THE DEVELOPMENT OF A REMOTE FIELD DATA ACQUISITION SYSTEM

Thesis for the Degree of M. S.

MICHIGAN STATE UNIVERSITY

THOMAS WAYNE BOUCHER

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ABSTRACT

THE DEVELOPMENT OF A REMOTE FIELD DATA ACQUISITION SYSTEM

by

Thomas Wayne Boucher

This work examines the characteristics of a computer compatible remote field data acquisition system. Both software and hardware characteristics are considered. The work then presents construction details and operational characteristics of a remote field data acquisition system developed for the Department of Entomology at Michigan State University.

The development indicates the flexibility available to the user when recording data in a computer compatible format. Sensors can be operated with a minimal amount of additional circuitry as nonlinear characteristics can be linearized by computer manipulation of the data.

The environmental parameters of temperature and relative humidity are measured and recorded by the developed system. The signal conditioning and sensors for the above measurements are described in this work. Low-power complementary-symmetry metal over silicon-integrated circuits are extensively used in the relative humidity circuits.

The system developed is but an elementary stepping stone to even more complex systems.

THE DEVELOPMENT OF A REMOTE FIELD
DATA ACQUISITION SYSTEM

By

Thomas Wayne Boucher

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CHAPTER I

INTRODUCTION

Natural scientists often find that extensive time delays occur when they attempt to acquire and process field data. Whether that entails verifying a theory in the area of pest management or the simple collection of data for analysis of possible factors affecting healthy apple growth, the traditional methods of data acquisition remain as time consuming, and often times frustrating, stumbling blocks. In the past, collection and cataloguing of viable data has taken up the complete lifetimes of many researchers. Due to this large degree of human interaction, development of useful ecosystem management strategies has been impeded. Furthermore, these same time delays make the implementation of these management strategies very difficult in many cases because real-time climatological and biological data is not available concerning the present state of the system being managed. The purpose of the research program reported in this thesis is to develop and evaluate useful techniques and methodologies which will substantially reduce these time delays.

The conventional approach entails either (1) the researcher manually making his own real-time measurements in the field or (2) he sets up a measurement system in which desired data is recorded on strip-chart recorders. The first method becomes progressively prohibitive as the number of observations increases or if a particular observation must be made continuously over extended periods of time. Not only that, but

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the time it takes to transcribe the data from an instrument to a notebook balloons correspondingly. Also, due to the nature of the recording medium, extensive time is required when the scientist converts the analog voltage output recorded on the chart paper to the corresponding parameter he attempts to measure and then again transcribes this into a computer-compatible form for purposes of data storage and/or analysis.

Consider the following example. A physiographer (one who studies the descriptions of the features and phenomena of nature) desires data concerning soil temperature at various soil depths. He is interested in the variation over a time period covering fall, winter and spring. The temperature variation at depths of 10, 20, and 40 centimeters is the scientist's major concern. He contacts one of the local growers -- one who has offered 60 acres of his fallow ground for use in the project. The physiographer then constructs three test sites. On each site, he places thermocouples at each of the three selected depths. Temperature readings are taken every three hours. The methodology consists of taking a potentiometer bridge out to each test site and connecting it to the thermocouple leads. The temperatures at each depth are recorded upon a chart prepared for the corresponding site. The process is repeated every three hours for the next nine months.

After several months, the physiographer realizes excessive manhours have been consumed in the course of implementing the data acquisition phase of this study. He therefore executes the following changes. Purchasing nine single-track strip-chart recorders, he has workmen install them at the test locations. The sensitivity of the recorders enables direct connection of the thermocouples. Additional equipment entails hookup leads and environmental shelters for the chart recorders.

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At the end of each week, a research assistant brings out new supplies of chart paper and verifies proper operation of the equipment. Returning with the collected data, he sits down to spend the next week transforming the recorded voltages into corresponding temperatures.

The transform process can be very lengthy and during the transcription mistakes may easily occur. After transformation, the data must again be plotted in order to easily recognize and verify trends within the data. Again, extensive human manipulation of the data results in long time delays and greater probability of error.

This paper describes a tool to aid in the systematic collection of data. It minimizes the time spent by researchers when collecting, cataloguing and transforming raw data. The tool incorporates the powerful computational abilities of a computer, which aids the researcher in data analysis. It allows one to quickly discern new relationships and verify old ones in any data base. An overview of the data acquisition and data managment system is provided in Chapter II, along with the required specifications for the system. The hardware implementation of this system and the software is given in Chapter III. Preliminary results of evaluating this automated data acquisition system are provided in Chapter IV. A summary of the results and a list of the potential uses and limitations of this system are given in Chapter V.

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CHAPTER II

REQUIREMENTS OF THE AUTOMATED REMOTE DATA ACQUISITION SYSTEM

This chapter establishes the criteria which must be considered when developing a remote, automated data acquisition and data-logging system, as well as the concomitant data management system. Also, the basic procedure to be followed when using an automated remote data logging system is described. The basic operations of the data collection process are formulated in Section 2.1. Also in this section, the desired user operational procedures are generalized. Once the desired operational format has been established, the general specifications and constraints remain to be determined. These specifications are described in Section 2.2. After establishing the above, Section 2.3 details the hardware specifications which must be met and Section 2.4 analyzes any specifications which the software must meet.

2.1 General Operational Procedure

The operational procedure should be easily followed by the specific user of the system. Figure 1 flowcharts the typical procedure used in the collection of data via automated data-logging techniques. The user determines the type of data he requires. He examines the properties of the sensors available to determine those which will monitor the desired data more effectively. If laboratory calibration is required, he performs such calibration before positioning his sensors at the field site. While positioning the sensors, the researcher locates a central field

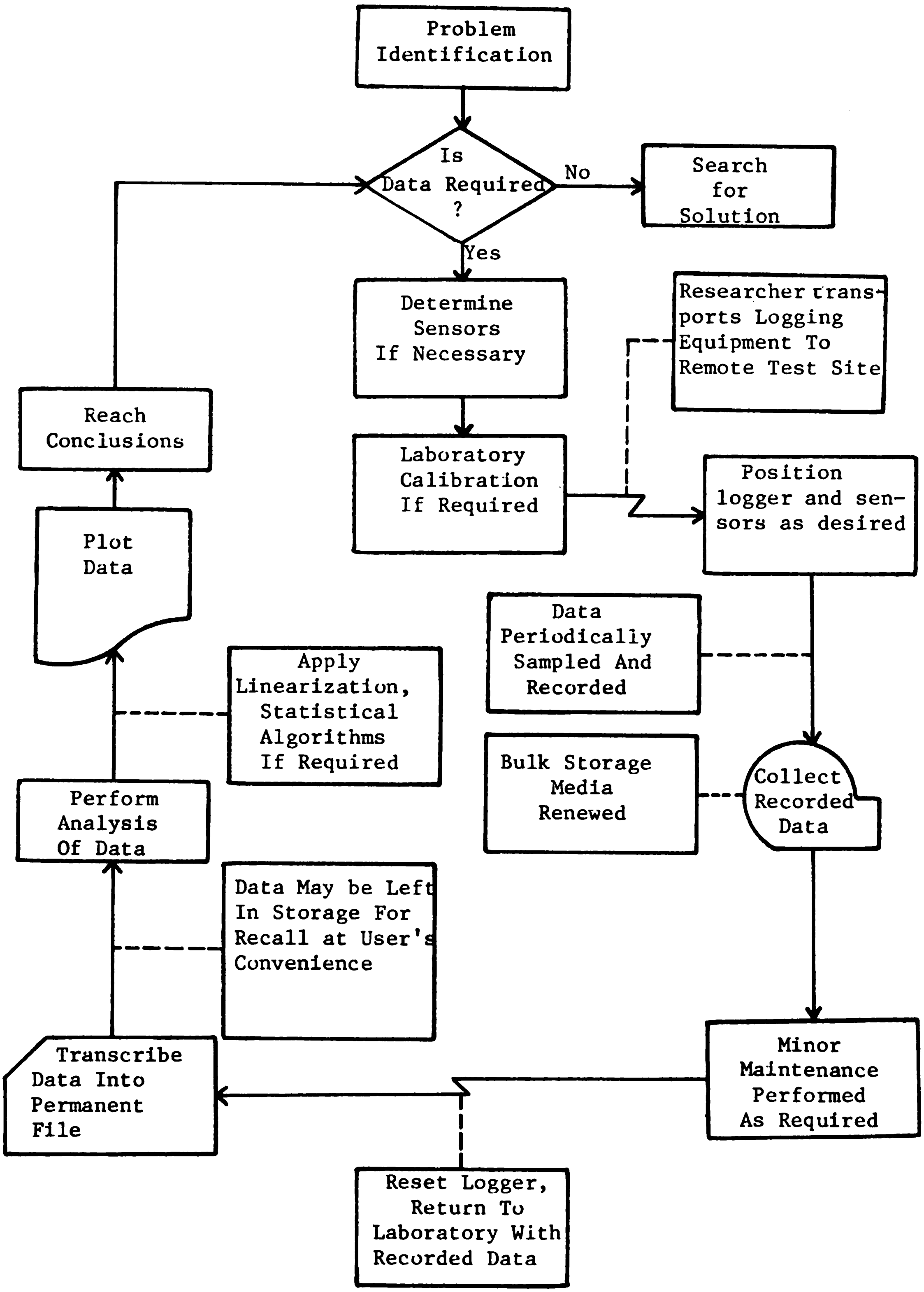

Figure 1. General Data Collection and Management Procedure

site where he places the recorder. After concluding that the system is as desired, he returns to the office. The system user determines either that sufficient data has been recorded or that the recording mechanism is in need of maintenance and replacement of the bulk storage media.

Returning to the field site, he/she retrieves the already recorded data from bulk storage and any minor maintenance is performed as required. The media upon which data is stored is replaced, whereupon the researcher proceeds back to the laboratory with data in hand. Immediately upon return, the user logs onto a main computer system and transfers the data from the bulk storage media into a permanent file. At the user's convenience, the permanent file is attached and data analysis is implemented as required or desired. The user then determines if more data would aid analysis. If deciding affirmatively, he continues to allow the system to operate as described above; otherwise, a return to the test site is made and the equipment is dismantled or moved to another location. A thorough inquiry of the system specifications and allowable constraints must be undertaken to adequately implement the above procedure.

2.2 General System Specifications

The primary users of this system will be natural scientists. The apparatus must therefore be designed such that the researcher obtains maximum satisfaction with a minimum of user frustrations. Theodore D. Sterling [1] has compiled the table which is reproduced in Table I, which sets forth many of the criteria for humanizing a computerized information system. His table applies specifically to software systems and, as such, must be carefully considered when structuring the data management portion of this work. However, many of the points covered in the

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TABLE I

Stanley House Criteria for Humanizing Information Systems

A. Procedures for dealing with users

1. The language of a system should be easy to understand.
2. Transactions with a system should be courteous.
3. A system should be quick to react.
4. A system should respond quickly to users (if it is unable to resolve its intended procedure).
5. A system should relieve the users of unnecessary chores.
6. A system should provide for human information interface.
7. A system should include provisions for corrections.
8. Management should be held responsible for mismanagement.

B. Procedures for dealing with exceptions

1. A system should recognize as much as possible that it deals with different classes of individuals.
2. A system should recognize that special conditions might occur that could require special actions by it.
3. A system must allow for alternatives in input and processing.
4. A system should give individuals choices on how to deal with it.
5. A procedure must exist to override the system.

C. Action of the system with respect to information

1. There should be provisions to permit individuals to inspect information about themselves.
2. There should be provisions to correct errors.
3. There should be provisions for evaluating information stored in the system.
4. There should be provisions for individuals to add information that they consider important.
5. It should be made known in general what information is stored in systems and what use will be made of that information.

D. The problem of privacy

1. In the design of a system all procedures should be evaluated with respect to both privacy and humanization requirements.
2. The decision to merge information from different files and systems should never occur automatically. Whenever information from one file is made available to another file, it should be examined first for its implications for privacy and humanization.

E. Guidelines for system design having a bearing on ethics

1. A system should not trick or deceive.
2. A system should assist participants and users and not manipulate them.
3. A system should not eliminate opportunities for employment without a careful examination of consequences to other available jobs.
4. System designers should not participate in the creation or maintenance of secret data banks.
5. A system should treat with consideration all individuals who come in contact with it.

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table can and should be reapplied when developing the hardware of data acquisition systems. The hardware should be constructed so that the user can easily set up and operate it. It should relieve the user of unnecessary hardware maintenance. It should include provisions for easy interfacing with various transducers. It should provide the ability to easily increase the number of data channels. In terms of user convenience, the entire recording system should be relatively compact. One person should be able to install it easily in any location. As such, the system must be portable. Its operation must be independent of the power line system for ease of installation in isolated areas. The power source must also be portable and able to provide operating power for a considerable length of time. In consultations with natural scientists, it is agreed that an ideal minimum time span of uninterrupted and unattended operation would be one month.

In addition to the harsh power requirement, climate conditions which the system may be subject to must be taken into consideration. System operation should cover an ideal temperature span of $-50^{o}C$ to $+50^{o}$ C or $-58^{o}F$ to $+122^{o}F$ with very little degradation in data handling ability or in accuracy of the recording process. The temperature range of operation of the system is just a singular aspect of a much greater problem. The recording units and sensors must either be capable of withstanding or be protected from the corrosive effects of humidity, condensation, and air borne chemical pollutants. Protection of the equipment from the weathering of wind blown sand, snow and/or ice must also be provided.

Weather is not the only culprit contributing to the destruction of viable data. Many small animals can wreak havoc with interconnecting cabl

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cables, sensors and quite possibly the recording instrument itself. Small animal instincts drive the animal to fashion nesting areas within small spaces contained in any equipment, and many exhibit extreme curiosity concerning the taste of various sensors and cables. Thus, the system physically must be quite durable.

In addition, since the recorded data provides input for a computer-based data management system, the recording process and media should be directly compatible with the computer. The computer processes information in the form of electrical signals which represent bits of information. Any compatible recording process must then be capable of transforming analog data signals into corresponding digital bits. The bulk storage must then be capable of directly interfacing with the computer. Some form of digital-to-analog conversion must be chosen to realize the desired transform and the transformed data must then be stored on some form of digital recording media.

2.3 Hardware Considerations

Before determining the hardware specifications which the sensors and the recorder must meet, it is advantageous to examine some characteristics of the data to be preserved. Most natural scientists are concerned with the representative environmental data listed in Table II [2]. For each of the various parameters, the range, accuracy, threshold value, and the maximum rate of change of the parameter per unit of time are specified. The fastest rate of change is 30 mph/sec. This quality of the wind speed is a limiting factor placed upon the response time of the recording system. If the recorder operation is such that periodic samples of the parameters are recorded, then the high rate of change of wind speed constrains the system to sample at a rate of twice

TABLE II

Representative Environmental Data Required [2]

Parameter	Number of measurements required per site	Range	Accuracy	Threshold	Maximum rate of change of the parameter per unit of time
Air Temperature	1	-49-48°C (-55-210°F)	±1°C	----	1°C/min
Soil Temperature	4 (0,1,3,5 in.)	-2-54°C (28-130°F)	±1°C	----	1°C/min (surface) 1°C/h (sub-surface)
Wind Speed	1	0-50 mph	±1 mph	1 mph	30 mph/sec
Wind direction	1	0-360°	±10°	1 mph	180°/min
Barometric pressure	1	27.0-31.5 in. Hg	±0.2 in. Hg	27 in. Hg	0.33 in. Hg/h
Humidity	1	0-95%	±1%	5%	20%/h
Precipitation	1	0-4 in. rainfall	0.1 in.	0.1 in.	15-20 in./h
Soil moisture	1	0-100% field capacity	±17%	0%	33%/h
Light intensity					
Low	1	0-300 cal/cm^2/d	±5 cal/cm^2/d	0	----
High	1	0-10 ft-candles	20%	----	----

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a minute if parameter changes are to be accurately followed. At the present time, wind speed is not a critical measurement parameter in this application. Initial system feasibility shall be demonstrated via measurement of both soil and air temperatures in conjunction with that of relative humidity. However, system design must take into consideration the possible future addition of wind speed transducers and that of other parameter sensors. Once the characteristics of the measurands have been laid down, a foundation exists which aids in the selection of the proper transducers to accomplish the measurement goals.

Table III pinpoints the important aspects of selecting instrumentation transducers [3]. It is quite possible that a specific transducer is chosen, but its input/output characteristics do not fit the requirements of the application, or it is found that signal amplification is necessary. When additional electrical processing or amplification is performed on a transducer output variable, the techniques are known as signal conditioning. Signal conditioning makes the recording of small variations in low level transducers possible. At the same time, it may compensate for any non-linearities in the transducer output.

The components of signal conditioning circuits must be able to operate throughout the same environmental temperature span as the transducers. In many cases, the signal conditioner itself provides temperature stabilization of the transducer output. It may be designed to offset zero shift in a transducer by superimposing an equal, but opposite, signal change on the transducer output.

When the transducer and its associated signal conditioning are connected together, it is of the utmost importance that one consider the effects of extraneous signals which could enter into the components.

TABLE III

Selecting Instrumentation Transducers

Characteristics of the Input Variable

- Range (maximum and minimum values to be measured)
- Overload protection
- Frequency response
  - Transient response
  - Resonant frequency

Transducer Input/Output Relation

- Accuracy
- Repeatability
- Linearity
- Sensitivity
- Resolution
- Friction
- Hysteresis/backlash
- Threshold/noise level
- Stability
  - Zero drift
  - Loss of calibration with time

Overall System

- Output characteristics
- Size and weight
- Power requirements
- Accessories needed
- Mounting requirements
- Environment of transducer location
- Crosstalk
- Effect of presence of transducer on measured quantity
- Need for corrections dependent on other transducers

Measurement Reliability

- Ease and speed of calibrating and testing
- Time available for calibration prior to and/or during use
- Duration of mission
- Stability against drift of zero point and proportionality constant
- Vulnerability to sudden failure (probability of proper performance for a given life time)
- Fail safety (will transducer failure represent system failure or invalidate data from other transducers)
- Failure recognition (will transducer failure be immediately apparent so that subsequent erroneous data can be rejected)

Purchase

- Availability and delivery; is item off-the-shelf?
- Any development necessary for operation
- Availability of calibration and test data from manufacturer
- Price
- Previous experience with seller

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A most frequently encountered source of error is the introduction of a 60-cycle power line signal. This signal can easily superimpose upon the transducer signal via the cable interconnect between the transducer and the signal conditioning circuits. In applications where dc analog voltages are measured, the 60-cycle component can be effectively attenuated by low-pass filtering, establishment of well-defined grounds, and/or implementation of electrostatic shielding. For a thorough discussion, see Chapter 17 of Practical Instrumentation Transducers [3].

Many problems are encountered in the process of connecting the transducer with the recorder. The output range of the transducer must be tailored to the input range of the recorder. The recorder should be able to withstand signals many orders of magnitude in excess of its input range, with little or no damage to its components. Since many transducers output a differential signal, the recorder should have bipolar inputs. The recorder must operate over the same extremes of climate conditions, under the same criteria of minimum power consumption. The recorder, as already noted, must be computer compatible; as such, a form of analog-to-digital conversion must be decided upon. The code type software manipulations can easily perform conversions. Prior consideration of the signals to be recorded shows that conversion speed is not a necessity. In the conversion process, errors may occur due to offset factors, gain factors and nonlinearities inherent in the converter. The converter should be designed to minimize these errors and maintain the minimal error over the entire span of temperature operation. A good discussion of analog-to-digital converters is given in Analog Devices' Analog-Digital Conversion Handbook [4].

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The system must process and convert several data channels. Economic factors indicate that multiplexing the various data channels into the A/D converter is desirable in terms of reduction in hardware components; thus, costs are lowered and portability increased.

A method of lowering power consumption, which has been used successfully, operates upon the principle of sampling the data at predetermined intervals and disengaging power to the system between sampling times. Again, the signals of concern vary slowly enough that the application of the above principle increases the operating life of the system, with no degradation of information. To implement the technique, some sort of timing mechanism must be incorporated into the system.

There remains one facet of the system which has not been touched upon. The hardware which provides the digital coding must be augmented by a storage media for the digital codes. A mechanism to store bulk quantities of data must be considered. The mechanism must exhibit low power dissipation, maintain portability criteria and promote ease of data collection while storing voluminous amounts of data. The storage media should maintain data integrity over long periods of time and in various environmental conditions. The media should be such that quick data transfer from the media to a mainframe computer is possible.

2.4 Software Data Management Considerations

Earlier in this chapter a reference was made to the article on "Humanizing Computerized Information Systems" [1]. Again, consider Table I from this article. Many of the guidelines proposed in the table should be followed if the software is to properly and efficiently implement user interactive data management. In a data management system, the language used should be both clear and easy for the operator to understand. The system should quickly react to any requests or to info

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inform of system inability to meet the request requirements. The system should eliminate unnecessary or redundant requests while providing cordial human information interfacing. The ability to deal with many different classes of individuals is a basic system criterion. The structure should be able to satisfy both the computer-oriented user as well as the researcher with little computer background. The system should be structured to allow alternatives both in input procedures and data processes. The software shouid be structured so as to efficiently implement the application of currently existing hardware. However, the software should be flexible in order to easily update the entire system with improved hardware developments. Another aspect which deserves consideration is that of data bank protection. The system should allow free access of all data to the user. The presentation of that data, however, should be accomplished in such a manner that the user does not accidentally destroy it. At the same time, authorized users should be able to quickly add to sections of the already catalogued data base.

Figure 2 illustrates typical user interactive data management. The user obtains the bulk storage media with the accumulated data from the field site. He reads this data, via a computer controlled peripheral, and it is placed into temporary storage. The user then requests printout of several lines of raw data. This enables him to eliminate gross malfunction of the logger system as a source of error, and at the same time, verify valid data transfer. If, at this point in time, invalid data appears, it may be easily deleted from the data base. Once satisfied that the data has been read and stored properly, the user then catalogues it permanently in the form of a permanent file. In effect, this negates the possibility of losing the valid data.

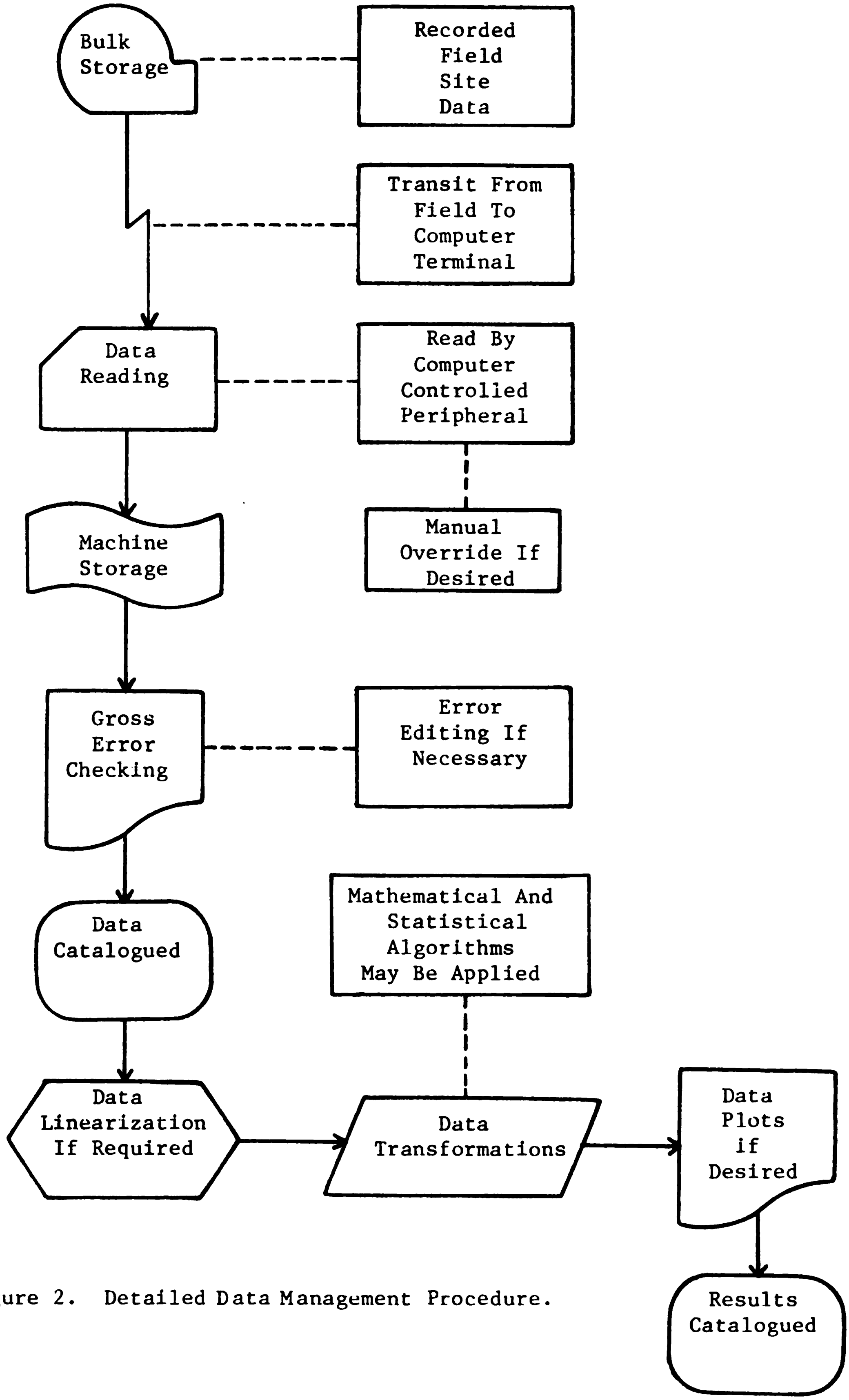

Figure 2. Detailed Data Management Procedure.

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Further data processing may be halted at this point until a later time or the user may directly proceed as follows.

He has the computer input the data into a linearization algorithm which compensates for the measured nonlinearities of the sensor which originally produced the signal recorded by the data logger. He then uses the computer to transform the linearized data into the corresponding parameter which the sensor measures (i.e., temperature, dew point, relative humidity, etc.). Using the computer, he tabulates the parameter values versus time and then plots a graph of it. Scrutinizing the data, he decides to apply a statistical algorithm to two of the data channels in hopes of discovering if a correlation exists between them. After this analysis, the results are catalogued for future referral by either himself or his colleagues.

The above represents a general approach to an automated data-management system. The realization of such a system develops in the succeeding chapters of this work.

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CHAPTER III

SYSTEM IMPLEMENTATION

3.1 Introduction

The system, as developed for use by the entomologists at Michigan State University, provides the topical material for this chapter. At the time of the inception of this project, specifications of the data loggers then available were considered. As a result, a logger manufactured by the "Incre-Data" Corporation was chosen as an ideal subcomponent for realizing the system. The logger model purchased has 20 channels for data input, and an input voltage range which is constrained to a span of 100 mV covering the values of -50 mV to +50 mV. In this chapter, Section 3.2 not only elaborates upon the characteristics of the sensors, but also details the construction of the signal conditioning required. The signal conditioning provides an input voltage representation of the data which falls within the above-mentioned range. Section 3.3 fullv develops the characteristics of the data logger, while documenting the information needed to operate the logger. The recovery of the data stored by the logger is facilitated by hardware components. Section 3.4 lists the properties and describes the operation of those components. Section 3.5 tabulates the programs available which form the basis for the software implementation of the Data Management System.

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3.2 Signals, Sensors and Signal Conditioning

The photograph in Figure 3 shows some of the various sensors available which record geophysical data. The host of devices ranges from the solar calorimeter in the background to the thermistor temperature indicator in the foreground. Some of them are direct reading, as is the thermometer, while others must be built into electrical circuitry, as do the soil moisture sensors, in order that the signal may be measured directly. Creation of sensors to measure various data is an on-line process with new products constantly entering the marketplace.

Currently, our attention is focused upon those sensors which measure temperature and relative humidity. Table II in Chapter II lists the signal characteristics along with the quality and quantity of the measurements to be made. Frank J. Oliver, in Practical Instrumentation Transducers [3] discusses the merits and deficiencies of many of these sensors.

Once the merits of the sensors were weighed, the actual design and implementation of the signal conditioning circuits remained. Protection of the electronics from the environment being a prime consideration, an aluminum casting, Figure 4, was purchased to house the attendant hardware. Its dimensions (6 1/2" high x 6 1/2" wide x 10 3/4" long) facilitate its use in portable applications. The casting is sealed by a large O-ring stretched around the perimeter of the lid. The lid is then held solidly in place by six hex bolts. The protection of interior components is insured by an air purging system. The valve installed on the top of the lid makes it possible to introduce dry nitrogen into the sealed casting, while a purge valve located on the side of the unit bleeds off any moisture containing air previously

Figure 3. Typical Physical Transducers

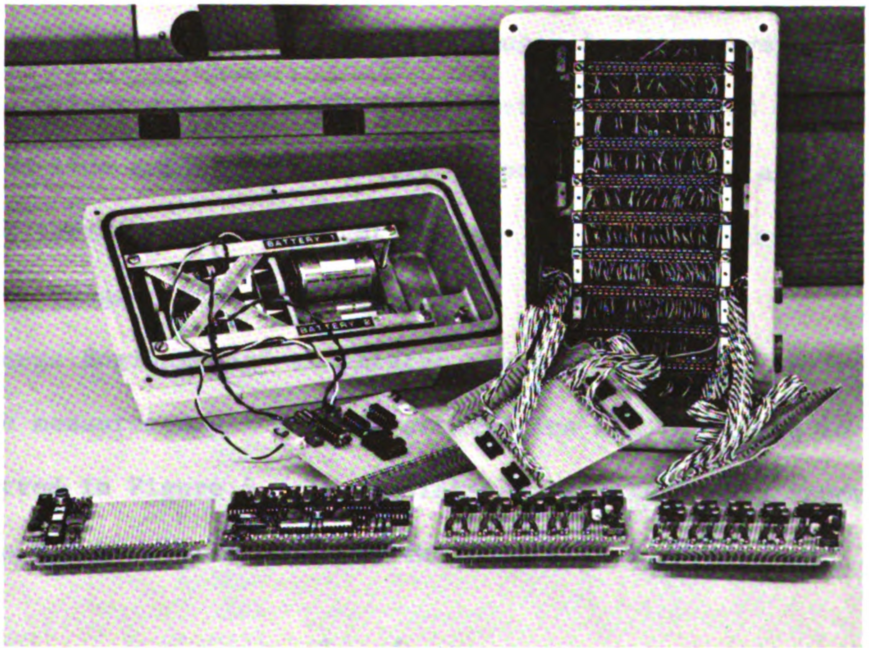

Figure 4. Signal Conditioning Unit

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trapped. Along the sides of the box, near the corners, four male connectors are mounted. Two of these connectors are 26 pin types positionally located side by side. These have been chosen to carry the conditioned signal to the logger and represent the outputs of the signal conditioner. The other two connectors contain 36 pins apiece and represent the sensor inputs to the unit. In Figure 4, the above-mentioned features are pointed out.

3.2.1 Temperature Measurements

Thermistors were decided upon as the elements best suited to sense the temperatures of both soils and air. These thermally dependent resistors possess extremely high sensitivity and are able to hold their original calibration for extended periods of time. Furthermore, unlike thermocouples, no reference temperatures are required. High sensitivity promotes their use in comparatively simple measuring circuits with little degradation of accuracy due to changes in other components. As an example, Oliver [3] states that 400 feet of No. 18 AWG copper wire transmission line subjected to a $50^{o}F$ temperature change affects the accuracy of thermistor measurement by only $0.1^{o}F$. This is well within the accuracy range stated in Table II.

An "Omega Engineering" thermister has been chosen to perform the temperature measurements. Its characteristics are tabulated in Table IV and plotted in Figure 5. Its resistance variation as a function of temperature can be approximated by the following formula.

$$R(T) = R_o(T_o)e^{\beta(\frac{1}{T} - \frac{1}{T_o})} \qquad (1)$$

TABLE IV

THERMISTOR CHARACTERISTICS

Temperature (°C)	Resistance (Kilohms)	Temperature (°C)	Resistance (Kilohms)
-30	88.5	- 6	22.31
-29	83.15	- 5	21.165
-28	78.2	- 4	20.08
-27	73.6	- 3	19.055
-26	69.25	- 2	18.095
-25	65.2	- 1	17.185
-24	61.4	0	16.325
-23	57.85	+ 1	15.515
-22	54.55	+ 2	14.75
-21	51.45	+ 3	14.025
-20	48.535	+ 4	13.345
-19	45.805	+ 5	12.695
-18	43.245	+ 6	12.085
-17	40.845	+ 7	11.505
-16	38.59	+ 8	10.96
-15	36.475	+ 9	10.44
-14	34.49	+10	9.95
-13	32.62	+11	9.485
-12	30.865	+12	9.045
-11	29.215	+13	8.625
-10	27.665	+14	8.23
- 9	26.2	+15	7.855
- 8	24.825	+16	7.5
- 7	23.53	+17	7.16
+18	6.84	+35	3.265
+19	6.535	+36	3.1335
+20	6.245	+37	3.0085
+21	5.97	+38	2.8885
+22	5.71	+39	2.7735
+23	5.46	+40	2.6633
+24	5.225	+41	2.5585
+25	5.0	+42	2.4585
+26	4.7865	+43	2.3635
+27	4.5835	+44	2.2715
+28	4.3885	+45	2.185
+29	4.2035	+46	2.1005
+30	4.0285	+47	2.02
+31	3.8615	+48	1.945
+32	3.7015	+49	1.8715
+33	3.5485	+50	1.8015
+34	3.4035		

Figu

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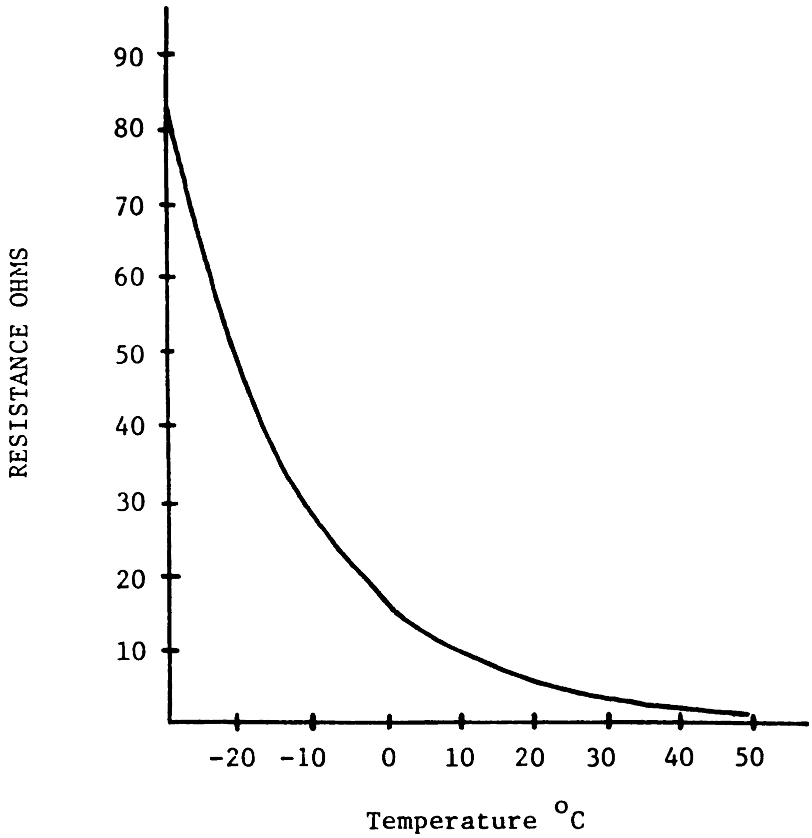

Figure 5. Resistance vs. Temperature Characteristics of "OMEGA" Thermistor.

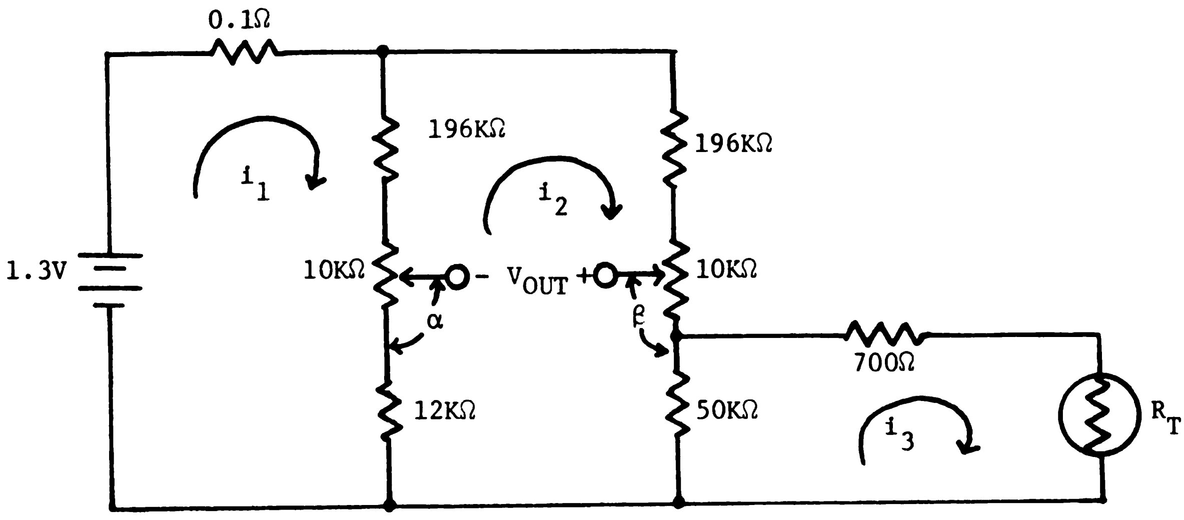

Figure 6. Fundamental Thermistor Bridge Network

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$R_o(T_o)$ = Thermistor resistance at absolute temperature T_o

= 5×10^3 ohms,

where $T_o = 298.15^{o}K = 25^{o}C$.

$R_o(T)$ = Thermistor resistance at absolute temperature T

β = Thermistor material constant

= 3.82×10^4 Kelvins

<u>Note</u>: The value of β is determined from measurements made at $0^{o}C$ and $50^{o}C$.

The thermistor is used in a circuit configuration known as the Wheatstone bridge (see Figure 6). The output voltage as a function of temperature can be expressed as:

$$V_{OUT} = 1.3V \left[\frac{(3.5 + \beta - \alpha)R_T + (\beta - \alpha - 1.5)5 \times 10^4\Omega}{(29.6 + 1.7\beta + \alpha)R_T + (21.1 + 1.7\beta + \alpha)5 \times 10^4\Omega} \right] \qquad (2)$$

where

$$R_T = 5 \times 10^3\Omega \exp \left[3.8 \times 10^3 \left(\frac{1}{T} - \frac{1}{298.15^{o}K}\right) \right] . \qquad (3)$$

The component's values indicated in the schematic were arrived at as follows: The 0.1Ω represents the internal resistance of the "Gould" rechargeable nickel cadmium batteries. The 196 kΩ resistors in two of the legs of the bridge were chosen out of convenience as they were available in abundance as a stock item. Their major function is that of current limiting the bridge in order that power consumption be minimized. The 15kΩ resistor in series with the 10 kΩ potentiometer forms the reference leg of the bridge. The reference value can be varied by appropriate adjustment of the potentiometer. The variation is reflected in the value of alpha which ranges from 0 to 1. The other leg of the bridge i

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bridge is composed of a 50 kΩ resistor in parallel with a series combination of thermistor and the interconnecting cable. The parallel network is placed in series with a 10 kΩ potentiometer, thus completing the other leg. Beta represents the variability of the 10kΩ potentiometer. A nominal dc resistance for the coaxial cable was measured to be 700Ω for a 15 foot length. By applying mesh analysis, the output voltage V_{OUT} can be determined in terms of the various circuit components.

Writing the loop equations,

$$-1.3V + .1\Omega i_1 + 196k\Omega(i_1-i_2) + 12k\Omega(i_1-i_2) + 10k\Omega(i_1-i_2) = 0, \tag{4}$$

$$(196k\Omega + 12k\Omega + 10k\Omega)\ (i_2-i_1) + 196k\Omega i_2 + 50k\Omega(i_2-i_3) + 10k\Omega i_2 = 0, \tag{5}$$

$$50k\Omega(i_3-i_2) + 700\Omega i_3 + R_T\ i_3 = 0 \tag{6}$$

Rearranging, the equations become:

$$218.001k\Omega i_1 - 218k\Omega i_2 = 1.3V, \tag{4'}$$

$$-218k\Omega i_1 + 474k\Omega i_2 - 50k\Omega i_3 = 0, \tag{5'}$$

$$-50k\Omega i_2 + (50.7k\Omega + R_T)i_3 = 0. \tag{6'}$$

Using (6'), solve for i_3 in terms of i_2.

$$i_3 = \frac{50k\Omega i_2}{(50.7k\Omega + R_T)} \tag{7}$$

Substituted into (5'), the equations reduce to:

$$(2.18001x10^5)\Omega i_1 - (2.18x10^5)\Omega i_2 = 1.3V \tag{8}$$

$$-(2.18x10^5)\Omega i_1 + \left[\frac{2.15318x10^{10} + 4.74x10^5 R_T}{5.07x10^4 + R_T}\right] \Omega i_2 = 0 \tag{9}$$

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Equations (8) and (9) can be put into matrix form and evaluated as follows:

$$\begin{bmatrix} 1.0\text{x}10^5(2.18001) & -1.0\text{x}10^5(2.18) \\ -1.0\text{x}10^5(2.18) & 1.0\text{x}10^5\left[\dfrac{2.15318\text{x}10^5 + 4.74R_T}{5.07\text{x}10^4 + R_T}\right] \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} 1.3 \\ 0 \end{bmatrix} \tag{10}$$

$$1.0\text{x}10^5 \begin{bmatrix} 2.18001 & -2.18 \\ -2.18 & \dfrac{2.15318\text{x}10^5 + 4.74R_T}{5.07\text{x}10^4 + R_T} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} 1.3 \\ 0 \end{bmatrix} \tag{11}$$

The determinant of the coefficient matrix is:

$$\Delta = (1.0\text{x}10^5)^2 \left[\frac{(2.18001)\ (2.15318\text{x}10^5 + 4.74R_T)}{(5.07\text{x}10^4 + R_T)} - (2.18)^2\right] \tag{12}$$

which can be reduced to the following form:

$$\Delta = (1.0\text{x}10^5)^2 \left[\frac{(2.284467753\text{x}10^5 + 5.58080474R_T)}{(5.07\text{x}10^4 + R_T)}\right] \tag{13}$$

Solving for i_1 and i_2 by Cramer's formula:

$$i_1 = \frac{\begin{bmatrix} 1.3 & -1.0\text{x}10^5(2.18) \\ 0 & 1.0\text{x}10^5\left[\dfrac{2.15318\text{x}10^5 + 4.74R_T}{5.07\text{x}10^4 + R_T}\right] \end{bmatrix}}{\Delta} \tag{14}$$

$$i_2 = \frac{\begin{bmatrix} 1.0\text{x}10^5(2.180001) & 1.3 \\ -1.0\text{x}10^5(2.18) & 0 \end{bmatrix}}{\Delta} \tag{15}$$

Equations (14) and (15) can be reduced to:

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$$i_1 = \frac{1.3}{1.0\text{x}10^5}\left[\frac{2.15318\text{x}10^5 + 4.74R_T}{2.284467753\text{x}10^5 + 5.58080474R_T}\right] \qquad (16)$$

$$i_2 = \frac{1.3}{1.0\text{x}10^5}\left[\frac{1.10526\text{x}10^5 + 2.18R_T}{2.284467753\text{x}10^5 + 5.58080474R_T}\right] \qquad (17)$$

The power supplied by the battery may be calculated by multiplying i_1 by the supply voltage.

$$P = 1.3i_1$$

$$= \frac{(1.3)^2}{1.0\text{x}10^5}\left[\frac{2.15318\text{x}10^5 \text{ x } 4.74R_T}{2.284467753\text{x}10^5 + 5.58080474R_T}\right] \qquad (18)$$

The greatest power dissipation occurs when the resistance of R_T attains a low value of 1.8015kΩ, then the maximum power dissipation becomes 15.86μW.

The bridge output voltage, as a function of i_1 and i_2 can be expressed as:

$$V_{OUT} = 1.0\text{x}10^4\left[\left(\frac{(1.2+\alpha+\beta)\ (5.07\text{x}10^4) + (6.2+\alpha+\beta)\ (700+R_T)}{5.07\text{x}10^4 + R_T}\right)i_2 - (1.2+\alpha)i_1\right] \qquad (19)$$

Substituting (16) and (17) into (19), the output voltage, as a function of the circuit resistances, is obtained.

$$V_{OUT} = 1.3\text{x}10^{-1}\left[\frac{(7.828+2.18\beta-2.56\alpha)R_T-(1.162892\text{x}10^5(1.8.8801\text{x}10^{-1}\alpha-9.6356\text{x}10^{-1}\beta)}{5.58080474R_T + 2.284467753\text{x}10^5}\right] \qquad (20)$$

By appropriate manipulations, (20) becomes:

$$V_{OUT} = 1.8235\text{x}10^{-1}(1 + 2.785\text{x}10^{-1}\beta - 3.27\text{x}10^{-1}\alpha) \text{ x}$$

$$\left[\frac{R_T - \left[1.48555\text{x}10^4 \left(\frac{1 + 8.88\text{x}10^{-1}\alpha - 9.636\text{x}10^{-1}\beta}{1 + 2.785\text{x}10^{-1}\beta - 3.27\text{x}10^{-1}\alpha}\right)\right]}{R_T + 4.093\text{x}10^4}\right] \quad (21)$$

If $\alpha = \beta = 0$, the bridge output is zero when $R_T = 14.855\text{k}\Omega$. The zero point can be shifted by appropriate adjustment of the α and β of the potentiometers. The range of zero shift extends from $0.43\text{k}\Omega$ to $41.0\text{k}\Omega$.

Substituting the expression (3) into (21) and algebraically manipulating the expressions, (21) becomes:

$$V_{OUT} = 1.8235\text{x}10^{-1}(1 + 2.785\text{x}10^{-1}\beta - 3.27\text{x}10^{-1}\alpha) \text{ x}$$

$$\left[\frac{\exp(3.82\text{x}10^3/T) - \left[1.0895\text{x}10^6 \left(\frac{1 + 8.88\text{x}10^{-1}\alpha - 9.636\text{x}10^{-1}\beta}{1 + 2.785\text{x}10^{-1}\beta - 3.27\text{x}10^{-1}\alpha}\right)\right]}{\exp(3.82\text{x}10^3/T) + 3.00223\text{x}10^6}\right] \quad (22)$$

The above expression relates the bridge output voltage to the variations in absolute temperature as measured on the Kelvin scale. It can be simplified, since once α and β are determined, the terms which contain them are constants.

Let

$$A = (1 + 2.785\text{x}10^{-1}\beta - 3.27\text{x}10^{-1}\alpha)$$

$$B = \left(\frac{1 + 8.88\text{x}10^{-1}\alpha - 9.63\text{x}10^{-1}\beta}{1 + 2.785\text{x}10^{-1}\beta - 3.27\text{x}10^{-1}\alpha}\right)$$

Equation (22) then simplifies to:

$$V_{OUT} = 1.8235\text{x}10^{-1}A \left[\frac{\exp(3.82\text{x}10^3/T) - 1.0895\text{x}10^6 B}{\exp(3.82\text{x}10^3/T) + 3.00223\text{x}10^6}\right] \quad (23)$$

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The previous expression can be solved for the absolute temperature in terms of the bridge output voltage, the result being:

$$T^{o}K = 2.561203x10^{2} \left[\frac{1}{1 + (6.70472x10^{-2}) \ln \left[\frac{(6.617x10^{-2})AB + V_{OUT}}{(1.8235x10^{-1})A - V_{OUT}} \right]} \right] \quad (24)$$

To express the above in degrees Celsius, subtract $273.15^{o}K$ from the above.

$$T^{o}C = T^{o}K - 273.15^{o}K$$

$$= 2.563x10^{2} \left[\frac{1}{1 + (6.7047x10^{-2}) \ln \left[\frac{(6.6174x10^{-2})AB + V_{OUT}}{(1.8235x10^{-1})A - V_{OUT}} \right]} \right] -2.7315x10^{2} \quad (25)$$

Conversion to the Farenheit scale is accomplished by the following formula.

$$T^{o}F = \frac{9}{5}(T^{o}C) + 32^{o}F \quad (26)$$

The temperature vs. voltage expressions developed above are used when executing data reduction, negating the construction of any complex hardware linearization circuitry. Since linearizing circuitry is not used, power consumption is considerably reduced.

Construction of the bridges commences with determination of component layout upon a 4½" x 6½" glass epoxy vector board. To fit the boards within the aluminum casting, it was necessary to reduce their dimensions to 4½" x 3½". They then plug into sockets mounted on aluminum stock 1/4" x 3/4" x 9". The sockets were then wired forming a backplane facilitating interconnection changes. The vector board itself has 44 metallic contact fingers (22 per side) along one edge of the 4½" width. These fingers provide the mating connections to the socket terminals. The set of fingers on one side are labeled alphabetically, while those on the other side are labeled numerically.

Since a maximum of 18 temperature measurements are desired at any one time, a corresponding equivalent number of bridges had to be constructed. Conservation of available space, as well as a savings in the quantity of components, is realized through construction of two boards each with nine bridge networks, all sharing the same reference leg. Also included as part of the board circuitry is a voltage divider network used to monitor the battery supply potential. Figure 7 diagrams the circuit topology which is implemented using wirewrap connections. The components are mounted on the alphabetically labeled side of the vector board and wirewrapped together on the reverse side. The contact finger terminations are listed in Table V. To implement ease of adjustment, the potentiometers are mounted along the top of the vectorboard, thus alleviating any need to remove the boards from their sockets.

Oscilloscope observations indicated the presence of power line frequency interference. This interference was attenuated by the addition of 5μF capacitors across the output terminals of the bridge. Capacitors were also installed from the output terminals to the negative terminal of the battery.

Chapter IV presents the measured response of the circuitry as well as the field data recorded.

3.2.2 Humidity Measurement

The sensor providing relative humidity indication is manufactured by the Physical-Chemical Research Corporation [5]. It is an electric hygrometric circuit element which senses changes in relative humidity

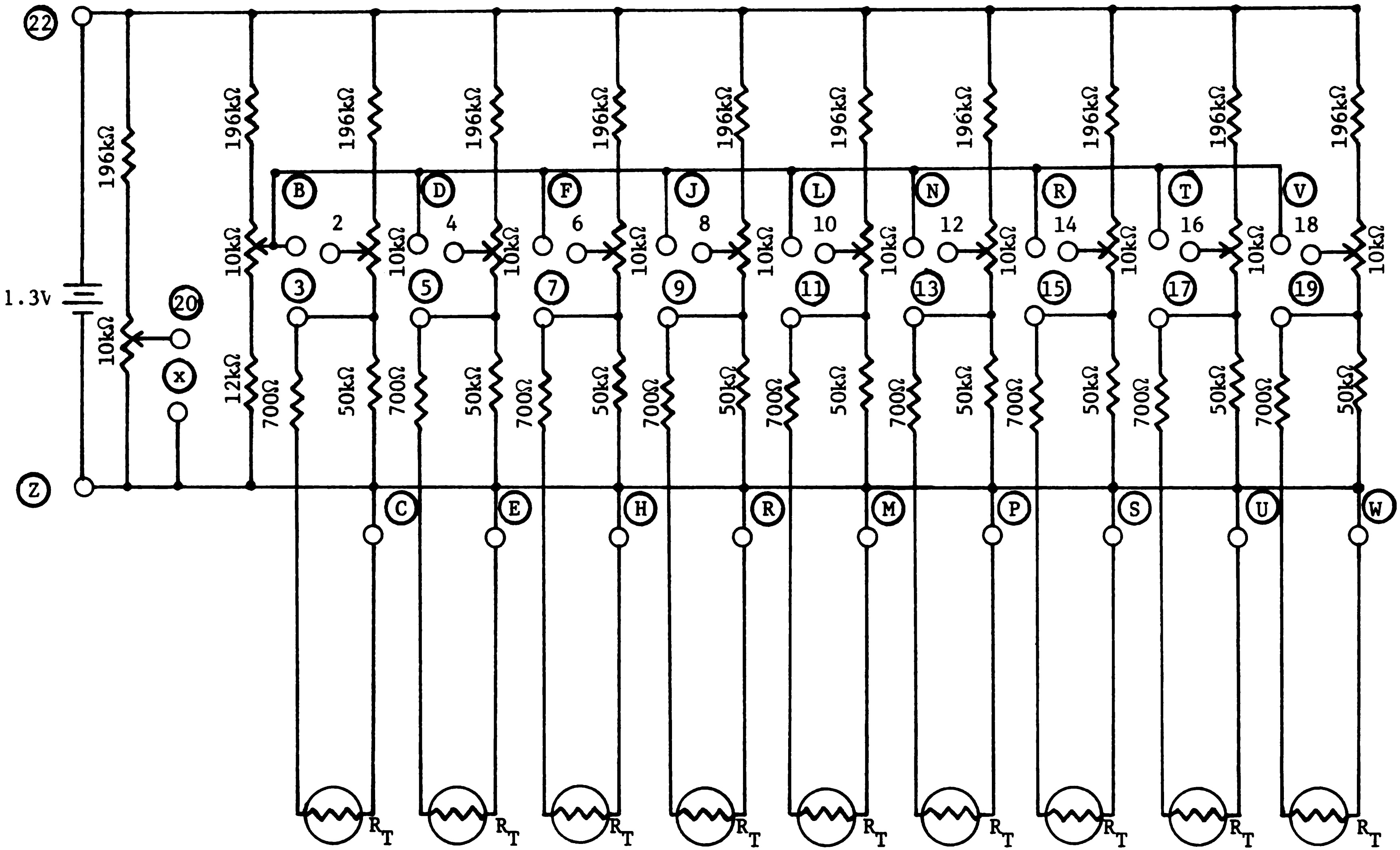

Figure 7. Electrical Topology of Thermistor Board

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TABLE V(a)

Thermistor Board Terminations

Thermistor Board #7

	A	No Connection	1	No Connection
Thermistor 1	B	Reference Leg Bridge	2	Output Bridge 1
	C	Power Supply Ground	3	Thermistor
Thermistor 2	D	Reference Leg Bridge	4	Output Bridge 2
	E	Power Supply Ground	5	Thermistor
Thermistor 3	F	Reference Leg Bridge	6	Output Bridge 3
	H	Power Supply Ground	7	Thermistor
Thermistor 4	J	Reference Leg Bridge	8	Output Bridge 4
	K	Power Supply Ground	9	Thermistor
Thermistor 5	L	Reference Leg Bridge	10	Output Bridge 5
	M	Power Supply Ground	11	Thermistor
Thermistor 6	N	Reference Leg Bridge	12	Output Bridge 6
	P	Power Supply Ground	13	Thermistor
Thermistor 7	R	Reference Leg Bridge	14	Output Bridge 7
	S	Power Supply Ground	15	Thermistor
Thermistor 8	T	Reference Leg Bridge	16	Output Bridge 8
	U	Power Supply Ground	17	Thermistor
Thermistor 9	V	Reference Leg Bridge	18	Output Bridge 9
	W	Ground	19	Thermistor
Monitor	X	Power Supply Ground	20	Power Supply Monitor
	Y	No Connection	21	No Connection
Power	Z	Power Supply Ground	22	Power Supply +

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TABLE V(b)

Thermistor Board Terminations

Thermistor Board #8

	A	No Connection	1	No Connection
Thermistor 1	B	Output Bridge 1	2	Reference Leg Bridge
	C	Power Supply Ground	3	Thermistor
Thermistor 2	D	Output Bridge 2	4	Reference Leg Bridge
	E	Power Supply Ground	5	Thermistor
Thermistor 3	F	Output Bridge 3	6	Reference Leg Bridge
	H	Power Suppply Ground	7	Thermistor
Thermistor 4	J	Output Bridge 4	8	Reference Leg Bridge
	K	Power Supply Ground	9	Thermistor
Thermistor 5	L	Output Bridge 5	10	Reference Leg Bridge
	M	Power Supply Ground	11	Thermistor
Thermistor 6	N	Output Bridge 6	12	Reference Leg Bridge
	P	Power Supply Ground	13	Thermistor
Thermistor 7	R	Output Bridge 7	14	Reference Leg Bridge
	S	Power Supply Ground	15	Thermistor
Thermistor 8	T	Output Bridge 8	16	Reference Leg Bridge
	U	Power Supply Ground	17	Thermistor
Thermistor 9	V	Output Bridge 9	18	Reference Leg Bridge
	W	Ground	19	Thermistor
Monitor	X	Power Supply Ground	20	Power Supply Monitor
	Y	No Connection	21	No Connection
Power	Z	Power Supply Ground	22	Power Supply −

through changes in impedance. A chemically treated styrene copolymer is processed into a plastic wafer. This nonconducting substrate is then integrated with an electrically conducting surface layer, and any changes in relative humidity cause its surface resistivity to vary.

The process of vapor absorption is slightly temperature dependent. Fortunately, the coefficient is approximately linear over a wide range of temperatures and relative humidities. For a given sensor resistance, it is necessary to add 0.2%/^{o}F (percent relative humidity per degree Farenheit) to the value indicated on the standard curve when the measurements are taken in temperatures above 77^{o}F; and for those measurements taken in temperatures below 77^{o}F, subtract 0.2%/^{o}F from the standard. The standard resistance versus relative humidity curve is given in Figure 8.

When designing the sensor into any circuitry, the following maximum ratings must be considered:

1. Only ac voltages of at least 20 Hz with zero dc component should be used (a sinusoidal waveform is preferred).
2. Maximum allowable current through the sensor is 1.0 mA.

Any dc component placed upon the sensor will generate polarization effects which shift the sensor calibration.

The sensor resistance undergoes a change of over four orders of magnitude as the relative humidity varies from zero to 100%. From an extremely high resistance of 40 MΩ to a low of 1.3 kΩ the relative humidity spanned is from 2% to 100%.

In order to make any meaningful measurement over the entire range, it is necessary to switch varying values of resistance into the reference leg of a bridge configuration. Since ac voltages must be applied

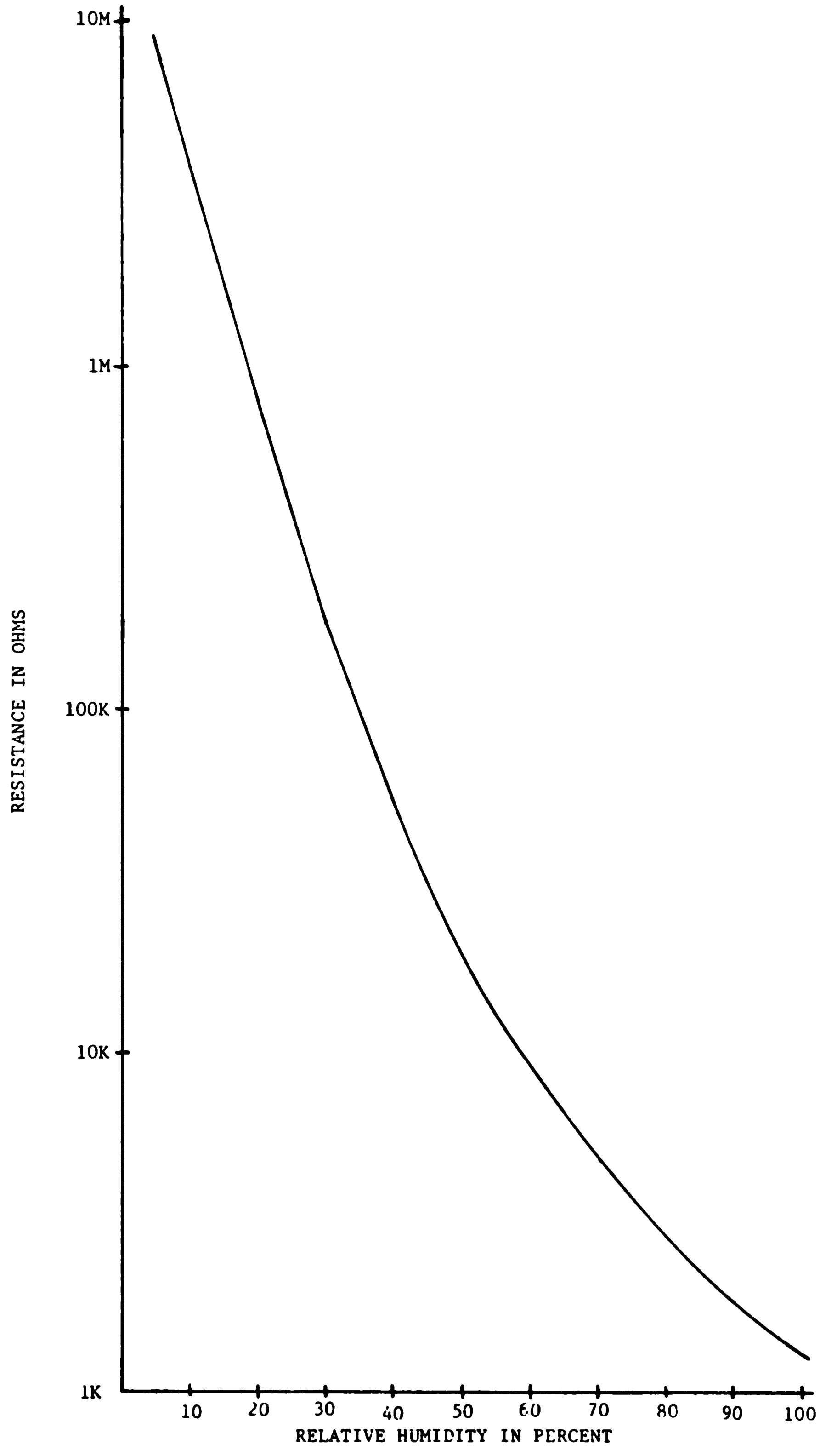

Figure 8. Plot of Sensor Resistance vs. Percent Relative Humidity for PCRC-11 Humidity Sensor

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to the sensor, a scheme for generating the required excitation was implemented. The ac signal magnitude varies as a function of the sensor resistance, but in order for the logger to accurately record the output of the bridge, the signal must be a slowly varying dc response. The requirement can be satisfied if the ac voltage is rectified and then low-pass filtered. If the reference signal is processed in exactly the same manner as the sensor signal, then a high degree of accuracy can be obtained. The difference between the two resulting dc signals then determines deviations from bridge balance. The output signal in conjunction with a window comparator determines if the proper range is realized. If the signal is within the comparator window, then its output disables the range control circuitry. When the signal strays from within the window, the comparator generates a signal which activates the control circuitry. The circuitry then searches until, as determined by the comparator, the proper range is found. The operation of the aggregate components is established in the block diagram of Figure 9.

Complementary Symmetry Metal Over Silicon (COS/MOS or CMOS) technology has created both analog and digital building blocks which operate over large temperature spans, with extremely low power dissipation, and which remain insensitive to power supply ripple and temperature changes. The circuits are able to operate from power sources ranging in value from a low of 3.0 volts to a high of +15.0 volts. COS/MOS digital circuits exhibit high noise immunity due in large part to their slower operating speeds and the low output impedance of the complementary gates. Different manufacturers have expanded their product lines of COS/MOS devices offering units with increased circuit

Humidity

Full Wave

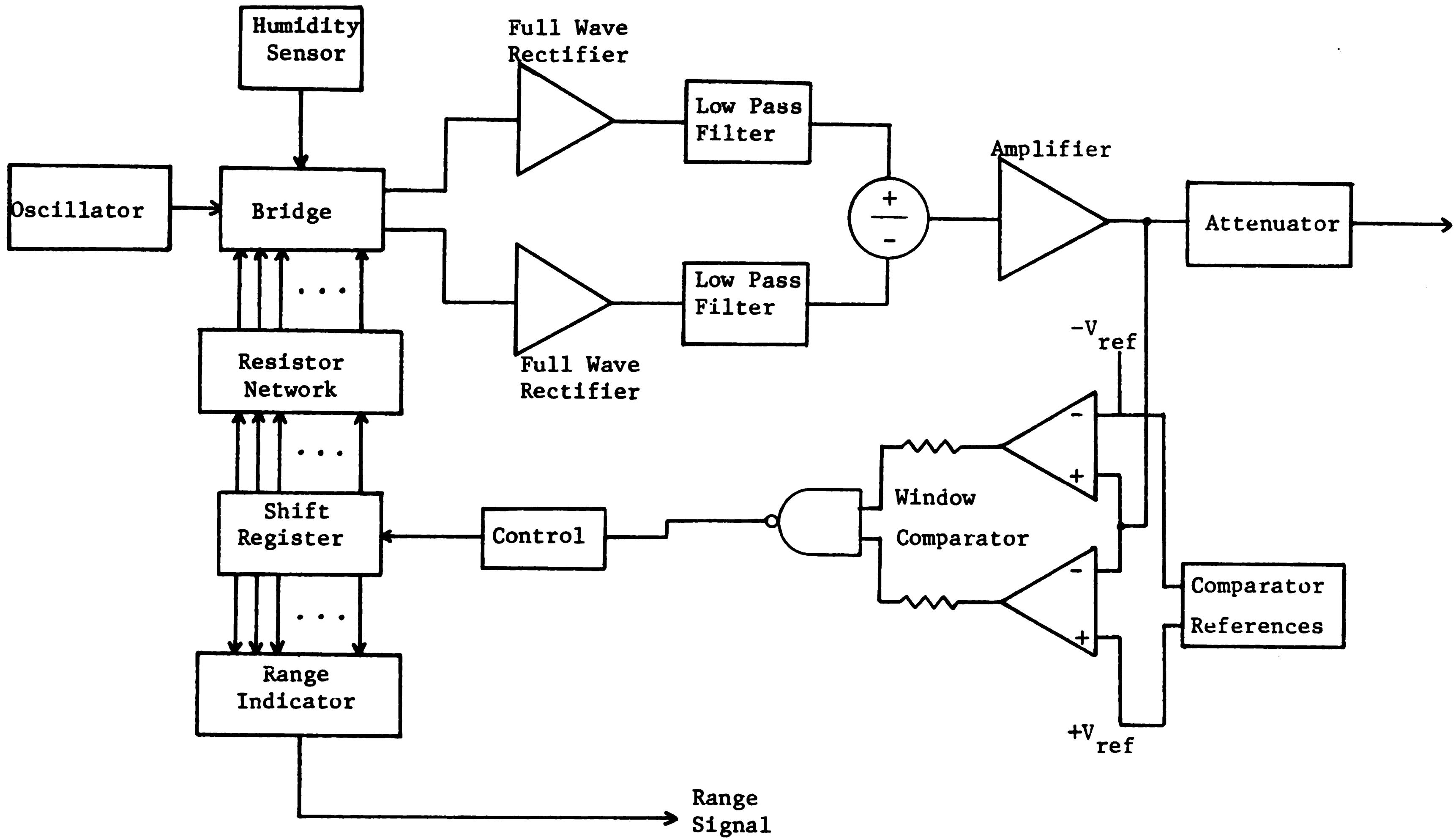

Figure 9. Block Diagram of Humidity Measurement Circuit

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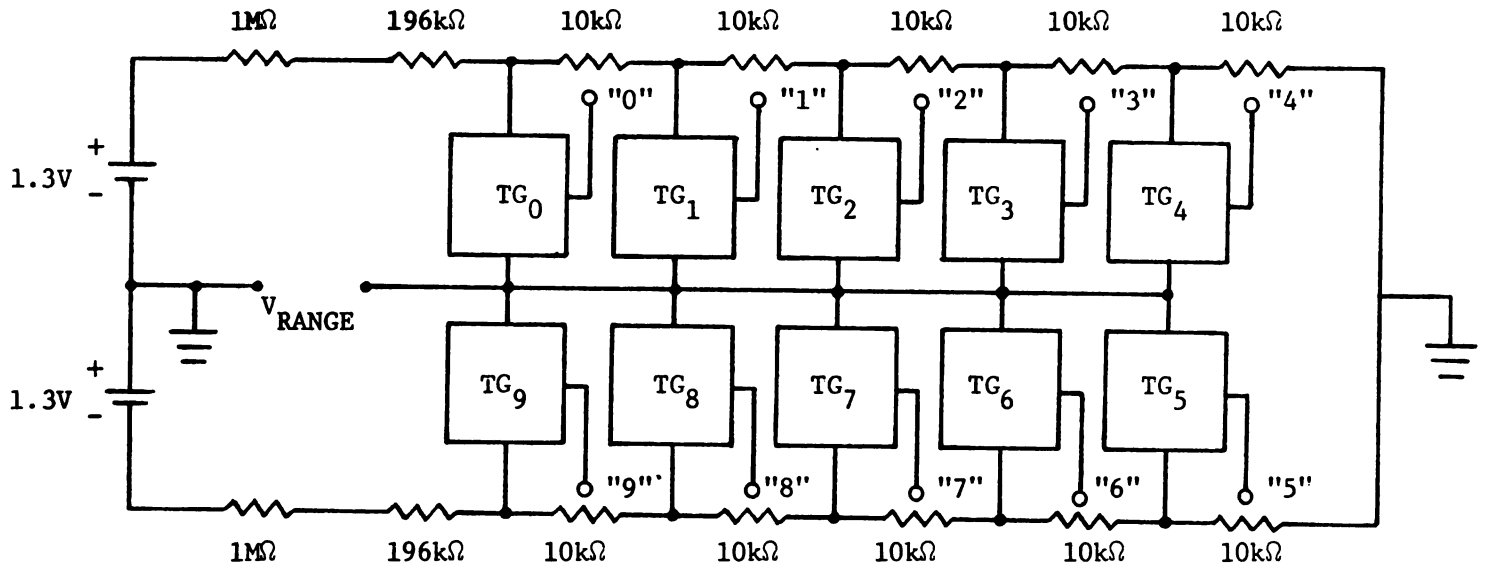
complexity. These various device types, their characteristics and typical application ideas, are completely documented in publications by RCA [6], Motorola [7], and Fairchild [8].

Having pointed out many of the practical features of COS/MOS IC's (integrated circuits), various devices have been incorporated into much of the humidity sensor signal conditioning electronics. For example, range indication is implemented using a resistor ladder network, COS/MOS CD4016 Quad Transmission Gate chips and a power supply. A schematic of the components' interrelationships is given in Figure 10. The control signals to the various gates are derived from a CD4017 Decade Counter/Divider. The counter, when driven by a clock signal, successively presents a "high" signal at the various output pins labeled 0-9. A "high" signal corresponds to the presence of the power supply value at the output. This "high" logic signal energizes the corresponding transmission gate which passes the ladder voltage to the output terminal. The ladder voltage ranges in value from -50 mV to +50 mV in steps of 10 mV. An output of -50 mV signifies that the "0" state of the shift register is high and a one-to-one correspondence is established up through state "9" when the output will be +50 mV.

The control signals which activate the range indicating transmission gates also affect corresponding gates which form part of the bridge which contains the humidity sensor. An oscillator energizes the bridge whose composition includes parallel combination of the sensor and a 500 kΩ resistor in one leg, a 1.1 kΩ resistor in series with a 200 kΩ resistor in each of two other legs, and a resistor-transmission gate network in the fourth and final leg as depicted in Figure 11. The same CD4017 Decade Counter/Divider that controls the gates in the range



TG - Transmission Gates

Figure 10. Detailed Circuit of Range Indicating Network

500kΩ

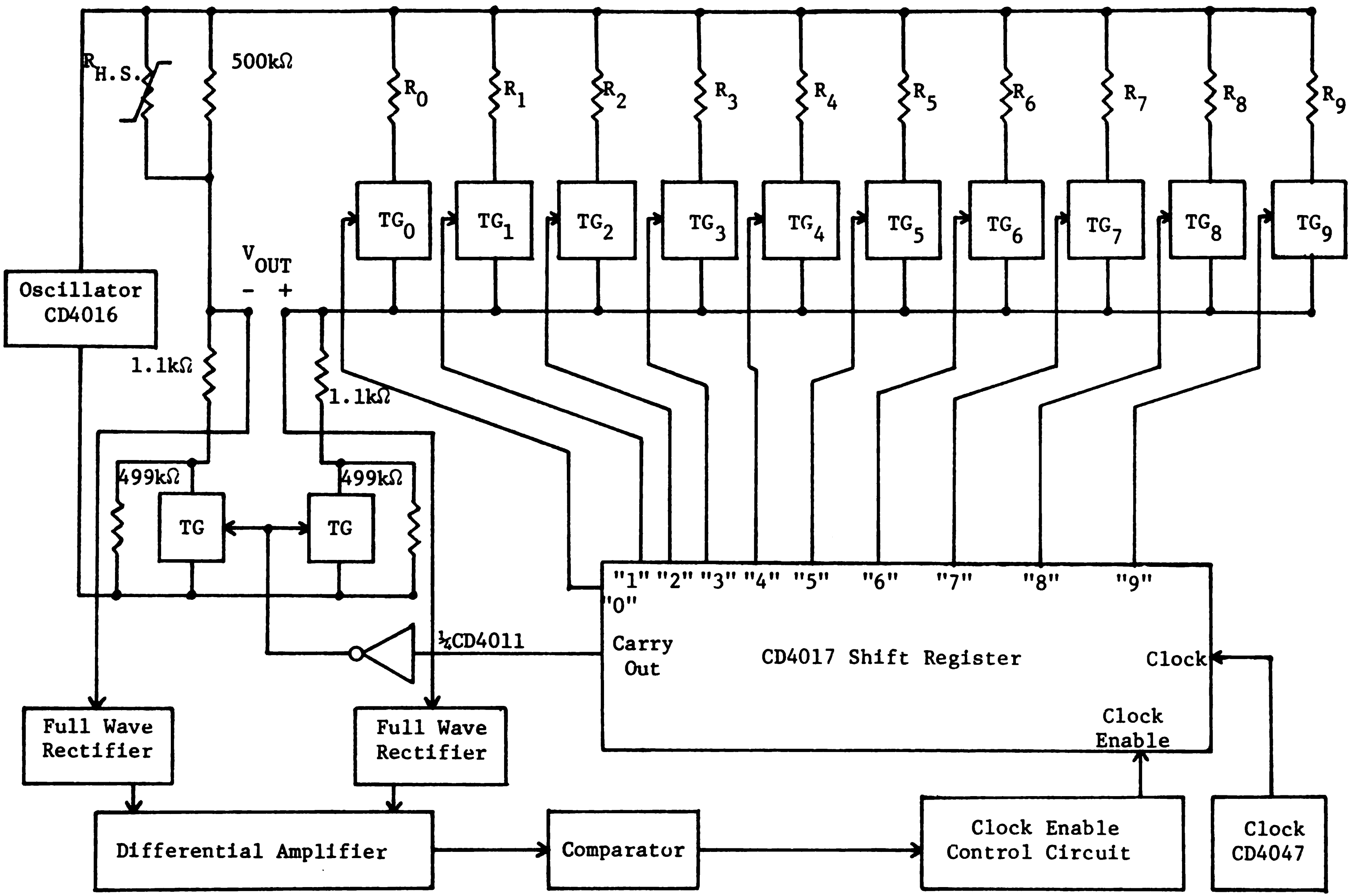


Figure 11. Details of Automatic Bridge

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indicator also controls the gates in the resistor-transmission gate network of the bridge. Transmission gates shunt the 200 KΩ resistors in the bottom legs of the bridge to increase the sensitivity of the bridge when the sensor and resistor network have low values of impedance. Then the transmission gates are "on", shorting the 200 kΩ resistors, which decreases the effective voltage between the bridge outputs and ground. These gates are controlled by the "carry out" pin of the CD4017, and when the lower-valued reference resistors are connected in the bridge, the carry out is "low". It is inverted and applied to the controls of the shunts, allowing them to short out the 200 kΩ resistors when the "carry out" is low.

The oscillator is comprised of a CMOS CD4047 Astable/Monostable Multivibrator operated in the astable mode; a CD4016 Quad Transmission Gate chip, which functions as a current switching device; and a CD4007 Dual Complementary Pair plus Invertor. The CD4007's main function is that of power-up control. When the glass epoxy board, on which the above active devices are mounted, has been inserted into the power socket, the batteries are connected to the devices. With initial connections, two rechargeable 6.25 900 mA-hour batteries are connected in series. The most negative potential connects to the $-V_{SS}$ terminations of the CMOS devices, while the most positive potential terminates upon $+V_{DD}$ pins of the CMOS. By referencing the CMOS outputs to the point of connection between the two batteries, symmetrical positive and negative going waveforms are generated. Initial power up procedure is hardware designed to minimize device failure due to improper application of signal sources. To avoid possible COS/MOS device destruction, it is imperative that all signal sources be disconnected from them before the power is removed from such circuitry. Similarly, the circuitry should be powered before applying any signals. For the above reasons, an oscillator hold off circuit was constructed which disables the oscillator until a capacitor reaches the switching point voltage value of a COS/MOS CD4007 invertor. When the invertor output goes low, the oscillator is enabled. The oscillator acts as the synchronizing element of all other COS/MOS circuitry. It functions as the clock input for the CD4017 decade counter/divider (derived from pin 13), and the outputs from pins 10 and 11 act as the gate controls for the CD4016 Quad Transmission gates. The outputs at pins 10 and 11 are guaranteed to have a 50% duty cycle, and the output at pin 10 is shifted 180^{o} from that at pin 11. The gates controlled by pin 10 are therefore on for 50% of the time, while the gates controlled by pin 11 are off; and for the other half of the period, when the gates connected to pin 10 are off, the gates connected to pin 11 are on.

The transmission gates form a switching network which alternately connects the positive potential and then the negative potential of a series combination of 1.5 V nickel-cadmium batteries. Via the above method, an alternating frequency signal of 500 Hz and zero dc component is derived to energize both the bridge network and the humidity-sensing transducer. The power supply as constructed upon one glass epoxy vector board is depicted in Figure 12.

The voltage which is developed across the network leg consisting of the parallel combination of the transmission gate and 200 KΩ resistor in series with the 1.1 kΩ resistor, is compared with the voltage developed across the similar network leg in the other branch of the bridge. Before comparison, each voltage is precision rectified and and low pass filtered, resulting in a pure dc signal.

Oscillator

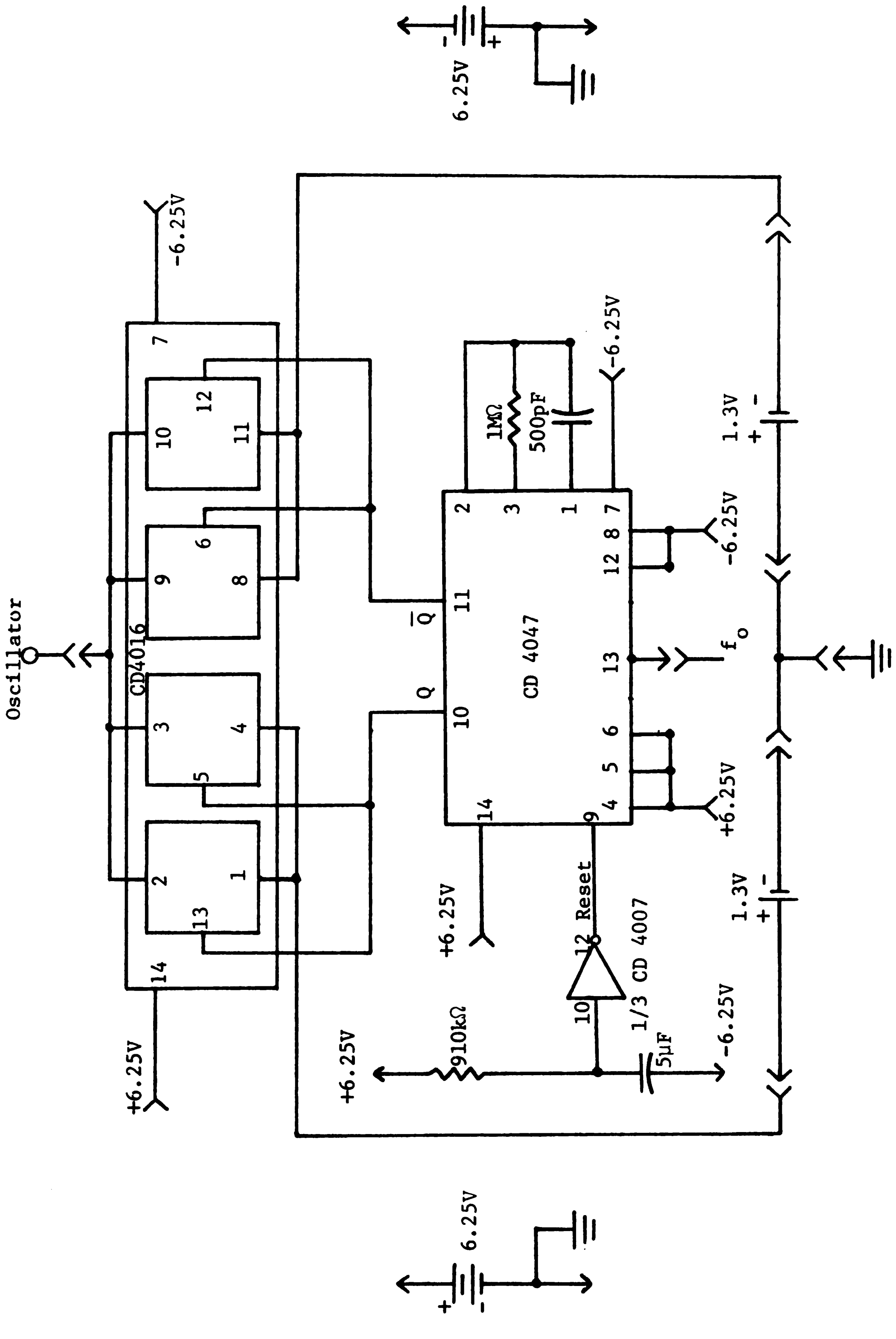


Figure 12. Oscillator and Power Supply

cis

cu

ini

op-

pos

Bec

iat

upo

inp

sig

pro

as

sum

ter

pos

at

sig

amp

Several techniques exist which use various devices to perform precise rectification [9], [10]. The configuration finalized in the circuit of Figure 13 is constructed using the following components:

- 2/3 Siliconex Micropower Triple Operational Amplifier Integrated Circuit (device type L144A),
- 2/6 RCA Ultra Fast Low Capacitance Matched Diode Array (type CA3039),
- 5 196 kΩ 1% Precision Resistors, and
- 2 .1 μF Ceramic Capacitors.

The circuit operation can be explained as follows. Making an initial assumption that the diodes are nonconducting implies that the op-amp [1] is operating in the open-loop mode. Any input at the positively-designated terminal of the op-amp is compared with ground. Because of the high open-loop gain, the amplified output causes immediate conduction of one of the diodes. Which diode conducts depends upon the polarity of the input signal with respect to ground. If the input signal is positive, diode (A) conducts and for a negative input signal, diode (B) conducts. Immediately upon conduction, the feedback provided by the diodes forces op-amp [1] into closed-loop operation.

In the case of conduction through diode (A), op-amp [1] operates as a voltage follower and the output mimics the input. Op-amp [2] sums the voltages at its inputs. The voltage applied at the negative terminal is amplified by a gain factor of -1, while the voltage at the positive terminal is amplified by a gain factor of +2. The net result at the output terminal is an exact replication of any positive input signal.

When diode (B) conducts, op-amp [1] operates as a non-inverting amplifier with a gain of 2. Op-amp [2] again operates as a summing

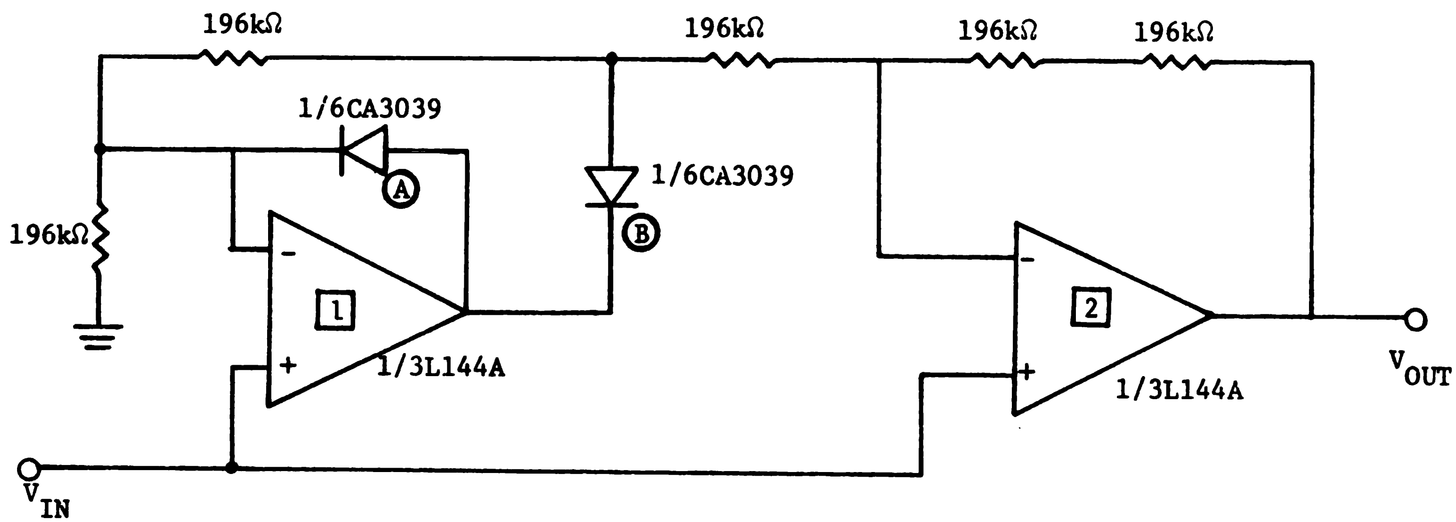
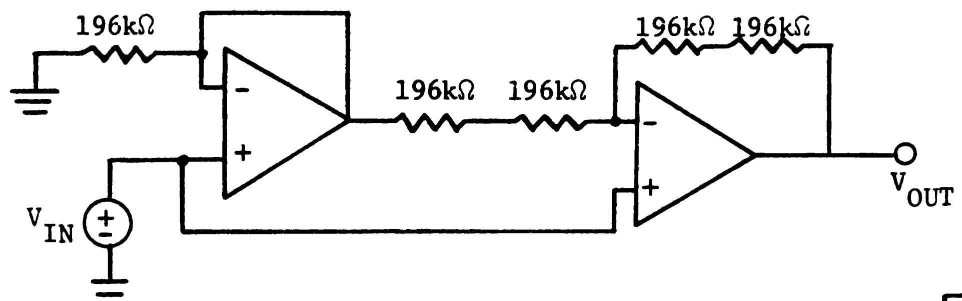


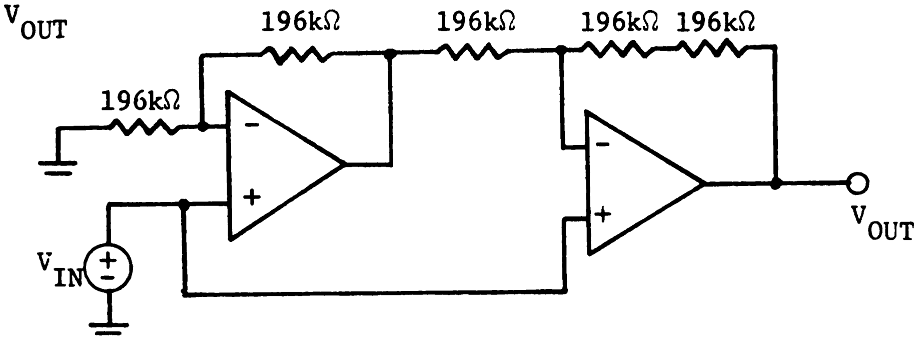
Figure 13. Precision Rectifier Circuit

amplifier. In this case, however, the signal at the negative terminal is amplified with a gain of -2 and that signal applied to the positive terminal is amplified by a gain of +3. Since the signal applied to the negative terminal of the summing amplifier has already been amplified by op-amp [1], the actual output due to just the signal at the negative terminal is $-4\ V_{IN}$, where V_{IN} is the input voltage to the precision rectifier. When added to the output due to the signal at the positive terminal alone (that is, $+3\ V_{IN}$), the net output is ($3\ V_{IN} + -4\ V_{IN} = -V_{IN}$). Recall that the input signal was negative with respect to ground, so that actual output result is positive. If the diagram of Figure 13 is decomposed into the two cases of positive and negative voltage inputs, as indicated in Figure 14(a) and 14(b), the analysis is easier to follow. Next, a further subdivision is performed by introducing the Thevenin equivalent voltage sources in Figure 14(c) for a positive signal and the Thevenin equivalents in Figure 14(d) for negative signals. Using superposition, the results indicated above are easily obtained.

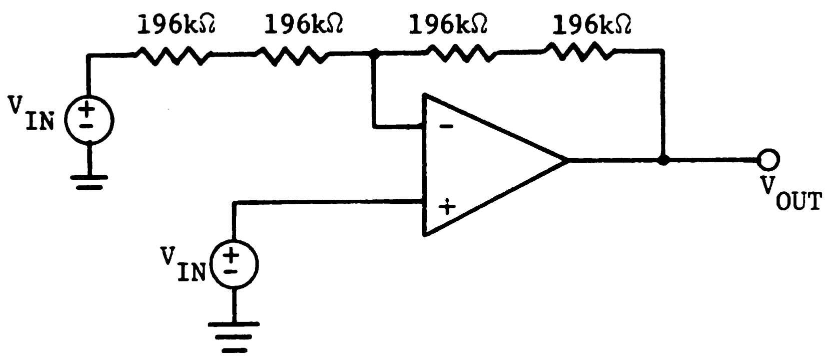
When a negative signal is applied, op-amp [1] is switched into a configuration in which the output voltage is double that of the input voltage. To prevent clipping of the output, it is important to restrict the input signal to magnitudes less than one-half of the clipping level voltage. The op-amps are powered by bipolar supplies of magnitude 6.25 volts, and since the bridge signal is derived from a bipolar supply of 1.3 volts, the rectifier operation is well within the bounds of the above constraint. Two identical networks were utilized in order to minimize signal shifts resulting from component value variations imparted by temperature changes. After rectification, the processed signals are amplified by a differential amplifier which incorporates



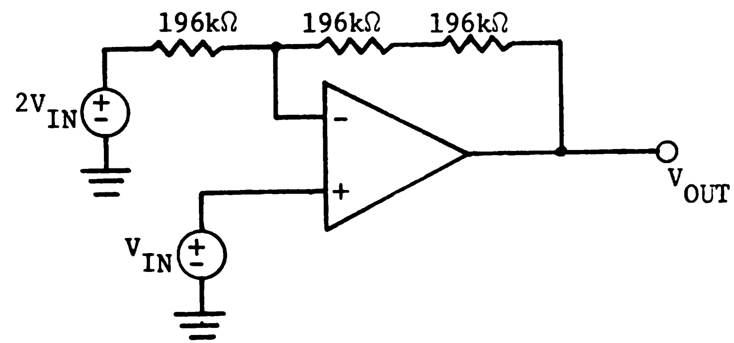
a.) Positive signal configuration



b.) Negative signal configuration



c.) Thevenin equivalents for positive signals



d.) Thevenin equivalents for negative signals

Figure 14. Operation of the Precision Rectifier

input filtering to remove the high-frequency hash generated during the rectification process.

The precision rectifier output obtained from the resistor-transmission gate network leg passes through a low-pass filter constructed of a 1 kΩ precision resistor and a 5 μF capacitor and the signal is then applied to the positive terminal of the differential amplifier. Similarly, the rectifier output obtained from the sensor leg of the bridge passes through a low-pass filter and is applied to the negative terminal of the differential amplifier. The gain of the differential amplifier has been adjusted to a value of 10 by appropriate choice of component value as depicted in Figure 15. The output of the differential amplifier provides the input to the window comparator. This input voltage is developed across a 20 kΩ potentiometer load, which serves the dual purpose of a voltage dividing attenuator and filter. The 20 kΩ load resistor is isolated by the voltage follower (1) in the window comparator circuit. The other two op-amps perform the comparator function. The low level reference applied to op-amp (2) sets its trip point and the high level reference sets the trip point for op-amp (3) . When an applied signal is within the comparator window as defined by the reference voltage, the outputs of op-amps (2) and (3) are both high. Since these outputs are directly connected to the inputs of one of the four two-input nand gates on the COS/MOS CD4011 IC, the output of the nand gate is low. The nand gate output is connected to the clock input of the CD4017 Counter/Divider and the clock signal is applied to the clock enable signal. By the stated change of connections, the counter/divider will only increment if the output of the comparator is "high;" that is, $+V_{DD}$. The nand gate

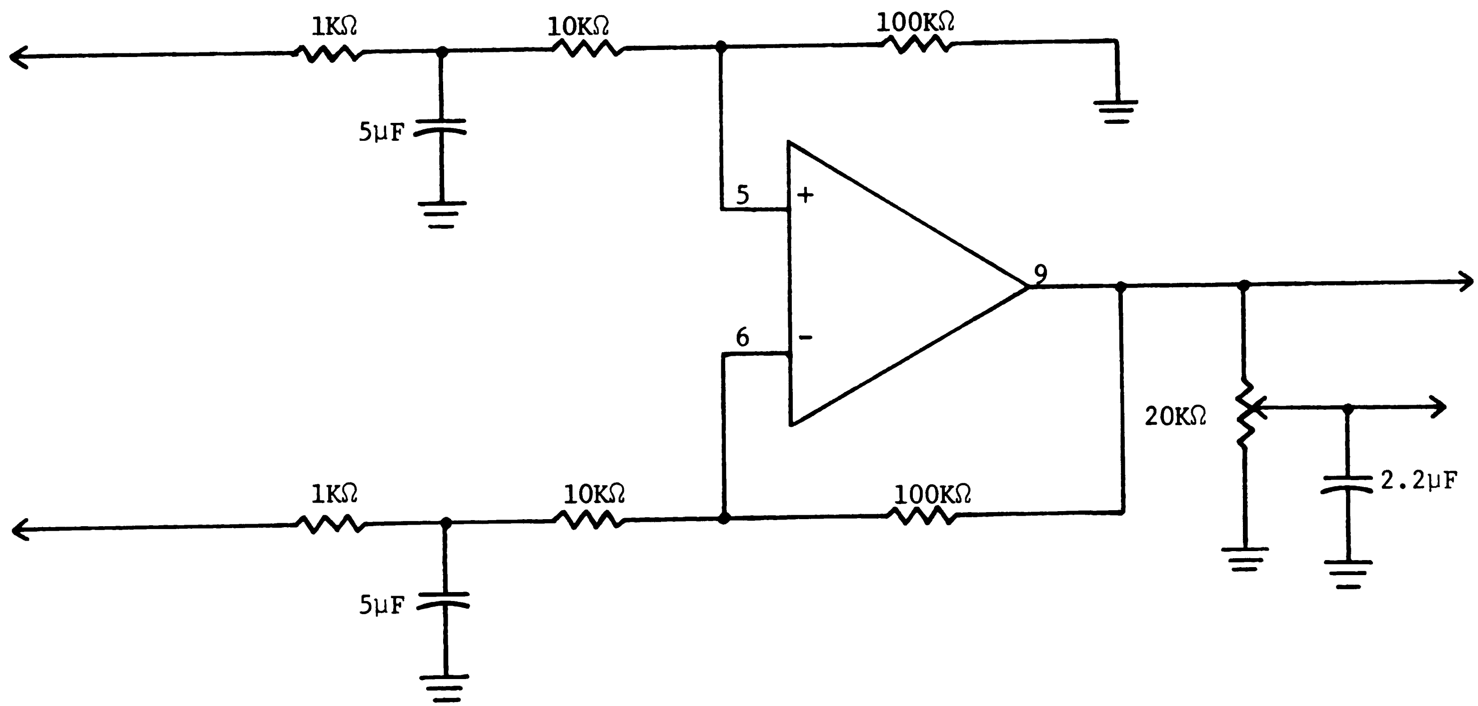
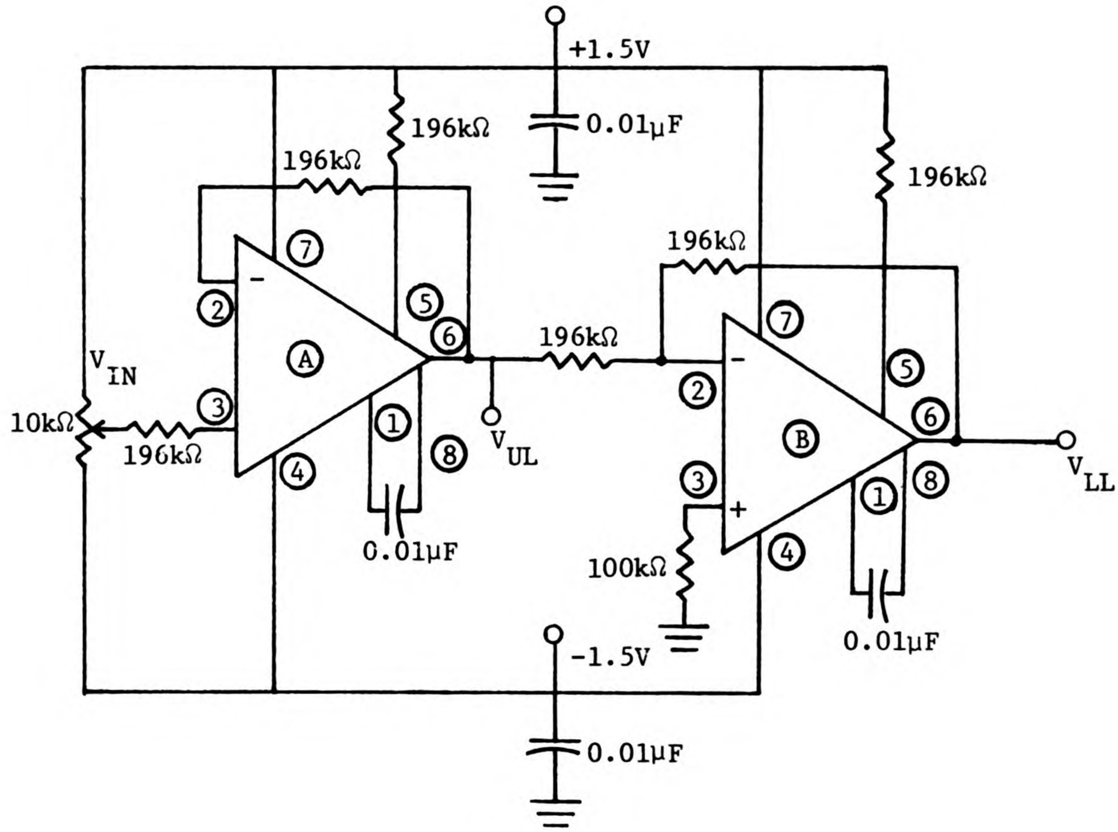


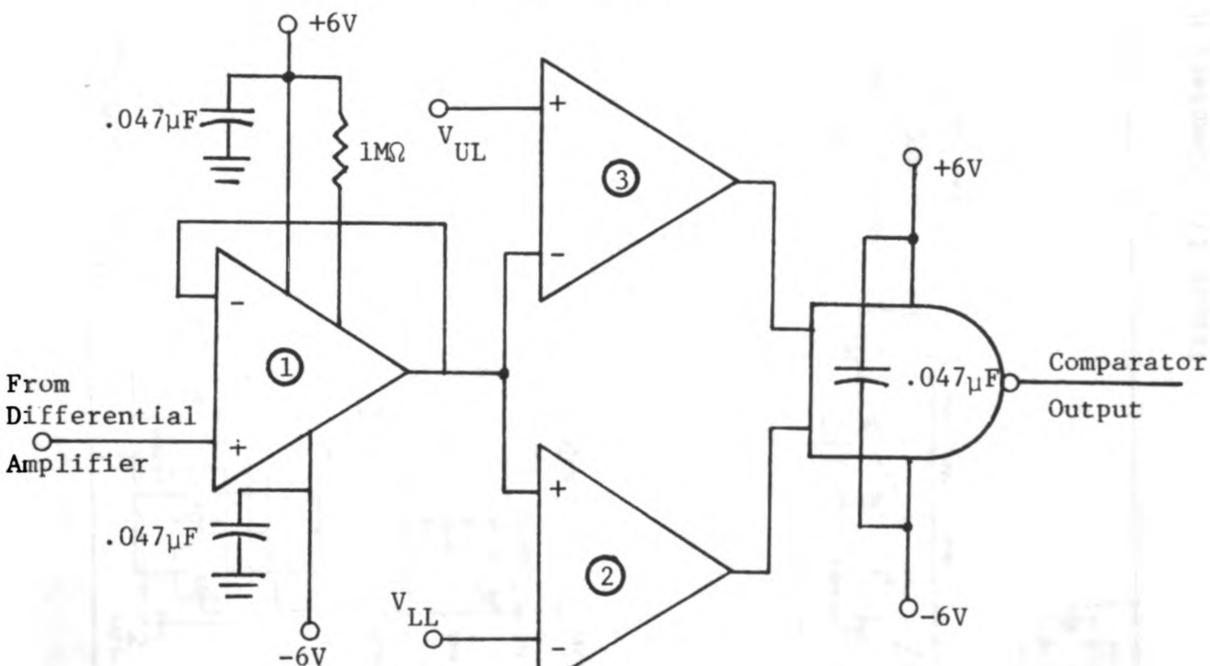
Figure 15. Differential amplifier and low pass filter network.

output goes "high" whenever the input signal leaves the window boundaries of the comparator. The comparator circuit was derived through slight modifications of a similar circuit described in application literature [11]. Both the upper and lower reference voltages are derived from circuitry which utilizes two RCA CA3078AT Micro Power Op-amps. The circuit diagram of Figure 16 lays out the component interconnections of the reference sources. The circled numbers in the diagram indicate the designations of the leads which protrude from TO-5 cans in which the IC's are packaged. The op-amp marked (A) is connected as a voltage follower. This amplifier takes the output from the potentiometer and isolates it from the rest of the circuitry. The follower output provides the upper level limit to the window comparator, and by cascading with an inverting op-amp, the lower level reference is generated. The above provides a positive reference and a negative reference of equal magnitude. By varying a single potentiometer, the reference voltages will track one another, allowing symmetrical variation of comparator window width.

The circuitry comprising the transmission gates, resistor networks, bridge components, precision rectifiers, and the difference amplifier is constructed upon a glass epoxy vector card. Because of the lack of any more useable space on the card, construction of a second card provided a foundation upon which to construct the voltage reference and window comparator circuitry. Since the power supplies energize other circuitry in addition to those which provide humidity indication, they were constructed upon a separate epoxy vector board. The entire circuit is depicted in Figure 17.



(a) Reference



(b) Window Comparator

Figure 16. Reference Sources and Window Comparator.

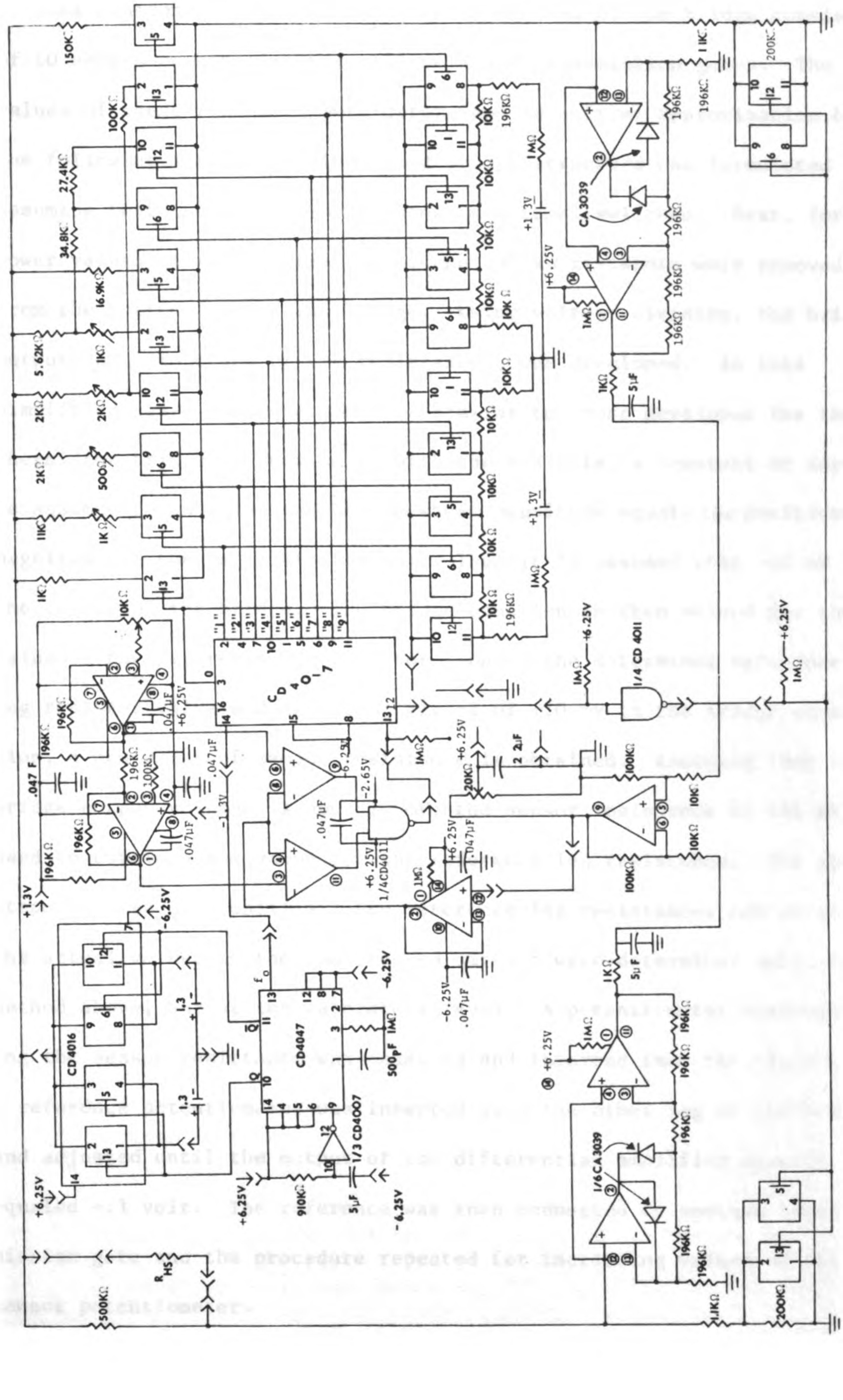


Figure 17. Complete Humidity Measurement Circuit

As mentioned previously, the reference leg of the bridge consists of 10 series combinations of resistors and transmission gates. The values of these resistors were determined to a first approximation by the following method. A simplified bridge structure was formulated assuming that the transmission gates were ideal switches. Next, for the lower values of sensor resistance, the 200 kΩ resistors were removed from the bottom legs of the bridge. Using voltage division, the bridge output, as a function of the resistances, was developed. In this simplified case, the equations are similar to those developed for the thermistor bridges. Continuing with the analysis, a constant dc supply is assumed to energize the bridge whose magnitude equals the positive magnitude of the oscillator signal. Then it is assumed that -10 mV is the output of the bridge. The bridge equation is then solved for the value of the reference leg resistor. Using the determined reference leg resistor value and an output signal of +10 mV in the bridge equation, a new value of sensor resistance is obtained. Assuming that the bridge output voltage is now -10 mV, the sensor resistance at +10 mV is used to obtain a new value for the reference leg resistance. The above steps are repeated until all ten reference leg resistances are obtained. The actual values in the constructed circuit were determined using the method above, but at the laboratory level. A potentiometer representing the sensor resistance was measured and inserted into the circuit. A reference potentiometer was inserted into the other leg of the bridge and adjusted until the output of the differential amplifier exactly equaled -.1 volt. The reference was then connected to another transmission gate and the procedure repeated for increasing values of the sensor potentiometer.

With the determination of the reference leg resistance values, the humidity sensing circuitry design is completed. The reader will find measured data concerning its operation in Chapter IV. This section concludes the development of signal sources which are inputted to the logger. The following section examines the characteristics of the logger itself.

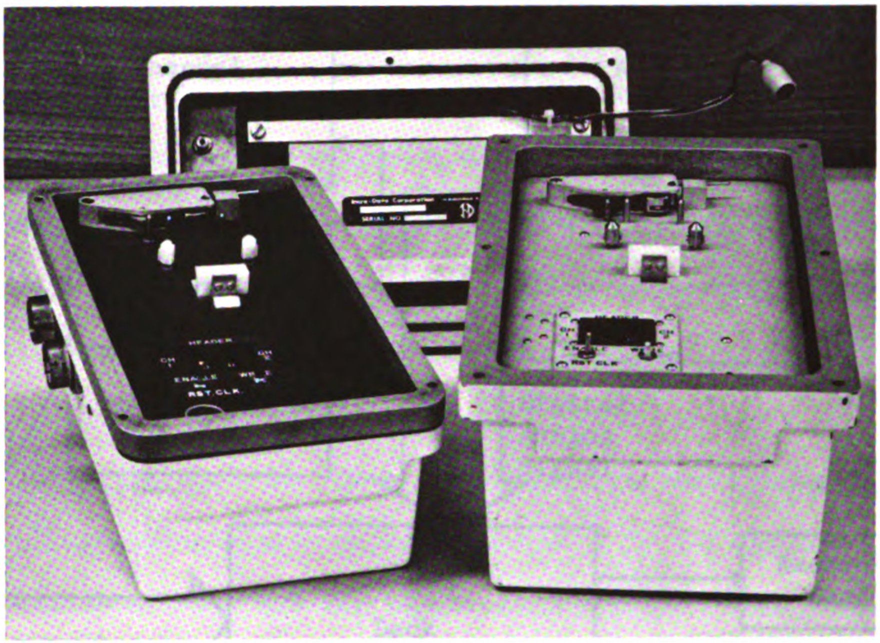
3.3 The Data Logger

Another important component of any data logging system is the recording unit. The recorder preserves the data. A modular unit (Incre-Logger; see Figure 18) establishes the intermediate function of data record storage and a magnetic tape provides a convenient medium for data storage. Compactness, ruggedness, self-contained power capability, and large capacity recording are all important characteristics possessed by the recording unit.

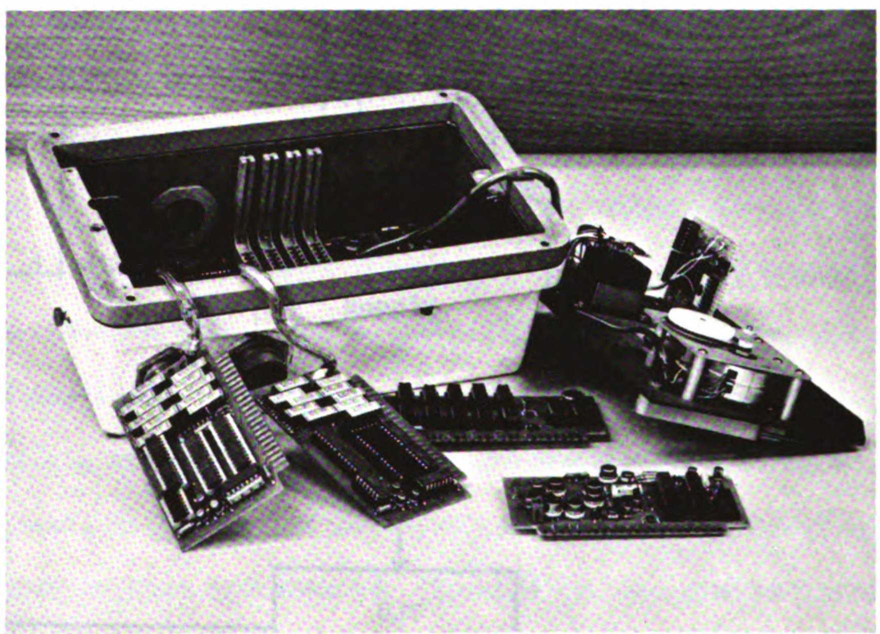
Taking the block diagram approach, as indicated in Figure 19, the recorder can be described through a breakdown into nine subsystem functions. Basic structural components consist of:

(1) Clock. The clock generates a continuous stream of voltage pulses. The pulses, being equally spaced in time, supply an accurate time reference. When appropriately counted, these time pulses provide longer interval periods.

(2) Counter/Divider. The counter/divider processes the clock pulses and provides an interval indicator. It determines the time interval which must elapse before the next period of data acquisition initiates. Also, it stores the elapsed number of hours and days since the circuitry was last reset.



Exterior



Interior

Figure 18. Exterior and Interior View of Incre-Logger

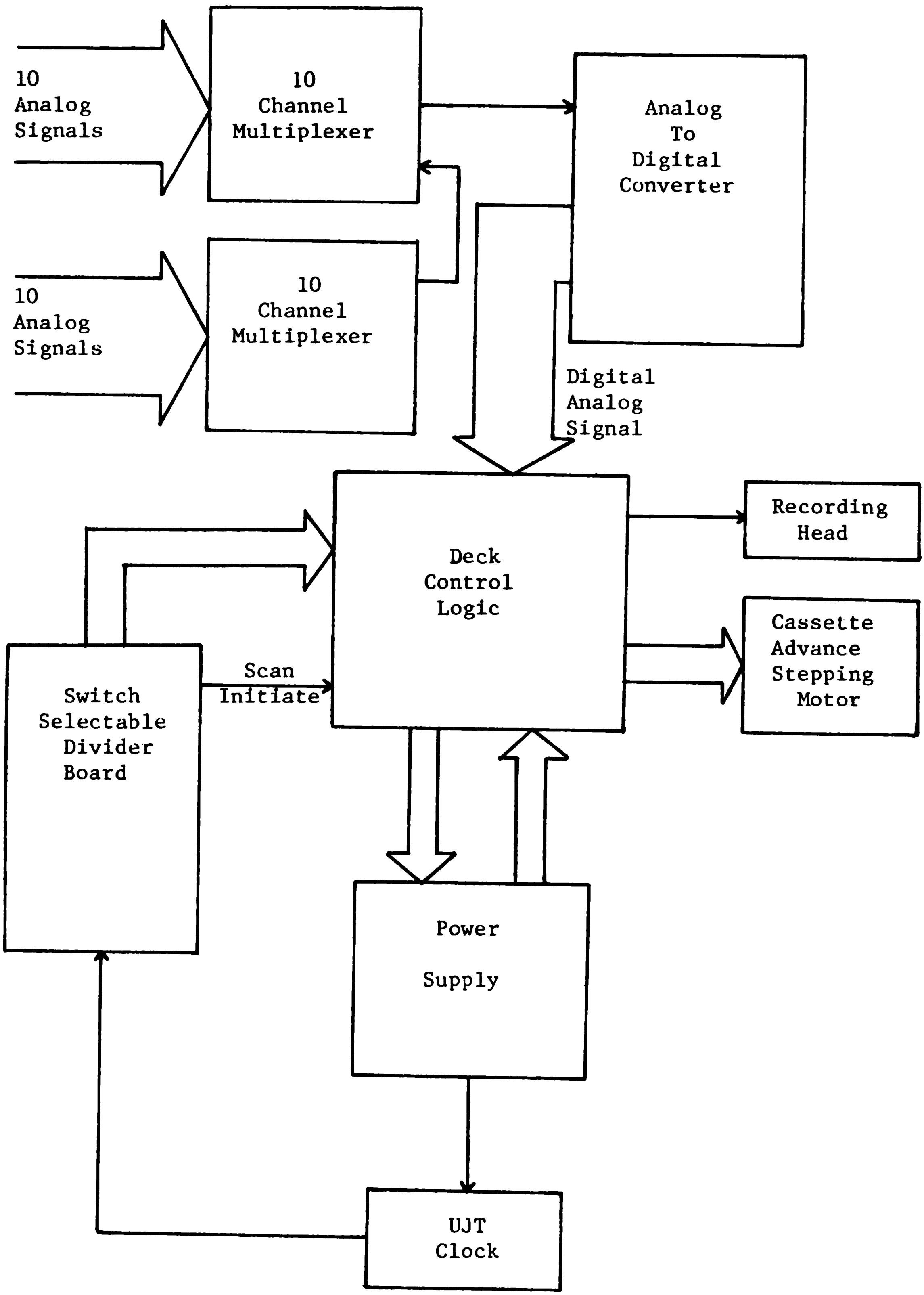


Figure 19. Block Diagram of Incre-Logger

(3) Deck Logic/Power Supply. This circuitry provides both power and control to the various subassemblies. Serial phase-encoded digital signals generated by the deck logic integrate with cassette motion to implement data storage.

(4) Multiplexer. The analog multiplexer sequentially selects each data channel and presents it as input to the A/D converter. Provision of a skip channel feature enables selected omission of specific data channels.

(5) A/D Converter. The converter transforms analog signals into corresponding binary representations. It implements the conversion process via the single-ramp circuit configuration.

(6) Cassette Transport. The transport consists of a logic controlled stepping motor which energizes a set of gears and pulleys moving the capstan and tape take-up reel.

Random transistor transistor logic (TTL) performs all logic functions necessary to the operation of the recording unit. Those circuits which remain energized continuously are implemented using low-power logic chips. Through the use of complementary unijunction transistor and various low-power TTL logic integrated circuits, development of a one pulse per second signal is realized. This signal is transferred to the counter/divider board where it inputs to a user-definable counting and dividing network. Every hour a four-bit binary counter is incremented and, at the end of twenty-four hours, another four-bit binary counter is also incremented. In this manner, elapsed time is indicated. Concurrent with the counting, a switch selects a particular divider output, routing it to a one-shot multivibrator. The resulting signal closes a relay providing the trigger for the sequence of events, resulting in data storage.

At the closure of the relay, the base of a power transistor receives current; immediately upon saturation, activation of the remaining circuitry ensues. The following chart enumerates the user available trigger intervals.

Switch Position	Time Interval
1	1 Sec.
2	5 Sec.
3	15 Sec.
4	30 Sec.
5	60 Sec.
6	5 Min.
7	10 Min.
8	15 Min.
9	30 Min.
10	1 Hr.

The main current board contains the power supply turn-on control, an inverter, voltage regulating elements, and function synchronizing logic.

A power transistor acts as a switch, turning the power both on and off. Since many of the analog operations are performed by operational amplifiers, they operate most efficiently when powered from a bipolar supply of 15 volts, an inverter converts the unipolar 6-volt battery supply to the higher bipolar voltage. A precision bipolar voltage regulating network ensures stability of the op-amp's power supply. The synchronizing logic, at turn-on, initiates itself, and the associated data conversion functions. During conversion, the logic ensures proper operation and timing of the various processes culminating in a correctly encoded data word. Integrating the cassette drive mechanism with the encoded data, the logic stores the information semi-permanently on magnetic tape. A turn-off pulse from the logic initiates shutdown of all circuitry exclusive of the clock, timing and counting.

The analog multiplexer sequentially directs each analog data channel to the analog-to-digital converter (ADC) inputs. The deck logic generates an analog multiplexer enable signal, activating the multiplexer clock. The clock inputs to a four-bit binary counter, whose outputs drive a BCD-to-Decimal decoder. The decoded signals energize relays which connect each data channel successively to the ADC. A last channel signal attains a high state indicating termination of the multiplexer board function and relinquishing control of the deck logic.

The ADC in the recorder uses the single ramp-type conversion technique. In the conversion process, first an analog voltage signal inputs to a comparator and the converter digital-outputs reset to zero. Secondly, a voltage ramp is generated providing a linear time increasing reference for the comparator. As the ramp increases, clock impulses input to a binary counter. When the ramp equals the analog input voltage, the comparator changes state disabling the clock and preventing further increase of the counter outputs. The counter outputs digitally representing the input analog signal. For a large magnitude of analog input, a correspondingly large binary number output realization results. The slope of the voltage ramp, the clock frequency, and the maximum count capability of the counter all play a role in determining the maximum input voltage able to be accurately converted. The model currently used can convert voltages within the range -51 mV to +51 mV. (Voltages less than -51 mV cause the converter to record zero input; voltages in excess of +51 mV cause the converter to record the maximum input of 377 octal equivalent.) Bipolar inputs become realizable if the input to the converter is offset by +51 mV. Thus, the converter actually converts zero volts when the input is -51 mV and 100 mV when the input is +51 mV. After conversion, the binary number is bussed to the deck logic. The logic processes the digital signal, eventually storing it on the cassette. A new signal transmits from the multiplexer and the ADC resets so that the process may be repeated.

The cassette transport mechanism implements tape motion. To ensure proper storage of the data, a stepping motor provides tape motion in small precise increments. Pulses received by the stepping motor synchronize with the data in order that data recording and tape motion become concurrent events.

Several manual controls provide the user with convenience features which assist one during operation of the equipment. A list of the features follows:

Manual Control	Function
Header Thumbwheel Switches (Set of two; Channel One and Channel Two)	The Header Thumbwheel Switches allow input of data by the user to label/date the set of data to be taken. The data format consists of four bits of BCD for each channel. Both channels are recorded as one 8-bit word when this feature is used.
Enable/Reset Switch	A return to the center switch which, when held in the enable position, allows the header data to be recorded when the write pushbutton is activated. When momentarily depressed to the reset position, the counter and clock circuits are all returned to the initial state.
Write Pushbutton	The Write Pushbutton initiates a scan of all data channels, recording them on the cassette whenever it is activated. When the Enable/Reset Switch is in the enable mode, this switch, when activated, causes the header data to be recorded.

In order to facilitate future cataloguing of logged data, cassettes which are retrieved from experimental sites should be marked with identifiers indicating test site location and the beginning date of the recording. The header data feature of the "Incre-Logger" can be used to identify recorded data. The 4-bit binary coded decimal (BCD) words can be used to convey information directly when interpreted as computer display code. As an example: Set the header data thumbwheel switches to "00" indication. Hold the "Enable/Reset Switch" in the header enable position. Energize the "Write Pushbutton." Repeating the above procedure for the header message "TEST TAPE," the code relationships which result are shown in Table VI. The string of five "00"'s before and after the Header words act as delimiters. The appendix provides charts for cross-referencing the CDC display code with that of the header words.

A specialized metal (aluminum) casting houses the entire electronics and mechanics of the recorder, completely encapsulating the unit. The casting consists of two parts: the top of the unit holds the rechargeable battery supply and the bottom is the recorder itself. An O-ring seal has been imbedded in the cover to ensure an airtight closure of the casting. A purge valve and vent screw allow dry nitrogen to be injected into the unit in order that damaging condensation may be prevented. Blueprints of the logger circuitry and operating notes are provided in the appendices.

3.4 The Reader System

As described previously, the recorder encodes the data and semipermanently stores that data on a cassette tape. To be useful, the data must be retrieved from the tape and in some manner processed such

TABLE VI

Header Data Display Example

Header Word	Octal	CDC Display Code
00	000	:
00	000	:
00	000	:
00	000	:
00	000	:
55	125	blank
24	044	T
05	005	E
23	043	S
24	044	T
55	125	blank
24	044	T
01	001	A
20	040	P
05	005	E
55	125	blank
00	000	:
00	000	:
00	000	:
00	000	:
00	000	:

that any useful information can be meaningfully presented to the researcher. The recorder itself stores extensive quantities of data; as such, any method of data retrieval employing a large amount of human interaction quickly becomes exhausting. The tape reader system then must perform the following functions to economically retrieve and process data: (1) accurately decode the data stored upon the cassette, (2) transfer the decoded data to a more permanent data storage medium, (3) operate quickly upon large quantities of information, (4) provide a method of data cataloguing and referencing while implementing ease of data retrieval, and (5) supply the user with easy-to-use data manipulation algorithms (Statistical Analysis programs and plotting programs).

The heart of the reader system is the instrument which reads and decodes data from the cassette magnetic tape. The "Incre-Data" Corporation Model 1550 cassette reader transcribes, decodes and provides computer compatible outputs of data recorded by "Incre-Data" Corporation data loggers. The photograph in Figure 20 shows a front panel view of the reader. Most of the control functions are positioned on the right hand side of the faceplate, and data display options are situated on the left side. Cassettes, which are to be read, are placed with the cutout centered in the middle of the reader faceplate.

The control mechanisms and indicators located on the right-hand side of the reader faceplate are identified as follows: Starting at the top of the right-hand side, there exists a rotary switch allowing the operator to determine transport "MODE" control of the tape movement. The four functions available allow the operator to: (1) "REWIND" the cassette; (2) read and transmit data from the cassette

Figure 20. Photograph of Cassette Reader

tape as it travels at a continuous speed of 12 inches per second across the playback head, when in the "CONTINUOUS" position; (3) read at a more relaxed rate of 3 inches per second (this speed allows the machine time to generate control signals allowing precise tape positioning) when placed in "INCREMENT" position; and (4) set the switch to "BACK ONE SCAN," allowing the tape to be reversed and run backward at a speed of 3 inches per second. (NOTE: Data is not read in this mode.) Directly underneath the transport "MODE" control lies a microswitch button labeled "EJECT". This switch will eject a loaded cassette from the reader provided the "MODE" switch is not in the "REWIND" position and the "LOAD" switch is deactivated. The four multi-colored lights indicate to the operator various reader operating conditions. The read indicator signifies that the power switch immediately to its left has been activated. The green light at the top of the column of indicators notifies the operator that the cassette has been inserted properly into the transport mechanism. The amber light directly below the green indicates whether the tape is either at its beginning point prepared to be processed, or that the end of the cassette tape has been encountered. When the tape is in motion, data transmission is signalled by the flickering of the blue indicator. The four rectangular pushbuttons light up when activated. The uppermost button labeled "LOAD" engages the playback head and pinch roller when the tape control is in any mode but "REWIND". The "LOCAL" button must be energized to properly perform any control functions from the front panel. When deactivated, the reader can be controlled remotely via back panel cable sockets. When the "ENABLE OUTPUT" switch is activated, data which is read transmits to an output jack mounted on the back panel of the reader. Tape motion commences or terminates when the "RUN" switch is momentarily activated. When the tape is in motion, the switch light is on. Both speed and direction of the tape is determined by the "MODE" switch position, independent of the "RUN" control. When the "MODE" switch is in the "REWIND" position, activation of the "RUN" pushbutton has no effect.

The display options on the left-hand side of the reader facilitate manual data recovery. Since large amounts of data are recovered, the manual recovery can be a tedious chore. The display options do prove useful when checking for data integrity or searching for particular data. Use of these controls is described in the appendix under reader operating instructions.

Once the data has been read from the tape, some scheme of transferring the data to computer storage must be worked out. The present system employes a Texas Instruments "Silent 700" Data Terminal (see

Figure 21. Photograph of Data Terminal and Cassette Reader

Figure 21) equipped with an acoustic coupler. At the time of the reader purchase, the necessary interface hardware was installed in the Model 1550. The interface electronics assist in the data transfer and permits computer control of the reader functions. In the transfer process, a thermally written hard copy is produced by the T.I. "Silent 700" terminal as data is simultaneously transferred via the acoustic coupler to the computer memory. An example of typical hard copy is given in Figure 22, where the data is delineated as three-bit octal words. The format for this data will be explained in the next section. With the completion of the data transfer, the operator may optionally select to resume control or terminate the computer link-up. If he opts to resume control, the data terminal keyboard facilitates the transmission of operator instructions. The data terminal also allows

```
000
000
000
000
040
010
011
031
125
011
031
125
001
125
040
005
031
040
125
040
001
026
005
125
000
000
000
000
000
000000377000000013031050066105123141157214233251267306324342360377377
000000377000000014032050066105123141160215233251267306324343361377377
000000377000000013032050066105123142160215233251267306324343361377377
000000377000000014032050067105123142160215233251270306324343361377377
000000377000000014032050067105123142160215233251270306324343361377377
000000377000000014032050066105123142160215233251270306324343361377377
000000377000000014032050066105123142160215233251267306324343361377377
000000377000000014032050066105123142160215233251270306324343360377377
000000377000000014032050066105123141160215233251270306324343360377377
000000377000000013032050066105123141157215233251267306324343360377377
000000377000000014032050066105123141160215233251267306324343360377377
000000377000000014032050066105123142160215233251270306324343360377377
000000377000000014032050066105123142160215233251267307324343360377377
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000000377000000014032050066105123142160215233251270306324343360377377
000000377000000014032050066105123142160215233251267306324343361377377
000000377000000013032050066105123142160215233251270306324343360377377
000000377000000013032050066105123142160215233251270306324343361377377
```

Figure 22. Typical Data Terminal Printout

on-line construction of programs by the operator. This feature allows the operator to construct special data processing algorithms which he applies to the previously stored information. In Section 3.5, some typical data processing algorithms are presented. In addition, the appendix to this paper includes detailed operating and maintenance instructions which apply to the aforementioned equipment.

3.5 Software Considerations

When developing data processing software, it is essential that programs be created in a manner which promote flexibility. The system must be capable of quickly responding to operative changes within the system. Any software developed must maintain the basic information flow designated by Figure 23. The system operator should be able to quickly and comfortably interface with the software package. It should provide a good description of the various manual controls and an outline of proper operating procedure. Provisions for automatically reading and processing the cassette header data, if made, would facilitate maintenance of data records. The records would include initial date and time of data collection, test site location and data channel designations.

Any researcher is severely handicapped if he lacks the knowledge to properly utilize analytic and scientific tools he may have access to. Such handicaps can be overcome by software which supplies the necessary information to the novice user. Mr. Richard K. Brandenburg, with the Michigan State University Mathematics and Science Teaching Center, has provided a simplified program "INTRO" which instructs persons in the use of the Model 1550 Cassette Reader. A listing of

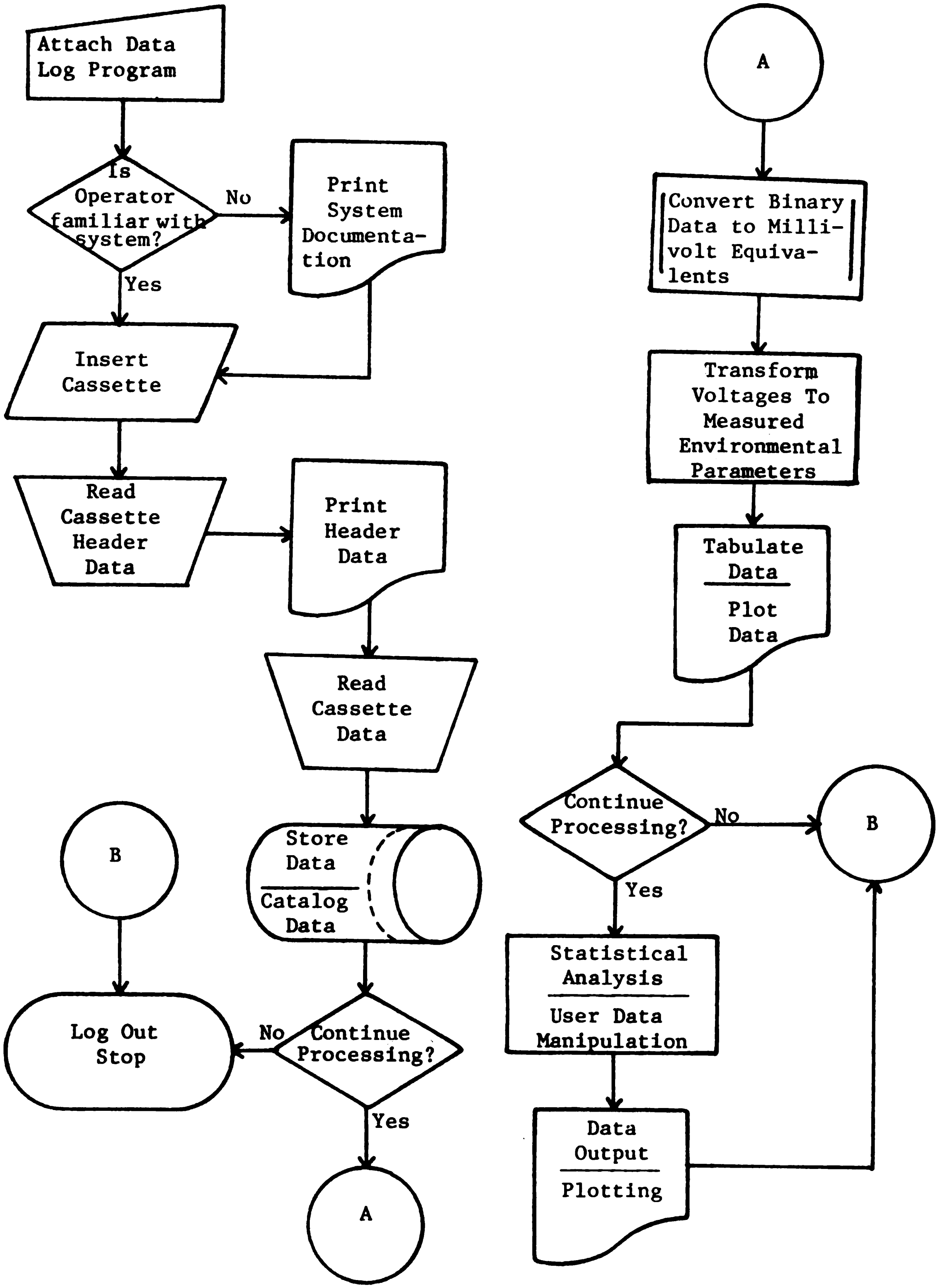

Figure 23. Software Flowchart for Information Flow

this program and an example of its operation are provided in the tables on the following pages.

The experienced user is capable of dispensing with the introduction and proceeds directly to the data transfer process. The researcher identifies each data tape processed by means of the header data feature described in Section 3.3. A program which, utilizes the header data, incorporates look-up tables to convey information regarding test site location, specific measurement use, and data channel identification. A typical header string, such as that given in Table VII, can be decoded as follows:

The beginning string of 00's precedes all information. The first header data word, other than 00, conveys the month in which the data was recorded. The second and third header words give the day of the month and the year. Two more header words of 00 separate the data from the two header words which give the time when the recording started. Two more 00 delimiters follow and then two header words of 55 appear. The consecutive 55's indicate that the next set of header words represent the user's name in display code format. Another consecutive appearance of 55's signifies that the display code message has been completed. The display code is the same code which is used in the CDC 6500 computer for transmitting alphanumeric information. The display code delimiters are followed by two consecutive 00's. Next, two header words give both the table and entry numbers from which additional alphanumeric data is obtained. The format is repeated until a set of five consecutive 00's is encountered. This set of delimiters signifies that all header data has terminated and further data is then recorded by the various sensors.

TABLE VII

Header Data Example

Header Data String	Information Conveyed	Octal Equivalents
00	Beginning Delimiters	000
00		000
00		000
00		000
00		000
02	February	002
15	15th	025
76	1976	166
00	Delimiters	000
00		000
15	3:35 p.m.	025
35		065
00	Delimiters	000
00		000
55	Display Code Delimiters	125
55		125
02	B	002
17	O	027
25	U User Name in	045
03	C Display Code	003
10	H	020
05	E	005
22	R	042
55	Display Code Delimiters	125
55		125
00	Delimiters	000
00		000
01	Table 1	001
01	Entry 1	001
00	Delimiters	000
00		000
02	Table 2	002
01	Entry 1	001
00	Delimiters	000
00		000
03	Table 3	003
02	Entry 2	002
00	Ending Delimiters	000
00		000
00		000
00		000
00		000

The tables and entries, mentioned in the header data description, store alphanumeric data which might be too lengthy to place directly on the tape. Information concerning test site location can be stored in the first table. The second stores information to be appended to a data analysis. The computer needs to be informed concerning the type of data signal recorded on each channel. Another computer stored table lists the channel designations and the computer uses this table when implementing processing procedures. Table VIII gives examples of the tables described.

After the header data has been processed, the channel data is transformed from the octal representation stored within the computer into first, the voltage signal originally inputted into the A/D converter, and then into the parameter of interest. Those parameters are temperature, battery supply monitoring, relative humidity range and a relative humidity signal.

Several routines have been developed to facilitate data reduction. The packed BCD header data is transferred to the CDC6500 computer in a three-digit octal format. Program OCTLHDR converts the three-digit octal number into its corresponding header word. Program OMVC allows the user to convert the octal numbers representing the voltages processed by the A/D converter into those voltages. In addition, since the voltages themselves correspond to other physical parameters, the two programs TEMPLIN and HMDTY convert those voltages into their temperature and relative humidity equivalents. Listings of these subroutines are provided in the Appendix. The algorithms were created as subroutines in order that they easily interface with any input/output programs.

TABLE VIII

Examples of Computer-Stored Tables

Table A

Location

1. Collins Road Site
2. Water Quality Management Pond Number One
3. MSU Horticultural Gardens
4. Mr. Smith's Apple Orchard

Table B

Time Scan Interval

1.	1 Second	6.	1 Minute
2.	5 Seconds	7.	5 Minutes
3.	15 Seconds	8.	15 Minutes
4.	30 Seconds	9.	30 Minutes
5.	60 Seconds	10.	1 Hour

Table C

Channel Designations

Page 1

CH. 1	ST1	Surface Temperature 1
CH. 2	TS1	Temperature Soil 6" Depth
CH. 3	TS2	Temperature Soil 3" Depth
CH. 4	ST2	Surface Temperature 2
CH. 5	RHR	Relative Humidity Range
CH. 6	RHS	Relative Humidity Signal
CH. 7	BSM	Battery Supply Monitor
CH. 8	ST3	Surface Temperature 3
CH. 9	ST4	Surface Temperature 4
CH.10	ST5	Surface Temperature 5
CH.11	TS2	Temperature Soil 1" Depth
CH.12	ST6	Surface Temperature 6
CH.13	NU	Not Used
CH.14	NU	Not Used
CH.15	NU	Not Used
CH.16	NU	Not Used
CH.17	ST7	Surface Temperature 7
CH.18	ST8	Surface Temperature 8
CH.19	ST9	Surface Temperature 9
CH.20	ST10	Surface Temperature 10

Page 2

CH. 1	SM1	Soil Moisture 6" Depth
CH. 2	SM2	Soil Moisture 12" Depth
CH. 3	TS1	Temperature Soil 6" Depth
CH. 4	TS2	Temperature Soil 12" Depth
CH. 5	NU	Not Used
CH. 6	NU	Not Used
CH. 7	NU	Not Used
CH. 8	BSM	Battery Supply Monitor
CH. 9	ST1	Surface Temperature 1
CH.10	ST2	Surface Temperature 2
CH.11	SM3	Soil Moisture 1" Depth
CH.12	TS3	Temperature Soil 1" Depth
CH.13	ST3	Surface Temperature 3
CH.14	RHS	Relative Humidity Signal
CH.15	RHR	Relative Humidity Range
CH.16	NU	Not Used
CH.17	NU	Not Used
CH.18	ST4	Surface Temperature 4
CH.19	ST5	Surface Temperature 5
CH.20	ST6	Surface Temperature 6

CHAPTER IV

CIRCUIT RESPONSE AND TEST RESULTS

This section presents curves which depict the thermistor bridge output voltage as a function of temperature for both the ideal case and the measured response of the actual circuit. In addition, data which indicates the measured response of the humidity instrumentation is provided. The output response of the Incre-Logger, reader and output terminal is presented and evaluated.

4.1 Thermistor Circuit Response

The equation relating the thermistor bridge output voltage as a function of thermistor temperature was developed in Chapter III. Equation (22) expresses the relation, while at the same time incorporating the effects of various settings of the two potentiometers. Both α and β represent fractions of the potentiometer settings. Figure 24 depicts the output voltage variation as a function of α, β and thermistor temperature. The optimum setting indicated in the graph occurs when $\alpha = \beta = 0.5$. When $\alpha = .5$, the potential measured between the potentiometer wiper and the negative terminal of the battery is given as 100 mV. In the actual circuit the potentiometer was positioned so that a potential of 91 mV was measured. The β of the other potentiometer was set by inserting a 5.6 kΩ resistor in place of the thermistor and adjusting the β potentiometer until a bridge output voltage of -43.6 mV was obtained. Since the output voltage is also a function of the

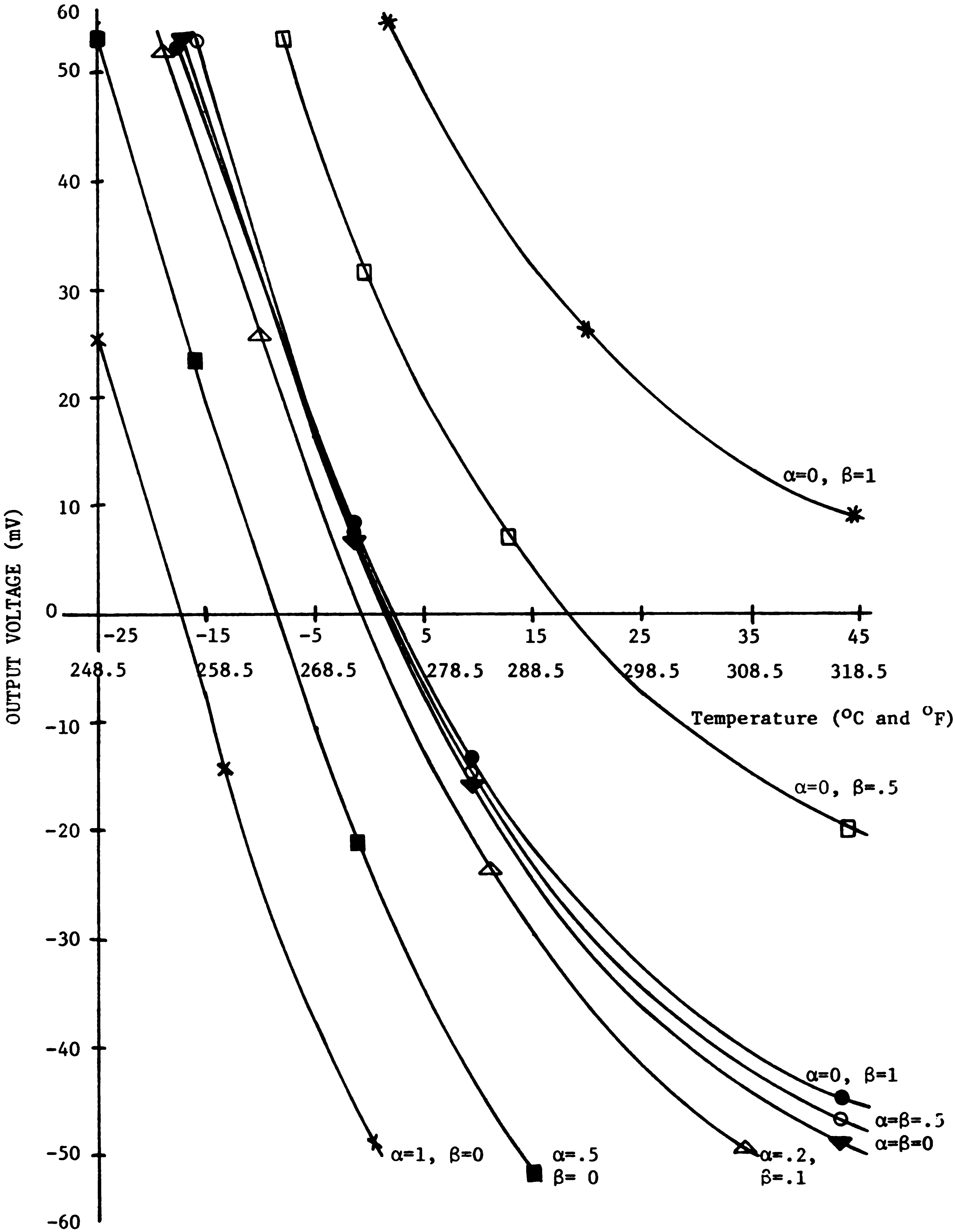

Figure 24. Theoretical Thermister Bridge Output as a Function of Potentiometer α and β Factors and Temperature.

battery supply voltage as depicted in Figure 25. The potential of the supply battery varies as a function of temperature, electrical load and the degree of charge held within the battery. As a result, it is necessary to monitor the supply voltage in order to maintain a high degree of accuracy. A voltage divider circuit consisting of one 196 kΩ resistor, one 10 kΩ potentiometer, and one 10 μF electrolytic capacitor is diagrammed in Figure 26. Eta represents the variability of the potentiometer. Using a battery with a mesured supply voltage of 1.364 volts, the potentiometer was adjusted until an output monitor voltage of +43.6 mV was obtained. Since

$$V_{OUT} = \frac{\eta \; 10 \text{ k } V_s}{206 \text{ k}} \tag{27}$$

$$\eta = \frac{206 \text{ k } V_{OUT}}{10 \text{ k } V_s} = \frac{(2.06 \times 10^2)(4.36 \times 10^{-2})}{1.364} \tag{28}$$

$$\eta = .65847$$

If a 1.5 volt battery is used in the circuit, the output voltage is 47.9 mV. By using the aforementioned value of eta, it is possible to operate the bridge circuits from a variety of battery supply potentials. It must be noted, however, that larger valued power sources decrease the range of measurement of the bridge.

Having made the potentiometer adjustments, measurements of the actual bridge response were performed. A procedure was devised which uses a "Yellow Springs" proportional temperature controller, an accompanying thermistor probe, a combination heater and magnetic stirrer, and 300 ml of a 50% alcohol-water solution to accurately record the circuit response as a function of temperature. The 300 ml of the alcohol-water solution was first cooled in the freezer compartment of

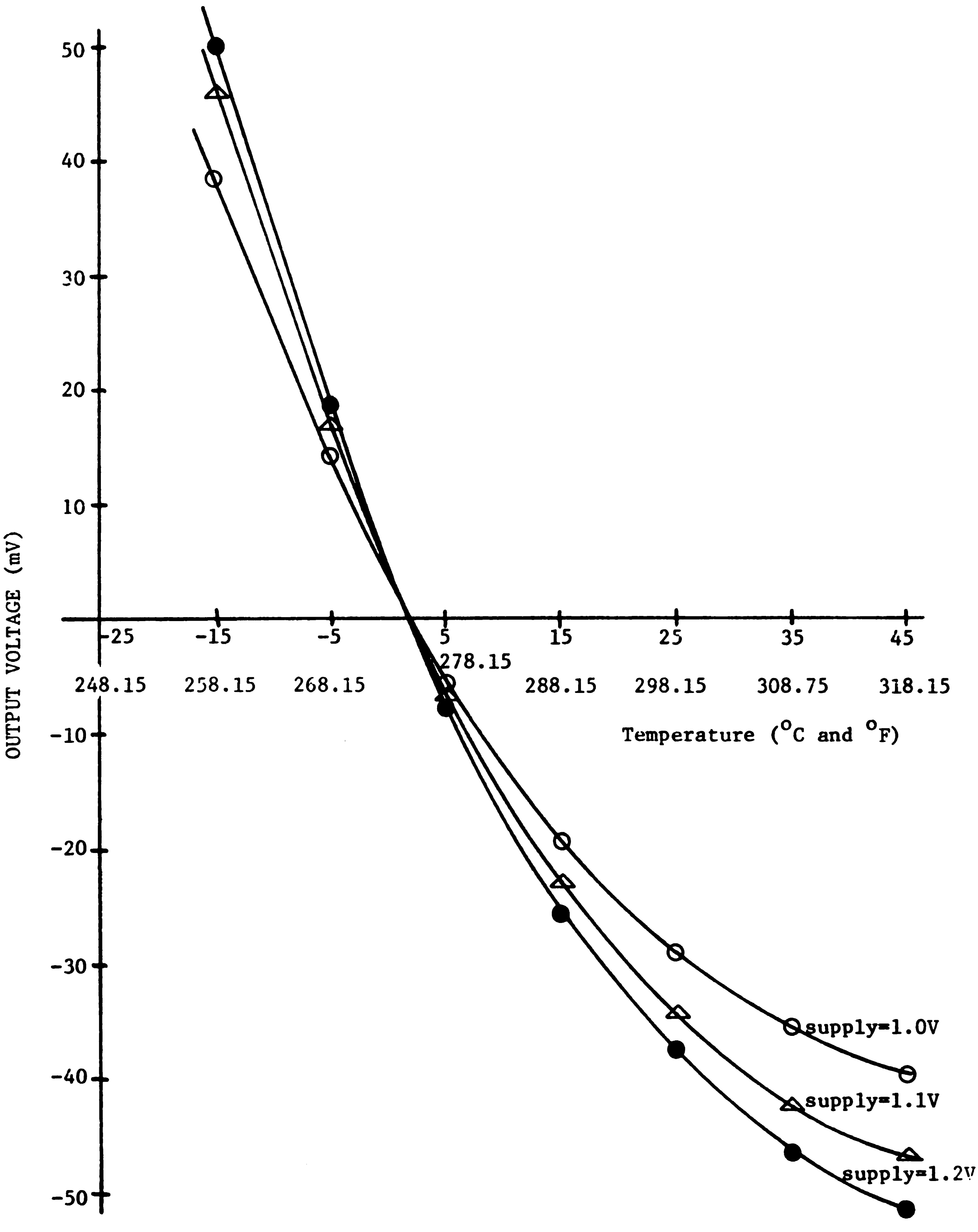

Figure 25. Graph of Theoretical Thermistor Output Variations with Supply Voltage Variations

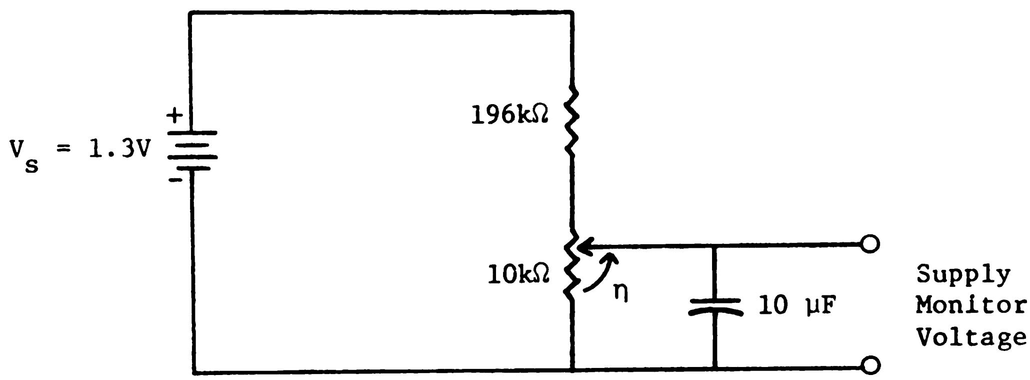

Figure 26. Voltage Divider for Monitoring the Power Supply

an available refrigerator. Next, a laboratory thermometer was used to measure the temperature of the solution. The solution was placed upon the heater-magnetic stirrer and both the proportional controller probe and the thermistor to be measured were placed in the solution. Using the proportional controller to power the heater unit, while the magnetic stirrer maintained a uniform temperature throughout the solution, the solution temperature was slowly raised. A Keithley 3½-digit multimeter continuously measured the bridge response, while at the same time, the laboratory thermometer measured the solution temperature. Table IX lists the recorded data points which were obtained using the above apparatus and the graph of the data appears in Figure 27.

4.2 Humidity Sensor Circuit Responses

The calibration of the humidity sensor and the corresponding measuring circuits was accomplished by the method described in Section 3.3. A set of potentiometers were connected in series and substituted for the humidity sensing element within the bridge circuit. Keithley multimeters monitored both the range and output signals of the humidity circuits as the potentiometers were varied over the span of 1.89 kΩ to 3.59 MΩ. This span corresponds to a relative humidity range of 10% to 89%. The potentiometers were adjusted so that a 10 mV change occurred at the output. They were then disconnected and their resultant resistance was measured. Table X lists the various voltage-resistance relationships and the equivalent relative humidity to which the resistance corresponds. A plot of the tabulated data is given in Figure 28.

The recorder-reader system has certain input-output characteristics. For any input voltage within the range -51.0 mV to +51.0 mV, the reader

TABLE IX

Bridge Output as a Function of Temperature

Temp °C	Voltage Out (mV)	Temp °C	Voltage Out (mV)
-10.0	+40.8	+ 0.4	+12.4
- 9.2	+39.3	+ 0.6	+12.1
- 8.0	+35.8	+ 0.8	+11.7
- 7.0	+35.0	+ 1.0	+10.6
- 6.0	+31.8	+ 1.2	+10.2
- 5.0	+28.4	+ 1.4	+ 9.8
- 4.4	+26.6	+ 1.6	+ 9.4
- 4.0	+25.5	+ 1.8	+ 9.0
- 3.6	+23.8	+ 2.0	+ 8.2
- 3.4	+23.3	+ 2.2	+ 7.7
- 3.2	+23.0	+ 2.4	+ 7.4
- 3.0	+22.4	+ 2.6	+ 6.9
- 2.4	+20.6	+ 2.8	+ 6.4
- 2.0	+19.2	+ 3.0	+ 5.7
- 1.4	+17.6	+ 3.2	+ 4.9
- 1.2	+17.1	+ 3.4	+ 4.6
- 1.0	+16.2	+ 3.6	+ 4.2
- 0.8	+15.1	+ 3.8	+ 3.8
- 0.6	+14.7	+ 4.0	+ 3.4
- 0.4	+14.4	+ 4.2	+ 2.8
- 0.2	+14.1	+ 4.4	+ 2.2
0.0	+13.8	+ 4.6	+ 1.8
+ 0.2	+12.9	+ 4.8	+ 1.6
+ 5.0	+ 1.1	+10.2	-10.2
+ 5.2	+ 0.5	+10.4	-10.4
+ 5.4	0.0	+10.6	-10.8
+ 5.6	- 0.2	+10.8	-11.0
+ 5.8	- 0.6	+11.0	-11.4
+ 6.0	- 1.2	+11.2	-11.8
+ 6.2	- 2.0	+11.4	-12.2
+ 6.4	- 2.2	+11.6	-12.4
+ 6.6	- 2.6	+11.8	-12.6
+ 6.8	- 2.9	+12.0	-13.0
+ 7.0	- 3.4	+12.2	-13.4
+ 7.2	- 3.9	+12.6	-13.8
+ 7.4	- 4.4	+12.8	-14.2
+ 7.6	- 4.9	+13.0	-14.6
+ 7.8	- 5.3	+13.4	-15.4
+ 8.0	- 5.5	+13.6	-15.8
+ 8.2	- 6.1	+13.8	-16.2
+ 8.4	- 6.5	+14.0	-16.4
+ 8.6	- 6.9	+14.4	-17.0
+ 8.8	- 7.3	+14.6	-17.4
+ 9.0	- 7.7	+14.8	-17.7
+ 9.2	- 8.0	+15.0	-18.0
+ 9.4	- 8.5	+15.2	-18.6
+ 9.6	- 8.9	+15.4	-19.0

Table IX (Cont'd)

Temp °C	Voltage Out (mV)	Temp °C	Voltage Out (mV)
+ 9.8	- 9.4	+15.6	-19.2
+10.0	- 9.8	+15.8	-19.4
+16.0	-19.6	+21.0	-27.0
+16.2	-20.2	+21.2	-27.2
+16.4	-20.6	+21.4	-27.4
+16.6	-20.8	+21.6	-27.8
+16.8	-21.0	+21.8	-28.0
+17.0	-21.3	+22.0	-28.2
+17.2	-21.7	+22.2	-28.5
+17.4	-21.9	+22.4	-28.7
+17.6	-22.1	+22.6	-28.9
+17.8	-22.5	+22.8	-29.0
+18.0	-22.8	+23.0	-29.4
+18.2	-23.3	+23.2	-29.6
+18.4	-23.5	+23.4	-29.8
+18.6	-23.7	+23.6	-30.0
+18.8	-23.9	+23.8	-30.1
+19.0	-24.2	+24.0	-30.3
+19.2	-24.4	+24.2	-30.6
+19.4	-24.8	+24.4	-30.8
+19.6	-25.1	+24.6	-30.9
+19.8	-25.3	+24.8	-31.0
+20.0	-25.5	+25.0	-31.4
+20.2	-25.9	+25.2	-31.7
+20.4	-26.2	+25.4	-31.8
+20.6	-26.4	+25.6	-31.9
+20.8	-26.8	+25.8	-32.1
+26.0	-32.6	+31.0	-37.2
+26.2	-32.8	+31.2	-37.3
+26.4	-33.0	+31.4	-37.4
+26.6	-33.2	+31.6	-37.5
+26.8	-33.3	+31.8	-37.7
+27.0	-33.5	+32.0	-37.8
+27.2	-33.7	+32.2	-38.0
+27.4	-34.0	+32.4	-38.2
+27.6	-34.1	+32.6	-38.4
+27.8	-34.3	+32.8	-38.5
+28.0	-34.6	+33.0	-38.6
+28.2	-34.8	+33.2	-38.8
+28.4	-35.0	+33.4	-38.9
+28.6	-35.1	+33.6	-39.0
+28.8	-35.2	+33.8	-39.1
+29.0	-35.4	+34.0	-39.3
+29.2	-35.7	+34.2	-39.5
+29.4	-35.8	+34.4	-39.6
+29.6	-35.9	+34.6	-39.8
+29.8	-36.0	+34.8	-39.9
+30.0	-36.2	+35.0	-40.0

Table IX (Cont'd)

Temp °C	Voltage Out (mV)	Temp °C	Voltage Out (mV)
+30.2	-36.5	+35.2	-40.2
+30.4	-36.6	+35.4	-40.3
+30.6	-36.8	+35.6	-40.4
+30.8	-37.0	+35.8	-40.5
+36.0	-40.7	+39.6	-42.8
+36.2	-40.8	+39.8	-42.9
+36.4	-40.9	+40.0	-43.0
+36.6	-41.1	+40.2	-43.1
+36.8	-41.2	+40.4	-43.2
+37.0	-41.4	+40.6	-43.3
+37.2	-41.5	±40.8	-43.4
+37.4	-41.6	±41.0	-43.6
+37.6	-41.7	+42.0	-44.1
+37.8	-41.8	+43.0	-44.6
+38.0	-41.9	+44.0	-45.2
+38.2	-42.0	+45.0	-45.7
+38.4	-42.1	+46.0	-46.2
+38.6	-42.3	+47.0	-46.7
+38.8	-42.4	+48.0	-47.1
+39.0	-42.5	+49.0	-47.5
+39.2	-42.6	+50.0	-47.9
+39.4	-42.7	+51.0	-48.4

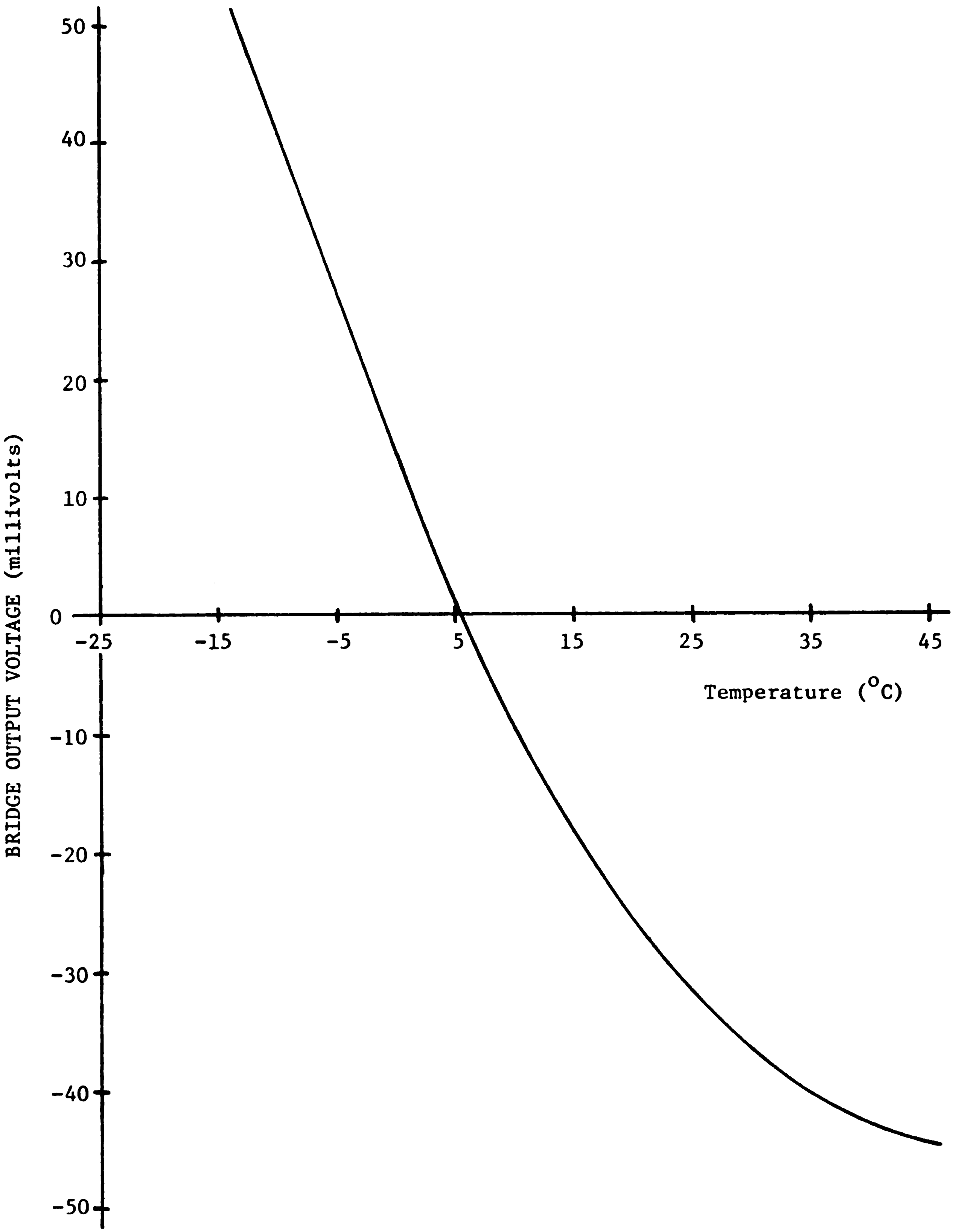

Figure 27. Graph of Measured Thermister Response

TABLE X

Resistance, Bridge Output Voltage, Range and Relative Humidity Tabulations

Range Indicator	V_{OUT}	Resistance	R.H.
	-50.8 mV	1.89 kΩ	89.0%
	-40.5 mV	3.62 kΩ	75.0%
	-30.0 mV	5.30 kΩ	67.5%
	-20.0 mV	7.02 kΩ	63.5%
	-10.2 mV	8.71 kΩ	60.5%
+50.9 mV	- 0.7 mV	10.36 kΩ	58.0%
	+10.1 mV	12.32 kΩ	55.8%
	+20.2 mV	14.17 kΩ	53.9%
	+30.0 mV	16.02 kΩ	52.25%
	+40.1 mV	17.93 kΩ	51.0%
	+50.6 mV	20.00 kΩ	49.5%
	-50.6 mV	19.6 kΩ	50.0%
	-40.6 mV	21.5 kΩ	49.0%
	-30.5 mV	23.5 kΩ	47.8%
	-20.2 mV	25.7 kΩ	46.4%
	-10.2 mV	27.7 kΩ	45.9%
+40.8 mV	0.0 mV	30.0 kΩ	45.0%
	+10.4 mV	32.3 kΩ	44.25%
	+20.4 mV	34.6 kΩ	43.8%
	+30.0 mV	37.0 kΩ	43.0%
	+40.0 mV	39.3 kΩ	42.5%
	+50.2 mV	41.7 kΩ	42.0%
	-50.5 mV	39.3 kΩ	42.5%
	-40.4 mV	41.8 kΩ	42.0%
	-30.4 mV	44.4 kΩ	41.5%
	-20.2 mV	47.0 kΩ	41.0%
	-10.2 mV	49.5 kΩ	40.1%
+30.5 mV	0.0 mV	52.2 kΩ	39.5%
	+10.3 mV	55.0 kΩ	39.1%
	+20.1 mV	57.8 kΩ	38.6%
	+30.5 mV	60.9 kΩ	38.2%
	+40.4 mV	64.0 kΩ	38.0%
	+50.6 mV	67.0 kΩ	37.5%
	-50.0 mV	65.2 kΩ	37.6%
	-40.0 mV	68.4 kΩ	36.8%
	-30.0 mV	71.5 kΩ	36.5%
	-20.3 mV	74.7 kΩ	36.2%
	-10.3 mV	78.0 kΩ	
+20.3 mV	- 0.2 mV	81.5 kΩ	
	+10.1 mV	85.1 kΩ	
	+20.4 mV	89.0 kΩ	

Table X (Cont'd)

Range Indicator	V_{OUT}	Resistance	R.H.
	+30.3 mV	92.7 kΩ	
	+40.0 mV	96.5 kΩ	
	+50.0 mV	101.6 kΩ	
	-50.2 mV	100.7 kΩ	
	-40.5 mV	104.6 kΩ	34.0%
	-30.4 mV	108.7 kΩ	
	-20.1 mV	113.2 kΩ	
	-10.4 mV	117.6 kΩ	
+10.1 mV	0.2 mV	122.4 kΩ	
	+10.3 mV	127.4 kΩ	
	+20.2 mV	132.4 kΩ	
	+30.0 mV	137.6 kΩ	32.0%
	+40.5 mV	143.1 kΩ	
	+50.2 mV	148.6 kΩ	
	-50.2 mV	148.6 kΩ	
	-40.0 mV	153.8 kΩ	
	-30.4 mV	159.9 kΩ	
	-20.5 mV	166.2 kΩ	
	-10.5 mV	172.4 kΩ	
-10.1 mV	0.0 mV	179.4 kΩ	30.0%
	+10.1 mV	186.7 kΩ	
	+20.0 mV	193.9 kΩ	
	+30.3 mV	202.0 kΩ	
	+40.1 mV	210.0 kΩ	
	+50.0 mV	218.0 kΩ	
	-50.5 mV	215.0 kΩ	
	-40.1 mV	225.0 kΩ	28.0%
	-30.2 mV	233.0 kΩ	
	-20.2 mV	243.0 kΩ	
	-10.4 mV	252.0 kΩ	
-20.3 mV	0.0 mV	263.0 kΩ	
	+10.0 mV	274.0 kΩ	
	+20.0 mV	285.0 kΩ	
	+30.1 mV	298.0 kΩ	
	+40.1 mV	311.0 kΩ	
	+50.2 mV	324.0 kΩ	
	-50.2 mV	327.0 kΩ	
	-40.2 mV	342.0 kΩ	25.0%
	-30.0 mV	357.0 kΩ	
	-20.2 mV	373.0 kΩ	
	-10.0 mV	390.0 kΩ	
-30.5 mV	0.0 mV	409.0 kΩ	24.0%
	+10.0 mV	429.0 kΩ	
	+20.1 mV	450.0 kΩ	
	+30.1 mV	474.0 kΩ	

Table X (Cont'd)

Range Indicator	V_{OUT}	Resistance	R.H.
	+40.0 mV	499.0 kΩ	
	+49.9 mV	525.0 kΩ	22.0%
	-50.1 mV	533.0 kΩ	
	-40.2 mV	562.0 kΩ	
	-30.2 mV	594.0 kΩ	
	-20.2 mV	630.0 kΩ	
	-10.0 mV	669.0 kΩ	
-40.6 mV	0.0 mV	712.0 kΩ	20.0%
	+10.1 mV	759.0 kΩ	
	+20.0 mV	812.0 kΩ	
	+30.0 mV	871.0 kΩ	
	+40.0 mV	938.0 kΩ	
	+50.0 mV	1.014 MΩ	18.0%
	-50.1 mV	1.01 MΩ	18.0%
	-40.1 mV	1.094 MΩ	18.0%
	-30.0 mV	1.193 MΩ	
	-20.0 mV	1.31 MΩ	
	-10.1 mV	1.444 MΩ	16.0%
-50.8mV	0.0 mV	1.624 MΩ	15.0%
	+10.1 mV	1.829 MΩ	14.0%
	+20.0 mV	2.09 MΩ	
	+30.1 mV	2.44 MΩ	12.0%
	+40.0 mV	2.89 MΩ	
	+50.0 mV	3.59 MΩ	10.0%

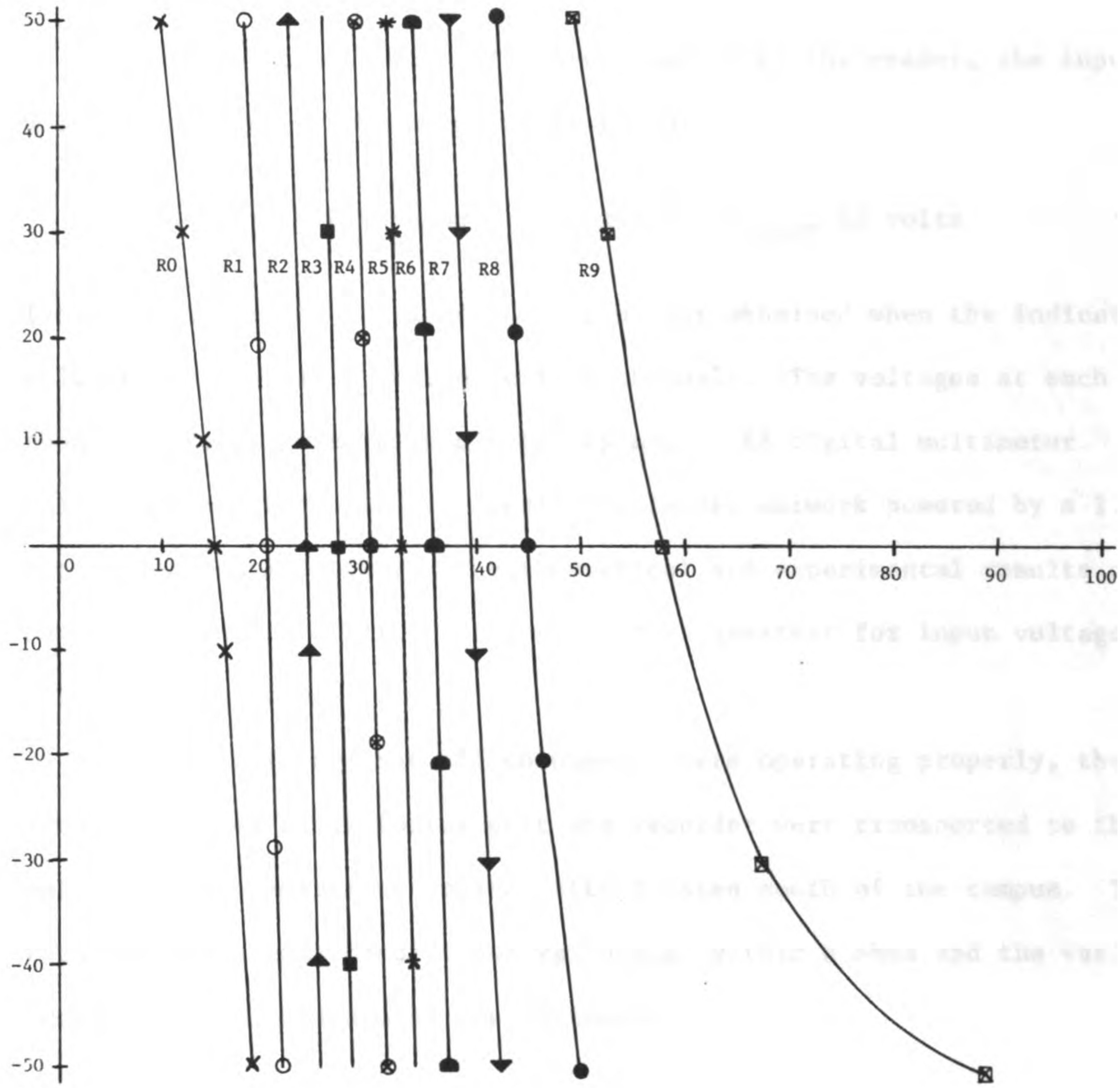

Figure 28. Measured Humidity Sensor Circuit Response. The RI's indicate auto-ranges.

output is a corresponding three-digit octal number representative of the input voltage. The ideal relationship can be expressed as follows.

4.3 Data Logger Calibration

Given the octal number XYZ as the output of the reader, the input voltage measured by the recorder is found.

$$(X \cdot 64 + Y \cdot 8 + Z \cdot 1) \cdot 4x10^{-4} - 5.1x10^{-2} = V_{INPUT} \text{ in volts} \qquad (29)$$

Table XI summarizes the Incre-Logger output obtained when the indicated voltages were applied to the various channels. The voltages at each channel were measured with a Keithley model 168 digital multimeter. The voltages were developed by a resistive ladder network powered by a 1.232 V nickel-cadmium battery. The theoretical and experimental results are summarized in Table XII. The deviation is greatest for input voltages which are negative.

After verifying that all components were operating properly, the sensors, signal conditioning unit and recorder were transported to the water quality management project site located south of the campus. The recorder and signal conditioner was placed within a shed and the various sensors were placed around its perimeter.

TABLE XI

Test Data Recorded on Digital Cassette Tape
by Incre Data "Incre-Logger" Model 5822 X/N 123

```
000001377015030044057072106121134147163212225240253266302315330344357
000001377015030044057072106121134147163212225240253266302315330344357
000001377015030044057072106121134147163212225240533266302315330344357
000001377015030044057072106121134147163212225240533266302315330344357
000001377015030044057072106121134147163212225240533266302315330344357
000001377015030044057072106121134147163212225240533266302315330344357
000001377015030044057072106121134147163212225240533266302315330344357
000001377015030044057072106121134147163212225240533266302315330344357
000001377015030044057072106121134147163212225240533266302315330344357
000001377015030044057072106121134147163212225240533266302315330344357
000001377015030044057072106121134147163212225240533266302315330344357
000001377015030044057072106121134147163212225240533266302315330344357
000001377015030044057072106121134147163212225240533266302315330344357
000001377015030044057072106121134147163212225240533266302315330344357
000001377015030044057072106121134147163212225240533266302315330344357
000001377015030044057072106121134147163212225240533266302315330344357
000001377015030044057072106121134147163212225240533266302315330344357
000001377015030044057072106121134147163212225240533266302315330344356
000001377015030044057072106121134147163212225240533266302315330344357
000001377015030044057072106121134147163212225240533266302315330344356
000001377015030044057072106121134147163212225240533266302315330344357
```

Days	Hours	Voltage Reference	Channel One	Channel Two	Channel Three	Channel Four	Channel Five	Channel Six	Channel Seven	Channel Eight	Channel Nine	Channel Ten	Channel Eleven	Channel Twelve	Channel Thirteen	Channel Fourteen	Channel Fifteen	Channel Sixteen	Channel Seventeen	Channel Eighteen	Channel Nineteen	Channel Twenty

TABLE XII

Comparison of the Input Voltage
to the Recorded Voltage of the Incre-Logger

Channel Number	Input Voltage (mV)	Octal Representation	Converted Octal (mV)	Error (mV)
1	-44.8	015	-45.8	+1.00
2	-40.35	030	-41.4	+1.05
3	-35.9	044	-36.6	+0.70
4	-31.4	057	-32.2	+0.80
5	-26.9	072	-27.8	+0.90
6	-22.45	106	-23.0	+0.55
7	-18.0	121	-18.6	+0.60
8	-13.45	134	-14.2	+0.75
9	- 9.0	147	- 9.8	+0.80
10	- 4.6	163	- 5.0	+0.40
11	+ 4.4	212	+ 4.2	+0.20
12	+ 8.8	225	+ 8.6	+0.20
13	+13.3	237	+12.6	+0.70
14	+17.7	253	+17.4	+0.30
15	+22.25	266	+21.8	+0.45
16	+26.7	302	+26.6	+0.10
17	+31.2	315	+31.0	+0.20
18	+35.65	330	+35.4	+0.25
19	+40.1	344	+40.2	+0.10
20	+44.65	357	+44.6	+0.05

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this research effort was to develop, analyze, and evaluate a system which can acquire data automatically at remote field sites. The data is acquired in a computer compatible format which enables the user of the system to quickly process the data. The equipment used is relatively maintenance free for extended periods of time and remains flexible enough to be easily reconfigured for many different types of applications.

The current system configuration consists of a continuously powered signal conditioning unit capable of operating for a period of two weeks. Various sensors which provide the input signals to the conditioning unit are processed and bused to a logger unit. The logger unit periodically samples the data, encodes it and stores it upon a magnetic cassette. A 6.25 volt, 7 amp-hour battery enables the logger to operate for a period of one week. The logging function is complemented by a cassette reader which decodes the stored data, transferring it to mass storage within the large computing unit on the M.S.U. campus.

The system, as a whole, is easily enlarged upon, as other transducers can be easily interfaced with the original equipment. The loggers are interchangeable and the signal conditioning unit is readily reconfigured.

The temperature bridge networks, when used in conjunction with the linearizing algorithms, are accurate and long lived. They are, however, prone to noise disturbances which are picked up within the high impedance components.

The humidity bridge network is especially unique in the approach used to implement the measurement. Very accurate readings can be obtained for relative humidity measurements above 60%. The present system does suffer from rather low range definition at low percentage relative humidities. It might be said that the sensitivity is too great for percentages below 50%.

At the present time, the weakest link in the system is the logger itself. It suffers two main deficiencies. One, the logger, while in the stand-by mode, consumes far too much power in the time keeping operations; and two, below freezing the power control circuitry malfunctions, causing complete dissipation of all available battery power.

By replacing the clock and divider circuits by COS/MOS devices, it would be possible to drastically reduce the power drain. The original clock and divider circuits consumed a continuous 50 mA in the stand-by mode. The clock itself uses 5 low power TTL IC's as well as several discrete components, while the divider board is a continuously powered behemoth of 12 low-power TTL IC's.

One of the loggers has had its clock circuitry replaced by five COS/MOS devices. The COS/MOS clock was constructed from the following:

1 CD4047 Astable/Monostable Multivibrator

2 CD4017 Decade Counter/Dividers

1 CD4013 Dual Typed Flip Flops

1 CD4011 Quad Two Input NAND Gates

The components were connected as shown in Figure 29. The circuit substitution has resulted in a measurable reduction in current drain

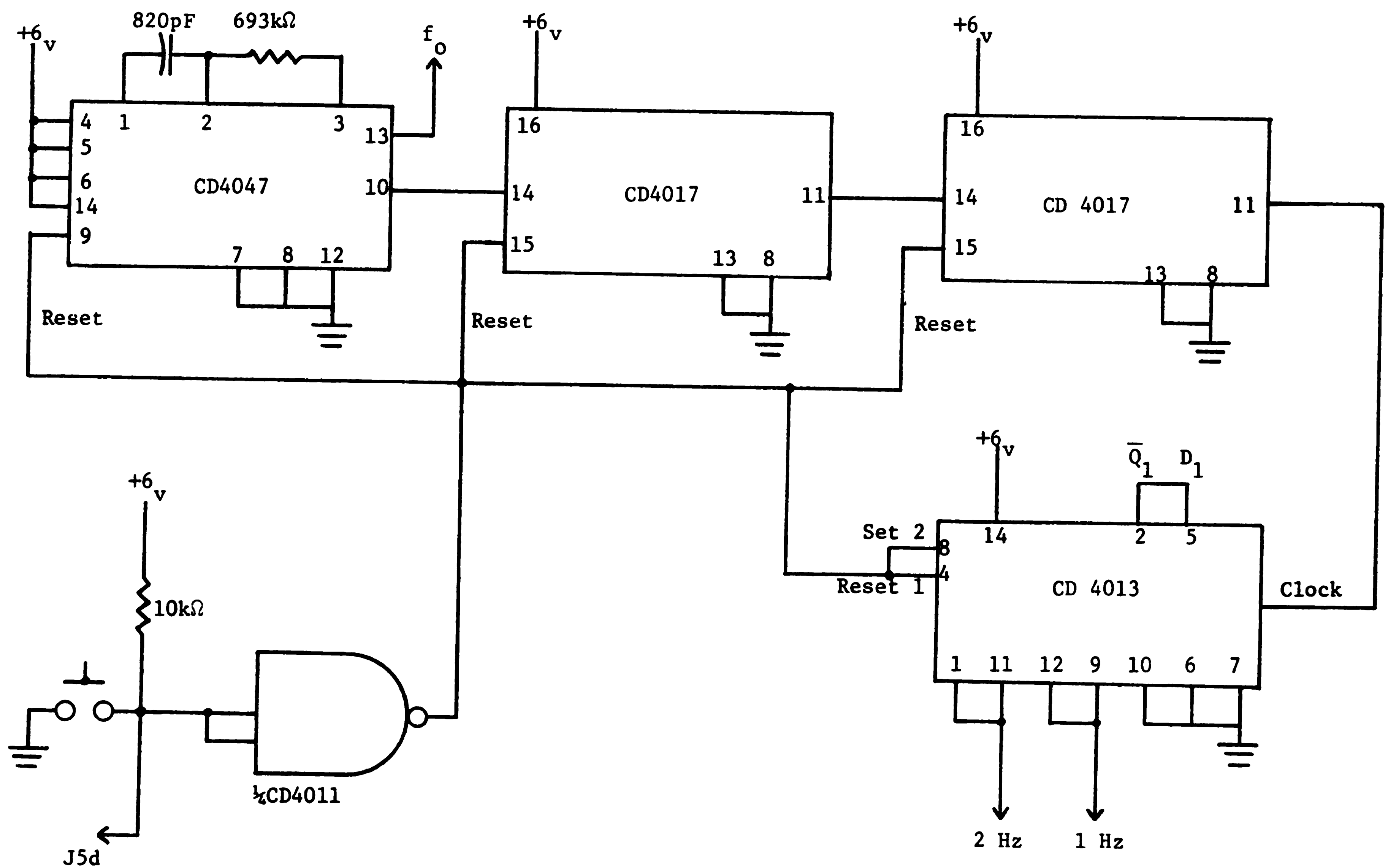

Figure 29. CMOS low-power clock

of 8 mA. If a corresponding COS/MOS divider board can be substituted for the present low power TTL circuits, an even greater savings in power can be realized.

The entire system as originally conceived was to operate for a period exceeding several months. However, during the course of my work with the system, I have come to feel that it is impossible to use the current power sources to maintain circuit operation over the desired time period unless some form of time multiplexing is incorporated. Using COS/MOS transmission gates, it is possible to de-energize many of the aforementioned circuits until just prior to sampling. After the data has been logged, the circuits should again be de-energized. This approach allows smaller resistances to be used for the bridge networks which can decrease the amount of induced noise within the system.

Since the initialization of this project, many medium scale COS/MOS IC's have been introduced. These IC's can greatly enhance the potential of the system. One in particular is the 1-to-8 or 8-to-1 Multiplexer/Demultiplexer. The device lends itself to the construction of simplified bridge switching networks such as that used in the humidity-measuring circuit described previously.

In conclusion, the circuitry developed provides a stepping stone to more accurate and longer lived instrumentation. During the present time period, it functions to provide scientists with data from remote environments. From both a meteorological and agricultural point view, the system provides a much needed service. When equipped with the appropriate transducers, the unit has many uses in all types of remote applications. The unit could conceivably be used to monitor the pollution of lakes and streams. When discreetly placed in public places, the unit could be used to monitor noise or air pollution. Indeed, the uses are limited only by the imagination of the user.

APPENDICES

APPENDIX A

LISTING OF SUBROUTINE "INTRO"

APPENDIX B

EXAMPLE ILLUSTRATING THE EXECUTION OF SUBROUTINE "INTRO"

INTRO

THIS IS THE FIRST OF TWO FORTRAN PROGRAMS DESIGNED TO AID IN THE READING AND INTERPRETATION OF DATA RECORDED WITH AN INCRELOGGER/TRANSDUCER SYSTEM USING THE 1550 CASSETTE READER, PROCESSED DATA MAY BE SUMMARIZED IN A TABLE,PLOTTED,AND/OR ADDED TO A NEW OR ALREADY EXISTING PERMANENT OR MAG.TAPE FILE. SOME STATISTICAL MANIPULATIONS OF THE DATA ARE ALSO AVAILABLE.

THE FOLLOWING INSTRUCTIONS SHOULD BE FOLLOWED CAREFULLY IN ORDER TO READY THE READER FOR DATA TRANSMISSION.

THE CONTROLS/SWITCHES SHOULD BE:

1. POWER SWITCH-ON. THE READ INDICATOR LAMP ALONG WITH THE DISPLAY LAMPS SHOULD NOW BE LIT.
2. THE"LOCAL" BUTTON SHOULD NOW BE LIT. IF IT IS NOT,THEN PRESS IT.
3. THE "LOAD","ENABLE OUTPUT",AND "RUN" BUTTONS SHOULD NOT BE LIT. PRESS THE ONES THAT ARE LIT.

THE READER SWITCHES SHOULD BE POSITIONED AS FOLLOWS:

SWITCH	POSITION
......	....
TAPE/MEMORY	TAPE(UP)
LATCHED/NORMAL	NORMAL(DOWN)
INTERNAL/EXTERNAL/MANUAL	EXTERNAL(CENTER)
WORD SELECT	(NOT OPERATIVE)
REPEAT MEMORY	OFF
DATA CONVERSION	OCTAL
MODE	INCRE

6. PRESS THE RESET BUTTON.

7. PRESS THE LOAD BUTTON ON.
THE TAPE WILL AUTOMATICALLY REWIND AND THE BOT (BEGINNING OF TAPE) LAMP WILL LIGHT.
8. PRESS THE RUN BUTTON ON.

THE TAPE TRANSPORT WILL NOW BEGIN WINDING THE TAPE ON THE LEFT REEL UNTIL THE BEGINNING OF THE DATE IS EN COUNTERED. THE TRANSPORT WILL THEN STOP AND THE BOT LAMP WILL GO OFF.

THE READER IS NOW READY TO TRANSMIT DATA.
PLEASE FOLLOW THE NEXT INSTRUCTIONS CAREFULLY!

WHEN THE TELETYPE PRINTS;

"END INTRO"
TYPE THE FOLLOWING RESPONSES,
ONE PER LINE;

1.OK-"SCRATCH"
2.OK-"ATTACH,A,INCRELOG."
3.OK-"USE,A"
4.OK-"RTL,100"
5.OK-"LENGTH,80."
6.OK-"RFL,10000."
7.OK-"READPT,XXX."

YOU SHOULD THEN GET THE RESPONSE;
"READY FOR TAPE"
PRESS THE "ENABLE OUTPUT" BUTTON, SO THAT IT LIGHTS. THE DATA WILL NOW BE TRANSFERRED TO TEMPORARY FILE XXX.

WHEN DATA TRANSMISSION STOPS,THE BLUE DATA LIGHT WILL NOLONGER BLINK, PRESS THE "ENABLE OUTPUT" AND "RUN" BUTTONS SO THEY ARE NOLONGER LIT. THEN PRESS THE "ESC" BUTTON ON THE TELETYPE. THE FOLLOWING RESPONSE WILL BE PRINTED.
EDT-PROCESSING TAPE
OK-

TYPE THE FOLLOWING RESPONSES, ONE PER LINE;
1.OK-"REWIND,XXX."
2.OK-"PROMPT"
3.OK-"FTN."
4.OK-"LGO,XXX,YYY,INPUT,OUTPUT."

PROGRAM INCRELOG WILL THEN TAKE CONTROL.

END INTRO

APPENDIX B

EXAMPLE ILLUSTRATING THE EXECUTION OF SUBROUTINE "INTRO"

APPENDIX C

PROGRAM OCTLHDR

APPENDIX C

PROGRAM OCTLHDR

```
THIS PROGRAM CONVERTS THE OCTAL NUMBER REPRESENTATION OF THE HEADER
DATA INTO THE PACKED BCD FORMAT ORIGINALLY ENCODED
   SUBROUTINE OCTLHDR(OCTL,HEADR)
   DIMENSION IDGT(2)
THE BIT MASKS ARE GENERATED
   JMSK1=MASK(4)
   JMSK2=MASK(1)
   IHEADR=0
   ITEMP=OCTL
   I=1
FOLLOWING STRIPS OFF 4 BITS OF EACH DIGIT
 1 IDGT(I)=ITEMP.AND.JMSK1
   IF(I.EW. 2)GO TO 2
   ITEMP=SHIFT(ITEMP,-4)
   I=I+1
   GO TO 1
 2 DO 4,I=1,2
   ITEMP1=0
   ITEMP=IDGT(I)
   DO 3,J=1,4
   ITMP1=ITEMP.AND.JMSK2
   ITEMP1=ITEMP1+ITMP1*2**(J-1)
 3 CONTINUE
   IDGT(I)+ITEMP1
 4 CONTINUE
   IHEADR=10*IDGT(2)+IDGT(1)
   RETURN
   END
```

APPENDIX D

PROGRAM OMVC

APPENDIX D

PROGRAM OMVC

```
C  TAKES AS INPUT 3-DIGIT OCTAL NUMBER AND CONVERTS IT INTO A
C  CORRESPONDING MILLIVOLT OUTPUT.  RETURNS BOTH THE OCTAL NUMBER AND
C  THE CONVERTED MILLIVOLT EQUIVALENT.
C  THE CONVERSION XXX = SUM*4.0E-4 - 5.1E-2 IS APPLICABLE ONLY TO
   INCRELOGGERS WITH BIPOLAR ±51 MV INPUT RANGES.
      SUBROUTINE OMVC(LLL,XXX)
      SUM=0.0
      XLLL=FLOAT(LLL)
1001  DO 1002,NNN=1,3
      XLLL=XLLL/10
      YLLL=AINT(XLLL)
      SUM=SUM+((XLLL-YLLL)*10)*8**(NNN-1)
1002  XLLL=YLLL
      XXX=SUM*4.0E-4+(-5.1E-2)
      RETURN
      END
```

APPENDIX E

PROGRAM TEMPLIN

APPENDIX E

PROGRAM TEMPLIN

```
C   THIS PROGRAM LINEARIZES THE TEMPERATURE-VOLTAGE RELATIONSHIP OF THE
C   THERMISTOR BRIDGE NETWORKS
       SUBROUTINE TEMPLIN(TEMP11, REF1, TEMPER, MODE1)
C   TEMP11 IS THE MILLIVOLT OUTPUT OF THE TEMPERATURE RECORDING CHANNEL
C   REF1 IS THE REFERENCE MILLIVOLT OUTPUT WHICH INDICATES THE STATUS
C    OF THE BRIDGE POWER SUPPLY.
C   TEMPER IS THE CALCULATED TEMPERATURE, MODE1 INDICATES WHETHER THE
C   TEMPERATURE IS IN DEGREES CENTIGRADE OR FARENHEIT
       COMMON COEFFICS(ALPHA,BETA,GAMMA,ETA)
       VSUP=(20.6/ETA)*REF1
C   VSUP IS THE SUPPLY VOLTAGE
C   ETA IS CALCULATED BY MEASURING THE SUPPLY VOLTAGE AND ADJUSTING THE
C   REFERENCE POTENTIOMETER SO THAT THE REFERENCE IS FIFTY MILLIVOLTS
       GAMMA1=TEMP11/VSUP
       ALEPH1=(ALPHA1+1.2)/21.8+GAMMA1
       RTEMP=(BETA1*(5.075E4)+3.75E3-1.0492E6*ALEPH1)/(e.56E1*ALEPH1-
       (BET $A1+5.0))
       RO=5.0E3
       TO=2.9815E2
       BETAO=3.873E3
       TEMPPP=1/(1/TO+(1/BETAO)*LN(RTEMP/RO))
C   TEMPPP IS THE MEASURED TEMPERATURE IN DEGREES KELVIN
       TEMPC=TEMPPP-2.7315E2
       TEMPF=1.8*TEMPC+3.2E1
       IF(MODE1.EQ.T)TEMPF=TEMPC
       TEMPER=TEMPF
       RETURN
C   TEMPC IS THE TEMPERATURE IN DEGREES CELSIUS
C   TEMPF IS THE TEMPERATURE IN DEGREES FARENHEIT
       END
```

APPENDIX F

PROGRAM HMDTY

APPENDIX F

PROGRAM HMDTY

```
C   THIS SUBROUTINE CONVERTS THE RANGE INDICATING VOLTAGE AND HUMIDITY
C   SIGNAL VOLTAGE TO THE CORRESPONDING HUMIDITY MEASUREMENT.  IT DETER-
C   MINES THE RELATIVE HUMIDITY THROUGH A PIECEWISE LINEAR APPROXIMATION
C   ALGORITHM
      SUBROUTINE HMDTY(OCTLR,OCTLH,HUMDTY)
      RANG=0.0
      HVOLT=0.0
C   THIS REOUTINE USES SUBROUTINE OMVC TO CONVERT THE OCTAL NUMBERS TO
C   CORRESPONDING VOLTAGE EQUIVALENTS
      CALL OMVC(OCTLR,RANG)
C   OCTLR IS THE OCTAL QUANTITY REPRESENTING THE RANGE
C   RANG IS THE CONVERTED RANGE INDICATING VARIABLE
      CALL OMVC(OCTLH,HVOLT)
C   OCTLH IS THE OCTAL QUANTITY REPRESENTING THE BRIDGE OUTPUT
      IRANG=INT(100*(RNAG+5.1E-2)+1)
      GO TO(100,200,300,400,500,600,700,800,900,999)IRANG
  100 IF (HVOLT) 120,110,110
  110 HUMDTY= -(5.0/5.0E-2)*HVOLT+1.5E1
      RETURN
  120 IF(HVOLT+1.01E-2)140,130,130
  130 HUMDTY= -(1.0/1.01E-2)*(HVOLT+1.01E-2)+1.6E1
      RETURN
  140 HUMDTY= -(2.0/3.0E-2)*(HVOLT+4.01E-2)+1.8E1
      RETURN
  200 HUMDTY= -(2.0/5.0E-2)*HVOLT+2.0E1
      RETURN
  300 HUMDTY= -(3.0/9.01E-2)*(HVOLT+4.01E-2)+2.5E1
      RETURN
  400 HUMDTY= -(2.0/7.02E-2)*(HVOLT+4.01E-2)+2.8E1
      RETURN
  500 HUMDTY= -(2.8/1.02E-1)*HVOLT+3.0E1
      RETURN
  600 HUMDTY= -(2.0/7.05E-2)*(HVOLT+4.05E-2)+3.4E1
      RETURN
  700 IF(HVOLT+2.0E-4)720,710,710
  710 HUMDTY= -(1.8/5.02E-2)*(HVOLT+2.0E-4)+3.6E1
      RETURN
  720 HUMDTY= -(1.6/4.8E-2)*(HVOLT+5.0E-2)+3.76E1
      RETURN
  800 IF(HVOLT+1.02E-2)820,810,810
```

```
810  HUMDTY= -(2.6/6.08E-2)*(HVOLT+1.02E-2)+4.01E1
     RETURN
820  IF(HVOLT+3.04E-2)840,830,830
830  HUMDTY= -(1.4/2.02E-2)*(HVOLT+3.04E-2)+4.15E1
     RETURN
840  HUMDTY= -(1.0/2.01E-2)*(HVOLT+5.05E-2)+4.25E1
     RETURN
900  IF(HVOLT+2.02E-2)920,920,910
910  HUMDTY= -(4.4/7.04E-2)*(HVOLT+2.02E-2)+4.64E1
     RETURN
920  IF(HVOLT+4.06E-2)940,930,930
930  HUMDTY= -(2.6/2.04E-2)*(HVOLT+4.06E-2)+4.9E1
     RETURN
940  HUMDTY= -(1.0/1.0E-2)*(HVOLT+5.06E-2)+5.0E1
     RETURN
999  IF(HVOLT-1.01E-2)950,960,960
960  HUMDTY= -(6.3/4.05E-2)*(HVOLT-1.01E-2)+5.58E1
     RETURN
950  IF(HVOLT+1.02E-2)970,980,980
980  HUMDTY= -(4.7/2.03E-2)*(HVOLT+1.02E-2)+6.05E1
     RETURN
970  IF(HVOLT+3.0E-2)990,991,991
991  HUMDTY= -(7.0/1.98E-2)*(HVOLT+3.0E-2)+6.75E1
     RETURN
990  IF(HVOLT+4.05E-2)993,992,992
992  HUMDTY= -(7.5/1.05E-2)*(HVOLT+4.05E-2)+7.5E1
     RETURN
993  IF(HVOLT+4.5E-2)995,994,994
994  HUMDTY= -(4.3/4.5E-3)*(HVOLT+4.5E-2)+7.93E1
     RETURN
995  HUMDTY= -(9.7/5.8E-3)*(HVOLT+5.08E-2)+8.9E1
     RETURN
     END
```

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