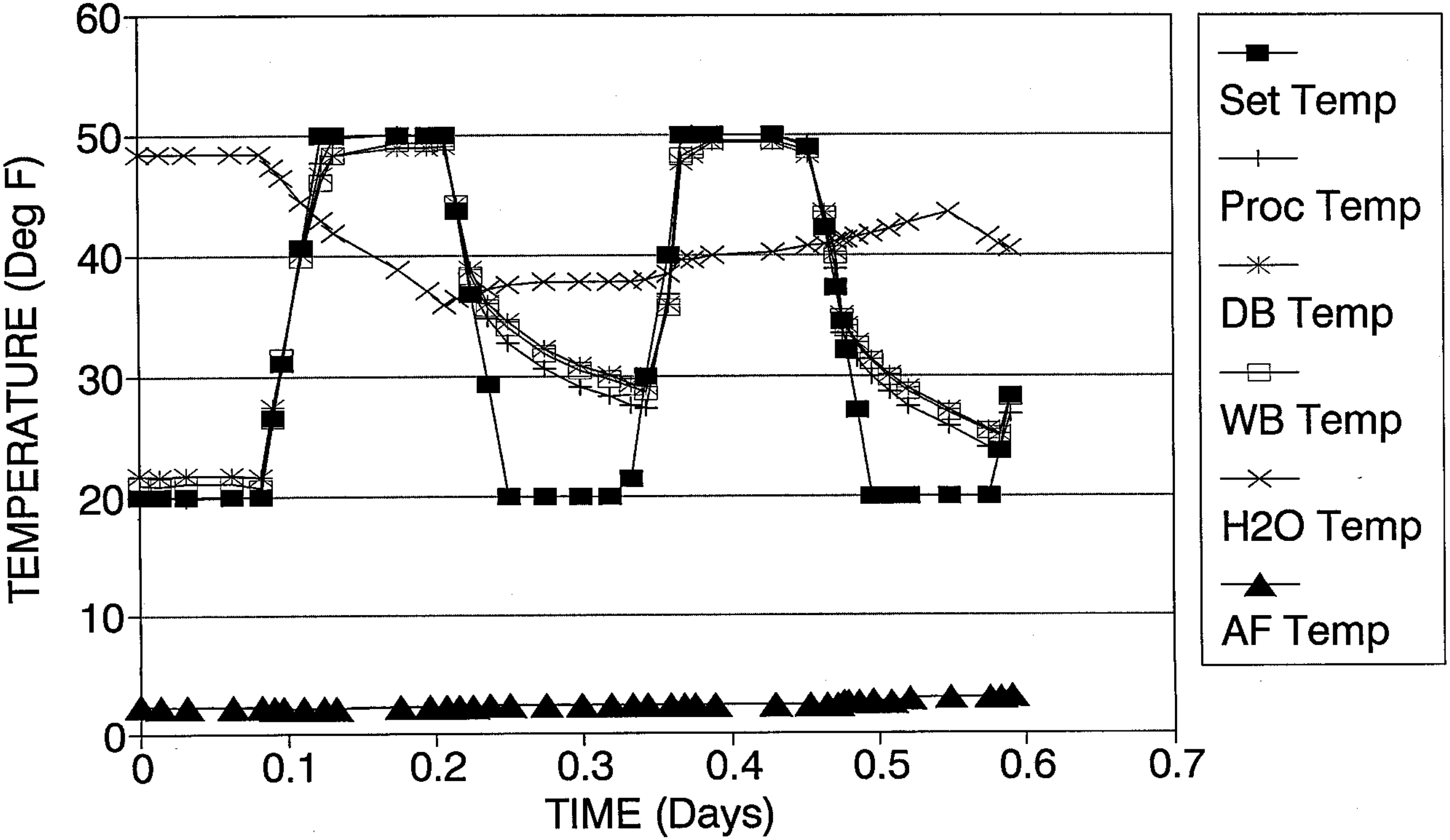


Figure 19A. ENVIRONMENTAL CHAMBER TEST #9A
Flap Not Opened During Cooling

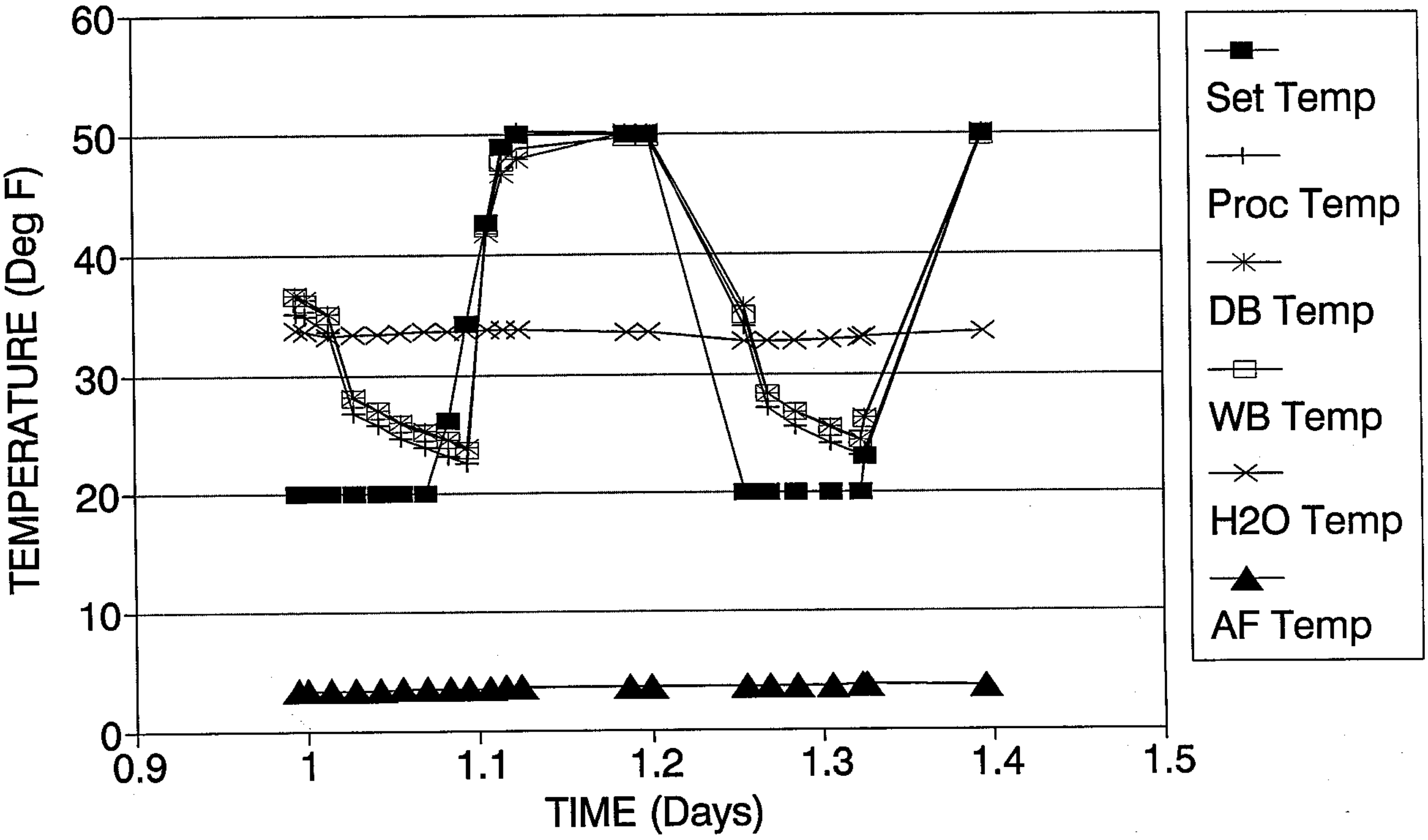


Figure 19B. ENVIRONMENTAL CHAMBER TEST #9B
Flap Opened During Cooling

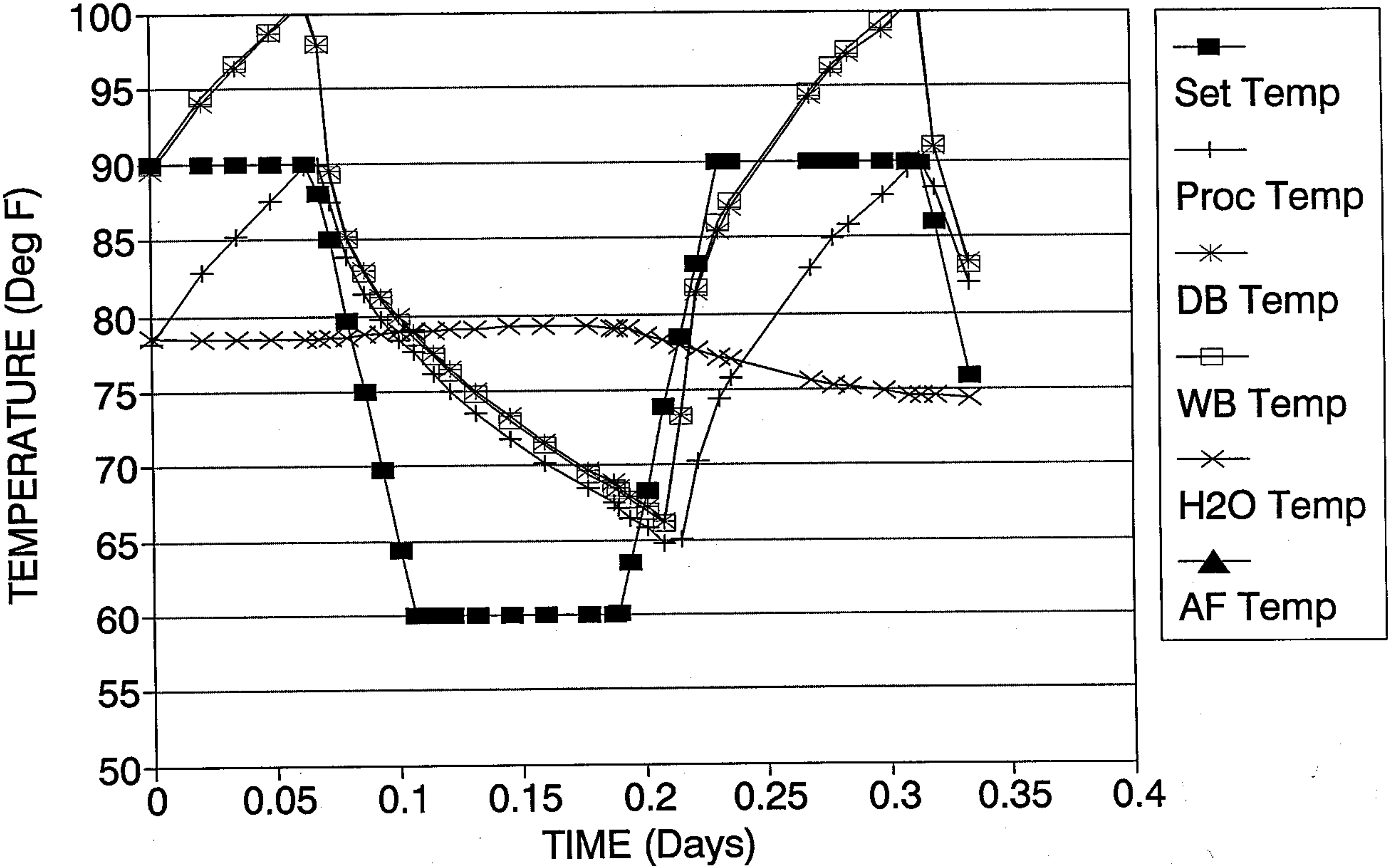


Figure 20A. ENVIRONMENTAL CHAMBER TEST #14
Specimens in Chamber, Specimen Heater

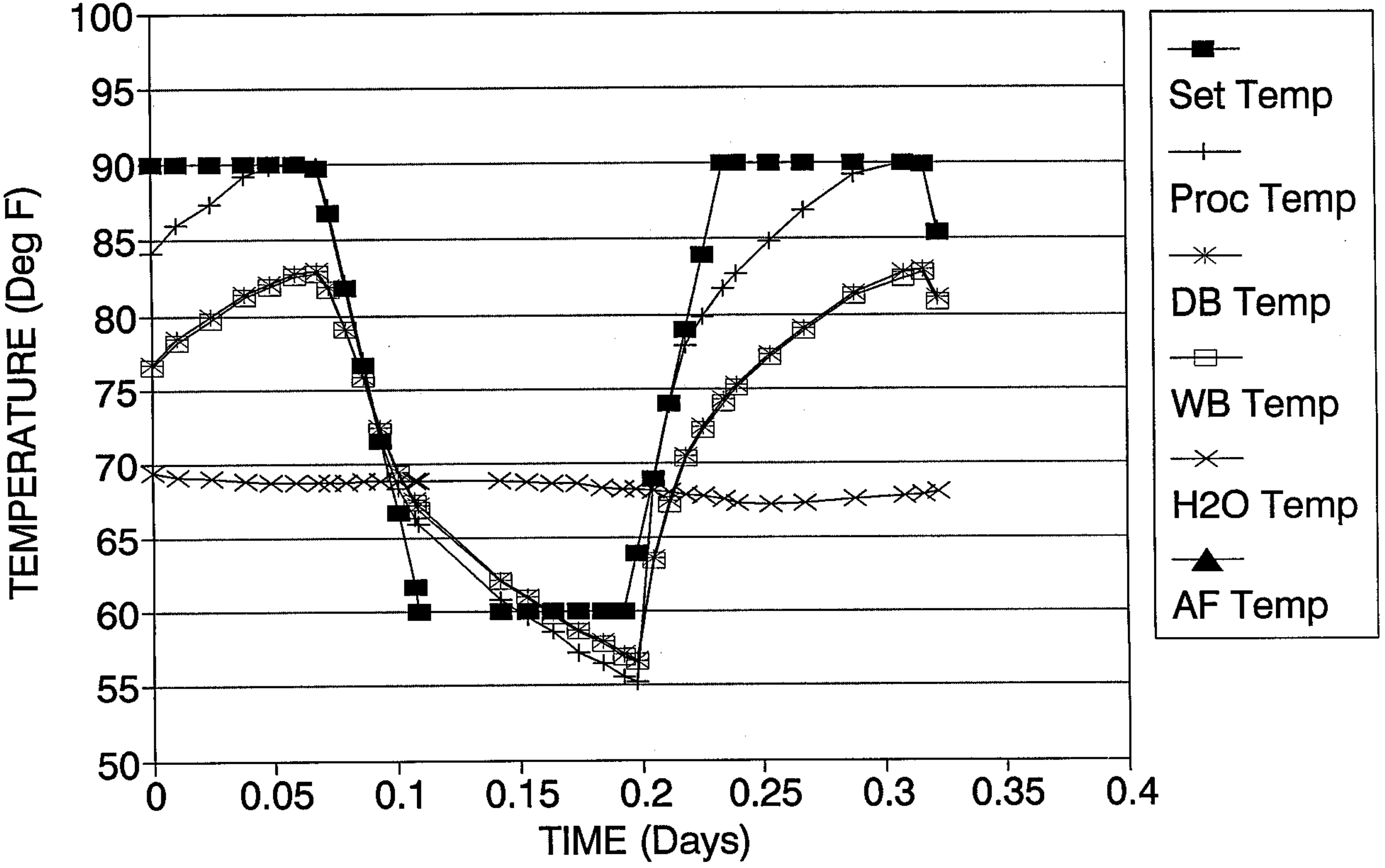


Figure 20B. ENVIRONMENTAL CHAMBER TEST #15
Specimens in Chamber, Main Heater

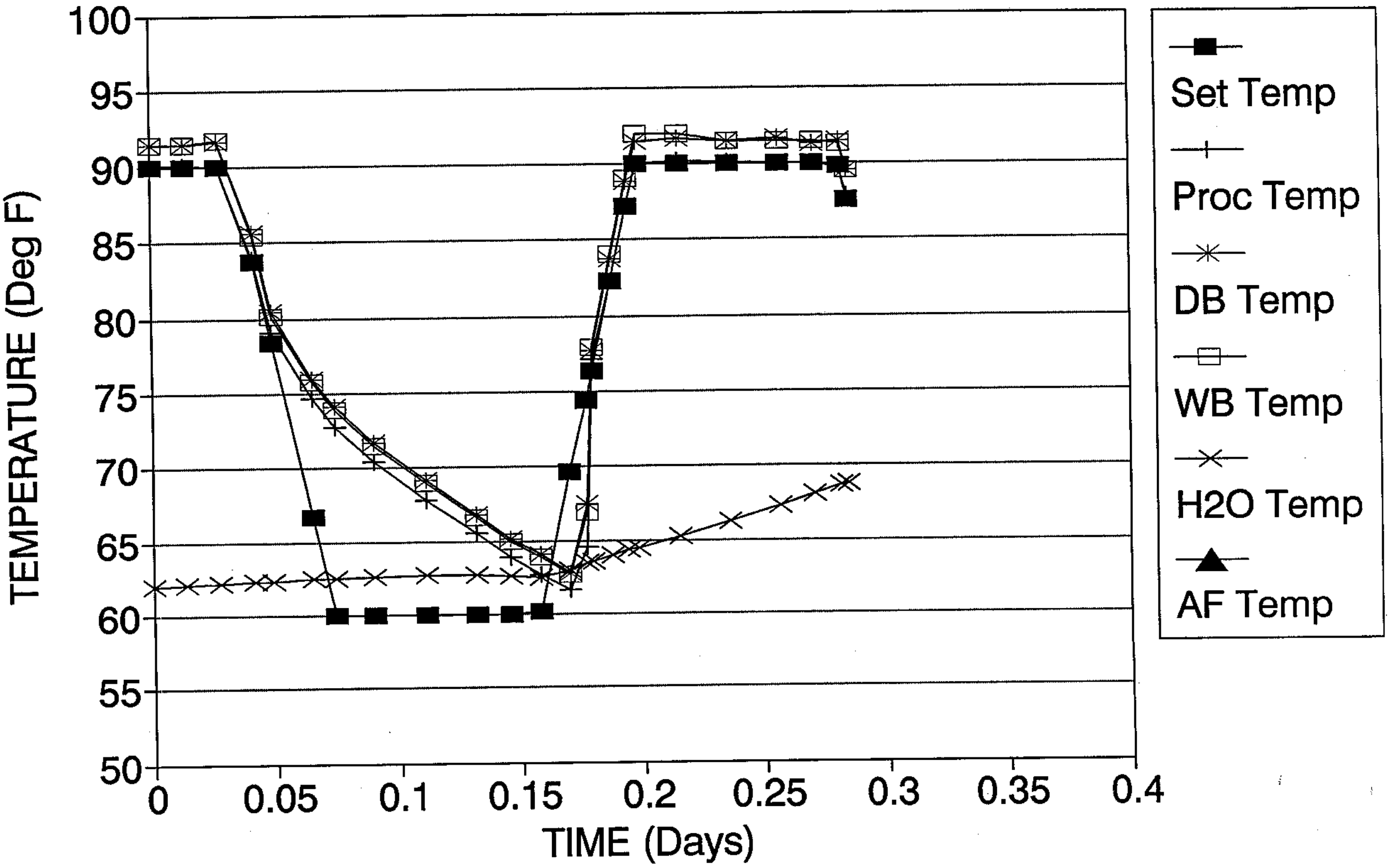


Figure 20C. ENVIRONMENTAL CHAMBER TEST #16
Specimens in Chamber, Both Heaters

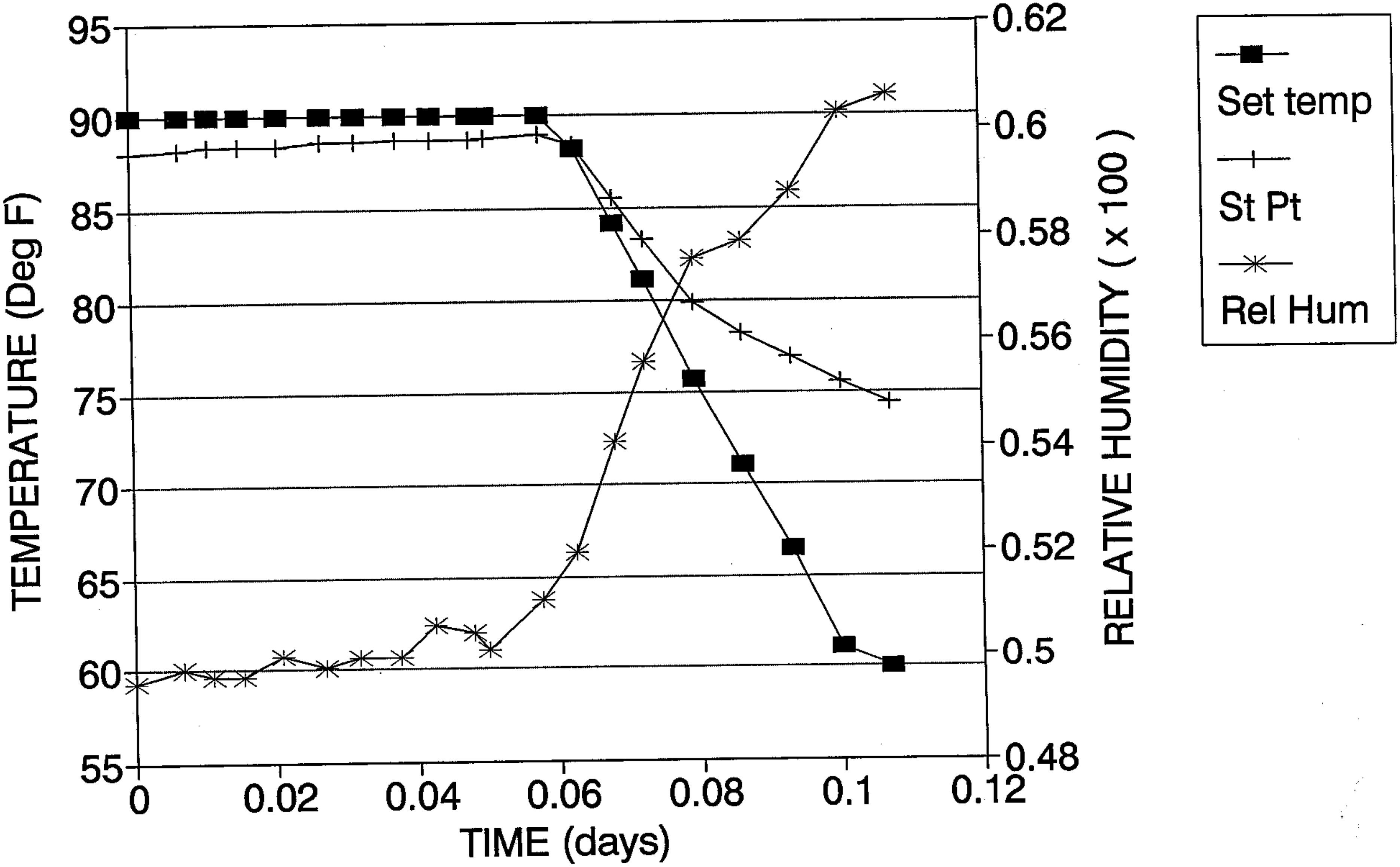


Figure 21A. ENVIRONMENTAL CHAMBER TEST #24
Temperature and Relative Humidity vs. Time

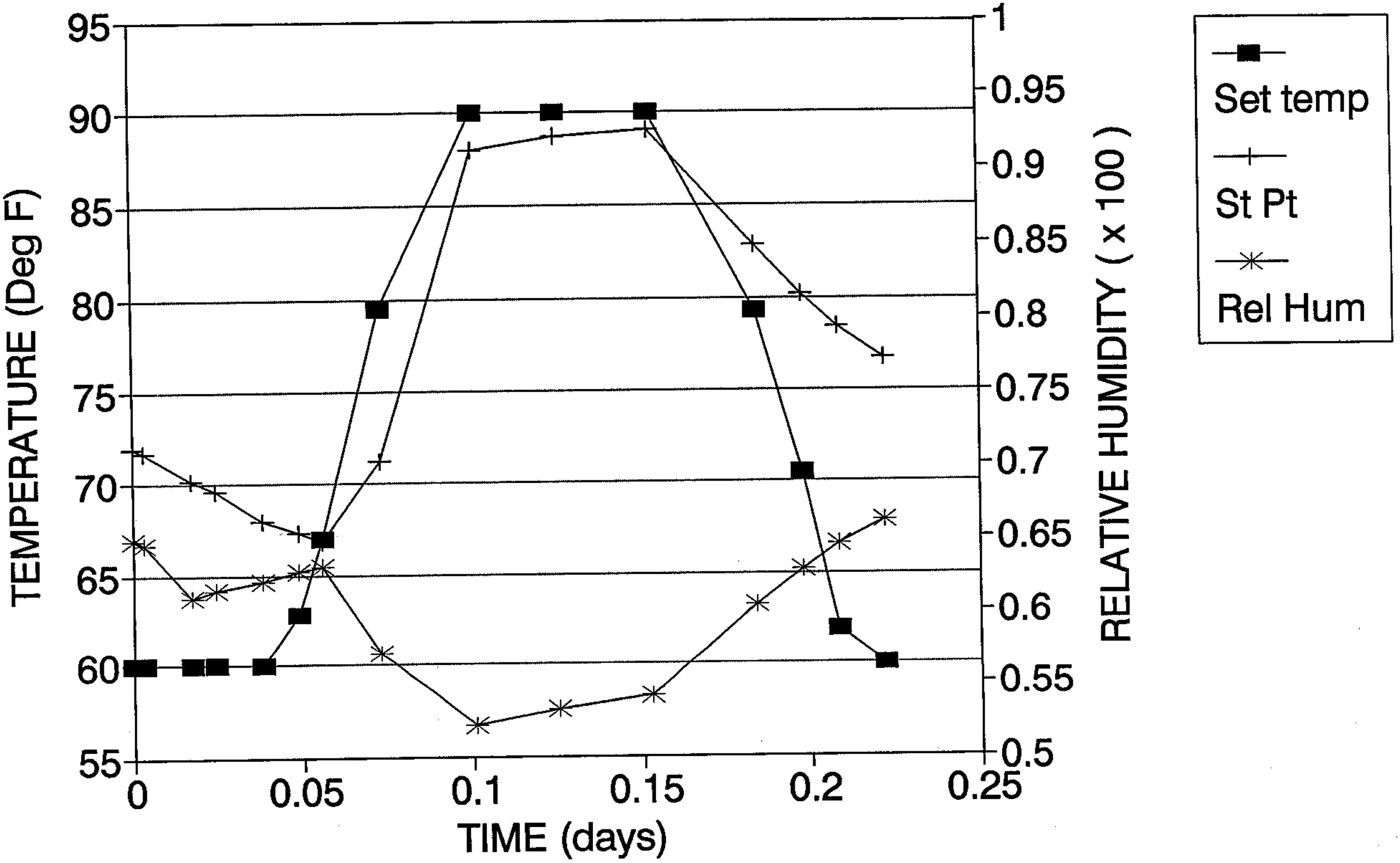


Figure 21B. ENVIRONMENTAL CHAMBER TEST #26
Temperature and Relative Humidity vs. Time

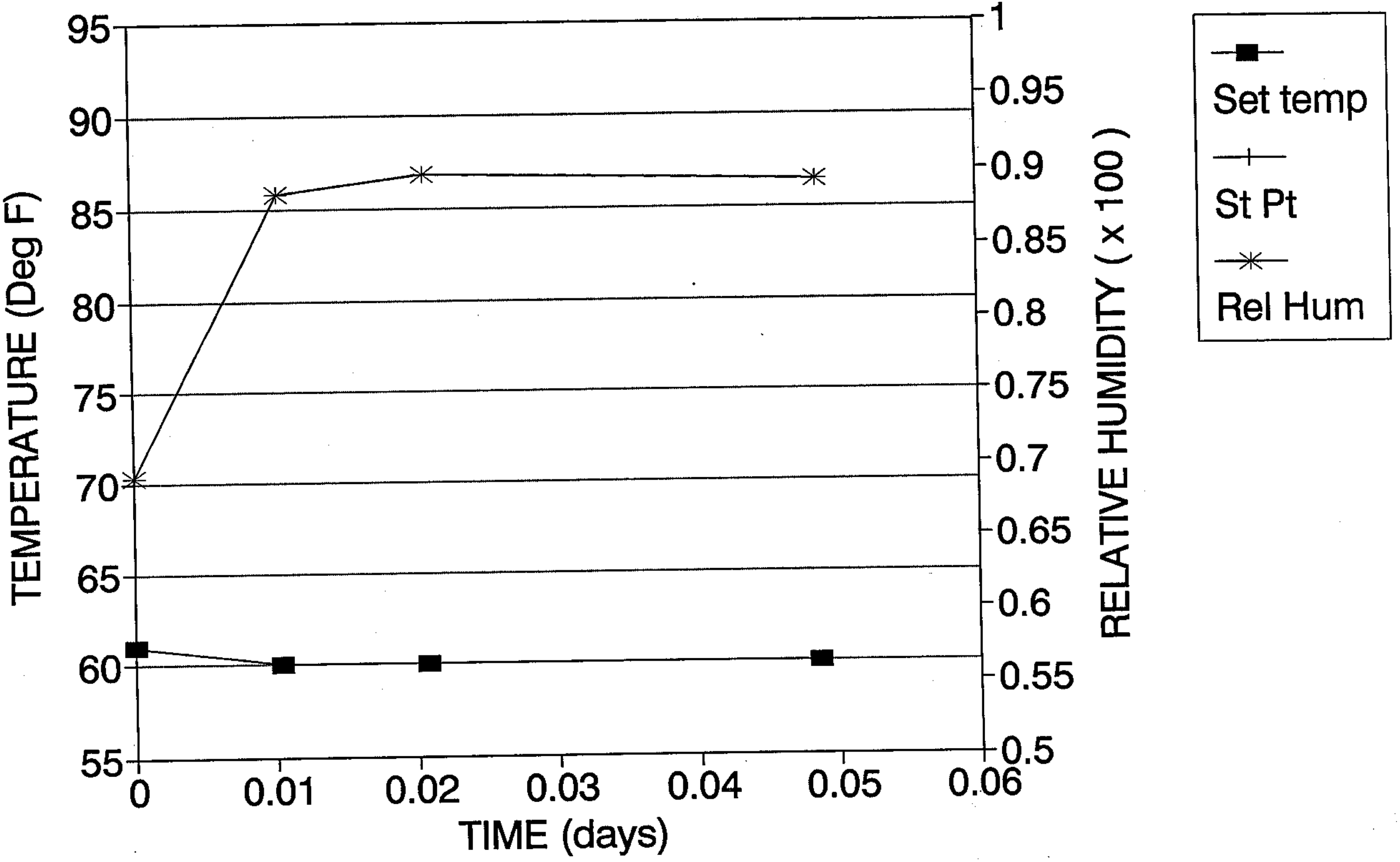


Figure 21C. ENVIRONMENTAL CHAMBER TEST #31
Temperature and Relative Humidity vs. Time

Table 2. Measurement of Concrete Temperature on Highway Surface

Used thermistor #2 (Orange-White). Values obtained for concrete with Styrofoam placed over the thermometer.

Date	Time	Resistance			Temperature			Difference	
		Air (KOhms)	Site 1 (KOhms)	Site 2 (KOhms)	Air (Deg F)	Site 1 (Deg F)	Site 2 (Deg F)	Concrete-Air(ave) (Deg F)	
30-Mar-92	15:38	3.68	2.78			64.11	75.12	11.01	
31-Mar-92	14:00	6.30	3.55	3.54	44.06	65.50	65.61	21.50	Cold wind
01-Apr-92	8:25	8.04	6.78	6.62	35.37	41.42	42.27	6.47	Sunny
01-Apr-92	12:30	4.92	3.67	3.32	53.12	64.22	68.11	13.04	Sunny
01-Apr-92	15:00	5.50	3.86	3.89	49.00	62.28	61.98	13.13	Overcast
02-Apr-92	8:00	7.00	6.22	6.31	40.27	44.52	44.00	3.98	Sunny
02-Apr-92	12:00	4.31	2.96	3.23	58.08	72.62	69.18	12.82	Windy
02-Apr-92	15:05	3.45	2.79	2.77	66.61	74.98	75.26	8.51	Partly cloudy
03-Apr-92	7:54	4.44	4.49	4.43	56.96	56.54	57.04	-0.17	Sunny
03-Apr-92	12:00	2.60	2.14	2.12	77.81	85.76	86.15	8.15	Sunny
03-Apr-92	15:00	2.77	2.37	2.37	75.26	81.56	81.56	6.30	Partly cloudy
06-Apr-92	8:08	6.00	5.35	5.38	45.82	50.02	49.81	4.09	Sunny
06-Apr-92	12:06	4.38	3.10	3.16	57.47	70.80	70.04	12.95	Overcast
06-Apr-92	14:58	4.40	2.86	2.92	57.30	73.99	73.16	16.27	Partly cloudy
07-Apr-92	8:00	6.00	5.70	5.78	45.82	47.69	47.18	1.61	Sunny
07-Apr-92	12:04	4.40	2.98	2.92	57.30	72.36	73.16	15.46	Sunny
07-Apr-92	15:05	4.24	2.56	2.55	58.70	78.43	78.59	19.81	Sunny
08-Apr-92	8:06	6.50	5.78	5.78	42.93	47.18	47.18	4.25	Sunny
08-Apr-92	11:58	4.44	2.91	2.85	56.96	73.30	74.13	16.75	Sunny/wind
08-Apr-92	15:00	4.10	2.41	2.50	59.97	80.88	79.39	20.16	Partly cloudy

Rough system thermistor calibrations were obtained during some of the early chamber tests by placing a mercury-in-glass thermometer inside the chamber. However, we wanted these thermistors to be calibrated much more carefully for the main data collection, so they were placed in a special isothermal housing which we had available and their resistance was compared to that of a standard platinum thermometer which was calibrated by the National Bureau of Standards. Figures 22A and 22B show the relationship between the logarithm of the resistance as a function of inverse absolute temperature for the two sensors which were used as the wet bulb and the dry bulb thermometers. Very smooth, linear curves were obtained. Calibration curves for each sensor were developed by first performing a least-squares fit of the data to a $1/T = A + B(\log R)$ curve. Then a difference plot was made between the actual values and the values interpolated from the least-squares curve-fit, and finally a quadratic was fitted to this difference curve. Figures 22C and 22D show the difference values, the quadratic difference fitted curve, and the final comparison with the values interpolated by the combined calibration. These curves show that a calibration accurate to 0.2°F (0.12°C) resulted.

In February 1992, tests were performed to check the amount of solution which was needed to fully impregnate the upper 1" of the specimens. At the end of February and into March, the potential of the rebar was measured with respect to a Cu-$CuSO_4$ half cell. Also, the differential potential of one layer of rebar with respect to the other layer of rebar was measured. This was done immediately before the impregnation of the specimens so that they could be monitored in place. It was quickly learned that, during temperature cycling, it would not possible to make measurements with respect to the half-cell because four of the eight specimens had a non-porous, insulating coating on their upper surface. Attempts were made to make contact with the under surface using a copper extension, but the results were not consistent. Consequently, the potential between the rebar layers, which could be measured during the cycling and which was stable, was the only means available to show any changes in the location of the chloride ions; this has turned out to be a most useful measurement. Monitoring of the specimens in this way was continued until 17NOV92.

Impregnation of specimens #7 was achieved during the week of 02MAR92. They were impregnated with either saturated CaOH or CaOH + 3%NaCl. The results of the impregnation of the first pair of specimens indicated that inadequate amounts of NaCl had been adsorbed immediately. Placing the specimen in a tray containing the solutions was tried. The first attempt resulted in NaCl contamination throughout most of the specimen (specimen #7E). With careful monitoring of a second pair of specimens, it was determined that soaking for about 3 hours following the vacuum impregnation resulted in NaCl contamination in the upper one third of the specimen. This procedure was used for the remainder of the specimens.

In May 1992, the thermistors inside concrete specimens were calibrated. The first series of measurements was found to have more scatter than desirable due to greater-than-expected thermal non-equilibrium during measurements. A second set of calibration points was taken with the chamber held at constant temperature for a longer time; this resulted in data which was much improved. During this same period, the limestone aggregate specimens were wired up, insulated, and sealed with silicone coating as required by experimental design. The silicone sealer used was obtained from the Rapid City office of the SD DOT.

The first series measurements of specimen impedance and temperature was carried out between 21MAY92 and 09JUN92. These measurements were for cycles between 20°F and 50°F for the limestone aggregate specimens. A small sample of these measurements is shown in Figure 23A, 23B, 23C, and 23D; in the symbol table on the figures, "B" indicates the "bottom" of the specimen and "T" indicates the top of the specimen. Many more graphs of this nature are available and we are continuing to study them.

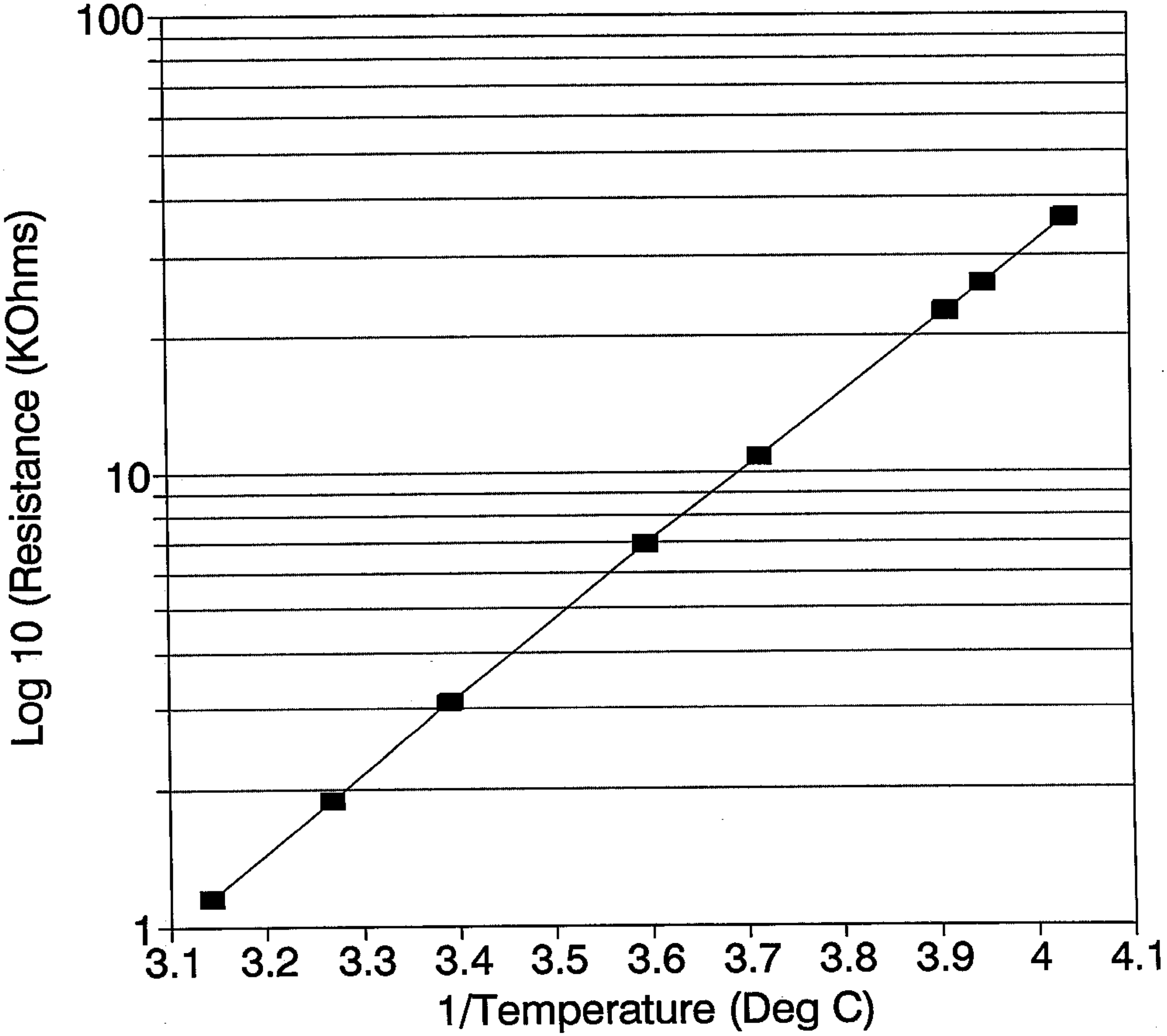


Figure 22A. CHANNEL #5 (Orange-Purple)

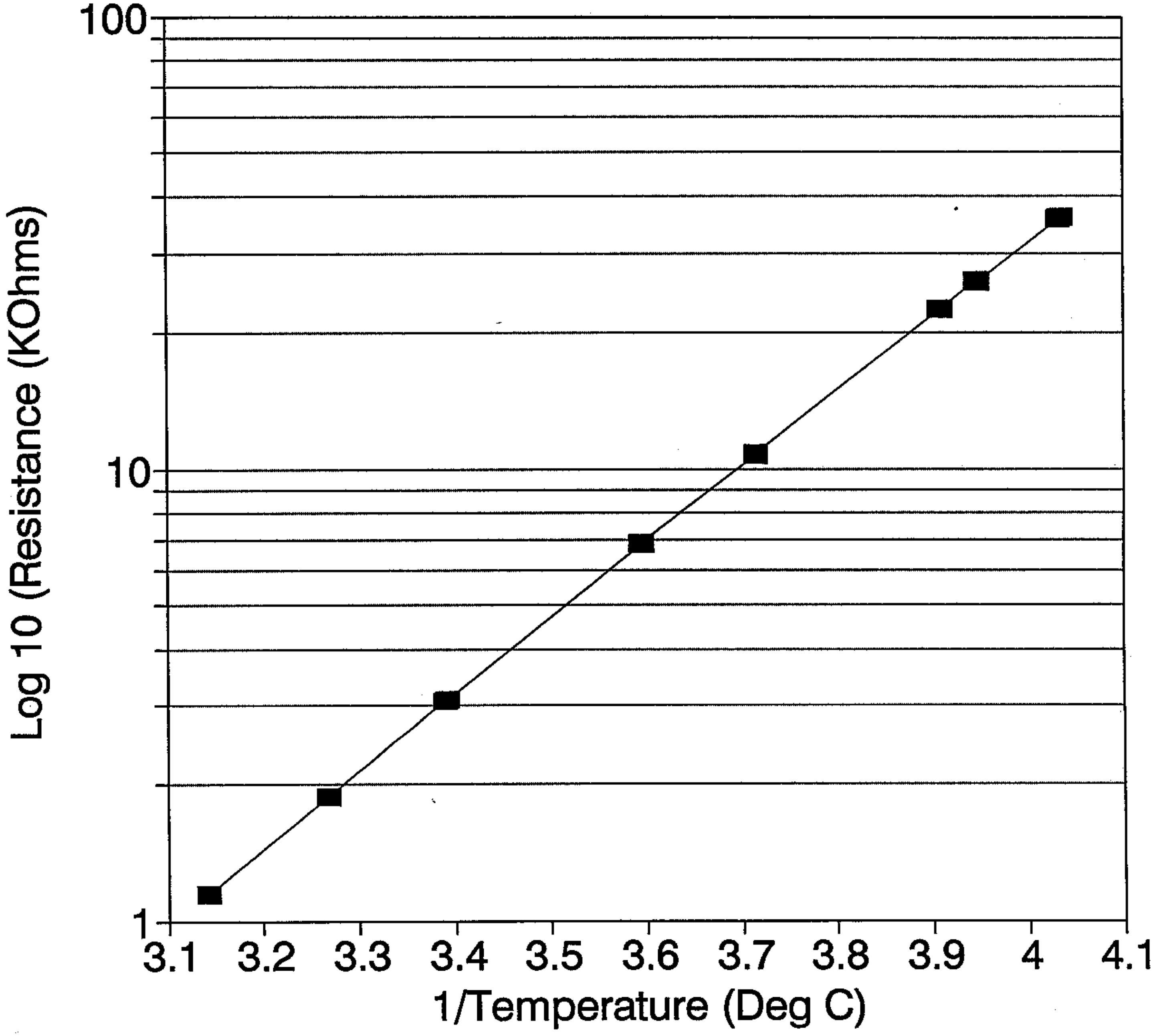


Figure 22B. CHANNEL #6 (Yellow-Blue)

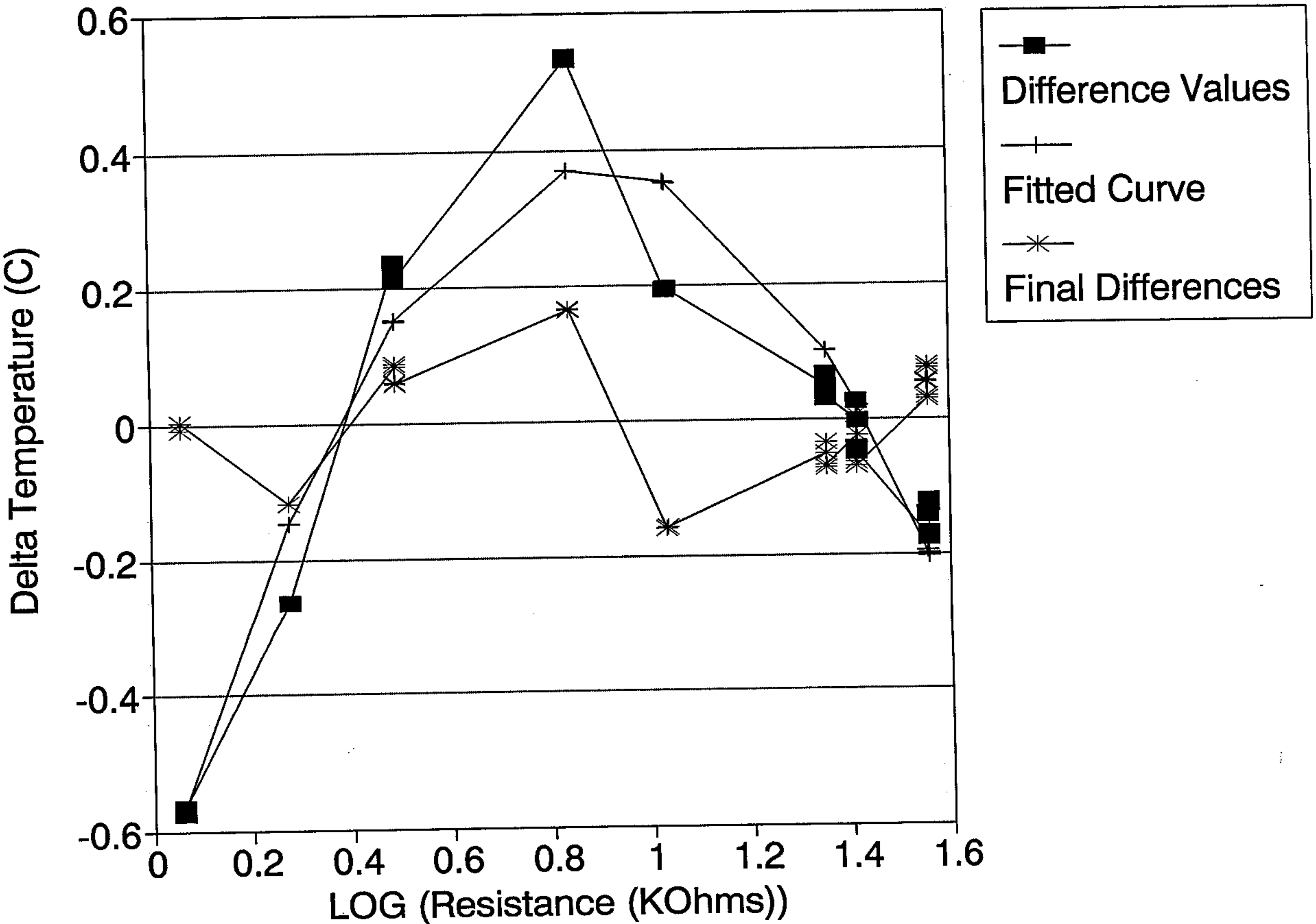


Figure 22C. CHANNEL #5 (Orange-Purple)

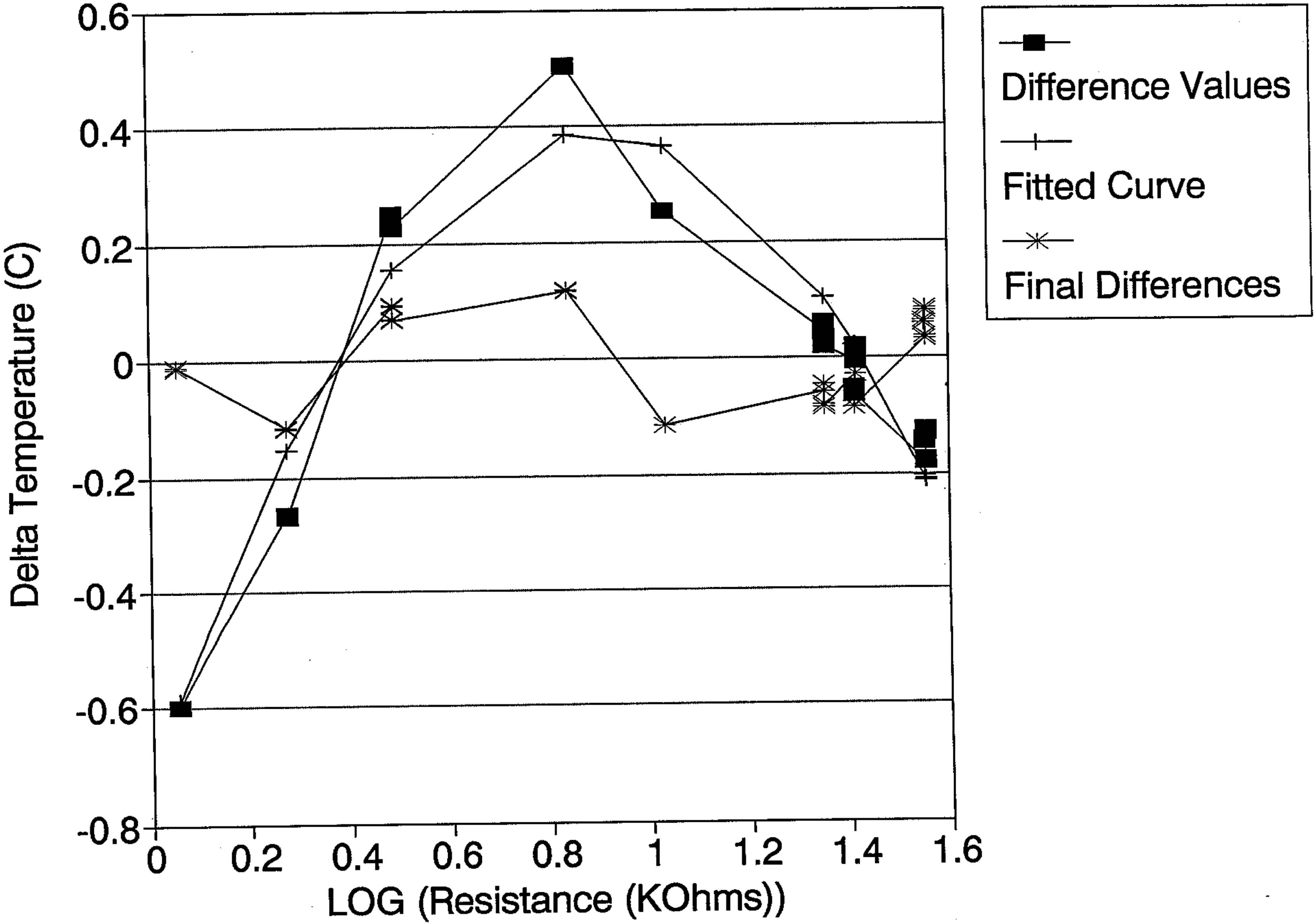


Figure 22D. CHANNEL #6 (Yellow-Blue)

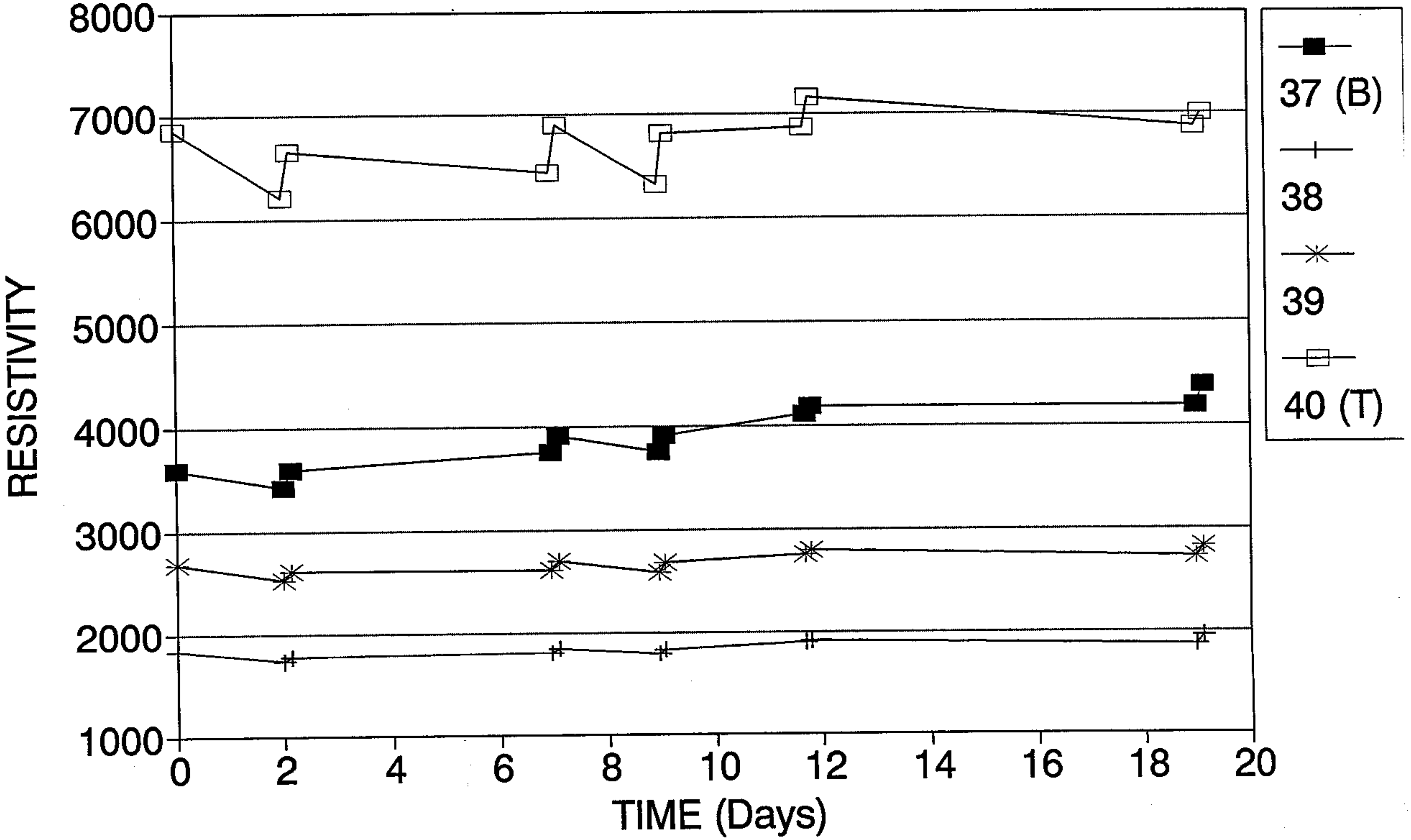


Figure 23A. BLOCK A
30Hz

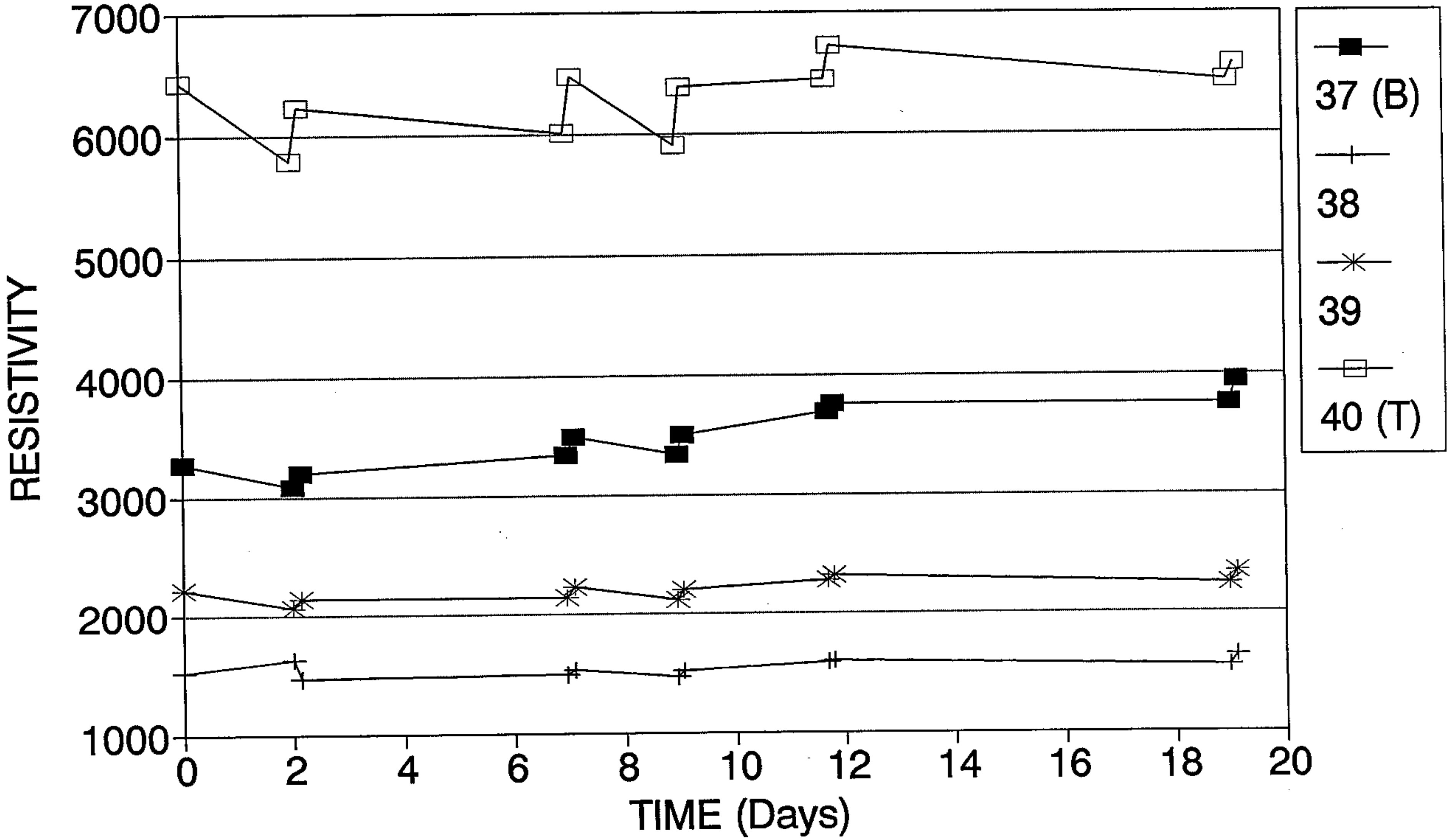


Figure 23B. BLOCK A
1000 Hz

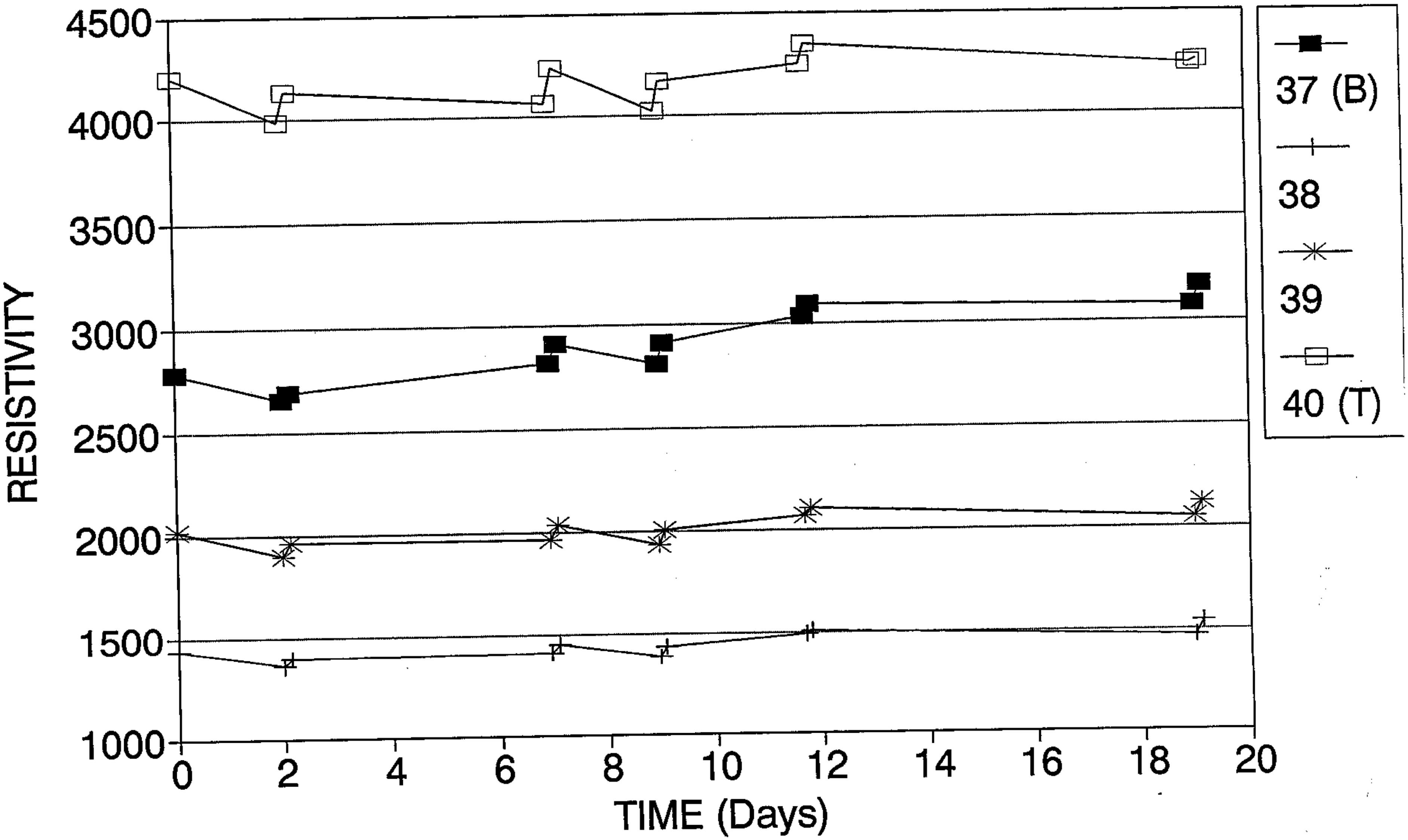


Figure 23C. BLOCK A
30 KHz

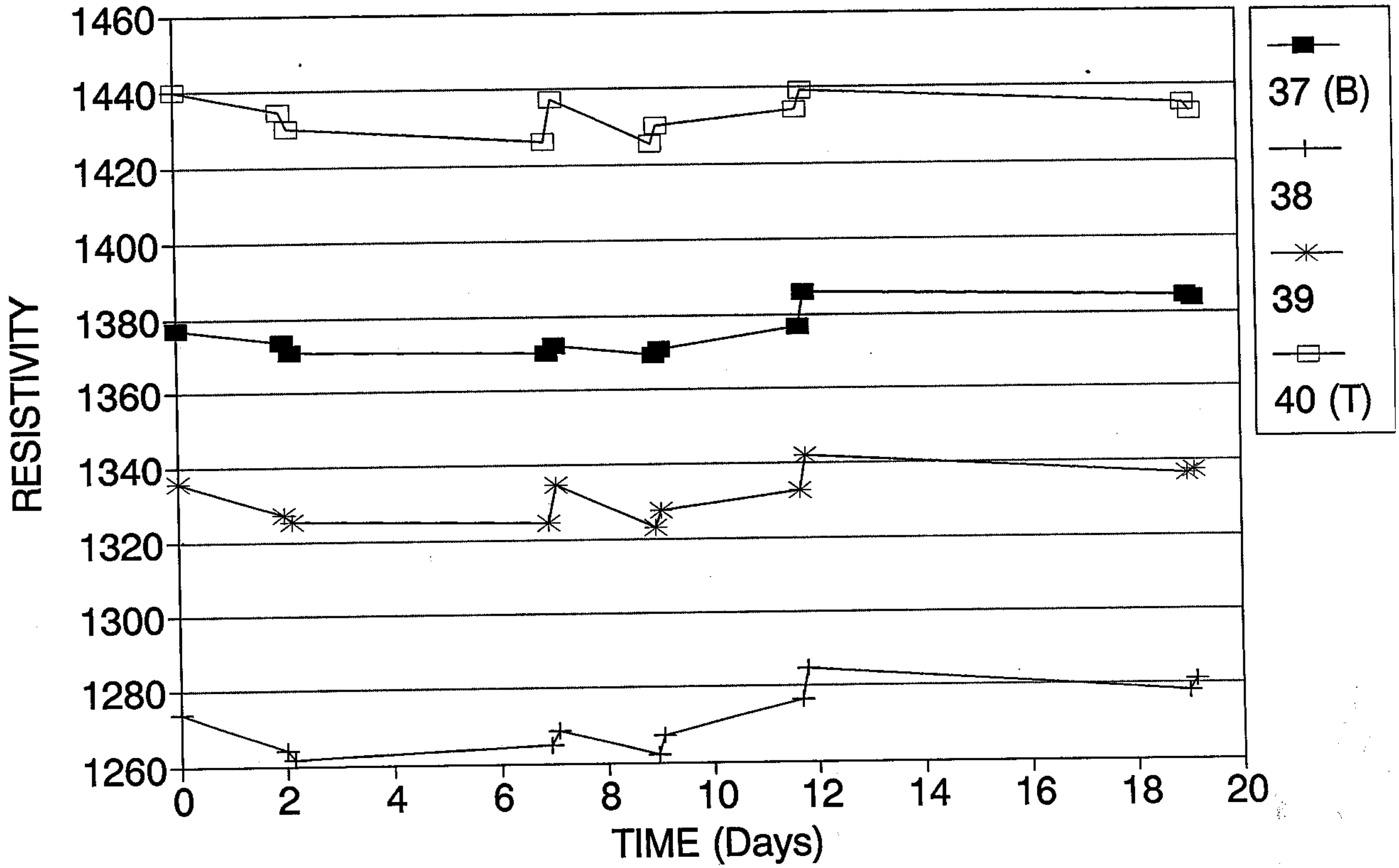


Figure 23D. BLOCK A
700 KHz

A second series of impedance and temperature measurements was made from 15JUN92 and 04NOV92. These measurements were for cycles between 60°F and 90°F. During the middle third of the measurement sequence, we noticed that the impedance of the concrete was increasing significantly indicating a rapid loss of moisture. Later, it was concluded that, with the chamber operating in this higher temperature range and with ambient temperature around it at -25°F, moisture was being drawn out of the chamber through leaks more quickly than the improved moisture source could replenish it. Thus, the humidity did not correspond to the dew point indicated by the moisture source temperature sensor. This was a puzzle because the wet bulb thermometer had been indicating humidities as high as 80%. However, following a check of the inter-calibration of the thermistors used as wet and dry bulb thermometers (the calibrations checked out), it was determined that the humidity was so low that the wick feeding moisture to the wet bulb was being strongly affected, and it was essentially dry at the sensor location.

In parallel with the measurements on the limestone specimens, preparations for series #8 specimens were made. These were the quartzite aggregate specimens. Forms were carefully cleaned and oiled, and rebar sections were cut and brazed ready for assembly. Also, we worked with Mr. Johnston on modifications to the specimen design. More iron wires for measurement of the corrosion potential were added. We also decided to use a carbon filament wire within the concrete as a reference electrode. This design facilitated better monitoring of the specimen during impregnation, and allowed better monitoring during the whole testing program; this also overcame the problem of the difficulty of use of the Cu-$CuSO_4$ half-cell during temperature cycling. Modifications were made to the forms to accommodate these additional sensors in the specimens.

Preparations and pouring of series #8 specimens (quartzite aggregate) were eventually made in late October. Specimens were poured on 27OCT92 and they were unmolded and placed in lime bath for cure on 28OCT92. Subsequently, they were left in the lime bath until 28NOV92 when they were removed and cleaned. All electrical connections were cleaned and the thermistors tested.

g) Seventh Period 16DEC92 - 30APR93.

During this period, we worked on the organization and analysis of the data and the preparation of the final report. Per instructions from the Technical Panel, no further experiments were performed on the concrete specimens in the environmental chamber.

Table 1. Specification of Concrete Specimens

	Specimen Identification							
Parameter	#7A	#7D	#7C	#7F	#7B	#7I	#7H	#7G
I	X	X	X	X	X	X	X	X
II	X	X	X	X				
III	X	X			X	X		
IV	X		X		X		X	

I -- Epoxy seal and thermal insulation on the sides.
II -- Top treated with waterproofing (simulated RACS).
III -- Sodium chloride treatment in top third of specimen.
IV -- Simulated crack (felt) in bottom half of specimen.

Monitoring of specimens #7 in a "humidity soak" chamber was continued. Data obtained for the rebar potential difference up to 28APR93 is shown in Figures 24A and 24B. For the convenience of the reader, Table 1 is duplicated above. These data show that, when dehydrated, all of the specimens which did not receive NaCl treatment (#7C, #7F, #7G, #7H) have a small positive potential difference, whereas all of the specimens which did receive NaCl treatment (#7A, #7B, #7D, #7I) have a small negative potential difference. As moisture was soaked into the specimens, there were some changes in behavior but eventually all the NaCl treated specimens developed a much larger potential difference.

The best presentation method that has been found to compare the seal - no seal cases was to display the "no seal" specimen data as a function of the "seal" specimen data for the otherwise equivalent specimens. These graphs are shown in Figures 24C, 24D, 24E, and 24F; Figures 24G and 24H show the data of the two previous graphs on an enlarged scale. On all of these graphs, the potential differences between the rebar layers within the two blocks are the same when the data points lie on the diagonal across the graph. Thus, comparing specimens #7B and #7A, it is seen that initially the potential differences for the two specimens are essentially the same. As moisture is adsorbed, the potential difference for #7B (no seal) remains almost unchanged for almost 60 days; the slight increase in this potential difference indicates that moisture is entering the concrete block almost symmetrically; the simulated crack causes the small asymmetry. In comparison, the potential difference for #7A (seal) changes due to the strong asymmetry of the entry rates of water vapor; here both the upper seal and the simulated crack in the lower half of the specimen work together to produce strong asymmetry. For a period of almost 100 days the potential for #7B changes whilst that for #7A remains essentially constant. This process corresponds to moisture infiltrating to the regions of both layers of rebar in #7B, the upper region with and the lower region without NaCl present so the potential difference changes, whereas for #7A the moisture has to infiltrate just from the lower surface; apparently it takes about 100 days of unidirectional moisture infiltration to fully penetrate to the upper region where NaCl is present in the environment of the rebar. Thereafter, the potential differences for both specimens again become equal as moisture reaches the upper region of #7A.

Similarly, the comparison of the potential differences between rebar layers in specimens #7D and #7I are initially the same, but the influence of the seal in specimen #7D is much stronger because of the absence of simulated cracks in both specimens. Even after approximately 180 days, the potential differences are a long way from again being equal due to the increased distance within solid concrete through which the moisture has to infiltrate.

These data are a very direct indication of the effect which the presence of a moisture-proof seal on the upper surface of the blocks and a simulated crack in the lower half of the blocks has on the moisture distribution. The differences between the no crack and crack pairs indicate that the simulation of a crack is working.

For the two no NaCl pairs, the potential differences are very much smaller. However, on the expanded scales of Figures 24G and 24H, there are small differences which show systematic behavior. For specimens #7F and #7G, both of which do not contain cracks, the initial and final potential differences are both closely equal and the excursions are below the diagonal. For specimens #7C and #7H, both of which do contain cracks, it appears that there were some initial differences between the specimens and the presence of the cracks accentuate these differences as the moisture enters. Despite the excursions, the potential differences do seem to be approaching similar values.

From the comparison of the NaCl and no NaCl pairs, the influence of the presence of NaCl, and, more specifically, the likely presence of Cl^- ions, has a very strong effect on the differential potentials.

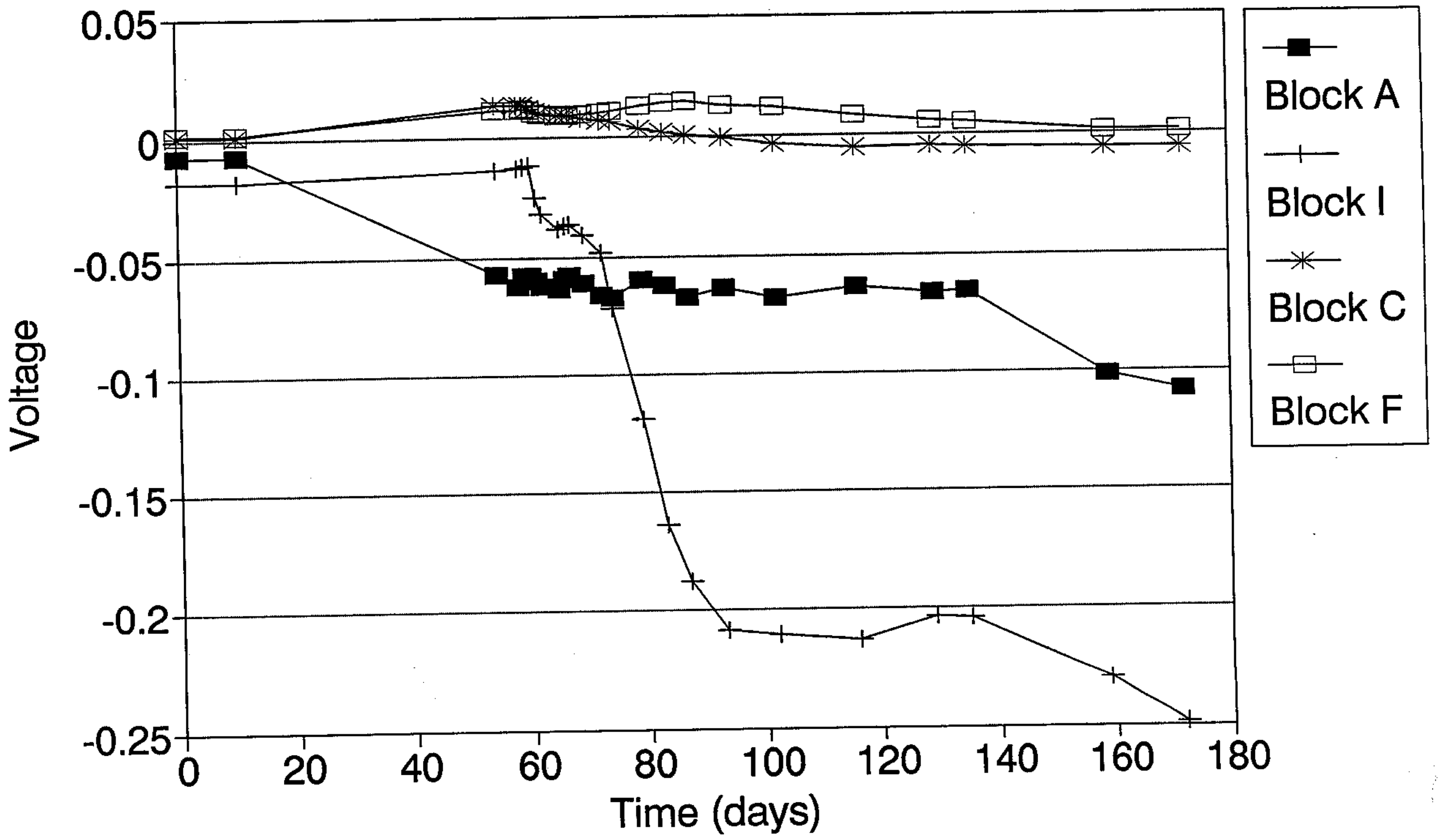


Figure 24A. Rebar Potential Difference vs. Time Blocks A,I,C,F in 100% Humidity

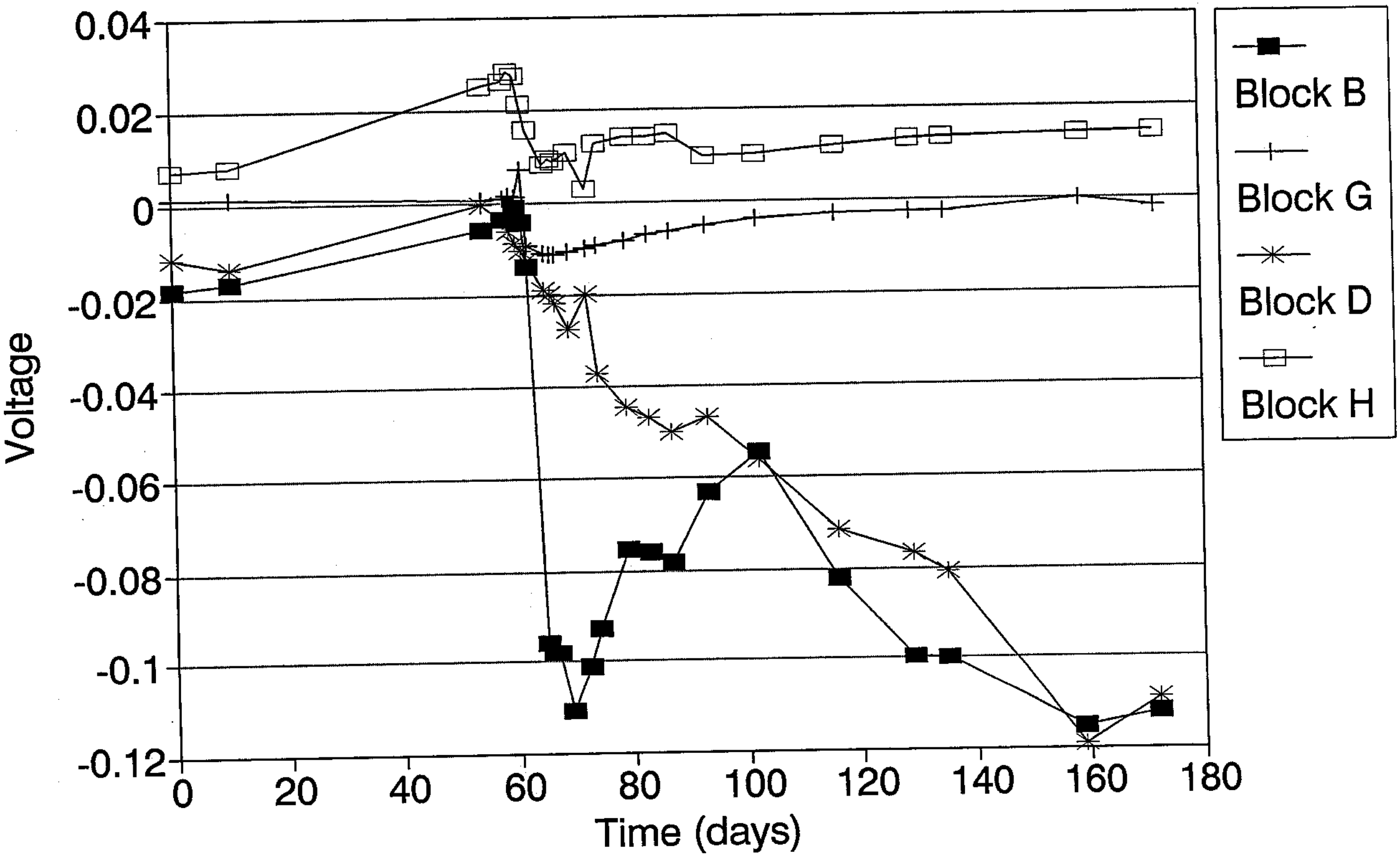


Figure 24B. Rebar Potential Difference vs. Time Blocks B,G,D,H in 100% Humidity

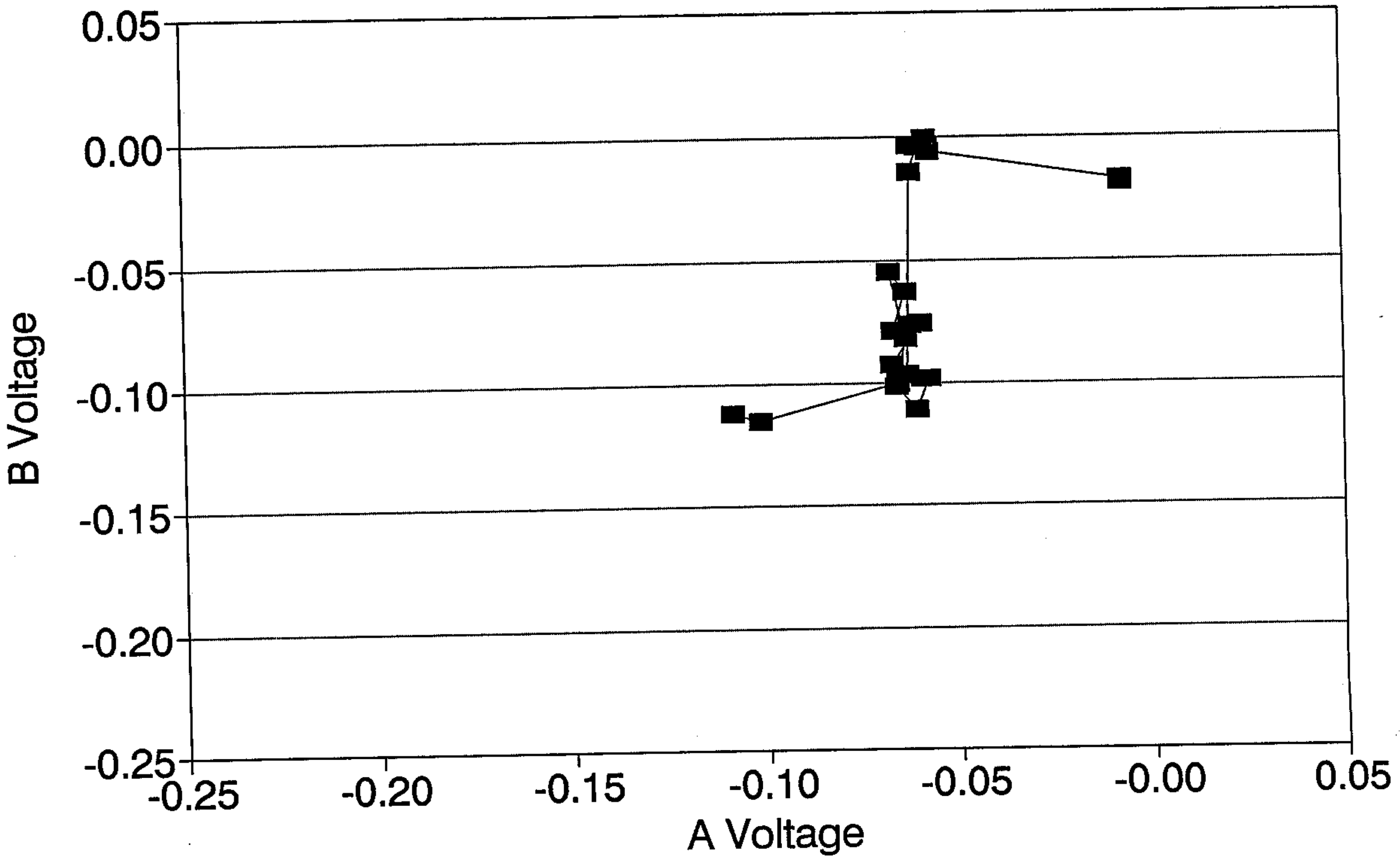


Figure 24C. Differential Potential B vs. A

B=No Seal, A=Seal, Both NaCl & Crack

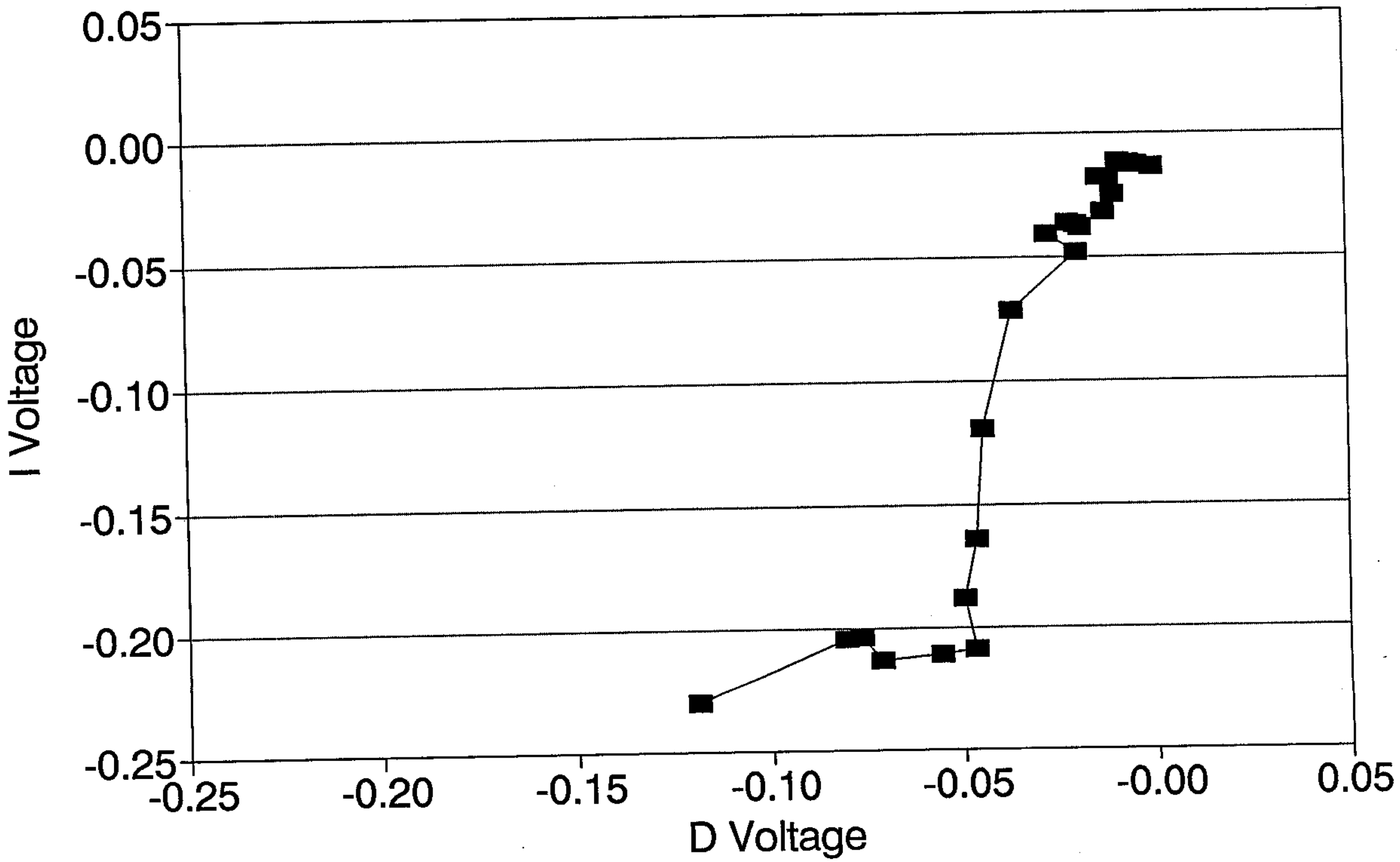


Figure 24D. Differential Potential I vs. D

I=No Seal, D=Seal, Both NaCl & No Crack

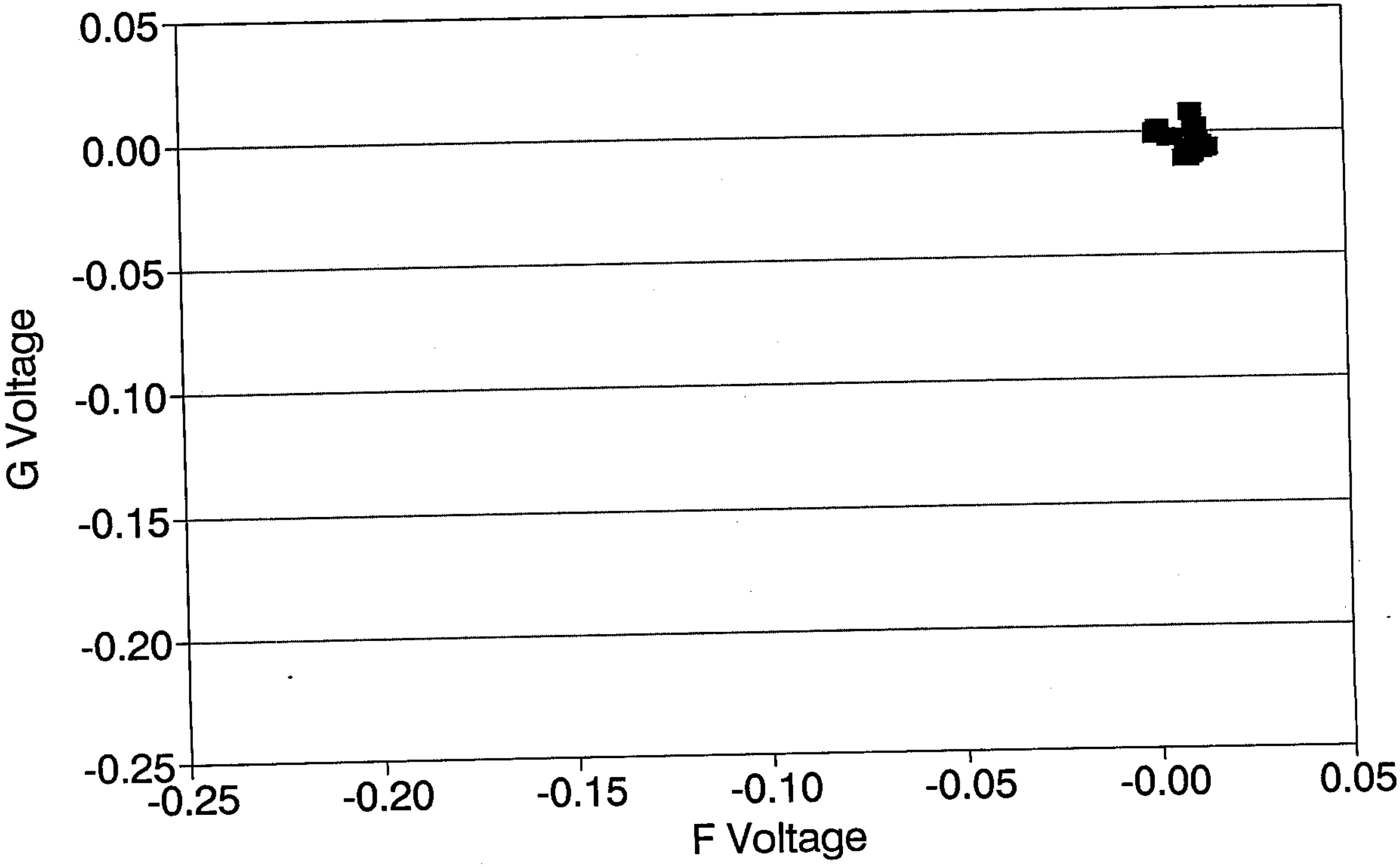


Figure 24E. Differential Potential G vs. F
G=No Seal, F=Seal, Both No NaCl & No Crack

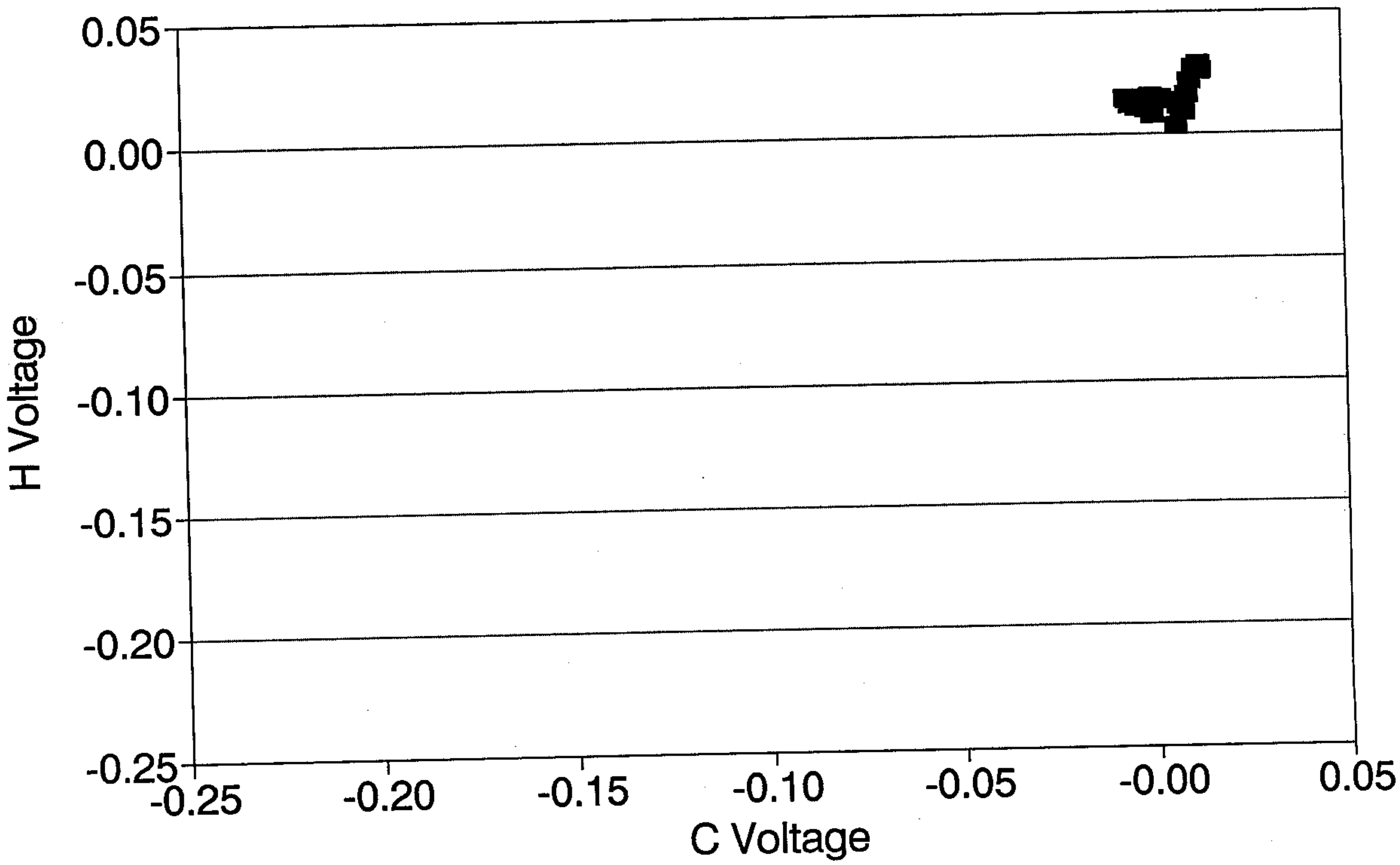


Figure 24F. Differential Potential H vs. C

H=No Seal, C=Seal, Both No NaCl & Crack

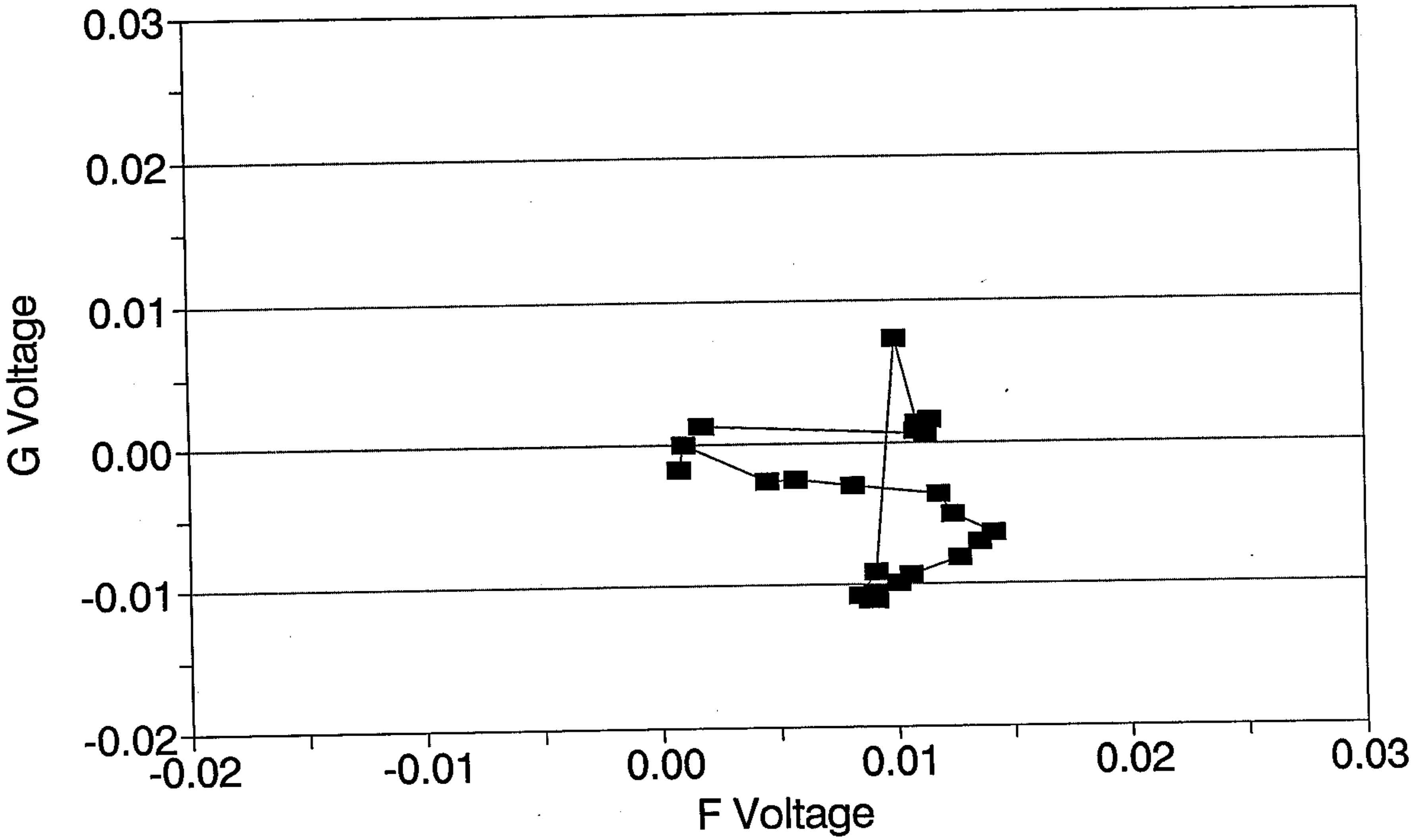


Figure 24G. Differential Potential G vs. F

G=No Seal, F=Seal, Both No NaCl & No Crack

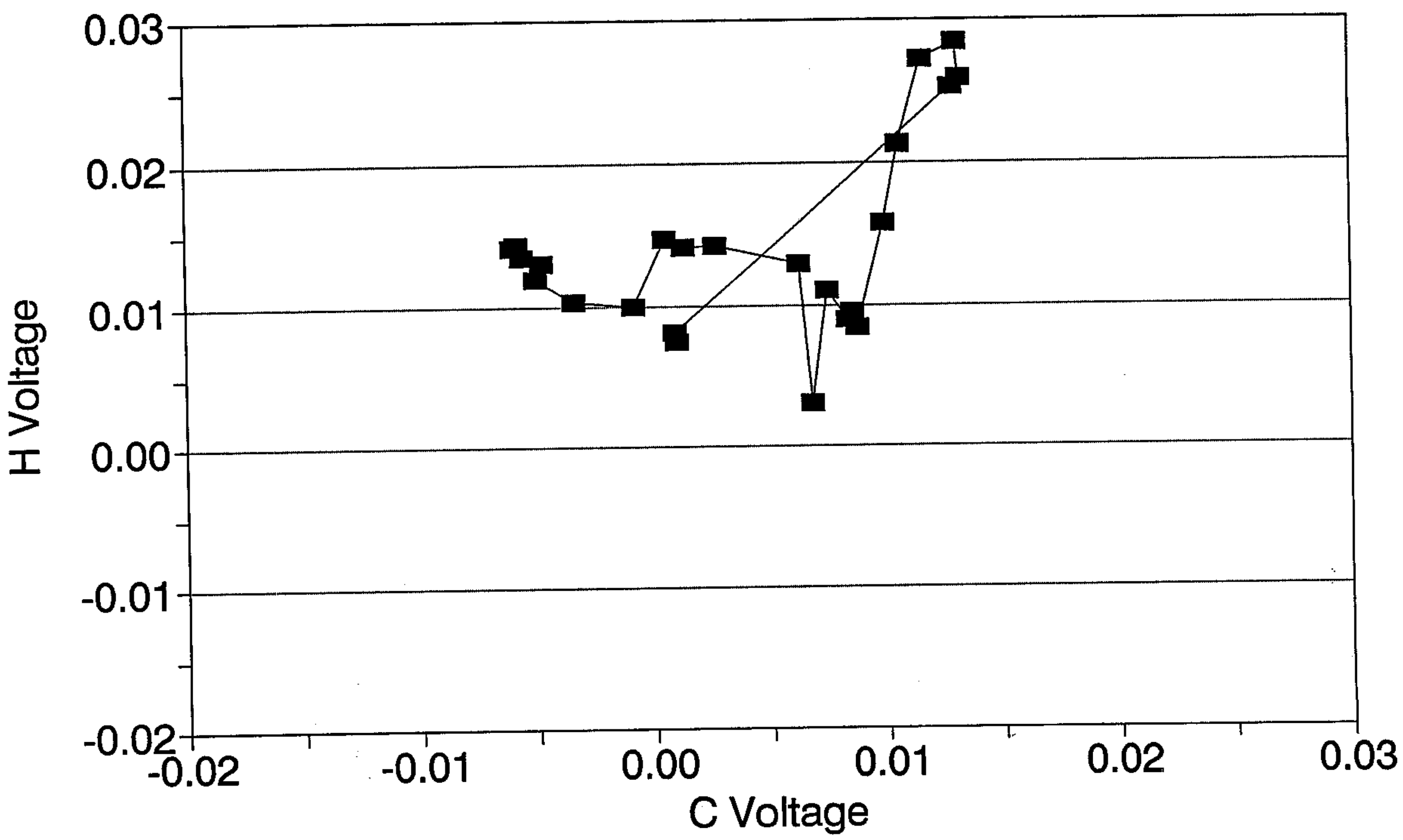


Figure 24H. Differential Potential H vs. C

H=No Seal, C=Seal, Both No NaCl & Crack

Also, under private funding, an experiment is being conducted on the related problem of moisture adsorption in a column of concrete. Figure 25 shows a schematic of the specimen configuration and instrumentation. Each specimen is a concrete cylinder 4" in diameter and 15" long, with 14 #16 gauge stove-pipe wires spaced at 0.5" intervals placed across diameters of the cylinders, 4 nichrome wire sensors each consisting two parallel wires of #22 gauge separated by 0.5", and three thermistors mounted inside heat-shrink tubing located as shown. The outer cylindrical surfaces were sealed with a water-proof epoxy. Two identical specimens, #9A and #9B, are each stood on small Plexiglas blocks inside a beaker. Saturated CaOH solution and saturated CaOH + 3%NaCl solution was poured into the beakers containing #9A and #9B respectively until the liquid level was approximately 0.25" above the base of the concrete cylinders.

Figures 26A and 26B show the ac impedance of cylinders #9A and #9B respectively as a function of time. Similarly, Figures 26C and 26D show the relative potentials for the lowest six single iron wire sensors. The resistance of each thermistor in both specimens and the derived temperatures are shown in Figures 26E and 26F. The first point to notice is that there is an exact correspondence between the thermistor resistance variations and the ac impedance variations with time for the first ten days of the experiment. Clearly, the ac impedance is a function of temperature. Although no immediate conclusions can be made from this observation, it will be useful for future work to have this piece of information available. We were also surprised not to see an effect in the impedance measured at 700 kHz. Based on previous observations, a significant effect was expected. For sample #9A which was in saturated CaOH solution, sensor 1 (the lowest) quickly showed a small decrease in potential; all the higher sensors showed a small increase in potential on the same time scale. As time passed, the potential of the lowest sensor increased slowly. For specimen #9B, all sensors started to show a slight increase in potential, but sensor 1 then quickly developed a potential of -0.2 volts; this potential then became essentially steady. The signals from the other sensors are not easy to interpret. Sensors 2 and 4 recorded a potential of ~0.05 volts, but then the potential at sensor 4 dropped to about zero, and some time later, the potential at sensor 2 dropped to about zero; the potentials at sensors 3 and 6 both became somewhat negative then came back close to zero.

One definite and important conclusion can be made. The measurements of the relative potential in the two specimens differ significantly, and the only difference is that one specimen is in a solution which contains NaCl. We understand that this result will be of no surprise to anyone who has worked on problems of corrosion and cathodic protection. But it is nice to see the effect of the presence of NaCl clearly demonstrated. We expect to add to these experiments the effect of a dc potential, in particular, measuring the dc potential as a function of the time for which it is applied, and then also monitoring the decay of the potential when the voltage source is removed.

The use of the carbon fiber reference electrode seem to work very well. The relative potentials measured by these built-in cells are very much more consistent than any results we have obtained using an external $CuSO_4$ half cell; we attribute this to the reduced uncertainly and temporal variation of the contact potential and resistance for the built-in unit as compared with an external unit. However, a number of improvements were immediately obvious for this experiment. First, the specimens do not need to be nearly as long. Four inches would probably be adequate. Also, it would be useful to have the density of the potential sensors doubled. Finally, the data would be much easier to interpret if the specimens were housed in an environment which had a more stable temperature. The inclusion of one thermistor and two two-wire sensors would be adequate. These specimens are relatively simple to fabricate, and they provide a simple means of performing tests to study the effects of various parameters. Further tests of this nature will be carried out.

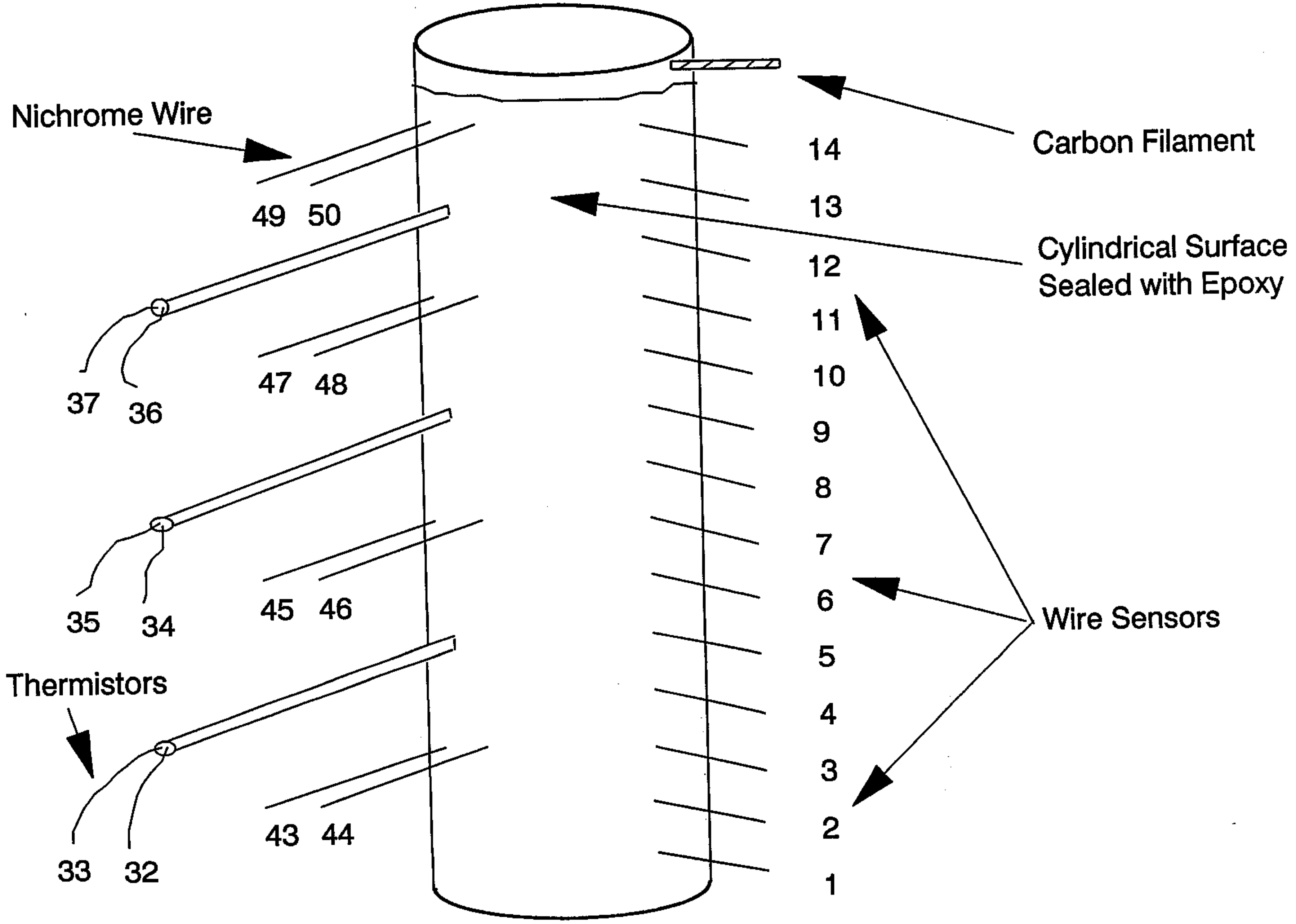


Figure 25. Schematic of Vertical Diffusion Specimens

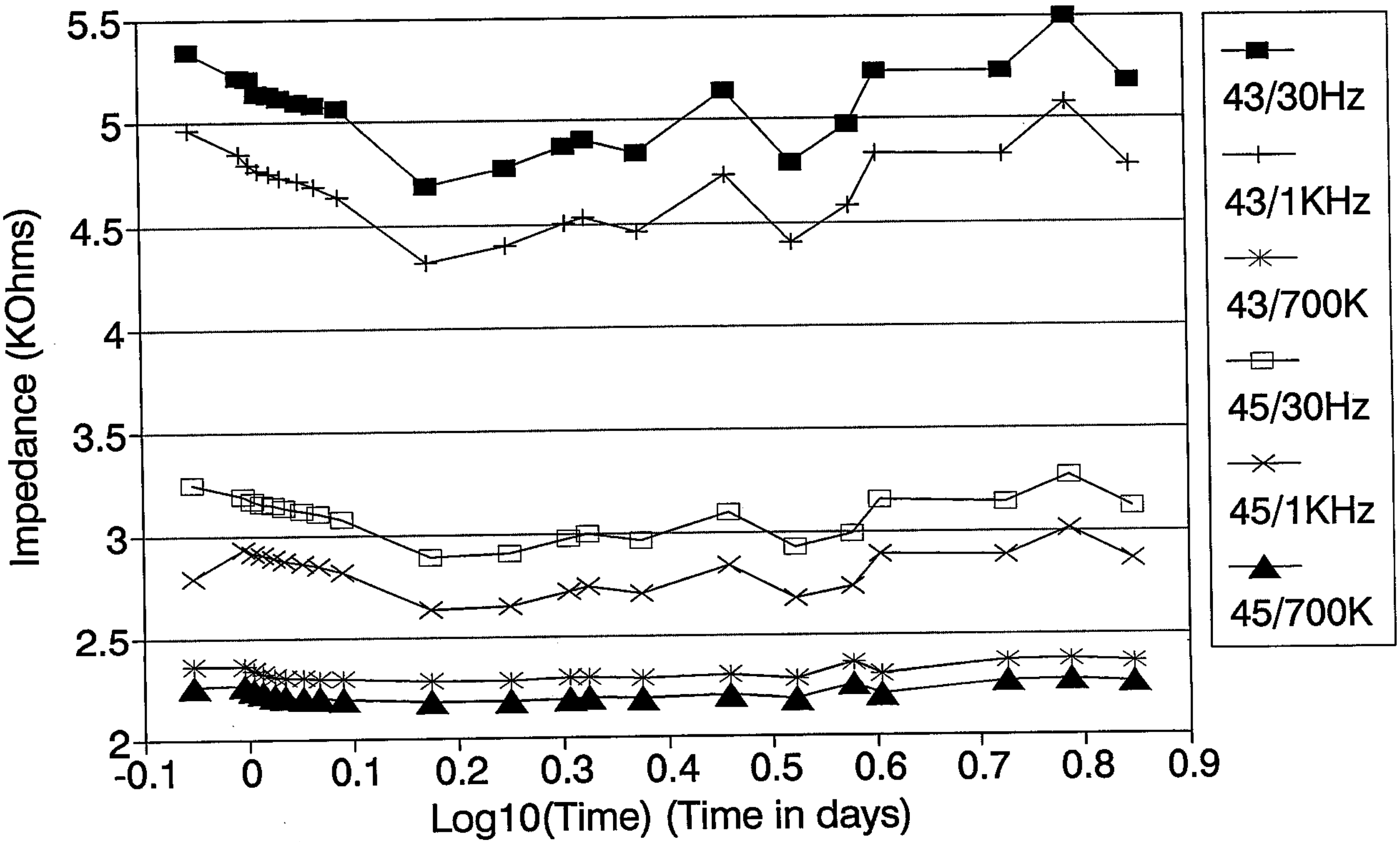


Figure 26A. CONCRETE CYLINDER A (CaOH)
AC Impedance vs. Time (43-44 & 45-46)

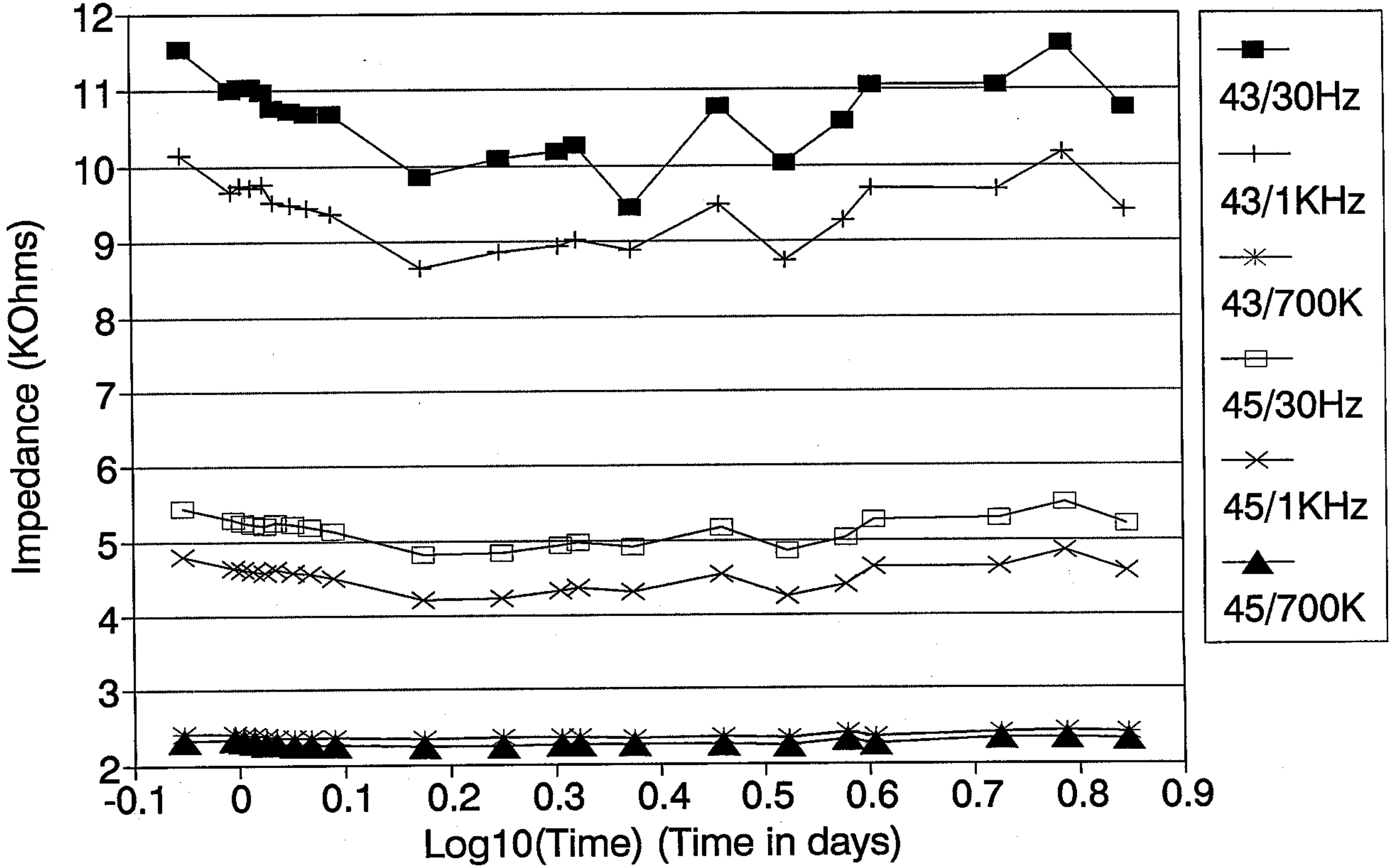


Figure 26B. CONCRETE CYLINDER B (CaOH + NaCl)
AC Impedance vs. Time (43-44 & 45-46)

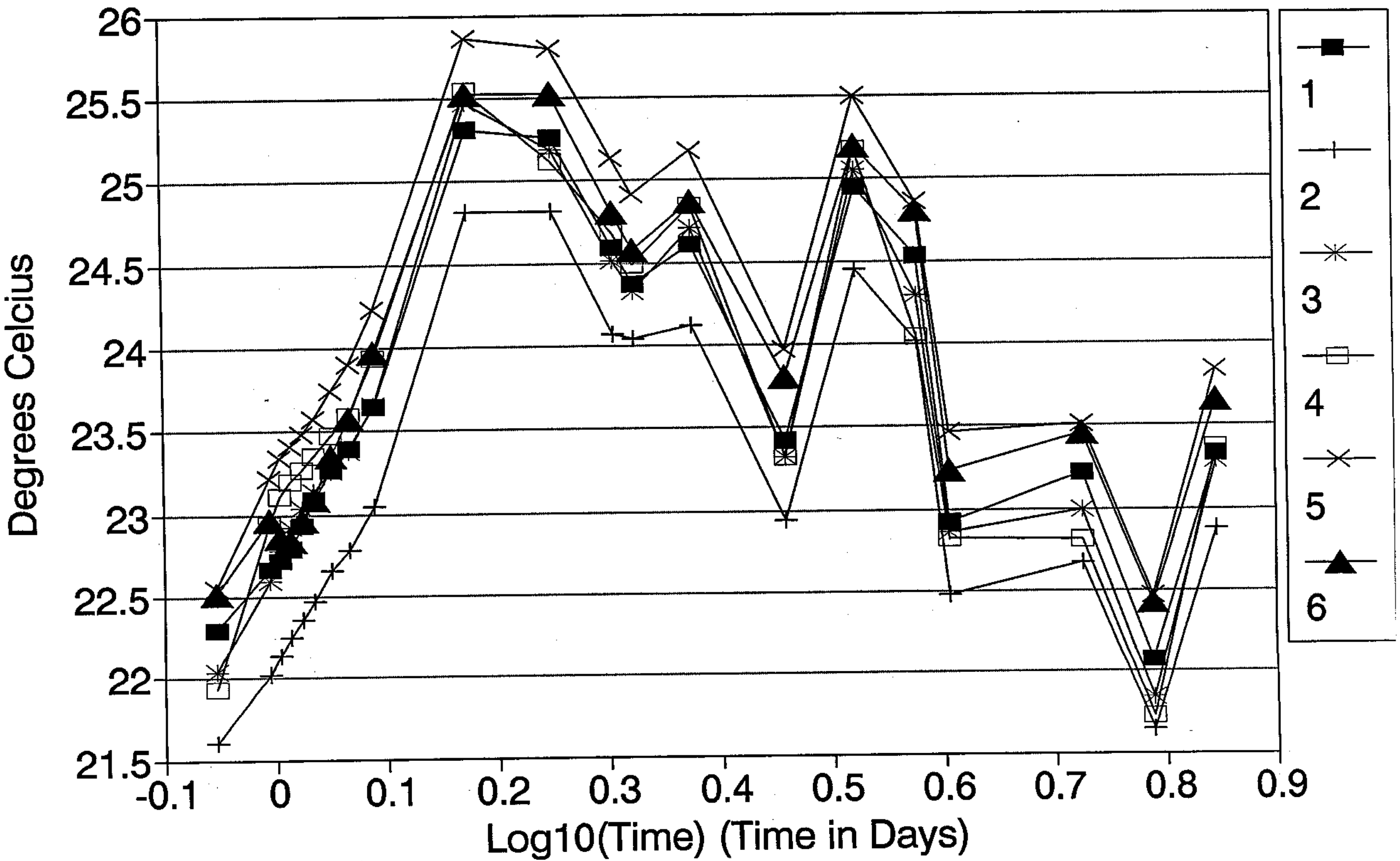


Figure 26C. CONCRETE CYLINDERS A & B
Temperature vs Time

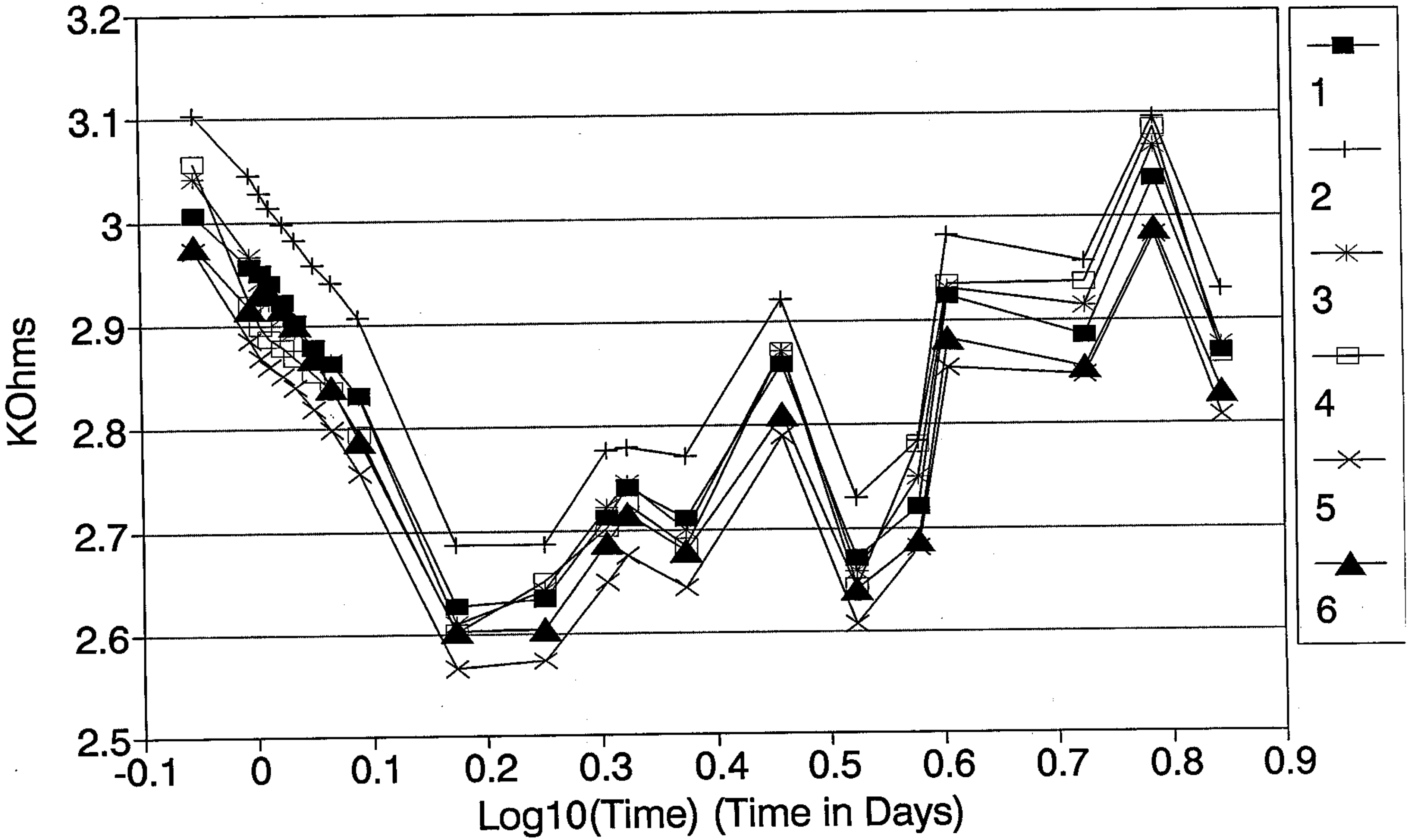


Figure 26D. CONCRETE CYLINDERS A & B
Thermistor Resistance vs Time

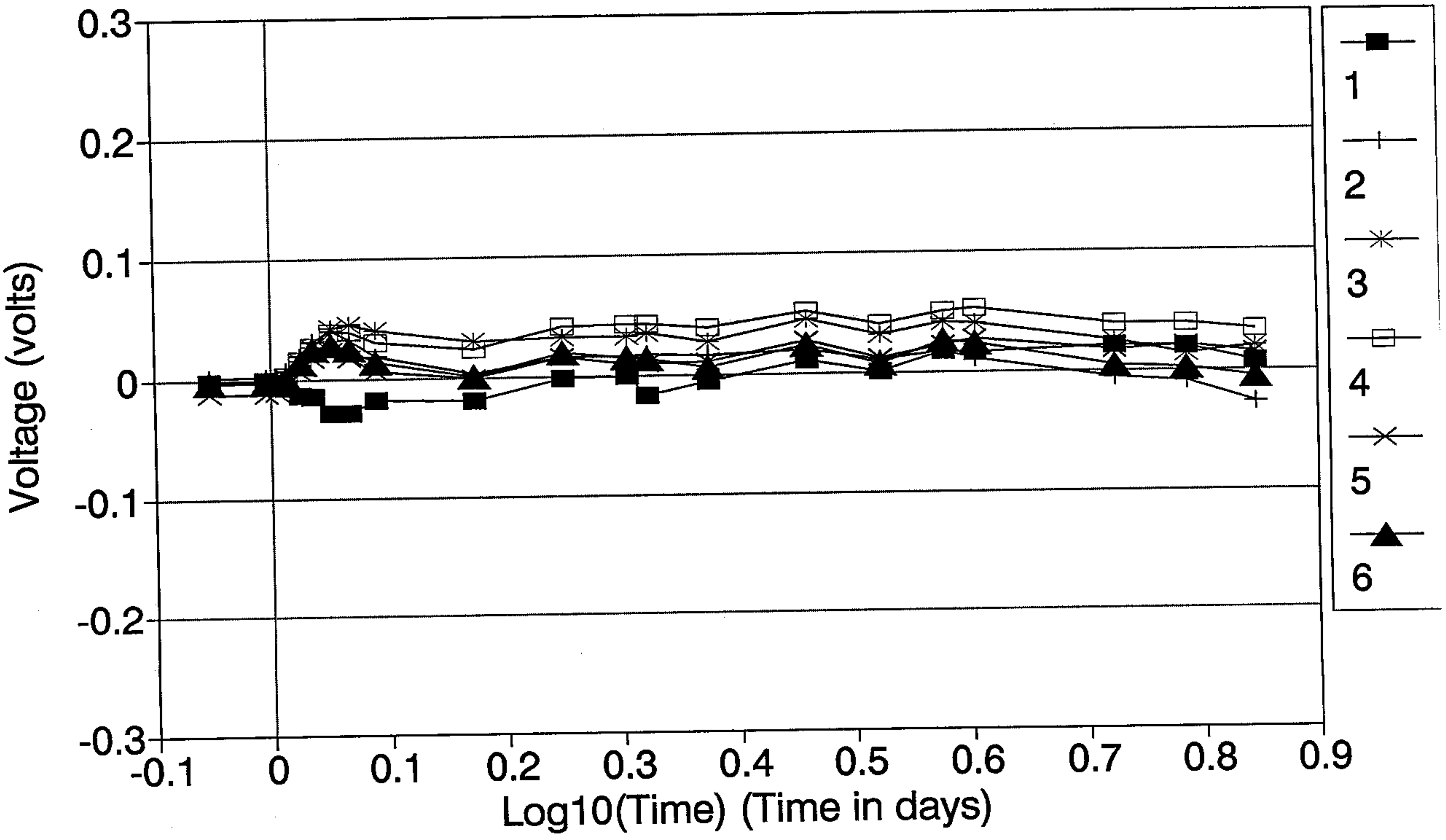


Figure 26E. CONCRETE CYLINDER A (CaOH)
Relative Potential vs. Time (123456)

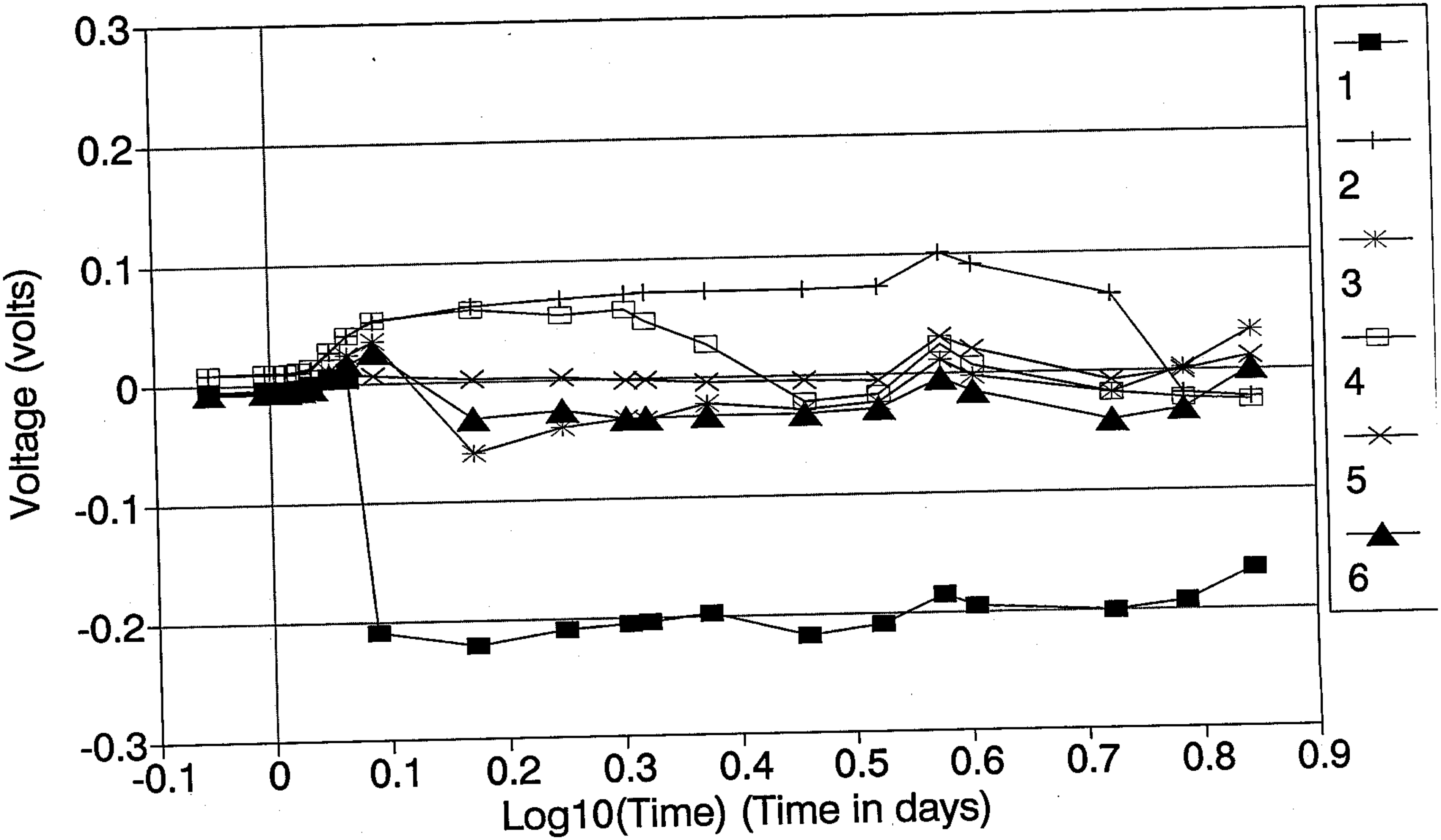


Figure 26F. CONCRETE CYLINDER B (CaOH + NaCl)
Relative Potential vs. Time (123456)

VI. PROBLEMS ENCOUNTERED

Overall, there were three major sources of delays and difficulties:

1) The even-greater-than-expected difficulty in detecting the chloride ions and achieving controlled impregnation. Monitoring techniques which were expected to be fairly simple, based on papers in the literature, turned out to be much more complicated. Implementation of the thermal cycling with the thermal mass of the specimens in the environmental chamber was more difficult than expected.

2) Delays in obtaining materials, especially those for the concrete and for the sensors; some delay was also caused by the addition of the simulation of cracks in the lower surface of the concrete.

3) The greatest problem was the requirement that we add to the project the simulation of solar radiation. This was not included in the project as proposed and as described in the contract. The restricted space in the freezer compounded the problems.

In any research project, some delays and difficulties are expected to be encountered. This is normal, since, if everything was known before-hand, the work would not be research. Also, at the outset, it was understood that the work we were attempting was a particularly "high risk" project.

Task 2 contained the bulk of the work of the project. It was in this task that we expected, and did indeed encounter, most of the delays and difficulties in actual performance of the work as it was originally proposed. Achieving controlled NaCl contamination of the upper one third of the specimen only, being able to verify the introduction, and being able to monitor the range of contamination in real time was expected to be difficult, and we were not disappointed. In retrospect, we should have included in the proposal, as a preliminary step, a systematic investigation of this process and development of the methods to monitor it without commitment to proceed further until these issues had been successfully resolved. The very tight space within even the largest chest freezer available to us increased the difficulties of achieving the temperature cycling and thus the time spent implementing it. This difficulty was anticipated and discussed with SD DOT personnel prior to submitting the proposal. But we were told that the proposal would not be funded if the capital expenditure for a walk-in coldroom was included; so we agreed to do the best we could without a walk-in coldroom.

Materials and components had to be tested. Only after suitable items were found could orders be placed for them. Nowadays, manufacturers do not carry inventory in many cases. As a result, we had a delay of nearly four months getting the bulk of the thermistors from Victory Engineering. Use of another manufacturer was impractical, since the cost would have increased by a factor of two or three, and the delivery time would have been at least doubled. Obtaining samples of the titanium oxide ribbon took months, as did the samples of the carbon filament material.

As indicated previously, some delay was caused to the project by the added requirement that a scheme be devised and tested for the simulation of cracks in the lower half of the concrete specimens. This was not terribly difficult, but it did cost us about two months to devise tests and to carry them out on candidate materials.

During the project we encountered some of the "normal" types of problems described above; we were able to solve them and maintain steady progress. The major problem was caused by the modification of the experiment to simulate direct sunshine on top of specimens. This modification led to a lot of extra work, and more importantly, to problems with the environmental chamber operation. These problems were in part due to having to work within the confines of a freezer. The original design of the experiment and the chamber, as proposed, were made taking into account the limitations of the space available in a freezer and the difficulty of attaining high humidity in a chamber with colder ambient conditions. Attempts to make the requested change resulted in a cascade of problems. Eventually, the problems were basically overcome. We can now achieve the 90% relative humidity indicated in the proposal, with slight limitations on the extent of the temperature excursions. We could possibly achieve the further request that has been made to create even higher humidities by putting a water spray of some form into the chamber so that the increased problems as seen in areas of higher humidity in the south-east corner of South Dakota could be investigated. But this would probably require a lot of effort because the incorporation of a water spray may cause serious problems with the simulation of the solar radiation, as it is currently implemented.

The final irony was the delay getting components for the second series of specimens, particularly the quartzite aggregate. After putting in (literally) hundreds of hours, which were not charged to the project, and finding ways around the problems encountered, we were held up for almost four months awaiting receipt of the quartzite aggregate. These concrete specimens were made and are ready for wiring, sealing, and insulating.

Toward the end of the project period, the research monitor suggested that the dehydrated limestone specimens be placed in a chamber where they could undergo a "humidity soak". That is, they be placed in a very humid environment without making contact with liquid water. This suggestion did not involve very much effort and was adopted. In addition, the principal investigator made the decision to continue monitoring the specimens during the process. It was of substantial benefit that these things were done, since, by monitoring the changes in the differential potential between the two layers of rebar, significant information about the influence of the simulated RACS and simulated cracks has been obtained.

VII. CONCLUSIONS AND RECOMMENDATIONS

The following conclusion can be drawn from the data collected and the observations made whilst performing the work described in the preceding sections:

1) The comparative experiment in its original form was feasible, and would probably have given useful information regarding the problem. However, it would certainly have fallen well short of being able to define the mechanisms involved, and it would not have answered all the questions regarding the possible benefits/detriments of chip seals.

2) It is very difficult to accurately simulate natural environmental diurnal temperature cycles within the laboratory. It is made even more difficult if the space available is severely limited.

3) It is not possible to simulate the effects of natural radiative cooling in a closed chamber. Although the effects of specimen scaling cause an increase in the ratio of surface area to volume as compared to an actual bridge deck, the specimen does not have the solid angle of an element of the upper surface subtended by a region which is close to absolute zero. Cooling has therefore to be achieved primarily by connective transfer, and this requires that a major portion of the surface of the surrounding container be at a significantly lower temperature than the specimen. As a result, there will always be a strong vapor pressure gradient away from the specimen towards a portion of the chamber walls. Consequently, the humidity near the specimen surfaces will be very low during the cooling period.

4) In the natural environment when forced convection is not present (no wind), the moisture in the air beneath the under side of the concrete will be kept high because of natural connective transfer (of both heat and moisture) and radiative heat transfer from the earth below (which will keep the temperature and hence also the saturated vapor pressure relatively high). Even if water is sprayed onto the lower surface of a model deck, the appropriate temperature gradient within the concrete will not be achieved. Therefore, we do not believe that the natural environment can be accurately simulated by a forced air system. It may be possible to achieve a better simulation for the lower specimen surface in the laboratory by supplying and removing heat from within the concrete specimen by some means.

5) The incorporation of moisture into RAC-sealed bridge decks could be a two-stage process. Moisture has to enter at the underside of the deck, since the upper surface is sealed; the data shown in Figures 24C through 24H support this fairly obvious fact. The critical issue is whether there is a monotonic temperature change throughout the thickness of the deck; that is, the temperature is lowest at the top surface and steadily increases down to the bottom surface. Such a temperature profile will result in a vapor pressure within the lower portion of the deck being higher than that in the upper portion of the deck. Under these conditions, if the lower surface is somewhat cooler than the surrounding air and the air is at saturation, then moisture will condense on the lower surface and the vapor pressure gradient will tend to drive the moisture directly to the upper surface. Alternatively, if a monotonic temperature change does not exist, even when the underside of a bridge deck is somewhat colder than the surrounding air and the air is at saturation, moisture will remain in the lower section of the deck. Then, when the upper portion of the deck is colder than the middle portion, the moisture will migrate to the underside of the RACS by this two-stage process. Further work should be performed on an actual bridge deck to determine which of these hypotheses is correct.

6) The data shown in Figures 24C through 24H indicate that the simulated cracks do have an effect. It is believed that the crack simulation is effective.

7) For monitoring specimens, some of which have a simulated RACS, the use of a $CuSO_4$ half-cell is both inconvenient and does not have good reproducibility. The differential potentials between layers of rebar and relative potentials between iron rebar or wires and a built-in reference electrode give much more consistent values than a half-cell. These potentials are useful and reliable for the monitoring.

8) Discussions with Mr. Johnston have revealed that the effects seen during the humidity soak test on specimens #7 seem to be reproducing the effects which are seen in bridge decks in the field. This includes both the behavior of rebar potentials as bridge deck dry and become wet again, and the effect of the presence of cracks upon the potentials during drying and wetting.

9) The use of the differential potential between rebar layers and relative potentials between stovepipe wire sensors and a carbon fiber reference electrode seem to work very well. The relative potentials measured by these built-in cells are very much more consistent than any results we have obtained using an external $CuSO_4$ half cell.

10) Our observation that the data obtained from the two-wire sensors under ac excitation does not follow the expectations from both theory and a number of measurements of the dielectric properties of concrete is interesting. An equivalent sensor also operated with ac excitation shows a strong and reproducible effect when used in saline solutions. This would seem to indicate that NaCl does not fully dissociate in water, and the sensor is then responding to the dipole moment of the remaining molecules. It seems that, in concrete, any NaCl present is either fully dissociated, or the remaining molecules are somehow bound to the matrix in such a manner that they cannot be rotated by an electric field of the strength we have been using. Tests should be performed with two-wire sensors using a range of ac voltages, but it seems that ac techniques cannot effectively detect non-polar ions and molecules.

11) The two wire sensors with ac excitation work well as a sensor of moisture in concrete (Figure 9). Measurements made with a high frequency signal (near 1 MHz) are the most sensitive. Resonant modes for water molecules are in this frequency range. However, a signal in the 3 kHz to 30 kHz produce the smoothest calibration curve. Thus, we were able to see the migration of moisture in the concrete, but not the migration of NaCl or its ions. Impedance measurements made with dc excitation have little sensitivity to moisture.

12) Victory Engineering thermistors mounted in a protective sleeve of heat shrink tube have worked very effectively as temperature sensors. They are very sensitive and stable.

13) We have some valuable, well instrumented specimens on which measurements have been made (Series #7: limestone aggregate) and some which are ready to be wired (Series #8: quartzite aggregate). These specimens could be used for further studies, both in the laboratory and in the field.

14) Overall, the instrumentation developed during the course of this research can be used to monitor temperature (using thermistors), moisture migration (using two-wire sensors operated at 3 kHz to 30 kHz), and chloride ion migration (using built-in relative potential cells of iron wires referenced to a carbon filament) in actual bridge decks either with or without rubberized chip seals.

15) In conducting this research, we have so far developed a great deal of useful information, but we are not presently in a position to answer all of the specific questions which were the objectives of the proposal we submitted. As indicated above, this is the result of the difficulty of the project, the serious delays in the acquisition of materials, and especially the mid-project changes which were made.

Generally, our most important recommendation is that one or more further research projects should be initiated on this problem. Rather than attempt additional laboratory simulation of Bridge decks both with and without simulated RACS, laboratory experiments should be designed to investigate specific mechanisms and effects within the concrete. Comparative experiments between RACS and non-RACS cases should be done in the field on actual bridge decks; meteorological data for the sites should be taken as part of the study. Fairly large slab mock-ups of bridge decks could perhaps be substituted for actual bridge decks. Findings from the project reported here should be used to guide the design of both the laboratory and field experiments.

The following specific recommendations are made:

1) Further attempts to study model bridge decks in a laboratory simulation of the natural environment should not be made. Simulation of the radiative cooling of the specimens simply cannot be accurately made in an enclosed chamber. Thus, the humidity profile around the specimens cannot be simulated.

2) In order to make the best progress on this problem, additional laboratory studies should first be made. These should include experiments such as monitoring specimens as they adsorb and lose moisture in a simple humidity soak environment and a very dry environment (to obtain data such as is shown in figures 24A through 24H), and simple comparative tests (such as those performed on specimens #9A and #9B) to further investigate the movement of moisture in concrete and to gain a much better understanding of the state of dissociation of NaCl within concrete and the migration of the molecules and/or ions.

3) Our procedures for achieving controlled impregnation and its monitoring appear to work. They should be checked and, if necessary, refined.

4) Further studies of moisture and ion migration in concrete under a temperature gradient should be performed in the laboratory. However, it would likely be simpler and more profitable to use internal heating and cooling within the specimens rather than simulation of the natural environment.

5) A question which should be asked is "Do RACS really seal against the infiltration of ponded moisture, or is the interfacial moisture being introduced through the seal?" Careful laboratory tests need to be carried out to determine the answer to this question if such tests have not been performed previously.

6) Based on conclusion #3, it would be appropriate to instrument one or more bridge decks to determine the actual temperature variations with time. Dry and wet bulb temperatures should be monitored close to both the top and bottom surfaces of the decks. Also, other meteorological data such as wind data and precipitation should be recorded at the site(s). Such measurements would have the greatest possibility for determining whether the incorporation of moisture into RAC-sealed bridge decks is a single or a two-stage process.

7) Based on our conclusions, it is recommended that a significant field experiment be performed. The experimental design could use either actual bridge decks or fairly large slabs constructed to the same specifications as a bridge deck. These experiments should be located at least in regions of both high and low humidity, and should represent both RACS and non-RACS decks. The decks should be fully instrumented with thermistors for temperature monitoring, single stovepipe (or equivalent) wire sensors with a reference electrode to monitor the presence of chloride ions, and two wire sensors to monitor moisture levels. Monitoring of the environmental conditions, as described in recommendation #5 should be made. Recommendation #5 could be incorporated as part of this experiment or performed separately.

XII. REFERENCES

[1] Kim, H. C., and S. S. Yoon, "Dynamic Dielectric Analysis during Early-Stage Hydration of Ordinary Portland Cement", Journal of Physics D: Appl. Phys., 21, 1215-1220, 1988.

[2] Bari, M. A., "Comment on Dynamic Dielectric Analysis during Early-Stage Hydration of Ordinary Portland Cement," Journal of Physics D: Appl. Phys., 23, 234-236, 1990.

[3] McCarter, W. J., and S. Garvin, "Dependence of Electrical Impedance of Cement-based Materials on their Moisture Condition." Journal of Physics D: Appl. Phys., 22, 1773-1776, 1989.

[4] McCarter, W. J. and P. N. Curran. "The Electrical Response Characteristics of Setting Cement Paste." Magazine of Concrete Research, 36(136): 42-49, March 1984

[5] J. G. Wilson and H. W. Whittington. "Comment on 'The Electrical Response Characteristics of Setting Cement Paste' by W. J. McCarter and P. N. Curran." Magazine of Concrete Research, 37(130): 52-56, March 1985.

[6] Olp, K., G. Otto, W. C. Chew and J. F. Young. "Electromagnetic Properties of Mortars over a Broad Frequency Range and Different Curing Times." J. Mater. Sci., 26, 2978-2984, 1991.

[7] Whittington, H. W., J. McCarter and M. C. Forde. "The Conduction of Electricity through Concrete." Magazine of Concrete Research, 33(114): 48-60, 1981.

[8] Wilson, J. G. and H. W. Whittington. "Variations in the Electrical Properties of Concrete with Change in Frequency." IEE Proc. 137A(5): 246-254, 1990.

[9] American Society of Testing and Measurement. 1990. "Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Frequencies of Concrete Specimens (ASTM C 215-85)." Annual Book of ASTM Standards, 120-123. Philadelphia, Pa.: ASTM.

[10] Russell, J. E., T. K. Oliver, and P. F. Gnirk, "Nondestructive Determination of Pavement Thickness Using Electrical Resistivity Techniques", report to SD DOT for State Study No. 648(69), April 1972.

[11] Soroka, Itzhak, Portland Cement Pastes and Concrete, Chemistry Publishing Co., Inc., 1980.

[12] Koryta, J. and J. Dvorak, Principles of Electrochemistry, John Wiley & Sons Ltd., 1987.

[13] Jackson, J. D., Classical Electrodynamics, John Wiley & Sons Inc., New York, 1962.

APPENDICES

Appendix A: CHRONOLOGICAL LISTING OF WORK PERFORMED AND DATA COLLECTED

Appendix B: LISTING OF DATA FILES

Appendix C: CITATIONS AND ABSTRACTS OF REFERENCES

Appendix D: PERSONNEL MANAGEMENT AND ADMINISTRATION

Appendix E: REPORTS, PROPOSALS, RELEVANT TRAVEL, VISITS AND CONTACTS

Appendix A: CHRONOLOGICAL LISTING OF WORK PERFORMED AND DATA COLLECTED

15AUG90-15DEC90

Began preliminary work. Started bibliographical search; got information on data acquisition systems, freezers, various materials. Made field trip to bridges with chip seals.

03JAN91-12APR91

Impedance data for specimen #1 (poured 28DEC90) which contained 4 sensors (Cu plates, Stainless Steel plates, Titanium plates, and Stainless Steel wires), at frequencies from 50 Hz to 1 MHz.

15APR91-17MAY91

Impedance data for specimen #2 (poured 29MAR91) which contained 4 sets of Stainless Steel wire sensors, at frequencies from 50 Hz to 1 MHz. The four regions of the specimen were soaked with different solutions.

17JUN91-18JUN91

Impedance data for specimen #3 (poured 29MAR91) which contained 9 sets of Stainless Steel wire sensors with different wire diameters and spacings, at frequencies from 50 Hz to 1 MHz and with dc. Included measurements with ac and dc in series simultaneously.

21MAY91-03JUN91

Impedance data for three specimens #4A, B, & C (poured 27APR91) each of which contained 2 sets of Stainless Steel wire sensors, at frequencies from 50 Hz to 1 MHz and with dc; included measurements before and after wetting.

Specimen #4A was mixed with pure water.
Specimen #4B was mixed with pure water and had a layer of crystalline NaCl added.
Specimen #4C was mixed with NaCl solution (10% saturated).

20MAY91-07JUN91

Impedance data for four specimens #5A, B, C, & D (poured 16APR91, all mixed with pure water) each of which contained 1 set of Stainless Steel wire sensors, at frequencies from 50 Hz to 1 MHz and with dc; included measurements taken before and after vacuum drying, and after soaking with various solutions:

Specimen #5A was soaked with NaCl solution (10% saturated) on 04JUN91.
Specimen #5B was soaked with pure water on 31MAY91.
Specimen #5C was soaked with NaCl solution (1% saturated) on 03JUN91.
Specimen #5D was soaked with Na|Cl solution (100% saturated) on 30MAY91.

16DEC91-24DEC91

Measurements on test blocks to determine the quantity of solution needed to saturate the concrete.

16DEC91-15JAN92

Large vacuum chamber would not pump down to required pressure. Found crack in one port and had to carefully repair to seal and prevent further propagation of the crack and to achieve the desired pressure.

Appendix A (continued)

20DEC91-30JAN92
Installed temperature controller and learned how to program it. Checked out operation controlling the chamber.

28DEC91-26JAN92
Redesigned and reconstructed environmental chamber to accommodate request to simulate sunlight on top of specimens, per request (presumably) of Research Board conveyed by Mr. Johnston; this was a modification of the design which was indicated in the proposal and the research agreement. The modification was a considerable problem because of the limitations of the space available inside the freezer, but we were informed that it was considered to be of importance since it may strongly influence the processes within the concrete specimens. Consequently, we attempted to accommodate the request. It has turned out that attempting to accommodate this change has caused serious problems both in terms of effort expended, time consumed, and the efficacy of the experiment. These will be described later.

28JAN92-31MAR92
Testing of environmental chamber. Adding modifications to regain ability to achieve necessary temperature cycle range.

27FEB92-17NOV92
Measurement of the potential of the rebar within the specimens with respect to a Cu-$CuSO_4$ half cell. Also, measured differential potentials of one layer of rebar with respect to the other layer of rebar. During temperature cycling it was not possible to make measurements with respect to the half-cell because four of the eight specimens had a non-porous, insulating coating on their upper surface. Attempts were made to make contact with the under surface using a copper extension, but the results were not consistent. Consequently, the potential between the rebar layers, which could be measured during the cycling and which was stable, was important to show any changes in the extent of the chloride ions.

02MAR92-08MAR92
Impregnation of specimens with either saturated CaOH or CaOH+NaCl. Results of impregnation of first pair indicated that inadequate amounts of NaCl had been adsorbed immediately. Placing the specimen in a tray containing the solutions was tried. First attempt resulted in NaCl contamination throughout most of specimen. With careful monitoring of a second pair of specimens, it was determined that soaking for about 3 hours following the vacuum impregnation resulted in NaCl contamination in the upper one third of the specimen.

30MAR92-08APR92
Measurement of temperature of concrete highway surface as a function of air temperature and atmospheric conditions.

06APR92-08APR92
Environmental Chamber test to determine effectiveness of containers of alcohol in bottom of freezer to enhance cooling rate during temperature decrease portion of cycle.

09APR92-15APR92

Calibration of system thermistors against standard platinum thermometer. Measurements conducted in previously constructed isothermal chamber. Calibrations smooth to within less than one quarter of a degree Fahrenheit were obtained.

09APR92-07MAY92

Modification of chamber to achieve better cooling rate and lower temperatures during 20-50-20° F cycles. Added metal ducting with internal baffles into lower portion of chamber. Also added a movable flap inside the chamber to control air flow through the metal ducting. A large container of antifreeze was also placed at the bottom of the freezer; this provided additional thermal capacity which was also needed to achieve better cooling.

08MAY92-01JUL92

Calibration of thermistors inside concrete specimens. First series of measurements were found to have more scatter than desirable due to greater-than-expected thermal non-equilibrium during measurements. Second set taken with chamber held at constant temperature for a longer time. Data much improved.

09MAY92-20MAY92

Wiring up limestone aggregate specimens, insulating, and sealing with silicone coating as required by experimental design.

12MAY92-14MAY92

Environmental chamber tests to determine the efficacy of the duct, flap and thermal reservoir. Found good improvement.

21MAY92-09JUN92

First series of specimen impedance and temperature measurements. These measurements were for cycles between 20°F and 50°F for limestone aggregate specimens.

12JUN92-26JUN92

Began analysis of data. Found that the moisture content of the concrete appeared to be decreasing slightly. Put in "larger" moisture source.

11JUN92-23JUN92

Environmental chamber tests for 60-90-60°F cycles. These immediately preceded and continued simultaneously with the specimen impedance and temperature measurements.

15JUN92-04NOV92

Second series of specimen impedance and temperature measurements. These measurements were for cycles between 60°F and 90°F. During the middle third of the measurement sequence, we noticed that the impedance of the concrete was increasing significantly indicating a rapid loss of moisture. Later, it was concluded that, with the chamber operating in this higher temperature range and with ambient temperature around it at -25°F, moisture was being draw out of the chamber through leaks more quickly than the improved moisture source could replenish it. Thus, the humidity did not correspond to the dew point indicated by the moisture source temperature sensor. This was a puzzle because the wet bulb thermometer had been indicating humidities as high as 80%. However, following a check of the inter-calibration of the thermistors used as wet and dry bulb thermometers (see below - calibrations checked out), it was determined that the humidity was so low that the wick feeding moisture to the wet bulb was being strongly affected, and it was essentially dry at the sensor location.

30JUN92-14AUG92

Environmental chamber tests during 60-90-60°F cycles to record difference between operation with and without heater directly over the specimens. These measurements were taken in parallel with continuing specimen impedance and temperature measurements.

01JUL92-15AUG92

Preparations for series #8 specimens. Worked on forms, carefully cleaning and oiling, cutting and brazing rebar sections ready for assembly. Worked with Mr. Johnston on modifications to the specimen design. Added more iron wires for measurement of corrosion potential. Decided to use a carbon filament wire within the concrete as a reference electrode. This design facilitated better monitoring of the specimen during impregnation, and allows continued better monitoring during the whole testing program; this also overcame the problem of the difficulty of use of the Cu-$CuSO_4$ half-cell during temperature cycling. Modified forms to accommodate these additional sensors in the specimens.

19AUG92-20AUG92

Checked inter-calibration of thermistors used as wet and dry thermometers. Calibrations found to be in good agreement.

19SEP92-07NOV92

Made several modifications to the environmental chamber to reduce moisture losses. These included additional sealing of ducts at entry to chamber, sealing joints and elbows in ducts with even greater care, and raising the chamber inside the freezer so that the lid seal was just above a seal placed around the top of the freezer. Also, changed the wet-dry thermometer system - unit now mounted immediately below chamber lid with short wick and water reservoir directly refilled. Monitored chamber and determined that 90% relative humidity was being achieved.

25OCT92-28OCT92

Preparations and pouring of series #8 specimens (quartzite aggregate). Specimens unmoulded on 28OCT92 and placed in lime bath for cure period.

28NOV92-01DEC92

Removed specimens from lime bath and cleaned them. Cleaned all electrical connections and tested thermistors.

01DEC92-28APR93

Monitored specimens #7 during humidity soak. Organized data and data analysis was preformed. Draft Final Report was prepared.

Appendix B: LISTING OF DATA FILES

DOT3-C08	Calibrations of System Thermistors derived from File DOT3-D08, 09APR92-15APR92.
DOT3-C11	Calibrations derived from File DOT3-D11, 08MAY92-01JUL92.
DOT3-D00	Directory File.
DOT3-D01	Impedance Data for Specimen #1, 03JAN91-12APR91, for 4 sensors (Cu plates, St St plates, Ti plates, St St wires), at frequencies from 50 Hz to 1MHz. Concrete specimen poured on 28DEC90.
DOT3-D02	Impedance Data for Specimen #2, 15APR91-17MAY91, for 4 sets of stainless steel wire sensors, at frequencies from 50 Hz to 1MHz. Concrete specimen poured on 29MAR91. Four regions of specimen soaked with different solutions.
DOT3-D03	Impedance Data for Specimen #3, 17JUN91-18JUN91, for 9 sets of stainless steel wire sensors, at frequencies from 50 Hz to 1MHz, and dc. Concrete specimen poured on 29MAR91. Includes measurements with ac and dc in series simultaneously.
DOT3-D4A	Impedance Data for Specimen #4A, 21MAY91-03JUN91, for 2 sets of stainless steel wire sensors, at frequencies from 50 Hz to 1MHz, and dc; includes wetting. Concrete specimen poured on 27APR91. Specimen mixed with pure water.
DOT3-D4B	Impedance Data for Specimen #4B, 21MAY91-03JUN91, for 2 sets of stainless steel wire sensors, at frequencies from 50 Hz to 1MHz, and dc; includes wetting. Concrete specimen poured on 27APR91. Specimen mixed with pure water and a layer of crystalline NaCl.
DOT3-D4C	Impedance Data for Specimen #4C, 21MAY91-03JUN91, for 2 sets of stainless steel wire sensors, at frequencies from 50 Hz to 1MHz, and dc; includes wetting. Concrete specimen poured on 27APR91. Specimen mixed with 10% Saline Solution.
DOT3-D5A	Impedance Data for Specimen #5A, 20MAY91-07JUN91, for 1 set of stainless steel wire sensors, at frequencies from 50 Hz to 1MHz, and dc. Concrete specimen poured on 16APR91; mixed with pure water. Test includes vacuum drying and soaking with distilled water on 21MAY91 and with 10% NaCl soultion on 04JUN91.

Appendix B (continued)

DOT3-D5B Impedance Data for Specimen #5B, 31MAY91-07JUN91,
for 1 set of stainless steel wire sensors,
at frequencies from 50 Hz to 1MHz, and dc.
Concrete specimen poured on 16APR91; mixed with pure water.
Test includes vacuum drying and vacuum soaking
with distilled water on 31MAY91.

DOT3-D5C Impedance Data for Specimen #5C, 03JUN91-07JUN91,
for 1 set of stainless steel wire sensors,
at frequencies from 50 Hz to 1MHz, and dc.
Concrete specimen poured on 16APR91; mixed with pure water.
Test includes vacuum drying and vacuum soaking
with 1% NaCl solution on 03JUN91.

DOT3-D5D Impedance Data for Specimen #5D, 30MAY91-07JUN91,
for 1 set of stainless steel wire sensors,
at frequencies from 50 Hz to 1MHz, and dc.
Concrete specimen poured on 16APR91; mixed with pure water.
Test includes vacuum drying and soaking
with saturated NaCl solution on 30MAY91.

DOT3-D06 Enviromental chamber test #1: 28JAN92.
Two concrete specimens in chamber.

Enviromental chamber test #2: 28JAN92-31JAN92.
8 Concrete specimens @ 20# in chamber.

Enviromental chamber test #3: 03FEB92-03FEB92.
8 Concrete specimens @ 20# in chamber; Pt thermometer.

Enviromental chamber test #4: 04FEB92-04FEB92.
8 Concrete specimens @ 20# in chamber; Pt thermometer.
Temp Cycle - Hold 22F 2Hr; Ramp 1Hr; Hold 52F 2Hr; Ramp 1Hr.
2 @ 100W Bulbs @ 85% Voltage; 2 Fans both @ 100% Voltage.

Enviromental chamber test #5: 12MAR92-14MAR92.
8 Concrete specimens @ 20# in chamber; Pt thermometer.
Temp Cycle - Start at 72F; 15 min Ramp to 160F; Hold 160F for 3Hr.
8 @ 40W Bulbs @ 100% Voltage; 2 Fans both @ 100% Voltage.

Enviromental chamber test #6: 30MAR92-31MAR92.
8 Concrete specimens @ 20# in chamber; Pt thermometer.
Temp Cycle - Start at 20F; 60 min Ramp to 60F; Hold 60F for 2Hr.
8 @ 40W Bulbs @ 100% Voltage; 2 Fans both @ 100% Voltage.

Enviromental chamber test #7: 06APR92-08APR92.
8 Concrete specimens @ 20# in chamber; Pt thermometer.
Temp Cycle - Start at 20F; 60 min Ramp to 60F; Hold 60F for 2Hr.
8 @ 40W Bulbs @ 100% Voltage; 2 Fans both @ 100% Voltage.
Alcohol containers in bottom of freezer.

Appendix B (continued)

DOT3-D07 CUSO4 Cell Voltages: 27FEB92-17NOV92.
Specimens 6A, 7A, 7B, 7C, 7D, 7E, 7F, 7G, 7H, and 7I.

DOT3-D08 System thermistor calibrations against STDPT162.
09APR92-15APR92.

DOT3-D09 Enviromental chamber test #8: 29APR92-06MAY92.
Chamber empty, no heating.
Cooling with antifreeze & baffles.

DOT3-D10 Highway Surface Temperatures: 30MAR92-08APR92.

DOT3-D11 Calibration of Thermistors 08MAY92-01JUL92.
Specimens 7A, 7B, 7C, 7D, 7F, 7G, 7H, and 7I.
Calibration over Range 22.7 to 106.2F.

DOT3-D12 Enviromental chamber test #9: 12MAY92-14MAY92.
Concrete specimens in chamber; 20F-50F cycles.
Antifreeze & baffles; without and with flap operation.

DOT3-D13 Specimen Tests: A.C. Impedance and Temperatures 21MAY92-09JUN92.
Specimens 7A, 7B, 7C, 7D, 7F, 7G, 7H, and 7I.
Measurements at temperatures of 20F and 50F,
and at frequencies of 30Hz, 1Khz, 30Khz, and 700Khz.

DOT3-D14 Enviromental Chamber Test #10: 11JUN92.
Chamber empty; Partial 60F-90F cycle; NO fans.
Antifreeze & baffles; flap closed throughout.

Enviromental Chamber Test #11: 12JUN92.
Chamber empty; Full 60F-90F cycle; NO fans.
Antifreeze & baffles; flap closed throughout.

Enviromental Chamber Test #12: 16JUN92.
Concrete in Chamber; Full 60F-90F cycle; Fans + Main Heater.
Antifreeze & baffles; flap closed throughout.

Enviromental Chamber Test #13: 17JUN92.
Concrete in Chamber; Full 60F-90F cycle; Fans + Both Heaters.
Antifreeze & baffles; flap closed throughout.

Enviromental Chamber Test #14: 18JUN92.
Concrete in Chamber; Full 60F-90F cycle; Fans + Specimen Heater.
Antifreeze & baffles; flap closed throughout.
Includes measurements on thermistors in concrete blocks.

Enviromental Chamber Test #15: 19JUN92.
Concrete in Chamber; Full 60F-90F cycle; Fans + Both Heaters.
Antifreeze & baffles; flap closed throughout.
Includes measurements on thermistors in concrete blocks.

Appendix B (continued)

Enviromental Chamber Test #16: 23JUN92.
Concrete in Chamber; Full 60F-90F cycle; Fans + Main Heater.
Antifreeze & baffles; flap closed throughout.
Includes measurements on thermistors in concrete blocks.

DOT3-D15 Specimen Tests: A.C. Impedance and Temperatures 15JUN92-04NOV92.
Specimens 7A, 7B, 7C, 7D, 7F, 7G, 7H, and 7I.
Measurements at temperatures of 20F and 50F,
and at frequencies of 30Hz, 1Khz, 30Khz, and 700Khz.
Data Sets 1 to 20.

DOT3-D16 Enviromental Chamber Test #17: 30JUN92.
Concrete in Chamber; Fans + Both Heaters.
Antifreeze bath in freezer. Additional baffles in tubes.
Includes measurements on thermistors in concrete blocks.
DB & WB Thermistors (both dry).
Test of cooling from ~75F (concrete in equilibrium) to ~30F.

Enviromental Chamber Test #18: 02JUL92.
Concrete in Chamber; Full 60F-90F cycle; Fans + Both Heaters.
Antifreeze & baffles; flap left closed throughout.
DB & WB Thermistors (both dry), Thermistors in concrete.
First test after calibration.

Enviromental Chamber Test #19: 07JUL92.
Concrete in Chamber; Full 60F-90F cycle; Fans + Both Heaters.
Antifreeze & baffles; flap left closed throughout.
DB & WB Thermistors (both dry), Thermistors in concrete.

Enviromental Chamber Test #20: 21JUL92.
Concrete in Chamber; Full 60F-90F cycle; Fans + Both Heaters.
Antifreeze & baffles; flap left closed throughout.
DB & WB Thermistors (both dry), Thermistors in concrete.

Enviromental Chamber Test #21: 14AUG92.
Concrete in Chamber; Full 60F-90F cycle; Fans + Both Heaters.
Antifreeze & baffles; flap left closed throughout.
DB & WB Thermistors (both dry), Thermistors in concrete.

DOT3-D17 Environmental Chamber Test #22: 19AUG92 & 20AUG92.
Check of WB and DB Thermistor Calibrations (both dry).
Concrete in Chamber; Full 60F-90F cycle; Fans + Both Heaters.
Antifreeze & baffles; flap left closed throughout.
Data taken at 15 second intervals.
Thermometers strapped together with copper wire, no insulation.

Environmental Chamber Test #23: 26AUG92.
Measurement of humidity in chamber, WB with moisture source.
Concrete in Chamber; Full 60F-90F cycle; Fans + Both Heaters.
Antifreeze & baffles; flap left closed throughout.
Data taken at 15 second intervals.
Thermometers strapped together with copper wire, no insulation.

Appendix B (continued)

DOT3-D18 Environmental Chamber Test #24: 26AUG92.
Measurement of humidity in chamber, WB with moisture source.
Concrete in Chamber; Full 60F-90F cycle; Fans + Both Heaters.
Antifreeze & baffles; flap left closed throughout.
Water Source Heater voltage changed to get required humidity.
Data taken at 15 second intervals.
Thermometers strapped together with copper wire, no insulation.

Environmental Chamber Test #25: 27AUG92.
Measurement of humidity in chamber, WB with moisture source.
Concrete in Chamber; Full 60F-90F cycle; Fans + Both Heaters.
Antifreeze & baffles; flap left closed throughout.
Water Source Heater voltage changed to get required humidity.
Data taken at 15 second intervals.
Thermometers strapped together with copper wire, no insulation.

Environmental Chamber Test #26: 28AUG92.
Measurement of humidity in chamber, WB with moisture source.
Concrete in Chamber; Full 60F-90F cycle; Fans + Both Heaters.
Antifreeze & baffles; flap left closed throughout.
Water Source Heater voltage changed to get required humidity.
Data taken at 15 second intervals.
Thermometers strapped together with copper wire, no insulation.

Environmental Chamber Test #27: 01SEP92.
Measurement of humidity in chamber, WB with moisture source.
Concrete in Chamber; Full 60F-90F cycle; Fans + Both Heaters.
Antifreeze & baffles; flap left closed throughout.
Water Source Heater voltage changed to get required humidity.
Data taken at 15 second intervals.
Thermometers strapped together with copper wire, no insulation.

Environmental Chamber Test #28: 02SEP92.
Measurement of humidity in chamber, WB with moisture source.
Concrete in Chamber; Full 60F-90F cycle; Fans + Both Heaters.
Antifreeze & baffles; flap left closed throughout.
Water Source Heater voltage changed to get required humidity.
Data taken at 15 second intervals.
Thermometers strapped together with copper wire, no insulation.

Environmental Chamber Test #29: 05SEP92.
Measurement of humidity in chamber, WB with moisture source.
Concrete in Chamber; Full 60F-90F cycle; Fans + Both Heaters.
Antifreeze & baffles; flap left closed throughout.
Water Source Heater voltage changed to get required humidity.
Data taken at 15 second intervals.
Thermometers strapped together with copper wire, no insulation.

Appendix B (continued)

Environmental Chamber Test #30: 24SEP92 & 30SEP92
Measurement of humidity in chamber, WB with moisture source.
Concrete in Chamber; Full 60F-90F cycle; Fans + Both Heaters.
Antifreeze & baffles; flap left closed throughout.
Water Source Heater voltage changed to get required humidity.
Data taken at 15 second intervals.
Thermometers strapped together with copper wire, no insulation.

Environmental Chamber Test #31: 08OCT92.
Measurement of humidity in chamber, WB with moisture source.
Concrete in Chamber; Full 60F-90F cycle; Fans + Both Heaters.
Antifreeze & baffles; flap left closed throughout.
Water Source Heater voltage changed to get required humidity.
Data taken at 15 second intervals.
Thermometers strapped together with copper wire, no insulation.

DOT3-D19 Soak Test on Spesimens #9a and #9B: 20APR93-26APR93
Test #17: Chamber containing specimens, DB & WB Thermistors (both dry)
2 Fans operating; Main heater and Specimen heaters operational.
Antifreeze bath in freezer. Additional baffles in tubes
Test of cooling from ~75F (concrete in equilibrium) to ~30F

Appendix C: CITATIONS AND ABSTRACTS OF IMPORTANT REFERENCES.

1. American Concrete Institute. Corrosion, Concrete, Chlorides. Steel Corrosion in Concrete: Causes and Restraints. Gibson, Francis W., editor. Detroit, MI: ACI; 1987.

2. American Concrete Institute. Permeability of Concrete. Whiting, David; Walitt, Arthur, editors. Detroit, MI: ACI; 1988.

3. American Society of Testing and Measurement. Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete (ASTM C 876-87). Annual Book of ASTM Standards. Philadelphia, Pa.: ASTM; 1990; 03.02: 429-433.
This standard is issued under the fixed designation C 876.
1) This test method covers the estimation of the electrical half-cell potential of uncoated reinforcing steel in field and laboratory concrete, for the purpose of determining the corrosion activity of the reinforcing steel.
2) This test method is limited by electrical circuitry. A concrete surface that has dried to the extent that it is a dielectric and surfaces that are coated with a dielectric material will not provide an acceptable electrical circuit. The basic configuration of the electrical circuits shown in the description.

4. American Society of Testing and Measurement. Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Frequencies of Concrete Specimens (ASTM C 215-85). Annual Book of ASTM Standards. Philadelphia, Pa.: ASTM; 1990; 04.02: 120-123.
This standard is issued under the fixed designation C 215. This test method covers measurement of the fundamental transverse, longitudinal, and torsional frequencies of concrete prisms and cylinders for the purpose of calculating the dynamic Young's modulus of elasticity, the dynamic modulus of rigidity (sometimes designated as "the modulus of elasticity in shear"), and the dynamic Poisson's ratio.

5. Ashworth, T.; Ashworth, E.; Ashworth, S. F. (South Dakota School of Mines & Technology, Rapid City, SD 57701). A New Apparatus for use with Materials of Intermediate Conductivity. Thermal Conductivity 21; 1990: 51-65.
Most geological materials have thermal conductivity values in the range 0.5 to 10 W/(m-K). This intermediate range of conductivity and other problems associated with natural material samples have prompted the development of a new apparatus. The factors considered in the design of the apparatus were the size of samples commonly available (standard rock cores have diameters of 1" to 2"), the need to obtain many values in a short time frame at low cost (high variability is encountered between samples), simplicity of specimen preparation (rock is often difficult to drill or to groove), and prevention of specimen modification. Functionally, the design of the apparatus is similar to that of a double bar apparatus or a comparative apparatus which uses standard reference materials on both sides of the specimen. Thermistors and heaters are embedded in copper disks. A thin disk of nylon provides thermal resistance between two copper disks. One such unit is placed at either side of the prepared rock specimen; the units serve as heat flux meters. The thermistors also measure the temperature difference across the rock specimen, which includes the effect of the boundary resistances. For materials of intermediate thermal conductivity, the boundary resistance is small yet significant; it is also quite variable. The design philosophy has been to minimize the uncertainty in the boundary resistance, rather than to minimize the actual resistance. Various materials have been tried to achieve this, with the greatest success having been obtained with PTFE tape. The paper includes a description of the apparatus, and reports the results of a study performed to prove the system, to quantify the contact resistance between different materials, and to determine the effect of specimen surface roughness and sample size.

6. Bari, M. A. (Department of Physics, Royal Holloway and Bedford New College, University of London, Egham, Surrey, TW20 0EX, UK). Comment on "Dynamic Dielectric Analysis During Early-Stage Hydration of Ordinary Portland Cement". J. Phys. D: Appl. Phys.; 1990; 23: 234-236.
   It is pointed out that the work done by Kim and Yoon in an earlier paper was not interpreted correctly. Measurements on the same sample at various stages of dehydration over an extended timescale are reported here.

7. Cady, Phillip D.; Weyers, Richard E. (Department of Civil Engineering, The Pennsylvania State University, University Park, PA). Chloride Penetration and the Deterioration of Concrete Bridge Decks., Cem. Concr. Aggregates; 1983; 5(2): 81-87.
   Chloride-induced corrosion of reinforcement is a major contributor to the problem of bridge deck deterioration. The chlorides are derived primarily from the application of roadway deicing salts. Empirical data from previous studies was synthesized with the diffusion theory in developing a predictive model for chloride infusion of bridge decks. The model includes the effects of subsidence cracking over the reinforcement. Primary input data consist only of av. reinforcement cover, which is easily obtainable with existing instrumentation. The model is intended to serve as a useful, rational means of providing information for life-cycle costing in bridge deck rehabilitation planning studies.

8. Camp, Paul R.; Bilotta, Stephen (Department of Physics, University of Maine, Orono, Maine 04469. Digital Equipment Corporation, 75 Reed Road, Hudson, Massachusetts 61749-2809). Dielectric Properties of Portland Cement Paste as a Function of Time Since Mixing. Journal of Applied Physics; 1989; 66(12): 6007-6013.
   The dielectric properties of Portland cement paste and mortar have been measured in the frequency range 100 Hz-7 MHz as a function of time since mixing. Over much of the spectrum, the ac conductance of the samples appears directly related to the amount of unbound water remaining in the sample and ionic conduction predominates. In addition, interesting structure was found in both the conductance and capacitance data at high frequencies as the free water content was reduced. We conclude that relatively simple measurements of this kind can be a useful tool in concrete research and may provide the basis for simple, in situ, nondestructive measurement of the degree of curing of concrete or for monitoring water migration in concrete structures. Measurements on sealed samples of partially or fully cured concrete reveal also the water-cement ratio of the original mix.

9. Dunster, Andrew M.; Parsonage, John R. (School of Biological and Chemical Sciences, Thames Polytechnic, Wellington Street, Woolwich, London SE18 6PF.). Conductivity of Hydrating Cement Pastes. Chemistry & Industry; 1992; (20 April): 303-304.
   Conductivity measurements provide a useful and somewhat neglected guide in the study of the molecular changes which occur during the Ordinary Portland cement hydration. In this paper, some results obtained from using a simple apparatus for carrying out such measurements are described.

10. El-Shabrawy, M.; Abdel-Raheem, A. H.; Emam, M. A. E.; Al-Hakeem, F. Corrosion Resistance of Concrete Specimens Subjected to Sulphate Solution. Proc. International Congress on Tunnels and Water; 15-18 June 1988; Madrid. Rotterdam: A. A. Balkema; 1988; 1: 101-109.
    Most damage to reinforced concrete structures is caused by sulphate attack from naturally occurring Na, Ca, and Mg salts in the soil. Four concrete mixes, covering most of those

used, were made up for each of three cements, ordinary Portland, blast furnace slag, and sulphate resisting. Comparisons were made between compressive and splitting tensile strengths for specimens aged 28-120 days and subject to attack by magnesium sulphate or control specimens cured by fresh water. Practical recommendations are made for protecting concrete against corrosion.

11. Fricke, Hugo (Walter B. James Laboratory of Biophysics, Biological Laboratory, Cold Spring Harbor, N. Y.). The Maxwell-Wagner Dispersion in a Suspension of Ellipsoids. J. Phys. Chem.; 1953; 57: 934-937.
    The dispersion equations are first derived for the conductivity and permittivity of a suspension of ellipsoids of vanishing volume concentration, in which the components are characterized by both conductivity and permittivity, by extending to complex admittances an earlier treatment of this system for the case of pure conductors. The expressions contain a "form factor" which is expressed in terms of elliptic integrals. Its numerical values are tabulated. For random orientation of the ellipsoidal axis, the suspension is shown to be electrically equivalent to a simple resistance-capacity network and to be characterized by three dispersion regions inside each of which, it behaves quantitatively like a Debye dipole system. This treatment is subsequently extended to more concentrated suspensions on basis of the semitheoretical general conductivity equation given in ref. 2.

12. Fukushi, Isao. Chlorides in Concrete. Koncurito Kogaku; 1987; 25(11): 40-3.
    The chlorides in cements, water, fine aggregates, admixtures and fresh concretes, and transport of chlorides in concretes are discussed.

13. Garboczi, E. J.; Bentz, D. P. Computational Materials Science of Cement-Based Materials. Materials Research Society Bulletin; 1993; March: 50-54.
    This brief review has demonstrated that computational materials science techniques using digital-image-based microstructure development models can adequately simulate many features of the microstructure of cement paste, mortar, and concrete. This is evidenced by the agreement between computed properties for simulated microstructures and available equipmental measurements. These kinds of simulations are providing, actually for the first time, quantitative understanding of microstructure-property relationships for cement-based materials. A computational materials science approach based on digital images, which can also be applied to other random grain materials like ceramics, opens up the real possibility of microstructural design, where the properties of a variety of microstructures can be evaluated before any real specimens are made, and an optimal microstructure can be chosen as a target for process development. A good example of where this approach might be particularly useful is in the area of interpenetrating phase composites, where material processing can be difficult and expensive. An example in cement-based systems would be the macro-defect-free (MDF) cements described in another article in this issue. If similar types of models can be developed to link processing to microstructure, prototype materials may be designed using the computer totally, with the necessary processing parameters and conditions being provided by the model.

14. Kawakami, Hideo. Mechanism of Chloride Penetration into Concrete. Konkurito Kogaku; 1987; 25(11): 49-52.
    The penetration path of chlorides into concretes and diffusion coefficients of Cl- in hardened cement and concrete are discussed.

15. Kim, H. C.; Yoon, S. S. (Physics Dept., The Korea Advanced Institute of Science and Technology, Chongryang, PO Box 150, Seoul, South Korea.). Dynamic Dielectric Analysis during Early-Stage Hydration of Ordinary Portland Cement. J. Phys. D: Appl. Phys.; 1988; 21: 1215-1220.
    Dynamic dielectric analysis and the measurement of heat evolution rate were performed during the hydration process of ordinary Portland cement with the water/cement ratio ranging from 0.4 to 0.6 at an environmental temperature of 20 degrees Celsius. The variations of complex dielectric permittivity and its water/cement ratio dependency were analyzed in terms of the Debye model of the dipole relaxation process and the effective dipole relaxation time. The dielectric permittivity at low and high frequency was approximately 160 and 80, which is nearly invariant with the water/cement ratio between 0.4 and 0.6. The calculated effective dipole relaxation time reflected the change of physical properties during hydration.

16. Lewis, Jennifer A.; Kriven, Waltraud M. Microstructure - Property Relationship in Macro-Defect-Free Cement. Materials Research Society Bulletin; 1993; March: 72-77.

17. Macphee, D. E.; Glasser, F. P. Immobilization Science of Cement Systems. Materials Research Society Bulletin; 1993; March: 66-71.
    The long-term nature of waste immobilization means that experimental monitoring of matrix performance over the lifetime of a waste repository is impractical. This imposes a need to develop models that will satisfactorily predict system performance under a range of conditions representative of the exposure environment. Such models are only developed from an understanding of the basic physico-chemical properties of the cement-waste system. To this end, studies of real waste and waste simulants in cement systems have received considerable attention over recent years and much information has been generated on cement hydration, leach characteristics, and matrix microstructure. More recently, the fundamental chemistries of cements containing nonradioactive priority industrial pollutants have been studied, and this article has set out to highlight recent uses of cements in these areas and to summarize some important results from studies of the interactions of specific waste species and cement systems.

18. McCarter, W. J.; Curran, P. N.; Wilson, J. G.; Whittington, H. W. (Department of Electrical & Electronic Engineering, Napier College, Edinburgh and Department of Electrical Engineering, University of Edinburgh). The Electrical Response Characteristics of Setting Cement Paste. Magazine of Concrete Research; March 1985; 37(130).
    Comment on named article by J. G. Wilson and H. W. Whittington with rebuttal by article authors W. J. McCarter and P. N. Curran. Discussion is about capacitances and the formation of a gas layer at electrodes due to electrolytic action.

19. McCarter, W. J.; Garvin, S. (Dept. of Civil Engineering, Heriot-Watt University, Edinburgh EH14 4AS, UK.). Dependence of Electrical Impedance of Cement-Based Materials on their Moisture Condition. J. of Phys. D: Appl. Phys.; 1989; 22: 1773-1776.
    This paper outlines an investigation into monitoring the moisture condition of cement-based materials using impedance spectroscopy techniques. Impedance measurements are made over the frequency range 20 Hz-110 MHz, and several parameters identified which could characterize the moisture condition of such materials.

20. Niklasson, G. A.; Berg, A.; Brantervik, K.; Hedberg, B.; Nilsson, L. O. (Chalmers University of Technology, S-412 96 Goteburg, Sweden (First three - Physics, last two - Dept. of Building Materials)). Dielectric Properties of Porous Cement Mortar Fractal Surface Effects. Solid State Communications; 1991; 79(1): 93-96.
We have studied the electrical properties of cement mortars in the frequency range 10E-4 to 10E7 Hz, for different water contents. The admittance scales as a power law with an exponent of about 0.7 in a wide frequency range. This behaviour is interpreted in terms of polarization and diffusion at fractal pore surfaces. We obtain a fractal dimension of 2.4, which is in good agreement with adsorption isotherm data for the mortar.

21. Olp, K.; Otto, G.; Chew, W. C.; Young, J. F. (Electromagnetics Laboratory, Departments of Electrical and Computer Engineering, and Civil Engineering, University of Illinois, Urbana, IL 61801). Electromagnetic Properties of Mortars over a Broad Frequency Range and Different Curing Times. J. Mater. Sci.; 1991; 26: 2978-2984.
A large dielectric measurement cell, with 54 ml sample volume, was designed and calibrated to operate over 1 MHz-3 GHz frequency range. The cell was used to measure the dielectric constants and conductivities of concretes over a broad frequency range and different curing times. The water/ cement/sand ratios of the concrete were changed to study the dependence of the electromagnetic properties on them. Chemical admixtures to retard and accelerate the curing process of concretes were also added. It was found that the electromagnetic properties of concretes vary significantly over the frequencies. Furthermore, during the curing process, the water/cement/sand ratios and chemical admixtures of concretes affected their electromagnetic properties. A relationship of the electromagnetic properties of concretes to their various physical states and constituent components could be used for the quality control of concretes in construction work.

22. Oshima, Hisaji; Ikenaga, Hirotake. Study on Movement of Chloride due to Bleeding and Drying of Concrete. Rev. Gen. Meeting, Tech. Sess. -- Cem. Assoc, Japan; 1979; 33: 95-97.
Chloride movement due to concrete bleeding increased the Cl-concentration at the surface but barely affects the deeper parts, at 4 cm. When the Cl^- movement resulted from drying, the highest concentration was at 2 cm.; surface Cl- is partially washed out by rain. The percentage of combined chloride for 3 mo. is about 75 of the initial Cl-concentration, i.e. 0.05% Embedded steel (12597-69-2) does not corrode regardless of the depth of the concrete on the steel. To prevent steel corrosion, the allowable Cl-concentration in sea sand must be limited and the depth of the covering concrete must be maintained.

23. Palmer, J. D. (JD Palmer Assoc. Eng. Ltd., London, ONT). Effects of Deicing Salts on Inanimate Materials; 1977: 151-9. NRCC NO 15019, Effect of Alkali Halides.

24. Pereira, C. J.; Hegedus, L. L. Diffusion and Reaction of Chloride Ions in Porous Concrete. Inst. Chem. Eng. Symp. Ser.; 1984; 87: 427-38.
The chloride-induced corrosion of steel reinforcing bars in concrete represents a problem of major economic significance. Reaction engineering techniques have been applied to describe the diffusion and reaction of chloride ions in porous concrete. All model parameters were extrapolated. from appropriately designed experiments, and excellent agreement was found between model predictions and experimentally detected chloride penetration patterns. The utility of the model is illustrated by simulating a variety of complex dynamic salting scenarios, with interesting implications to the practitioner.

Appendix C (continued)

25. Perez-Pena, M.; Roy, D. M.; Tamas, F. D. (Materials Research Laboratory, The Pennsylvania State University, University Park, Pennsylvania 16802.). Influence of Chemical Composition and Inorganic Admixtures on the Electrical Conductivity of Hydrating Cement Pastes. J. Mater. Res.; 1989; 4(1): 215-223.

Electrical conductivity of cementitious materials with a wide range of chemical compositions has been studied during the first 24 hours of hydration. Relationships between heat of hydration and electrical conductivity curves are discussed. Results are tentatively explained in terms of some physical and chemical parameters. Further evidence that the electrical conductivity of hydrating cement pastes is related to the hydration mechanisms operating in these systems was obtained. The order in which the cations of the inorganic admixtures (chlorides and hydroxides) were found to increase the peak and rate of development of the electrical conductivity is the same order that they have been found to increase the heat liberated upon hydration of systems containing these admixtures.

26. Rashed, Ahmed I.; Williamson, Robert Brady (Department of Civil Engineering, University of California, Berkeley, CA). Microstructure of Entrained Air Voids in Concrete, Part I. J. Mater. Res.; 1991; 6(9): 2004-2012.

The microstructure of air voids in both air-entrained and non air-entrained paste, mortar, and concrete has been studied at different ages (5 min to 60 days) in order to understand how air-entrained voids form in Portland-cement systems. Scanning electron micrographs of air voids are presented for different ages. The solidification process of portland-cement paste and mortar was frozen at different ages using a low temperature scanning electron microscope and freeze drying. At very early ages the air voids show thin shells made of very fine particles. The packing of the cement grains behind the air void varies, depending on the water-to-cement ratio. Air voids appear to have the same interface with the cement paste matrix as aggregates. No readily visible difference was found between entrapped and entrained air voids.

27. Roy, D. M.; Scheetz, B. E.; Silsbee, M. R. (Processing of Optimized Cements and Concretes Via Particle Packing). Materials Research Society Bulletin; 1993; March: 45-49.

Recent advances in optimizing cement and concrete products by using calculated packing diagrams appear to offer the promise of superior products via increased packing efficiency. Further research is needed, however, to fully tap the potential of these techniques. For instance, the effect of surface forces on the packing of fine particles cannot be fully dealt with using current techniques. However, the use of calculated packing diagrams has been shown to be of immediate use in the optimization of fine and coarse aggregate distributions.

28. Russell, James E.; Oliver, Thomas K.; Gnirk, Paul F. (South Dakota School of Mines and Technology.). Nondestructive Determination of Pavement Thickness Using Electrical Resistivity Techniques; December, 1971. South Dakota Study No. 648 (69) FHWA No. HP589606 (5112) P (Revised April 1972).

The non-destructive determination of both cured and fresh concrete pavement thickness was studied using electrical resistivity techniques. Used measurements at 100 Hz.

29 Schwan, H. P.; Schwarz, G.; Maczuk, J.; Pauly, H. (Electromedical Division, Moore School of Electrical Engineering, University of Pennsylvania, Philadelphia 4, PA). On the Low-Frequency Dielectric Dispersion of Colloidal Particles in Electrolyte Solution. Journal of Physical Chemistry; 1962; 66: 2626-2635.

Determinations of the dielectric properties of suspension of spherical colloidal particles are reported over the frequency range from 20 Hz to several hundred kiloHertz. Very large dielectric constants are observed at low frequencies. Since the experimental data approach constant values at very low and high frequencies, they can be described by a fairly well defined spectrum of relaxation times. Simple relationships exist between particle size, low frequency dielectric increment, and average relaxation time. Several physical processes, such as relaxation due to Maxwell-Wagner effects, to electrophoretic particle acceleration, or to the presence of a frequency-independent surface conductance, are shown not to account for the observed data. Surface conductance and capacitance data are determined, the conductance having one frequency-independent and one frequency-dependent part.

30\. Schwarz, Gerhard (Electromedical Division, Moore School of Electrical Engineering, University of Pennsylvania, Philadelphia 4, PA). A Theory of the Low-Frequency Dielectric Dispersion of Colloidal Particles in Electrolyte Solutions. Journal of Physical Chemistry; 1962; 66: 2636.

It is proposed that the low-frequency dielectric dispersion observed with colloidal particles suspended in electrolytes is due to the polarization of the counterion atmosphere around the particles by an external electric field. A simplified theory of this effect is developed for particles of spherical shape. The displacement of counterions in the double layer is shown to be equivalent to the existence of a surface capacitance displaying a diffusion-controlled relaxation. This effect can be expressed by an additional "apparent" dielectric constant of the suspended particles, exceeding their actual dielectric constant at low frequencies by many orders of magnitude. The theory is applied to the special case of particles suspended in a fairly well conducting electrolyte. Such colloidal systems display a particularly well pronounced low frequency dispersion effect. The results of previous experimental investigations with suspensions of uniformly sized polystyrene spheres are used in order to test the theory. Assuming reasonable values for the density and the mobility of the counterions in the double layer, the theory agrees very well with the static dielectric increment and the characteristic frequency of the dispersion as experimentally observed. A distribution of activation energies of the counterion motion on the particle surface is introduced to account for the relaxation spectrum of the dispersion curves.

31\. Scuderi, C. A.; Mason, T. O.; Jennings, H. M. (Materials Science and Engineering, and Civil Engineering, Northwestern University, The McCormick School of Engineering and Applied Science, Science and Technology Center for Advanced Cement-Based Materials, Evanston, IL 60208). Impedance Spectra of Hydrating Cement Pastes. Journal of Material Science; 1991; January 15: 349-353.

Complex impedance spectra were obtained over the frequency range 5 Hz to 13 MHz on Portland cement pastes with water/cement ratios of 0.3, 0.35, and 0.4 at various hydration times from 6 h to 24 days. Features of the spectra which could be associated with the bulk material and which could be separated from the electrode arc, were studied. The overall bulk resistance of each paste was thereby determined as a function of hydration time. Bulk features evolved from a simple high-frequency intercept to an intercept with a single arc, then an intercept with two overlapping arcs, and back to an intercept with a single arc. A plausible equivalent circuit was developed involving an electrode R/C network and constant phase element in series with one or two bulk R/C networks and a bulk resistor. Possible physical interpretation is discussed but assignment of equivalent circuit elements to microstructural features and/or processes will require microstructural characterization and knowledge of pore-phase chemistry and properties.

32. Shah, S. P.; Ouyang, C.; Lange, D. A. Fracture Behavior of Cement-Based materials. Materials Research Society Bulletin; 1993; March: 55-59.
Our understanding of the fracture process zone and fracture mechanisms that lead to quasi-brittle response in cement-based materials has been enhanced through novel experimental techniques. Laser holographic interferometry provides a means of measuring the size and location of the fracture process zone. Acoustic emission measures and characterizes microcracking during loading. Microscopic surface analysis quantifies the tortuosity of the main crack propagation. All of these techniques provide valuable experimental evidence that permits refinement of fracture mechanics models and improved understanding of quasi-brittle behavior in cement-based materials.

33. Taylor, Michael A.; Arulanandan, K. (University of California, Davis, California 95616.). Relationship between Electrical and Physical Properties of Cement Pastes. Cement and Concrete Research; 1974; 4: 881-897.
Many aspects of mechanical behaviour of engineering materials, specifically concrete and soils, can be explained from a knowledge of physico-chemical and /or particle geometry factors. A qualitative measure of the above factors has been used to describe a modeled structure of the cement gel system, and attempts have been made to correlate the engineering properties of hardened cement pastes with their microstructure. This paper presents the results of preliminary investigations which suggest that some of the important mechanical properties of mature cement pastes may be predicted quantitatively from the measurements of their electrical properties at early ages.

34. Wagner, K. E.; Draper, E. A.; Skalny, J. Use of Complementary Imaging Techniques in Concrete Deterioration Studies. Materials Research Society Bulletin; March 1993: 60-65.
In today's economic and ecologic environment, inadequate durability of concrete and short service life of concrete structures have become important issues. In view of the enormous cost of infrastructure rehabilitation, concrete and other cement-based materials are now receiving long-due attention by materials scientists and governmental and industrial agencies responsible for the rehabilitation. One important aspect will be the proper and cost-effective use of classical as well as advanced materials evaluation techniques, some of which were highlighted above.

35. Whittington, H. W.; McCarter, J.; Forde, M. C. (Department of Electrical Engineering (HWW) and Department of Civil Engineering (JMcC,MCF), University of Edinburgh, Edinburgh, Scotland.). The Conduction of Electricity through Concrete. Magazine of Concrete Research; 1981; 33(114): 48-60.
This paper examines the relationship between mix proportions, electrical properties of the constituents of concrete, and the over-all electrical resistivity for concrete. The mechanisms for the conduction of electricity through the heterogeneous medium of concrete are discussed and an electrical model is proposed. Analysis from a purely theoretical standpoint is also described and the values of electrical resistivity obtained experimentally are shown to compare favourably with the theoretical model.

36. Whittington, H. W.; Wilson, J. G. (Department of Electrical Engineering, University of Edinburgh, School of Engineering, The King's Buildings, Edinburgh EH9 3JL, UK.). Low-Frequency Electrical Characteristics of Fresh Concrete. IEE Proceedings; 1986; 133A(5): 265-271.
The paper describes the development of a nondestructive test method, which is based on measurement of the electrical parameters, for the assessment of the condition of structural concrete. The basic physical chemistry of concrete is explained and brief details are given of the equipment for the given test technique. The results of experiments made using the technique are given and discussed in terms of their use as a quality indicator for structural concrete.

37. Wilson, J. G.; Whittington, H. W. Variations in the Electrical Properties of Concrete with Change in Frequency. IEE Proc.; 1990; 137A(5).
The paper proposes some mechanisms which control the conductivity and dielectric constant of concrete over the frequency range 1-100 MHz, and, from these, a model is developed. The electrical response of this model is compared with experimental measurements and the validity of the model discussed.

38. Worthington, J. C.; Bonner, D. G.; Nowell, D. V. (Division of Civil Engineering(JCW,DGB) and Chemical Sciences(DVN), Hatfield Polytechnic, Hatfield, Hertfordshire, England.). Influence of Cement Chemistry on Chloride Attack of Concrete. Materials Science and Technology; 1988; April: 305-313.
Note: Paper presented at the conference "Cement and Concrete, " University of Oxford, 29-30 September, 1986, organized by The Institute of Metals.
The effect of introducing chloride (in the form of NaCl) into the mixing water of an ordinary Portland cement (OPC) and a sulphate resistant Portland cement (SRPC) has be investigated over a range of hydration times. A simplified system of C3A, CaSO4, and Ca(OH)2 was also studied to facilitate clarification of results. A further investigation involving exposure of hardened cement pastes of chloride solutions was studied over a range of exposure times. The hexagonal beta-monochloroaluminate has been identified by X-ray diffraction (XRD) in both sets of experiments; semiquantitative studies using XRD and thermogravimetry show increasing amounts of chloroaluminate formation with time. From the system using C3A, CaSO4 and Ca(OH)2, it was clearly shown that chloroaluminates do not form in the presence of sulphate ions. The order of preference of formation was found to be ettringite > chloroaluminate > monosulphate.

39. Yonezawa, T.; Ashworth, V.; Procter, R. P. M. Pore Solution Composition and Chloride Effects on the Corrosion of Steel in Concrete. Corrosion (Houston); 1988; 44(7): 489-99.
The corrosion mechanism of mild steel in concrete and the threshold chloride content are discussed in relation to results obtained by electrochemical measurement, pore solution analysis, and SEM observation. Mortar of concrete provides better protection to steel than alkali solutions. One of the protective mechanisms provided by steel-mortar interface. For the protective mechanisms of mortar, adhesion between the steel and mortar is necessary. Formation of voids at the steel-mortar interface is essential for active corrosion to start. The critical threshold chloride content is not detected simply by a parameter of the pore solution, such as $(Cl^-)/(OH^-)$ ratio. The threshold depends on the steel-mortar interfacial conditions.

Appendix C (continued)

40. Yonezawa, Toshio. Determination of Chlorides in Hardened Concretes. Konkurito Kogaku; 1987; 25(11): 122-126.
The detection of total chlorides and solution chlorides in hardened concretes, preparation of hardened concrete samples, detection of Cl^- in aqueous sample solutions, detection of chloride penetration depth in concrete, and extent of pore solution from hardened cement in high-pressure vessels for Cl^- detection are discussed.

41. Young, J. Francis (Civil Engineering & Materials Science & Engineering, University of Illinois at Urbana-Champaign.). Research on Cement-Based Materials: Expanding Our Horizons. Materials Research Society Bulletin; March 1993: 33-37.

42. Zukoski, C. F.; Struble, L. J. Rheology of Cementitious Systems. Materials Research Society Bulletin; March 1993: 39-42.
Gaining a fundamental understanding of the flow behavior of cementitious systems is complicated by the complexities of the underlying hydration reactions. Despite these complications, cement pastes have many of the same properties that are observed in nonreactive flocculated systems. Furthermore, techniques developed and validated using model materials have been successfully applied to cement pastes. Thus fruitful comparisons can be made between these two widely separated bodies of knowledge. The role of material properties, shear, and dispersing additives in controlling microstructure and flow properties, as well as final strength and porosity, offers a rich field of study for those interested in truly complex fluids.

Appendix D: PERSONNEL MANAGEMENT AND ADMINISTRATION

Overall, personnel changes have had some detriment effects on the project.

In the proposal it was indicated that Dr. E. Ashworth, Mr. L. R. Johnson, and Dr. J. A. Weyland would act as Associate Investigators, and Ms. Cheryl Strachen was hired as the Graduate Research Assistant at the beginning of the project. As of 1 January 1991, Dr. E. Ashworth joined the project in accordance with the plan specified in the proposal.

Early in the second period, an unexpected change was made in the Senior Personnel working on the project as discussed with Mr. Johnston at our 04 February 1991 meeting. Due to increasing commitments in other areas, Dr. Weyland requested to be allowed to discontinue work on the project. Although he will not be performing any physical work on the project, he is still available for consultation and can give input whenever appropriate. Since Dr. Weyland's contribution was to be mainly in terms of sharing his experience for the benefit of the design of the systems and of the experiment, no significant impact was expected upon the project. In reality, Dr. Weyland was unable to keep current on the project, and his input into the solution of the problems encountered was not available, and it was missed.

Ms. Strachan continued in the capacity of half-time Graduate Research Assistant; she is working mainly on the "physical" aspects of the project (specimen preparation, etc.) with Mr. L. R. Johnson. Mr. Johnson, however, was having difficulty putting in much time because of other commitments. An additional person (Mr. Li Qin, an M.S. candidate in Electrical Engineering) was hired at the beginning of the Spring 1991 semester; his principal responsibility was to help design and implement the data acquisition system, but he is also very good at general laboratory work and equipment fabrication and will assist, like all personnel on the project, where ever needed.

In the quarterly report for the third period, it was reported that there had been no changes in the Senior Personnel working on the project this quarter. There was the oversight because Mr. Johnson had stopped working on the project, but was expected to return to it later in the summer. He did not do so. Ms. Strachan continued in the capacity of half-time Graduate Research Assistant; still working mainly on the "physical" aspects of the project. Mr. Li, however, unexpectedly left the project without any notice in early May and without documenting any of his work. Consequently, all of his efforts on the data system, which he was doing effectively, were lost. An additional person (Mr. Michael Martin, a Physics major who has just completed his junior year) joined the project during the summer period.

In the fourth quarter, Ms. Strachan and Mr. Martin continued to assist on the project with the understanding that he would only be able to continue until the end of the Fall Semester due to expected workload in the Spring Semester. It was later found that Ms. Strachen had not been putting in very much effort due to family problems and commitments. In the fifth quarter, both these people continued on the project, but Ms. Strachen continued to have the same problems.

Since June, 1991, the only Senior Personnel working on the project have been the Principal Investigator (Dr. T. Ashworth) with some assistance for Associate Investigator Dr. E. Ashworth. In December, 1991, Mr. Martin completed his obligation, and due to her continuing problems, Ms. Strachen had to be terminated on the project. However, we were very fortunate to have Mr. James Peterson (who at the time was a sophomore student in Physics) join the project as an undergraduate assistant; he has been a valuable asset to the project. Because of his situation, Mr. Peterson was eligible for Work Study designation and he has cost the project only a few percent of his actual wages. In addition, he has proved to be a capable and reliable worker without who's help the progress made since the main problems were encountered could not have been accomplished. Since January, 1992, he has continued to work on the project.

Appendix E: REPORTS, PROPOSALS, RELEVANT TRAVEL, VISITS AND CONTACTS

In the first period, Dr. T. Ashworth and Dr. E. Ashworth conducted closely related work on the thermal conductivity of rocks and concrete as a function of moisture content. A paper was prepared which was presented at the 2nd ASTM Insulating Materials: Testing and Applications Conference in October 1991. The paper was also submitted for inclusion in ASTM STP 1116 as a fully refereed article.

Also, they submitted a proposal for possible inclusion in the State DOE-EPSCoR proposal. The work will involve moisture movements in porous materials. Dr. E. Ashworth will act as principal investigator.

In the second period, the paper submitted by to the 2nd ASTM Insulation Materials Conference was accepted for publication in ASTM STP1116. It describes measurements of the effect of moisture on the thermal conductivity of four types of concrete.

The research group met with the Project Monitor on 04 February, 1991. Discussions were held with Dr. Ramakrishnan regarding concrete specimen fabrication. During a visit funded from other resources, Dr. E. Ashworth participated in discussions with members of the faculty of Hydrology and Water Resources Department of the University of Arizona, and returned with a number of references to study on saturated/unsaturated flow.

In the third period, there was no activity in this category, but in the fourth period, Dr. T. Ashworth attended the 11 Symposium on Thermophysical Properties (June 24-27, 1991, University of Colorado, organized by ASME). Dr. E. Ashworth attended the 32 U.S. Rock Mechanics Symposium (July 9-12, 1991, University of Oklahoma); she presented a paper at this meeting.

Dr. T. Ashworth traveled to Brookings, South Dakota to present a progress report on his project within the EPSCoR contract (Study of Synergistic Mechanisms in Deicing Materials which Lead to the Prevention of Ice Adhesion) on 13 August, 1991.

A verbal report on the project was given by Dr. T. Ashworth to the South Dakota Department of Transportation Research Review Board on 15 August, 1991.

In the fifth period, Dr. T. Ashworth traveled to Gatlinburg, Tennessee to attend the 2nd Symposium on Insulation Materials: Testing and Applications, and presented a paper entitled "Thermal Conductivity of Several Concretes as a Function of Moisture." The paper was fully refereed and has been published in Insulation Materials: Testing and Applications, Second Volume, (eds.: Graves and Wysocki), ASTM STP 1116, pp. 415-429. In addition to attending the symposium, visits were made to Vanderbilt University in Nashville and to the TVA Raccoon Mountain Project (energy storage facility).

In the sixth period of the project, Dr. T. Ashworth worked with two on-campus groups who are studying various aspects of concrete. One project was for DOT (Dr. M. R. Islam, Department of Geological Engineering) and valuable contributions were made in the form of measuring the chloride penetration of concretes with aggregate supplements such as fly ash. The second project involves the early stages of cure of concrete, The work is with Dr. M. R. Hansen, Department of Civil Engineering. A proposal to expend this work is in initial stages of preparation for development of a monitoring scheme for fresh concrete.

The principal investigator attended the 1992 International MinExpo in Las Vegas, and visited SAIC to discuss research opportunities.