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THE DESIGN, DEVELOPMENT AND TESTING OF A PRECISION TEMPERATURE MONITORING SYSTEM

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Mark Allen Shell

June 1986

DEDICATION

This thesis is dedicated to my wife, Tammy, and to my daughter, Elizabeth Ann. Their constant understanding, love, and support have made this project possible.

ACKNOWLEDGMENTS

The author would like to thank Dr. Donald W. Bouldin for his continuous encouragement over the last four years. His guidance on this and other projects has been greatly appreciated.

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Finally, I would like to acknowledge my parents, Bill and Peggy Shell. Their love, dedication, and support over the years have been unfailing. Thanks Mom and Dad.

ABSTRACT

The purpose of this project was to develop an accurate and reliable system which can monitor multiple temperature points located in widely separated locations in a cost effective manner.

In the system that was designed and constructed, each unit consisted of fifteen thermistor-type temperature probes which were interfaced to a commercially available single-board computer. Design modifications were instigated for the single-board computer to increase its resolution and a program that implements the nonlinear relationship between resistance and temperature in thermistors was developed. The calculated temperatures were transmitted over a serial communications link to a customized data logger where they were averaged over various times and stored. A central minicomputer called several of these temperature units over standard phone lines and collected the averaged data.

This thesis describes the work related to the theoretical considerations involved in the use of thermistors as temperature sensors, the design of the thermistor drive circuit, the modifications to the single-board computer's analog section, and the software that was written for the precision temperature microcomputer.

The resulting system design exceeded all initial design specifications for accuracy, resolution and scan speed. A complete network of four temperature systems was constructed and installed at the Vermont Yankee nuclear power plant in September, 1984. Since then, all of the units have been functioning normally.

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CHAPTER I

INTRODUCTION

Background Information

Precision temperature monitoring as discussed in this thesis refers to the measurement of temperature to an absolute accuracy of better than ±0.05 degrees Celsius (Kelvin). This level of precision is usually confined to laboratory or other controlled environments with special considerations being given to potential sources of error. Such errors depend on the type of instrument used in making the temperature measurement. For example, with conventional mercury thermometers, correction factors are used to compensate for part of the thermometer being exposed to a temperature that is different from the temperature being measured. In platinum resistance temperature devices (RTDs), provisions are made to correct for the resistance of the electrical leads of the probes. Many other such provisions exist, all of which lead to the fact that automated temperature measurement, by any method, is limited by practical constraints to an accuracy of about 0.05 Kelvin. This order of accuracy is not available with present commercial instruments under commonly encountered field conditions, with the exception of one known instrument. This is the patented PTS-80A precision temperature monitor manufactured by the author's company, Environmental Systems Corporation located in Knoxville, Tennessee. [1] This instrument uses platinum RTDs to make temperature measurements in the field with an absolute accuracy of better than ±0.05 Kelvin.

This thesis describes the work undertaken by the author to totally redesign the PTS-80A using the latest technologies and methods and also to incorporate certain modifications to allow the new unit, the PTS-80B, to meet the more stringent requirements and unique problems of monitoring temperatures at a nuclear power plant. There are several major differences between the two instruments:

1. the PTS-80A uses RTDs while the PTS-80B uses thermistors;
2. the PTS-80A is based on several interconnected printed circuit boards while the PTS-80B is built around a single-board computer;
3. the PTS-80A displays only one of eight temperatures on a LED display but the PTS-80B can display all fifteen temperatures on a display terminal and can transmit them over a serial communications link to a data logger;
4. the PTS-80A is calibrated using cumbersome DIP switches while the PTS-80B is calibrated using a convenient software calibration routine.
5. the PTS-80A's probes must be recalibrated when moved to a different channel but the PTS-80B's probes can be accurately transfered between channels.

Although this project was undertaken to meet the requirements of a particular client, plans are under way to patent this new device and to actively pursue its marketing in the power plant testing area and in the pharmaceutical industry.

Design Goals

A thermistor is a thermally sensitive resistor, i.e., a device that exhibits a change in electrical resistance in response to a change in its thermal temperature. [2] Unlike RTDs, which consist of wire-wound elements or metal films that exhibit small changes in resistance with temperature, thermistors are ceramic semiconductors which exhibit large, although nonlinear, changes in resistance with changes in temperature. These large changes result in almost an order of magnitude increase in sensitivity of the thermistor over the RTD. [3] Another major advantage of the thermistor is its availability in relatively high nominal resistance values compared to the RTD. The RTD used in the PTS-80A has a nominal resistance of 100 ohms at 25 degrees Celsius but the thermistor chosen for the PTS-80B has a resistance of 2000 ohms at the same temperature. This makes it possible to make remote measurements without the need to compensate for the resistance of the wire leads. Since both the resistivity and temperature coefficient-of-resistance of copper wire are much lower than those exhibited by thermistors, very long cables (several thousand feet) may be used between the sensor and the PTS-80B. This high resistance also reduces the effect of contact resistance in the electrical connections of the cable. Other problems with RTDs are their inherent instability over time, their susceptibility to changes in their resistance-temperatue relationship due to shock and vibration, and the hysteresis effect which they exhibit when thermally cycled. All of these problems are greatly reduced by the use of ultra-stable thermistors. Thermistors are inherently resistant to changes in characteristics caused by shock, vibration, and hysteresis due to the fact that their temperature dependent resistance is the result of the chemical mixture of the semiconductor oxides used in their manufacture. RTDs, however, depend on metal grain boundaries to produce their temperature characteristics. These boundaries are prone to shifting due to mechanical and thermal stresses and the passage of time. The primary reason for the drift of a thermistor is the exposure of the thermistor to atmospheric oxygen. [4] The PTS-80B uses thermistors manufactured by Thermometrics Incorporated of Edison, New Jersey. These devices are hermetically sealed and are stable to 0.02 percent per year. This stability was very important to the primary client of the PTS-80B. Some of these probes were installed in areas of the Vermont Yankee nuclear power plant and can only be removed for calibration during a plant shutdown, while a few probes are subjected to such high levels of radioactivity that they can never be directly handled and must be completely replaced instead of recalibrated. The use of thermistors instead of RTDs required the development of a completely new drive and monitoring circuit for the PTS-80B. This circuit and its development is discussed later in this thesis.

A second major design change from the PTS-80A was the replacement of the eight small circuit boards with one single-board computer and a thermistor driver board. The single-board computer that was selected is a unit designed and manufactured by the author's company. This board consists of a Z80 microprocessor, random access memory, programable read-only memory, serial communications ports, and sixteen differential analog inputs. It has been used by ESC in its ambient air quality data loggers since 1980 and has proved to be extremely reliable, achieving a mean time between failures of over three years. A problem with the PTS-80A has been its lack of long-term reliability. This problem is most likely caused by its multitude of boards and the associated interconnections. It was hoped that the use of a single-board computer would increase the reliability of the precision temperature system.

The PTS-80A measures up to eight temperatures and displays one of these on a five digit LED display. The temperature that is displayed is selected by an eight position thumb-wheel switch. This display method is not convenient for situations where multiple temperatures are monitored. The PTS-80B is designed to operate with a CRT terminal unit, and can therefore display all fifteen temperatures simultaneously. In addition, these temperatures and a system offset voltage are transmitted in a packed string via a standard serial port. These strings can be stored on a serially connected magnetic tape unit or, in the case of the nuclear power plant system, received by a modern microprocessor based data logger, averaged over some convenient interval, and reported on demand to a central computer over dial-up telephone lines.

The final major improvement of the PTS-80B over the PTS-80A was the method by which calibrations are performed and the resulting coefficients made available to the microprocessor. These coefficients are used by the units to compute new temperatures based on the measured resistance of the probe. The RTD based PTS-80A uses the second-order Callendar Van Dusen equation and thus requires two calibration points. The corresponding two equation coefficients are manually calculated from these calibration points. The resulting coefficients are entered into the system via a set of DIP switches for each probe. Since a third-order equation is used in the PTS-80B, three calibration points and and three coefficients are needed for each probe. Obviously, a much more "user-friendly" method of entering these three calibration points was needed for the new instrument. The resulting solution was a software routine that can be used to calibrate a particular probe and automatically compute and store the equation coefficients in non-volatile memory. This method is much easier to use and, if a printing terminal is available, a permanent record of the calibration results can be generated to fully document the procedure.

The total system accuracy from front to back was targeted to meet or exceed the ±0.05 Kelvin accuracy of the PTS-80A over a range of zero degrees Celsius to 60 degrees Celsius. The resolution was to be 0.01 Kelvin and the sampling rate was to exceed one scan of all fifteen temperature probes every minute.

Chapter Contents

The theoretical considerations for the overall design of the PTS-80B are given in Chapter II. The general characteristics of thermistors are presented as well as the empirical equations that have been developed to describe their temperature versus resistance curve. Chapter III describes the process by which the hardware design and system configuration were obtained. Block diagrams of the system are given as well as the schematic diagrams of the thermistor driver circuit. An explanation is given in Chapter IV for the selection of BASIC as the programming language used. Overall software flowcharts are provided and the algorithms for coefficient determination, temperature computation, and probe calibration are described. Chapter V details the performance of the new temperature system including the testing methods used and the accuracy obtained. Also in this chapter is an explanation of a procedure by which a probe can be moved from one channel to another on the same PTS-80B or to a different PTS-80B without recalibrating the probe. Finally, Chapter VI presents a summary and the conclusions of the project.

CHAPTER II

THEORETICAL CONSIDERATIONS

Thermistor Characteristics

The resistance versus temperature curves of a typical thermistor and a typical RTD are shown in Figure 1. Notice the very steep slope of the thermistor curve over the temperature range and also the extreme non-linearity over even a small range of temperatures. These characteristics result in some of the advantages of the thermistor over the RTD but also make designing temperature sensing instruments based on thermistors more difficult. Most RTD based instruments force a constant current through the RTD. The resulting voltage is thus proportional to the resistance of the RTD and, since the temperature versus resistance curve is almost a straight line, the voltage is also proportional to the temperature. This makes the design of moderately accurate (±0.1 Kelvin) RTD thermometers fairly simple. Designing with thermistors can take advantage of the greater sensitivity of the device but must deal with the non-linearity of its temperature versus resistance curve.

If the logarithm of the resistance is plotted as a function of the temperature of the thermistor, the curve shown in Figure 2 results. This relationship is less curved than the linear plot and is the method used by thermistor manufacturers to show the characteristics of various devices. A further flattening of the curve is obtained if the logarithm of the resistance is plotted as a function of the inverse of the absolute temperature as shown in Figure 3. A standard curve fitting technique can be used to approximate the resulting relationship between resistance and temperature. This technique is to consider the logarithm of the resistance as a polynomial in inverse temperature:

$$\ln R = A_0 + A_1 T^{-1} + A_2 T^{-2} + A_3 T^{-3} + \cdots + A_n T^{-n} \qquad (1)$$

or, similarly, the same relationship may be expressed as the inverse temperature in terms of

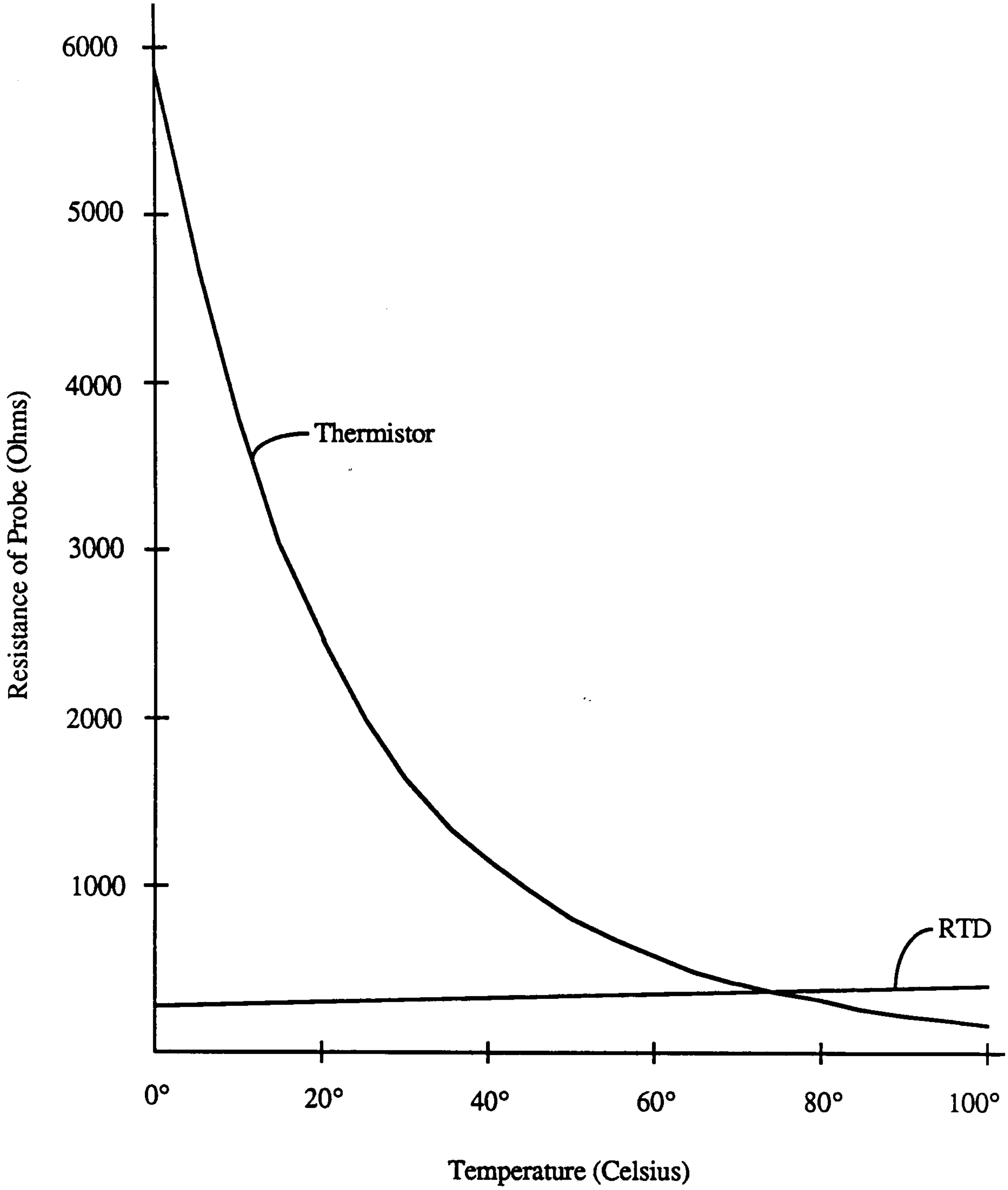

Figure 1. Resistance Versus Temperature Graph.

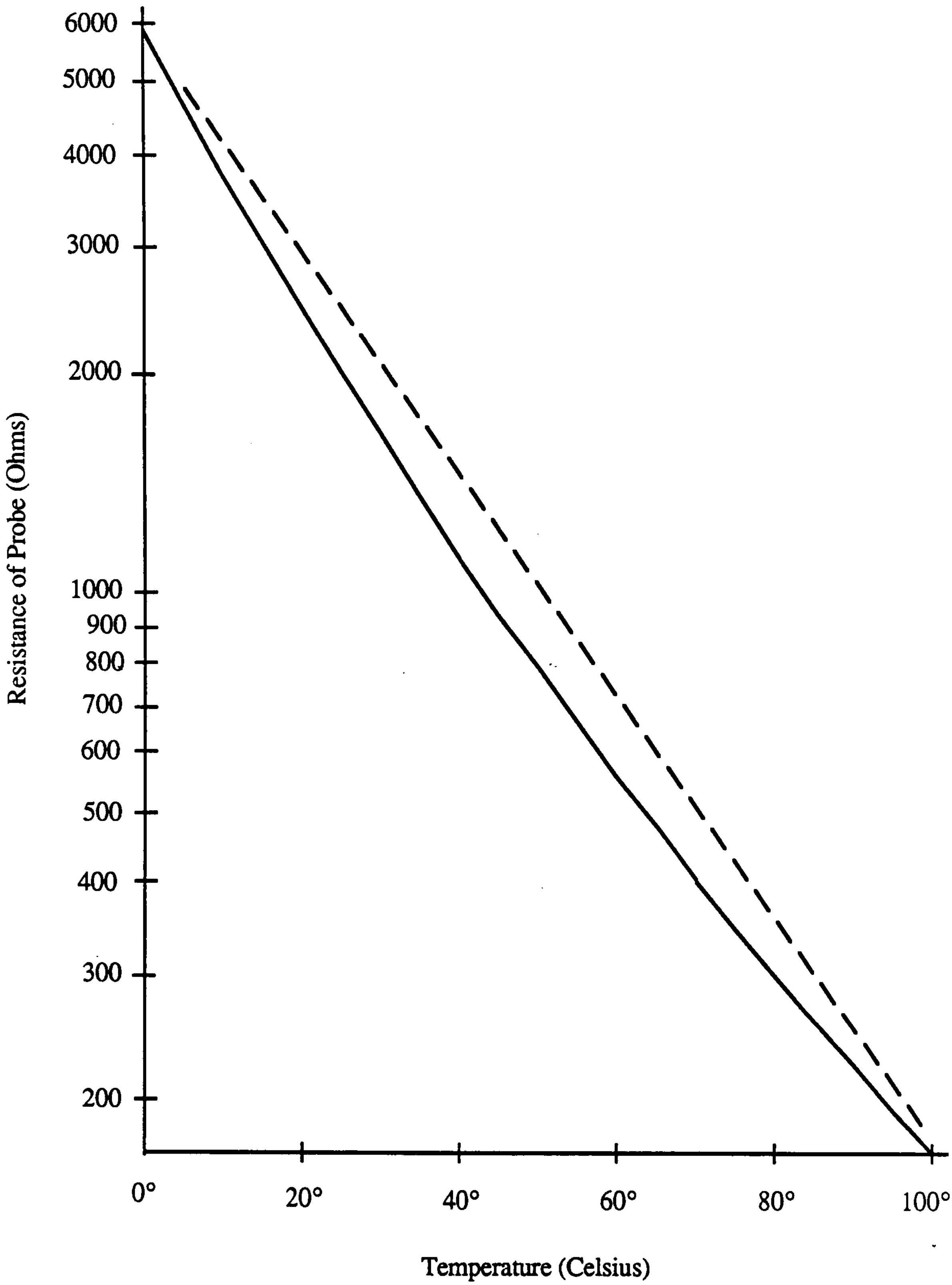

Figure 2. Logarithm of Resistance Versus Temperature Graph.

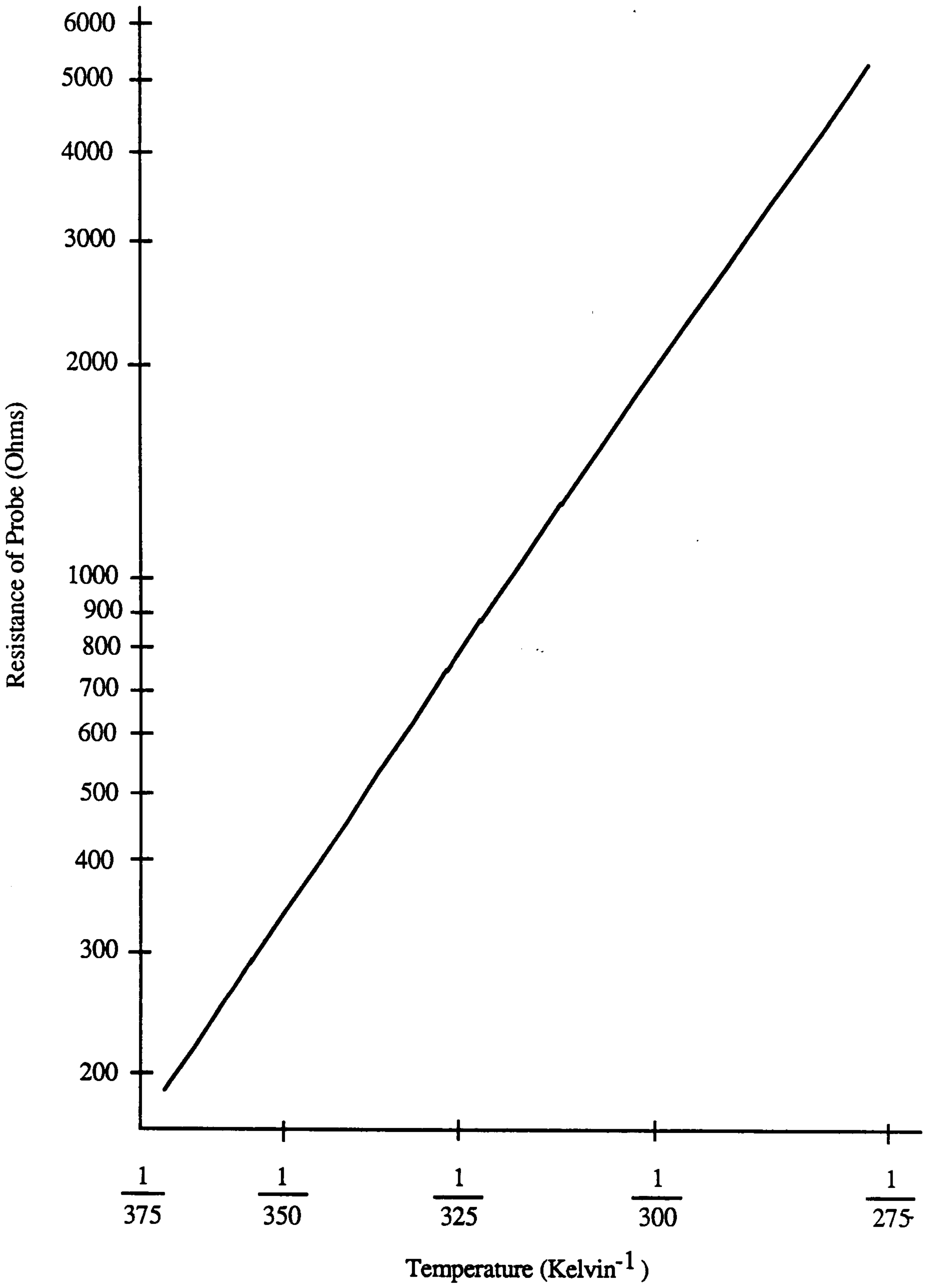

Figure 3. Logarithm of Resistance Versus Inverse Temperature Graph.

a polynomial in the logarithm of the resistance:

$$T^{-1} = a_0 + a_1 \ln R + a_2(\ln R)^2 + a_3(\ln R)^3 + \cdots + a_n(\ln R)^n. \qquad (2)$$

Since the temperature is normally computed from a measured value of resistance, the discussion will concentrate on Equation 2. As expected, the order of the polynomial required depends on the temperature range specified and the degree of accuracy required over this range.

Steinhart and Hart Equation

The use of Equation 2 has been investigated by Steinhart and Hart [5] for thermistors operated in the oceanographic range of minus two to plus thirty degrees Celsius. They found that excellent results can be obtained with a third-order polynomial. They also found that there was no significant loss in accuracy by eliminating the squared term. The resulting Steinhart and Hart equation is:

$$T^{-1} = a_0 + a_1 \ln R + a_3(\ln R)^3. \qquad (3)$$

The work of Steinhart and Hart was confirmed by studies conducted by B.W. Mangum at the National Bureau of Standards and R. Koehler at the Woods Hole Oceanographic Institute. Investigations conducted at Thermometrics, Incorporated, indicate that the Steinhart and Hart equation is valid in the range of zero to 60 degrees Celsius. The differences between computed and measured data points were found to be below 0.001 Kelvin. Over a range of 60 to 150 degrees Celsius, the computation was found to track experimental data within 0.0015 Kelvin. [6]

Temperature Measurement Circuits

The usual circuit for measuring temperatures with thermistors in a laboratory environment is the Wheatstone bridge as shown in Figure 4. This circuit is a very

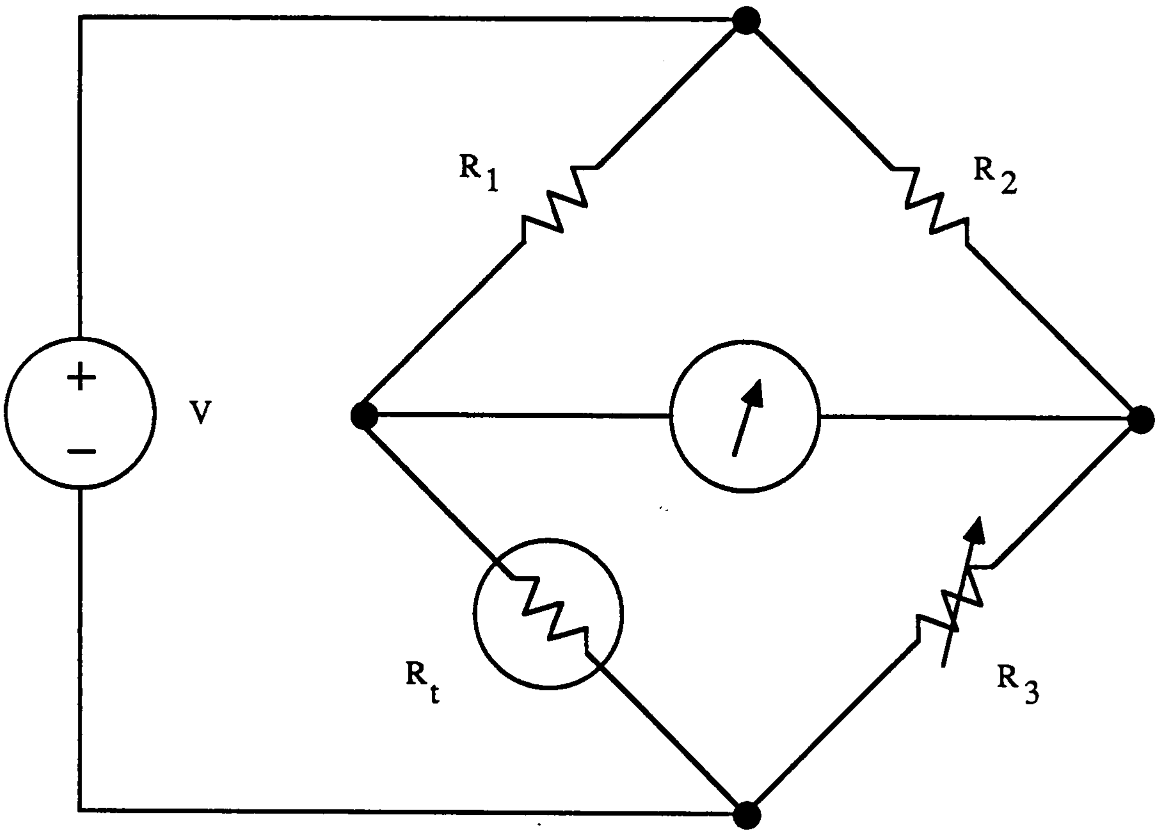

Figure 4. Wheatstone Bridge Circuit.

sensitive and accurate method of measuring the resistance of a component. The temperature is then computed from the measured resistance by using an equation such as the Steinhart and Hart equation. To balance the bridge, R_3 is adjusted until the current through the ammeter is zero. This condition is met when:

$$R_t = R_3 \frac{R_1}{R_2}. \qquad (4)$$

The fixed resistors, R_1 and R_2, are typically well matched (equal resistance and temperature coefficients). Therefore, when the bridge is balanced, R_3 is equal to the resistance of the thermistor. This circuit is used in the laboratory because of its high sensitivity and its ability to measure the resistance of the thermistor under conditions where very small currents are forced through the device. Very small currents are necessary because of the problem of thermistor self-heating. Self-heating is caused by the thermal dissipation of the device and can be expressed by:

$$\Delta T = P_t / \delta = (I^2 R_t) / \delta \qquad (5)$$

where δ is the dissipation constant of the thermistor in Watts per Kelvin. The dissipation constant of thermistors used for resistance thermometry generally fall in the range of 1.0 to 5.0 Milliwatts per Kelvin. A modern Wheatstone bridge can make accurate (±0.02 Ohm) measurements of resistance using only 10 microamperes of current. This limits the self-heating error in a 2,000 Ohm thermistor to 1 Millikelvin. Since the fixed resistors and the variable resistor in the bridge circuit can be measured very accurately using standards traceable to the National Bureau of Standards (NBS), a very accurate measurement of the resistance of the thermistor can be made. This is the method used by thermistor manufacturers and the NBS when precise measurements of thermistor characteristics are made. For obvious reasons, this method is not applicable to multichannel, automated temperature monitoring under field conditions.

Most of the commercially available temperature systems that use thermistors utilize a simple resistor network to partially linearize the response curve over a limited temperature range. The voltage divider circuit shown in Figure 5 is an example. Recall that Thevenin's theorem dictates that all resistor networks can be converted to a single resistor in series with a voltage source. Therefore, any resistive linearization circuit can be reduced to a voltage divider. An analysis of this circuit is sufficient to describe any of these linearization techniques. Assuming that the driving voltage, V, is held constant, the output voltage, V_{out}, is given by:

$$V_{out} = V \cdot R / (R+R_t). \qquad (6)$$

The normalized response curve for this circuit (with typical circuit components) is shown in Figure 6. Notice that for a small temperature range, T_a to T_b, the response curve is almost linear. This circuit design requires a compromise between absolute accuracy and temperature range. For example, this configuration typically yields an accuracy of 0.05 Kelvin over a 20 Kelvin range, an accuracy of 0.1 Kelvin over a 30 Kelvin range, but an accuracy of only 0.5 Kelvin over a 50 Kelvin range. In addition, the circuit complexity is increased due to the necessity of limiting the current through the thermistor to reduce self-heating and the necessity to operate over a reasonable output voltage range. Obviously, this circuit is not suited to very accurate temperature measurement over a broad temperature range.

In order to meet the design goals of this project, a better method of measuring temperatures using thermistors was developed. Instead of attempting to linearize the thermistor curve, the resistance of the device is measured and the temperature is computed by a microprocessor using the proven Steinhart and Hart equation. This approach is similar to the Wheatstone bridge approach described above, except that the resistance of the thermistor is determined using a circuit that is more applicable to automated data collection. This circuit is shown in Figure 7. The constant current source forces a current through the fixed resistance, R_1, and the resistance of the thermistor, R_t. If the voltage developed across these two components are known, then the resistance of the thermistor can be

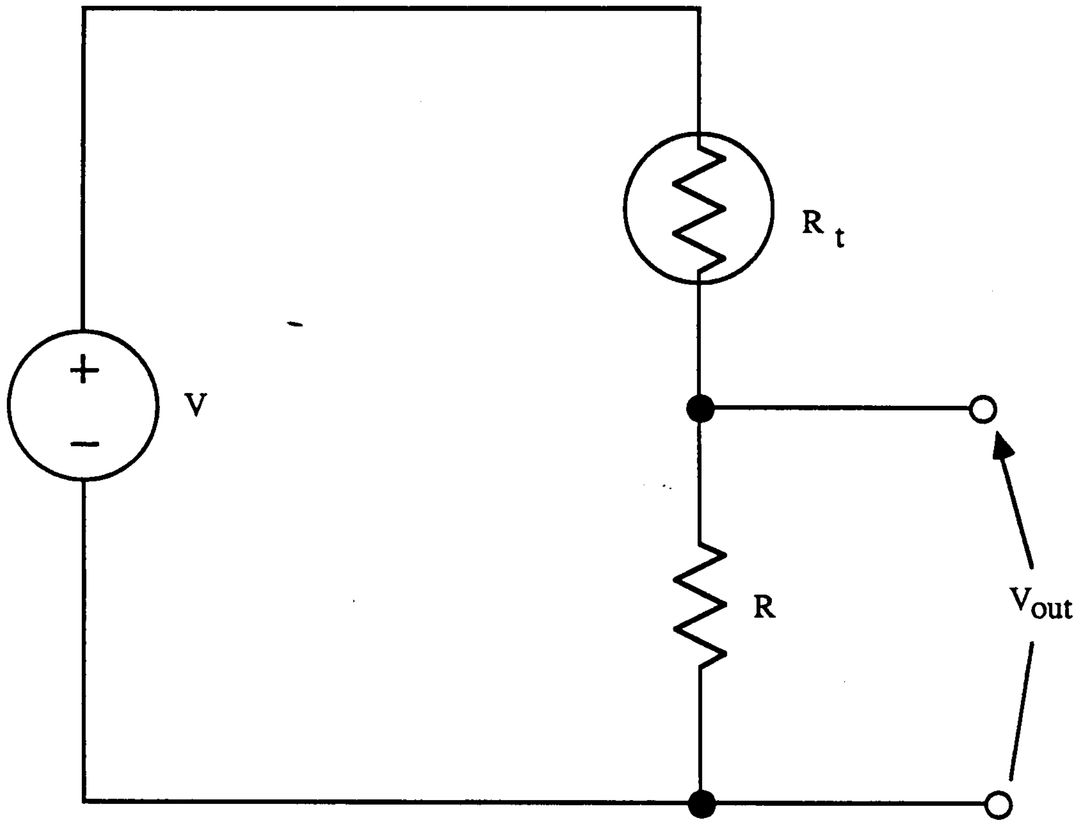

Figure 5. Voltage Divider Circuit.

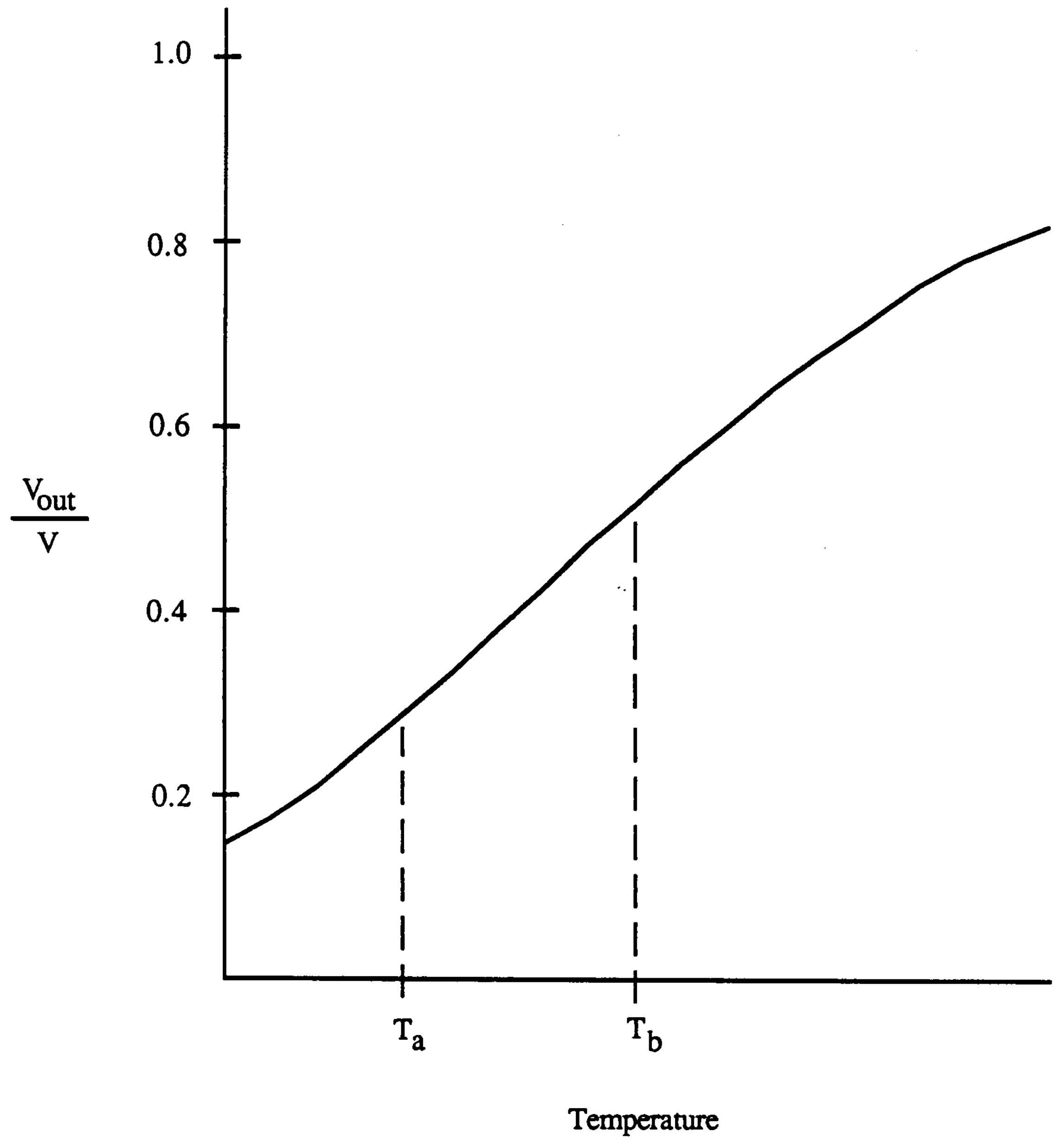

Figure 6. Voltage Divider Temperature Response.

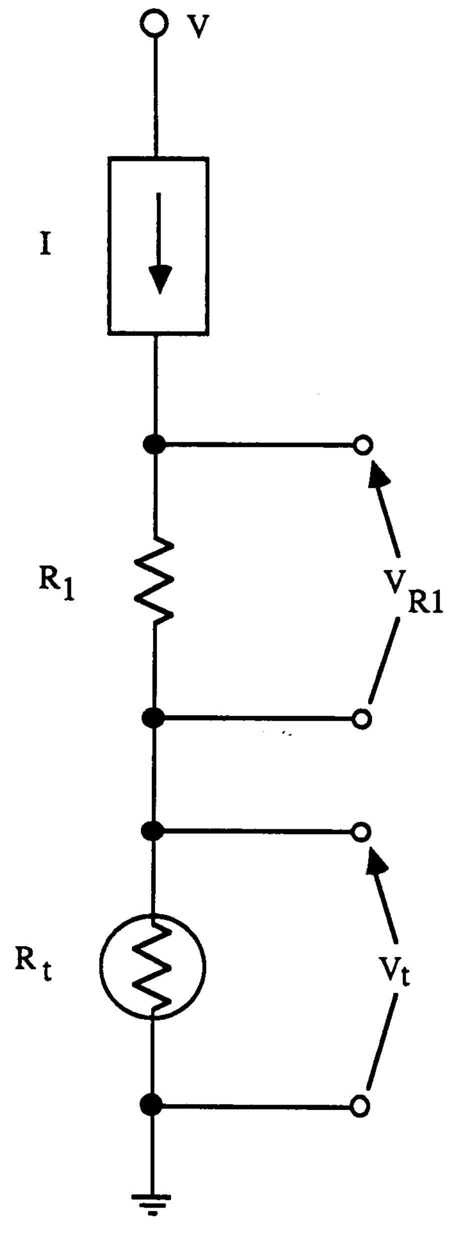

Figure 7. Direct Measurement Circuit.

computed by:

$$R_t = R_1 \cdot V_t / V_{R1}. \qquad (7)$$

This circuit provides a simple yet useful technique of accurately measuring temperature using thermistors. Some constraints are placed on the particular components selected for use in this design. The current and the thermistor resistance must be kept low to avoid self-heating errors but they must be large enough to provide a reasonable value of voltage which can be measured. The range of the voltage measurement device (an analog to digital converter) must be large enough to measure the maximum voltage at the lowest temperature, yet be sensitive enough to detect small changes in voltage at the highest temperature. The choices that were made in the design of the PTS-80B are described in the following chapter.

CHAPTER III

HARDWARE DESIGN

System Overview

Figure 8 shows the overall system block diagram for each of the four sites at the Vermont Yankee nuclear power plant. The PTS-80B collects temperature data from the thermistor probes located up to one thousand feet from each site. These data are then transmitted to the AQM-8000B data logger via a standard RS-232C serial link where they are averaged for various time intervals and stored in battery backed CMOS RAM. Simultaneously, the data logger is collecting analog voltages from up to 16 sensors, performing various functions (such as computing vector averages on wind speed/wind direction data), and storing the resulting averages in CMOS RAM. Several times each day, a central minicomputer calls each of the four sites over the public switched telephone network and collects the averaged temperatures and analog data. A CRT or other serial terminal can be connected to the PTS-80B to perform calibrations on the temperature probes or connected to the AQM-8000B to check and possibly modify its initialization parameters.

A block diagram of the PTS-80B is shown in Figure 9. It consists primarily of a single-board computer, thermistor driver circuits, an internal fixed resistor, an A.C. power supply, and a battery. Fifteen thermistors are driven with constant currents and the resulting voltages are connected to fifteen of the double-ended analog input channels available on the single-board computer. The sixteenth channel is used to monitor and compensate for any system zero drift of the analog section. The measured voltages are converted to temperatures by a program stored in EPROM. The coefficients for the Steinhart and Hart equation for each probe are stored in battery backed CMOS RAM. After the temperatures of all of the probes have been computed, they are transmitted in a

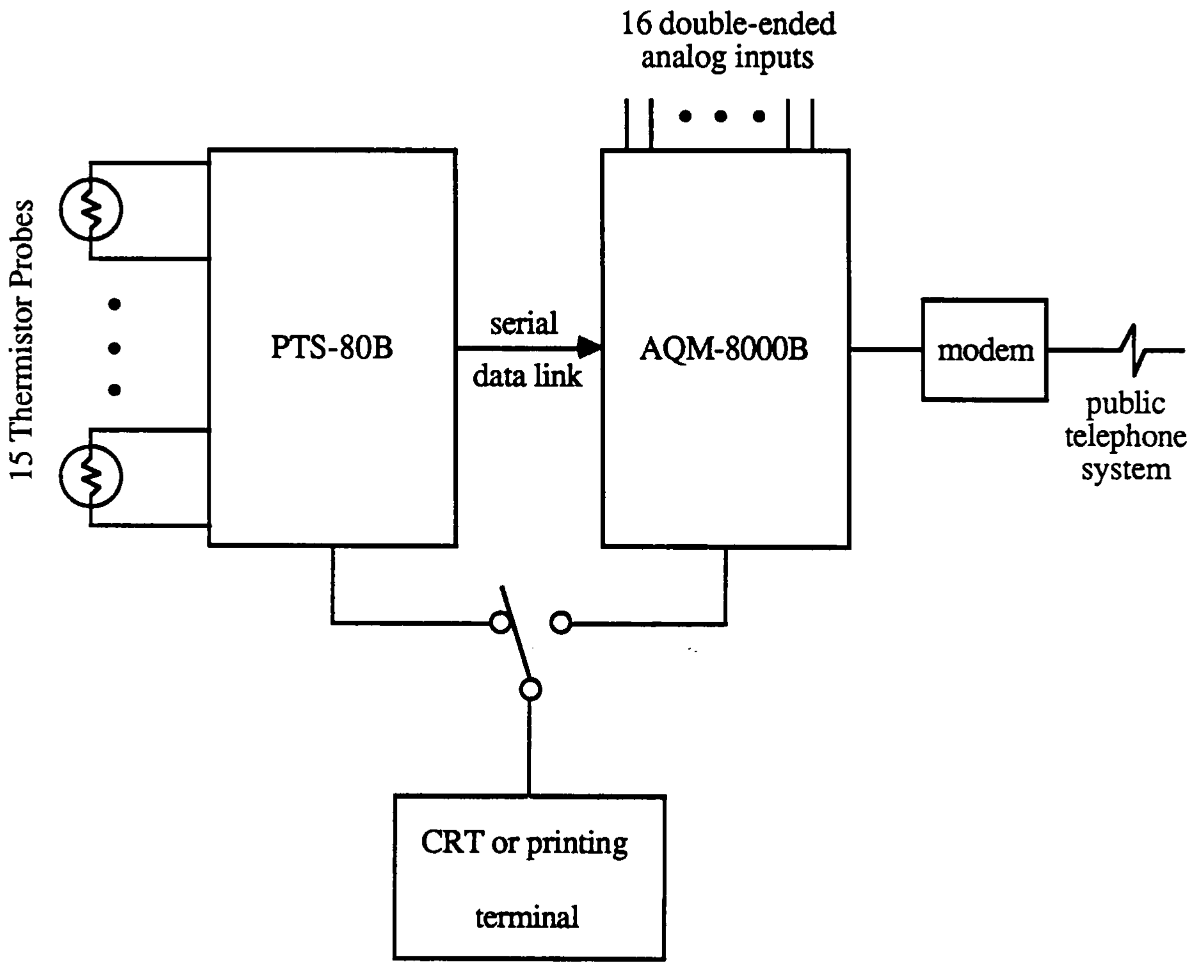

Figure 8. Overall System Block Diagram.

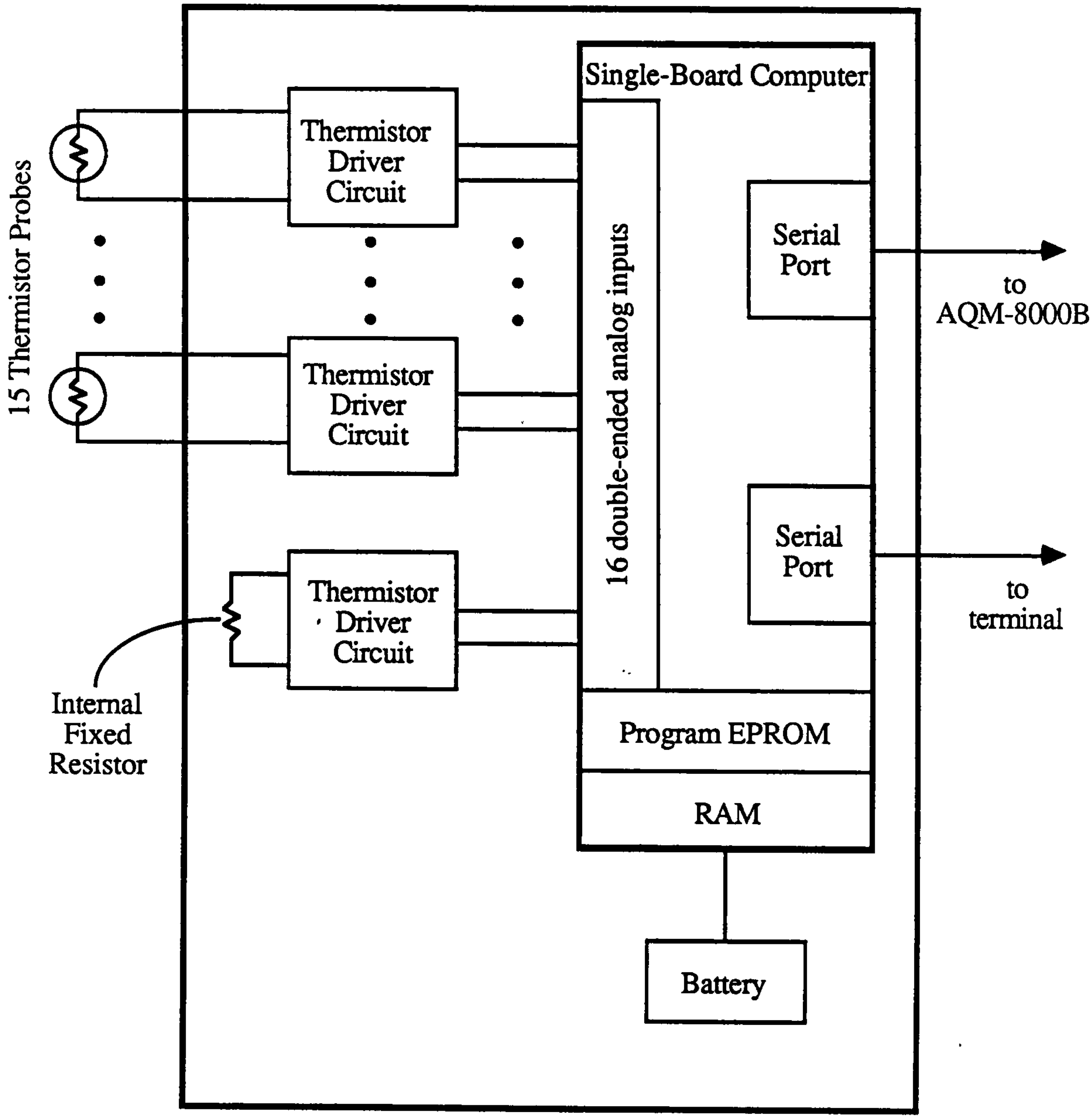

Figure 9. Block Diagram of the PTS-80B.

packed format to the data logger via one of the serial ports. The other serial port can be used by an operator to instruct the software to enter a calibration mode for one of the probes and allows the coefficients for that probe to be modified.

Component Selection

There were two major areas that required extensive hardware design in the PTS-80B: the thermistor driver circuit and the modifications necessary to the single-board computer. The initial design of the thermistor drive circuit is shown in Figure 10. A constant current source drives a current through a precision resistor, R_p, and the thermistor probe, R_t. The differential voltages across the two resistors are multiplexed to one of the analog inputs of the single-board computer. The multiplexer is controlled by the software routine via a digital control output line from the single-board computer.

Since the current through the thermistor needs to be known to a high accuracy, the circuit is designed to measure this parameter every time a scan is made. Consequently, the current source does not need to be long-term stable, that is, as long as the value of the current does not drift so far as to cause over-voltage values, or does not drift over the short time between reading the precision resistor and the thermistor, then the source is sufficiently stable. A high quality, low drift, and inexpensive current source is the National Semiconductor LM334. It will deliver a current based on only one external resistor, R_{set}, and is virtually immune to small power supply fluctuations. The dual two-to-one multiplexer in the circuit is critical to the precision and accuracy of the system. This is the only part of the analog circuit that is different between measuring the precision resistor and the thermistor. It should be well matched between inputs and the total leakage currents should be low. The National Semiconductor LF13333 is a set of four JFET switches with low leakage specifications in both the ON and the OFF states. This device has been used with success by the author in previous projects and was selected again for this design.

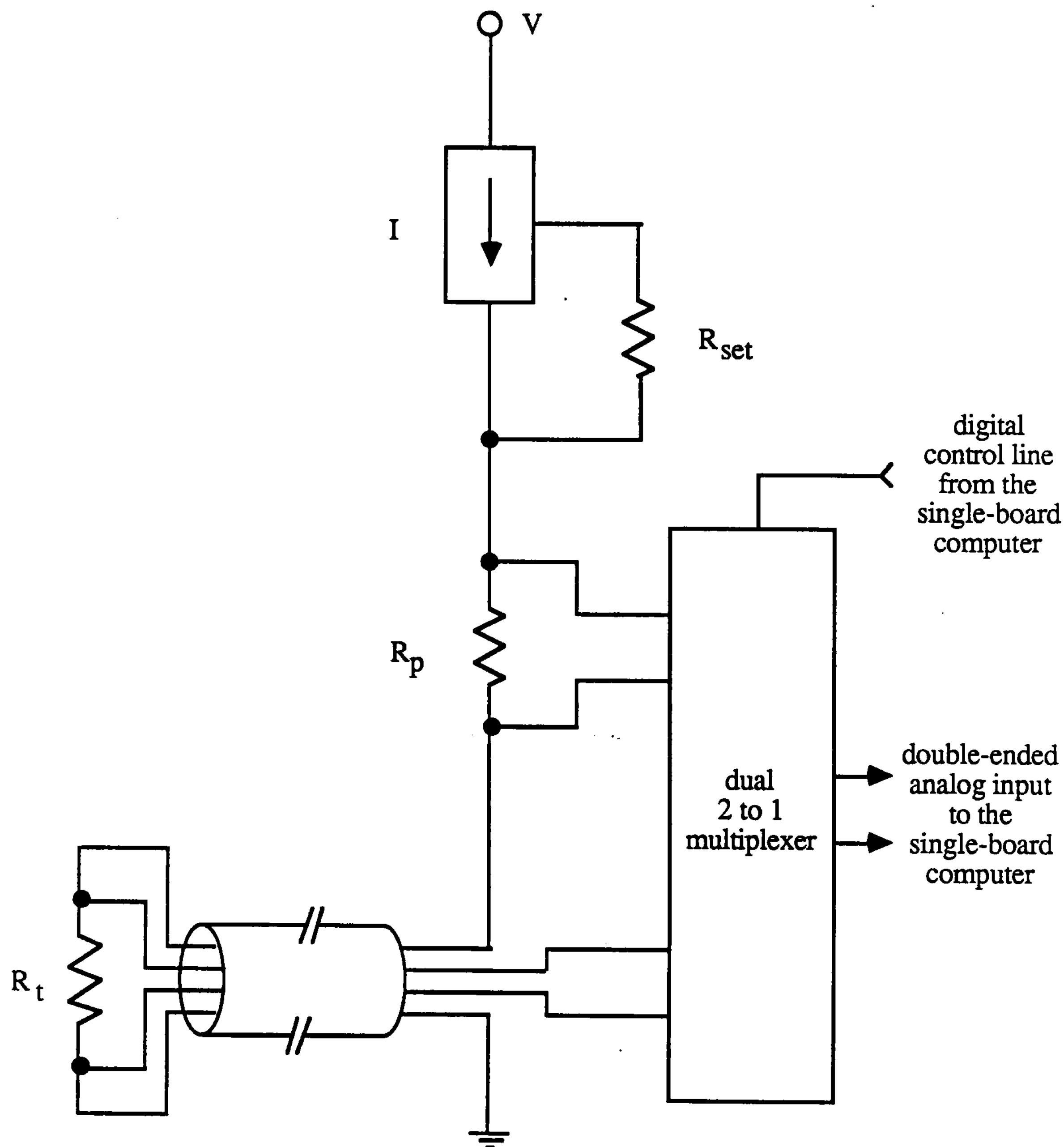

Figure 10. PTS-80B Thermistor Driver Circuit.

Before the values of the other components in the circuit could be determined, it was necessary to first compute the nominal value of the thermistor to be used. Two considerations entered into this decision:

1. The value should be large to provide a large voltage across the thermistor. This reduces the error effects of thermocouple voltages and the resistance of the wire leads.
2. High values for the thermistor imply low current values to limit the error resulting from self-heating. If the current is very low, leakage currents in the multiplexer and on the circuit board can produce significant errors.

The high stability thermistors from Thermometrics are available in values from 1000 to 15,000 ohms at a tolerance of ±20 percent. Table 1 shows these nominal values at 25 degrees Celsius and the maximum value of each type over the range of zero to 60 degrees Celsius (i.e., the value at zero degrees plus 20 percent). Rearranging Equation 5 yields an equation for the maximum current allowable through a thermistor to maintain a specified self-heating error:

$$I = \sqrt{\frac{\Delta T \cdot \delta}{R_t}} . \qquad (8)$$

The maximum allowed current is at a minimum when the thermistor resistance is at a maximum, so the maximum allowable current for each of the thermistor values in Table 1 is computed for a maximum error of 0.01 Kelvin and a dissipation constant of 0.003 Watts/Kelvin. The results are labeled I_{max} in Table 1. The maximum voltage over the temperature range is given by:

$$V_{max} = I_{max} \cdot R_{max} \cdot \qquad (9)$$

This value is also presented in Table 1. Obviously, the largest value of thermistor should be chosen to reduce errors caused by noise and thermocouple effects. However, the small currents required for these large valued thermistors can lead to errors resulting from leakage currents in the multiplexer.

Table 1. Circuit Parameters for Various Thermistor Values.

R (25° C)	R_{max}	I_{max}	V_{max}
1000 Ω	3530 Ω	92 µA	0.325 V
1200 Ω	4236 Ω	84 µA	0.356 V
1500 Ω	5296 Ω	75 µA	0.398 V
1700 Ω	6002 Ω	70 µA	0.424 V
2000 Ω	7061 Ω	65 µA	0.460 V
4000 Ω	14123 Ω	46 µA	0.650 V
5000 Ω	17634 Ω	41 µA	0.728 V
7000 Ω	24715 Ω	35 µA	0.861 V
10000 Ω	35308 Ω	29 µA	1.029 V
12000 Ω	42369 Ω	27 µA	1.127 V
15000 Ω	52962 Ω	24 µA	1.261 V

The allowable error in the resistance of the thermistor is given by:

$$\varepsilon = \frac{R_t(T) - R_t(T+\Delta T)}{R_t(T)} = \frac{\Delta R_t(T)}{R_t(T)} \quad . \qquad (10)$$

This allowable error in the measurement of the resistance is a function of both the accuracy of the temperature to be measured (ΔT) and the temperature at which the measurement is made (T). Since,

$$\Delta R_t(T) = \frac{d\,R_t}{d\,T}\,\Delta T \qquad (11)$$

when ΔT is small, then Equation 10 becomes:

$$\varepsilon = \frac{d\,R_t}{d\,T} \cdot \frac{\Delta T}{R_t(T)} \quad . \qquad (12)$$

If the Steinhart and Hart equations are written as resistance as a function of temperature we have:

$$R_t = \exp\,(A_0 + A_1 T^{-1} + A_3\,T^{-3}) \quad . \qquad (13)$$

Then, taking the derivative with respect to T:

$$\frac{d\,R_t}{d\,T} = \exp\,(\,A_0 + A_1 T^{-1} + A_3\,T^{-3})\,(\,-A_1 T^{-2} - 3A_3 T^{-4}) \quad . \qquad (14)$$

Now, substituting Equations 13 and 14 into Equation 12, we have:

$$\varepsilon = (\,-A_1 T^{-2} - 3A_3 T^{-4})\,\Delta T \quad . \qquad (15)$$

This equation shows that the allowable error, ε, gets smaller for increasing T. Therefore, the allowable error is minimum when the temperature is the greatest. By substituting the maximum temperature into Equation 10, the minimum allowable error in the resistance measurement of R_t that can be tolerated can now be expressed as:

$$(\varepsilon)_{min} = \frac{R_t(T_{max}) - R_t(T_{max} + \Delta T)}{R_t(T_{max})} \quad . \qquad (16)$$

The intrinsic value of resistance of a thermistor at any temperature can be expressed as the ratio of the resistance of the thermistor to the resistance at 25 degrees Celsius. This intrinsic resistance is the same for any nominal value of thermistor and can be expressed as:

$$\rho\,(T) = R_t\,(T) \,/\, R_t\,(25°\,C)\,. \qquad (17)$$

This function holds for any value of thermistor so, in the general case, Equation 16 becomes:

$$(\varepsilon)_{min} = \frac{\rho\,(T_{max}) \; - \; \rho\,(T_{max} + \Delta T)}{\rho\,(T_{max})}\,. \qquad (18)$$

Over the temperature range of zero to 60 degrees Celsius and with a maximum error (ΔT) of 0.01 Kelvin, the minimum allowable uncertainty in the resistance measurement of the thermistor is:

$$(\varepsilon)_{min} = \frac{\rho\,(60°\,C) - \rho\,(60.01°\,C)}{\rho\,(60°\,C)} = \frac{(0.27985) - (0.27976)}{(0.27985)} = 0.03\,\%\,. \qquad (19)$$

The resistance of the thermistor is computed from the measured voltages and the known value of the precision resistor by:

$$R_t = \frac{V_t}{V_p}\,Rp\,. \qquad (20)$$

The precision resistor can be specified to an accuracy of 0.01 percent which means that the maximum uncertainty of the voltage ratio ($V_t \,/\, V_p$) can be no greater than 0.02 percent. Now, since:

$$\frac{V_t}{V_p} = \frac{I_t \cdot R_t}{I_p \cdot R_p}\,, \qquad (21)$$

and since R_t and R_p are fixed, then this relationship implies that I_t cannot vary by more than 0.02 percent from I_p. From this reasoning, the following relationships must be valid:

$$\Delta I \,/\, I \le 0.02\,\% \quad \text{and} \quad I \ge \Delta I \,/\, 0.0002\,. \qquad (22)$$

This gives a method of choosing a thermistor based on the value of current error expected between the thermistor and the precision resistor. Since the LM13333 has a maximum ON leakage current of 10 nanoamperes, the current through the thermistor should, therefore, be at least 50 microamperes (10 nanoamperes / 0.0002). The largest value thermistor available from Thermometrics that would allow at least 50 microamperes of current is the 2000 ohm thermistor which will allow up to 65 microamperes without exceeding 0.01 Kelvin self-heating error. The resistor, R_{set}, is determined by the equation relating the current and the set resistor for the LM334:

$$I = 67.7 \text{ mV} / R_{set} \ . \qquad (23)$$

For a value of 65 microamperes, R_{set} should be no less than 1041 ohms. A metal-film resistor with a nominal value of 1100 ohms (±1.0 percent) was selected. This yields a maximum current of:

$$I_{max} = \frac{67.7 \text{ mV}}{R_{max}} = \frac{67.7 \text{ mV}}{(1100 - 1\%)} = 62.2 \, \mu\text{A} \qquad (24)$$

and a maximum self-heating error of:

$$\Delta T = \frac{(I_{max})^2 (R_{max})}{\delta} = \frac{(62.2 \, \mu\text{A})^2 (7061)}{(0.003)} = 0.0091 \text{ Kelvin} \ . \qquad (25)$$

The maximum voltage generated across the thermistor is then:

$$V_{max} = I_{max} \cdot R_{max} = (62.2 \, \mu\text{A}) (7061 \, \Omega) = 0.439 \text{ Volts} \ . \qquad (26)$$

The full-scale voltage of the single-board computer was set for 0.500 Volts to allow for up to a 10 percent variation due to possible gain drift. The value of the precision resistor was selected to be 6810 ohms. This value is near the high range of the expected thermistor values and should yield the most precise measurement of the current with the lowest amount of noise.

In the digitization of analog voltages, two major factors can contribute to errors: gain drifts and zero offset drifts. The gain and zero of the analog section of the single-board computer can be adjusted during calibration procedures but any short-term drift, or drift due to changes in the ambient temperature, must be corrected if high precision is to be maintained. Due to the ratiometric nature of the calculations, any gain drift is the same for all temperature measurements and is cancelled from the equations. For example, suppose that the measured voltages across the precision resistor, V_p, and the thermistor, V_t, are incorrect by a certain factor, α. The equation used to compute the resistance of the thermistor, given the resistance of the precision resistor and the voltages across each, is Equation 20. This now becomes:

$$R_t = \frac{\alpha V_t}{\alpha V_p} R_p \,. \qquad (27)$$

This equation shows that if both of the measured voltages deviate by the same factor from the actual voltages, then the computed resistance of the probe is unaffected. In other words, a gain drift is unimportant as long as it is not so large as to cause an over-range condition in the analog section of the single-board computer.

Of major concern in the design was the offset voltage drift of the analog amplifier and the analog to digital converter. This factor can have profound effects on the measurement accuracy if uncorrected, especially at high temperatures when the low resistances of the thermistor leads to low measured voltages. A method was developed to automatically compute the offset voltage during every scan of the thermistor probes so that this factor can be removed when the thermistor resistance is computed. The measured voltages across the thermistor and the precision resistor can now be expressed as:

$$V_t = I \cdot R_t + V_0 \quad \text{and} \quad V_p = I \cdot R_p + V_0 \,. \qquad (28)$$

Solving these expressions simultaneously for R_t gives:

$$R_t = \frac{V_t - V_0}{V_p - V_0} R_p \,. \qquad (29)$$

To compute V_0, the sixteenth channel of the single-board computer is configured the same as the other fifteen except that, instead of a precision resistor and a thermistor probe, two temperature-stable precision resistors, R_1 and R_2, are connected in series with a constant current source as shown in Figure 11. The measured voltages across these resistors are offset by the same amount (V_0) as the voltages across the thermistors and the precision resistors on all of the other channels:

$$V_1 = I \cdot R_1 + V_0 \quad \text{and} \quad V_2 = I \cdot R_2 + V_0 . \qquad (30)$$

Solving these expressions for the offset voltage yields:

$$V_0 = \frac{R_2 V_1 - R_1 V_2}{R_2 - R_1} . \qquad (31)$$

Note that the current in this circuit does not have to be exactly the same as in the probe driver circuit for the fifteen thermistors. To determine the optimum value for R_1 and R_2 let $R_2 = n \cdot R_1$, Equation 31 then becomes:

$$V_0 = \frac{nR_1V_1 - R_1V_2}{nR_1 - R_1} = \frac{nV_1 - V_2}{n - 1} . \qquad (32)$$

Taking the partial derivative of V_0 with respect to n gives:

$$\frac{\partial V_0}{\partial n} = \frac{V_2 - V_1}{(n - 1)^2} . \qquad (33)$$

But to a very close approximation, $V_2 = n \cdot V_1$, so Equation 33 becomes:

$$\frac{\partial V_0}{\partial n} = \frac{(n - 1)\, V_1}{(n - 1)^2} = \frac{V_1}{n - 1} . \qquad (34)$$

Since the partial derivative is at a minimum for the largest possible value of n, R_1 should be made as small as possible and R_2 should be made as large as possible. To maintain consistency, the current through the zero offset circuit was set to the same value as the current through the thermistor driver circuits. Further, R_2 was selected as 6810 ohms; the same value as the precision resistor, R_p, in the thermistor driver circuit. This resistance is near the high limit of the expected thermistor resistance range. The other resistor in the circuit, R_1, was set at 600 ohms; near the low limit of the resistance range. All of these resistors (R_1, R_2, and the fifteen R_p's) were selected to have very low drift, high

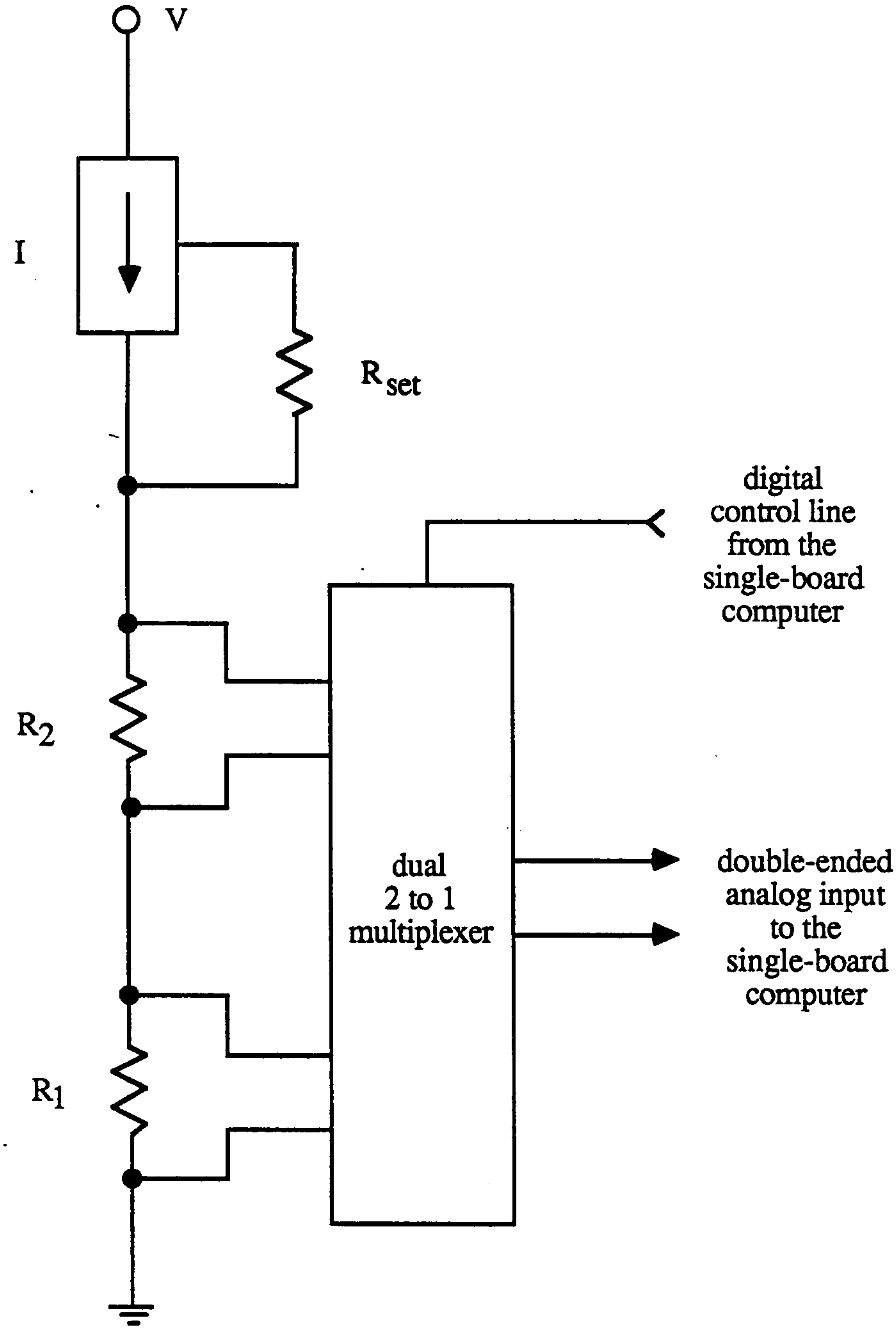

Figure 11. Offset Voltage Measurement Circuit.

precision (0.01 percent), and very low temperature coefficients (three parts per million per Kelvin).

RMC-80 Single-board Computer

Figure 12 shows a block diagram of the RMC-80 single-board computer manufactured by the author's company, Environmental Systems Corporation. This board has all of the necessary hardware to perform a wide range of analog voltage collection, processing, and storage. It is normally used as an environmental data logger in remote data acquisition settings to scan voltages generated by meteorological and ambient air quality instrumentation. The software for this application is written in Z80 assembly code and is tailored to the specific needs of the air quality monitoring field. Data is collected from the integrating analog to digital converter (A/D), averaged into five minute and hourly averages, and stored in battery-backed CMOS RAM. Periodically, a central computer will contact the logger via a dial-up modem attached to one of the serial ports and collect the averaged data. A second serial port is used to provide access to the data logger by on-site personnel using a portable terminal. The arithmetic processing unit (APU) is used to perform the floating point functions required to generate vector averages of wind speed and wind direction data while the battery-backed real-time clock maintains the time-of-day to allow proper time tagging of the averaged data. The digital input and output lines are used to initiate calibration cycles and monitor status conditions of the instrumentation.

Several of these same features were needed in the design of the PTS-80B while some of the capabilities were unused. Because of the complexity of the Steinhart and Hart equation and the desire to make the software in the PTS-80B easily modified, BASIC was chosen as the programming language. An EPROM based BASIC interpreter from Mark Williams Company was purchased and ported to the RMC-80 board. The PTS-80B program was written completely in BASIC except for the software driver for the A/D converter which was programmed in assembly language. The BASIC program is stored in

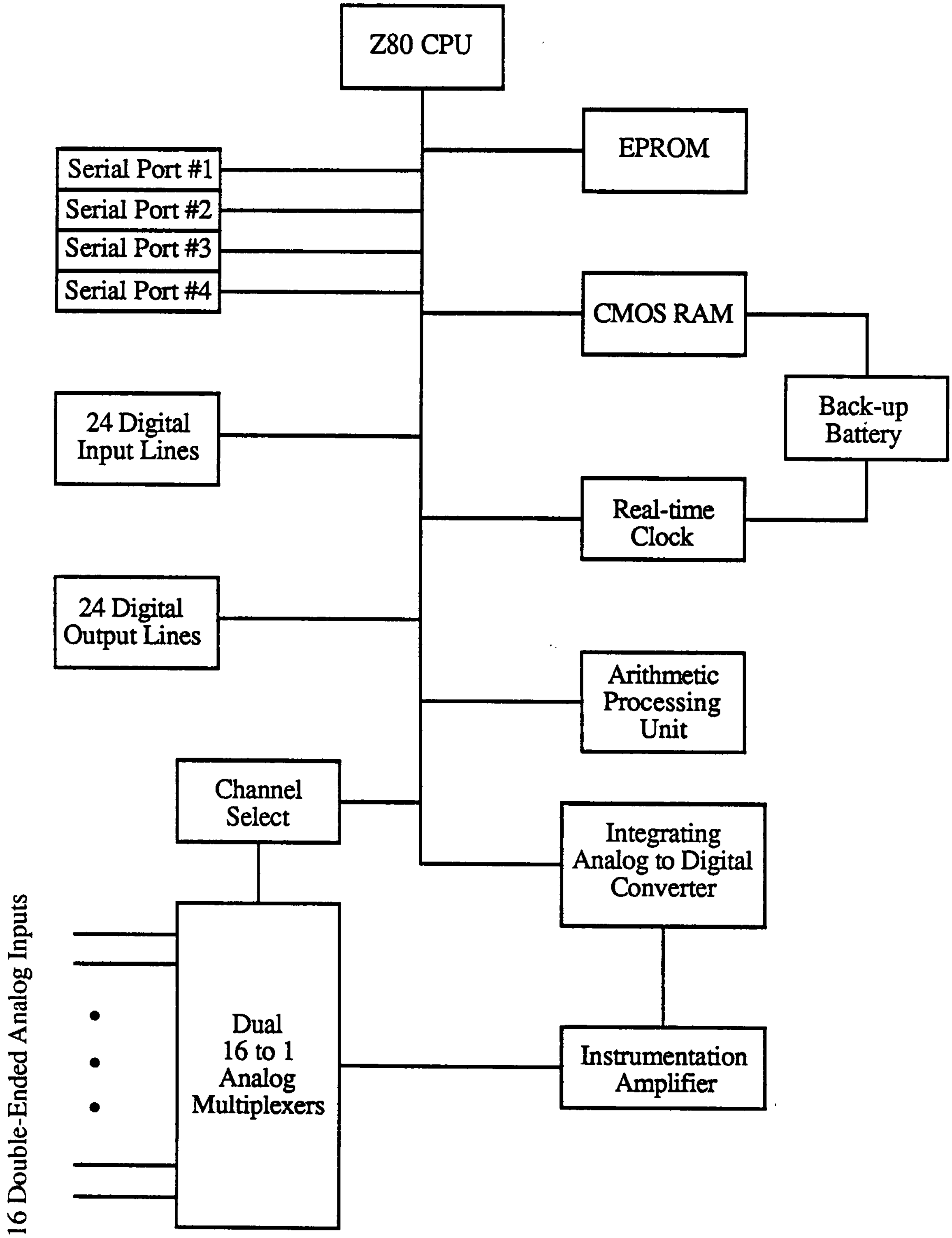

Figure 12. RMC-80 Single-Board Computer Block Diagram.

EPROM while the BASIC variables and the thermistor calibration points are stored in battery-backed CMOS RAM. Because of the use of BASIC, the APU was not needed for the PTS-80B. BASIC performs all of its mathematical functions in software and because the scan speed of the unit was not critical nor demanding, this situation produced acceptable results. Also, the real-time clock was not necessary because the temperature data were not stored long-term in the PTS-80B and did not need to be time-tagged. One of the serial ports was used to communicate with the BASIC program. This port was used to run calibration procedures and to monitor the calculated probe temperatures. A second serial port was used in a write only mode to transmit strings of temperature to a properly programmed AQM-8000B data logger. This data logger received the temperature data, averaged them over five minute and hourly intervals, and stored them with data taken from its sixteen analog voltage inputs. The remaining two serial ports on the PTS-80B were unused.

None of the digital input lines were utilized and only one of the digital output lines was used. This output line was used to control which of the analog voltages from each probe (the voltage across the precision resistor or the voltage across the thermistor probe) would be selected by the corresponding LF13333 to be measured by the single-board computer. When this control bit is a "one", the voltages across the 6810 ohm precision resistors are presented to the input multiplexers on the RMC-80 board. Conversely, when this bit is a "zero", the voltages available at the multiplexers are the voltages across the fifteen thermistor probes and the voltage across the 600 ohm resistor, R_1. One of the sixteen available differential voltages is selected by the software to be passed to the instrumentation amplifier where it is amplified and converted to a single-ended voltage that is applied to the input of the dual-slope integrating A/D converter. The A/D integrates for exactly 32 cycles of 60 Hertz (533.3 milliseconds) to reject any A.C. noise that may be on the signal and reports the digitized voltage to the microprocessor. This voltage is stored until all of the voltages have been collected at which time the software uses the Steinhart and Hart equation and the calibration points for each probe to compute the probe's temperature. These temperatures and the calculated digital offset, V_0, are displayed on the local terminal and transmitted to the data logger over the serial link.

Analog to Digital Converter Modification

The RMC-80 board is designed around a 12-bit plus sign, dual-slope integrating A/D converter, the ICL7109 from Intersil, Incorporated. This device is more than adequate for the requirements of air quality monitoring but does not have the resolution to measure the voltages associated with the PTS-80B. To determine the number of bits of resolution necessary to handle the zero to 60 degree Celsius range to an accuracy of ±0.01 Kelvin, first define the minimum voltage change, ΔV, that can be detected by a A/D with a resolution of 'b' bits at a full-scale voltage of V_{fs}:

$$\Delta V = V_{fs} / 2^b . \qquad (35)$$

Now, the minimum detectable voltage change must be less than minimum expected voltage change over the temperature range. This occurs at the high end of the temperature range:

$$\Delta V \leq V_{59.99} - V_{60.00} \cdot \qquad (36)$$

Combining Equations 35 and 36,

$$V_{fs} / 2^b \leq V_{59.99} - V_{60.00} \cdot \qquad (37)$$

Realizing that:

$$V_{fs} = R_{max} \cdot I$$

$$V_{59.99} = R_{59.99} \cdot I$$

$$\text{and} \qquad V_{60.00} = R_{60.00} \cdot I \qquad (38)$$

allows Equation 37 to be rewritten as:

$$R_{max} / 2^b \leq R_{59.99} - R_{60.00} \cdot \qquad (39)$$

Rearranging, Equation 39 becomes:

$$2^b \geq \frac{R_{max}}{R_{59.99} - R_{60.00}} \quad . \qquad (40)$$

Solving for the number of bits required yields:

$$b \geq \frac{\ln\left(\dfrac{R_{max}}{R_{59.99} - R_{60.00}}\right)}{\ln(2)} \quad . \qquad (41)$$

Noticing that the maximum resistance occurs at the minimum temperature (zero degrees Celsius) and inserting the proper values for the 2000 ohm nominal value thermistor, the minimum number of bits required for the A/D converter can be computed as:

$$b \geq \frac{\ln\left(\dfrac{5884.54}{559.88 - 559.70}\right)}{\ln(2)} = 14.9967 \text{ bits} . \qquad (42)$$

This equation shows that the resolution of the A/D converter must be at least 15-bits. The ICL7109 with its 12-bits will not handle the resolution required for this application, thus a modification was developed to handle 15-bit resolution on the RMC-80 single-board computer. Fortunately, a 15-bit plus sign integrating device, the TSC800 manufactured by Teledyne Corporation, is available. This chip is almost pin-for-pin compatible with the popular ICL7109 integrated circuit. Both are integrating A/Ds and both interface to the microprocessor bus in a similar manner. The only differences are in a few of the pin connections and in the value of the integration resistor that is used. To use this device on the RMC-80 board, a simple adapter printed circuit board was designed that mated with the existing ICL7109 socket and provided a socket for the TSC800. This printed circuit board rearranged the connections where appropriate and allowed space to mount the new integration resistor. The new 15-bit converter operates off of the same clock signal as the old 12-bit converter, but because of the extra bits, the new converter takes eight times longer to perform one conversion. Again, the scan speed was not critical so no effort was made to increase the clock speed even though the TSC800 will operate at up to four times faster than the clock speed used in the PTS-80B design.

CHAPTER IV

SOFTWARE DESIGN

Language Selection

Several software programming languages were investigated for this project; assembly language, "C", and BASIC were all considered. The main criteria for the language were the initial programming time required, the ease of testing the program, the ability to handle the floating point mathematics required by the Steinhart and Hart equation, and the ability to easily modify the program should these thermistor equations need to be changed. BASIC was the language that best met these criteria. The author was familiar with BASIC and did not have to learn to program in a language like "C", so the initial programming time was minimized. Assembly language with the APU chip on the single-board computer would have handled the tasks required but since execution time was not critical, the difficulty of debugging and modifying assembly language programs made this option less acceptable. The particular BASIC that was chosen was the XY-BASIC interpreter published by Mark Williams, Incorporated. This interpreter is designed to be PROM-based so it could be burned into EPROM and it has the capability to automatically run application programs also stored in EPROM. All of the floating point functions that were needed in the program were provided by the BASIC software so the APU math chip was not needed. The cost savings incurred by not having to include this relatively expensive chip almost offset the cost of buying the software license for each unit. XY-BASIC is a general purpose interpreter written for the Z80 microprocessor and can be run on almost any Z80-based computer system. The only requirement necessary to port this BASIC to the RMC-80 single-board computer was to provide the proper I/O device drivers and allocate BASIC its RAM workspace. The I/O drivers are the hardware specific kernel routines that are written in assembly language and allow BASIC to communicate with the serial input and output ports on the computer board. In addition, an initialization routine was included to provide some custom processing before BASIC is invoked on start-up, and an assembly language subroutine was included which simplifies driving the A/D converter from a BASIC program.

Program Flow

Figure 13 shows the relationship between the various modules that comprise the PTS-80B software program. When the computer is reset or when power is first applied, the assembly language initialization routines are invoked. These routines initialize the serial input/output ports on the RMC-80 single-board computer and test an area of RAM to determine if this is a "cold" or "warm" start. If the area of RAM does not contain a particular test pattern, then the code assumes that this is the first time that this PTS-80B has been operated and therefore initializes all RAM areas, sets default values for all thermistor calibration points, and then transfers control to the BASIC interpreter. If the test pattern matches in RAM, then the program assumes that the program has been operating before and does not alter any stored information before transferring to BASIC. XY-BASIC then loads and begins executing the proper BASIC application program stored in EPROM. As the application program is interpreted, all input and output statements such as "INPUT" and "PRINT" are executed using the assembly language I/O drivers that receive and transmit characters to and from the serial ports. When the application program needs to read data from the A/D converter, it calls an assembly language subroutine that controls the A/D conversion process and returns the digitized voltage data.

The BASIC application program consists of three main procedures: determining the calibration coefficients, computing the probe temperatures, and calibrating new and existing probes. A flowchart of the application program can be found in Figure 14. After the assembly language initialization procedure is complete, the application program first computes the equation coefficients for each of the fifteen thermistor probes from the

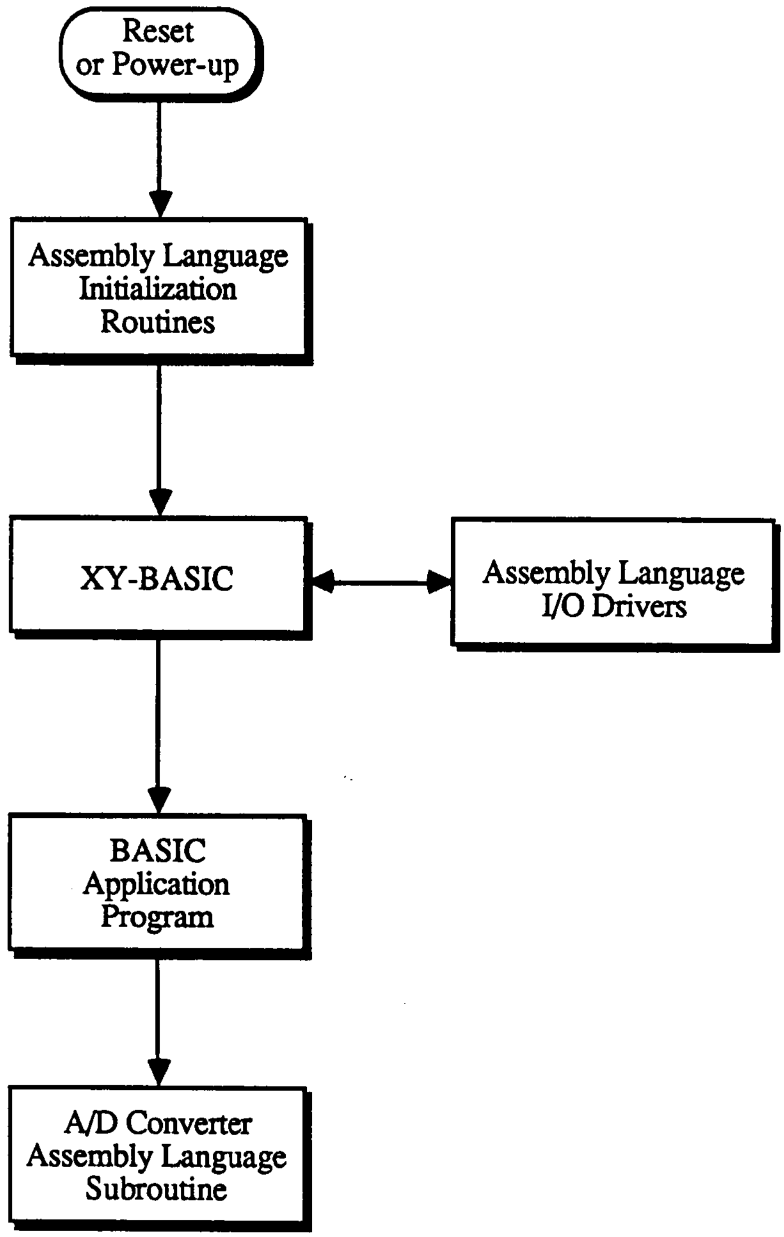

Figure 13. Overall Program Flow in the PTS-80B.

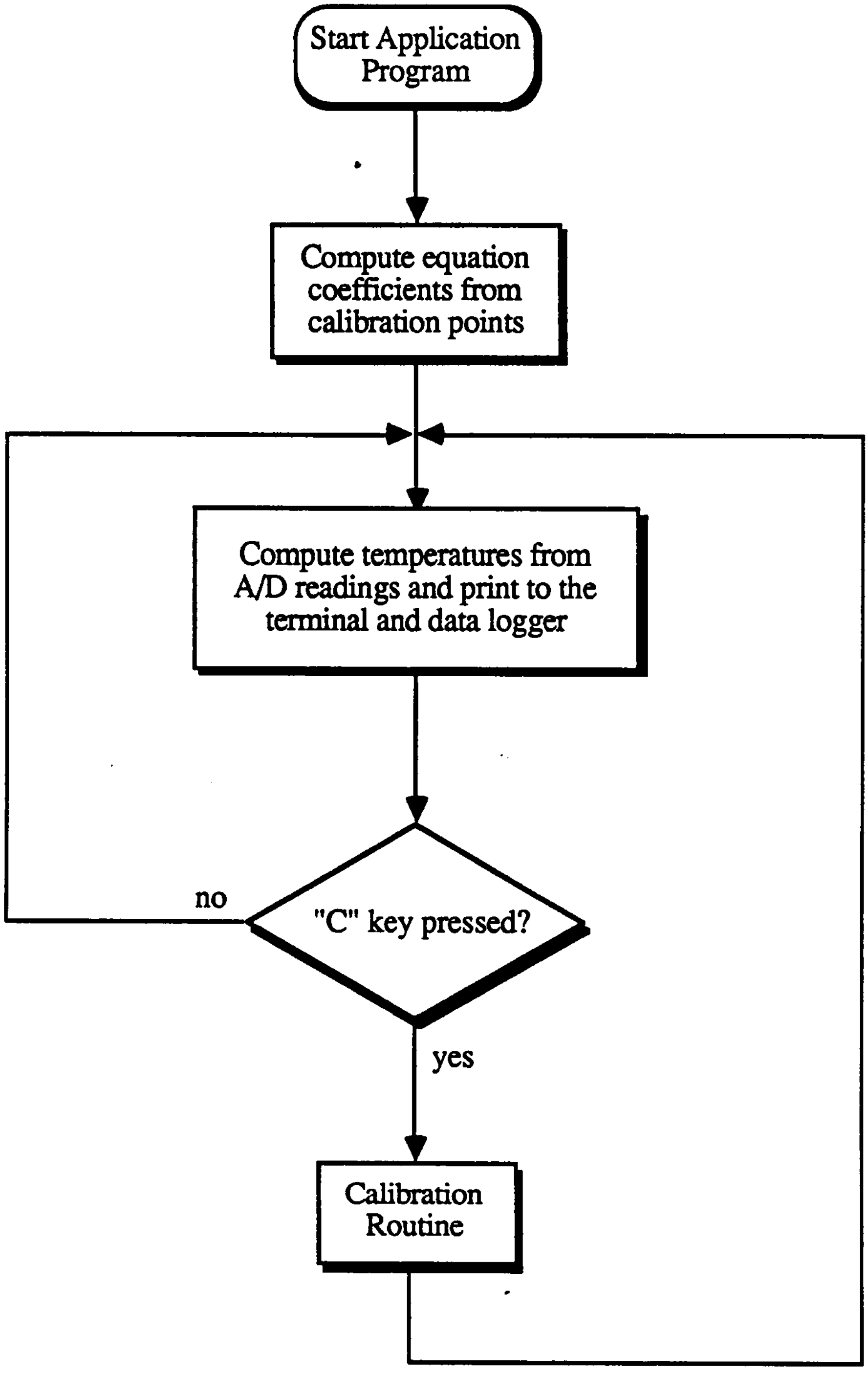

Figure 14. Application Program Flowchart.

calibration points that are stored in CMOS RAM. The program then enters an endless loop which computes the temperature of each probe based on the coefficients and the readings from the A/D converter. The temperatures are printed to the console port of the PTS-80B and to the serial port that connects to the data logger. This step is repeated continuously until the power is interrupted or until the "C" key is pressed on a terminal connected to the console port of the unit. If a "C" is pressed, the program enters the calibration mode where one or more of the probes may be calibrated and new equation coefficients entered. Each of the three main procedures in the application program will be described in detail in the following sections.

Coefficient Determination

The Steinhart and Hart equation requires that three coefficients, a_0, a_1, and a_3 be maintained for each of the fifteen thermistor probes. To compute these coefficients, each probe must be calibrated at three different temperatures, T_1, T_2, and T_3. The corresponding resistances measured at these temperatures, R_1, R_2, and R_3, can then be used to calculate the equation coefficients. Reasonably, the coefficients should be stored in battery-backed CMOS RAM so that they would be retained in the event of a power fail. However, the PTS-80B does not directly store the coefficients; it stores the calibration temperatures and resistances instead. There are several reasons for this. First, during the recalibration of a probe it is desirable to display the previous calibration points so that a comparison to the new points can be made. Second, the calibration points are more easily transferred accurately to a manual record of the calibration. The calibration points consist of a temperature to the nearest 0.01 degree Celsius and a resistance value accurate to four significant digits. The coefficients would have to be recorded as a ten significant digit number in scientific notation. The likelihood of an undetected error is much greater if a technician must record a coefficient for which he has no intuitive feel compared to a temperature and resistance pair that would be obviously incorrect if the decimal point were misread. Third, if only one of the calibration points needs to be changed, then it is necessary to have the other two original calibration points available when the equation coefficients are re-computed. The original calibration points cannot be extracted if only the coefficients are known.

In order to compute the fifteen coefficients from the calibration points during the beginning of the application program, and to re-compute the coefficients after a calibration, a set of equations expressing the coefficients in terms of the calibration points was needed. To derive these expressions, the Steinhart and Hart equation is written at each of the three calibration points:

$$T_1^{-1} = a_0 + a_1 \cdot \ln R_1 + a_3 (\ln R_1)^3 , \qquad (43)$$

$$T_2^{-1} = a_0 + a_1 \cdot \ln R_2 + a_3 (\ln R_2)^3 , \qquad (44)$$

$$T_3^{-1} = a_0 + a_1 \cdot \ln R_3 + a_3 (\ln R_3)^3 . \qquad (45)$$

Solving Equation 43 for a_0 gives:

$$a_0 = T_1^{-1} - a_1 \cdot \ln R_1 - a_3 (\ln R_1) \ . \qquad (46)$$

Substituting Equation 46 into Equation 44, it can be shown that:

$$a_1 = \frac{T_2^{-1} - T_1^{-1}}{\ln (R_2 / R_1)} + a_3 \frac{(\ln R_1)^3 - (\ln R_2)^3}{\ln (R_2 / R_1)} \ . \qquad (47)$$

Also, substituting Equation 46 into Equation 45, it can be shown that:

$$T_3^{-1} = T_1^{-1} + a_1 \cdot \ln (R_3 / R_1) + a_3 [(\ln R_3)^3 - (\ln R_1)^3] . \qquad (48)$$

Now, if Equation 47 is substituted into Equation 48 and rearranged, an equation expressing the coefficient a_3 in terms of the calibration points can be found:

$$a_3 = \frac{(T_3^{-1} - T_1^{-1}) \cdot \ln (R_2 / R_1) + (T_1^{-1} - T_2^{-1}) \cdot \ln (R_3 / R_1)}{[(\ln R_1)^3 - (\ln R_2)^3] \cdot \ln (R_3 / R_1) + [(\ln R_3)^3 - (\ln R_1)^3] \cdot \ln (R_2 / R_1)} \ . \qquad (49)$$

This equation is used to compute a_3 from the calibration points. Equation 47 is then used to compute a_1 from the calibration points and the newly computed a_3. Both of these coefficients are used in Equation 46 to compute the remaining coefficient, a_0. Note that the temperatures in these equations and in the Steinhart and Hart equation are expressed in Kelvin while the calibration temperatures are stored as degrees Celsius. This set of three equations are grouped together to form a subroutine in the BASIC application program which is called fifteen times at the beginning of the program to compute the Steinhart and Hart thermistor equation coefficients from the calibration temperatures and resistances. This subroutine is also called from the calibration routine to re-compute the coefficients after one or more of the calibration points have been changed.

Temperature Calculation

Once the coefficients are computed from the calibration points, the application program enters an endless loop to read the voltages across the precision resistors and thermistor probes, calculate the temperature of the probes, and print these temperatures to the attached terminal and to the data logger. Figure 15 is a flowchart of the the routine that performs these functions. First, the program calls a BASIC subroutine that reads the voltages from the A/D converter. The voltages are returned in two floating point arrays of sixteen voltages each; one array contains the voltages across the sixteen precision resistors and the other array contains the voltages across the fifteen thermistor probes and the one voltage generated by the 600 ohm resistor. A system digital offset voltage is computed from the data digitized on channel number sixteen and the known values of the precision resistor and the 600 ohm resistor using Equation 31. For each of the fifteen thermistor probes, the resistance is computed from the digitized voltages, the digital offset value, and the known value of the precision resistor using Equation 29. With the resistance of the probe and the equation coefficients, the Steinhart and Hart equation (Equation 3) can be used to compute the absolute temperatures of the probes. Finally, the temperatures are converted to degrees Celsius and, along with the digital offset value, printed to the local terminal and to the attached data logger. The digital offset value is retained by the data logger to provide a check of the overall drift of the analog section over time. If the digital

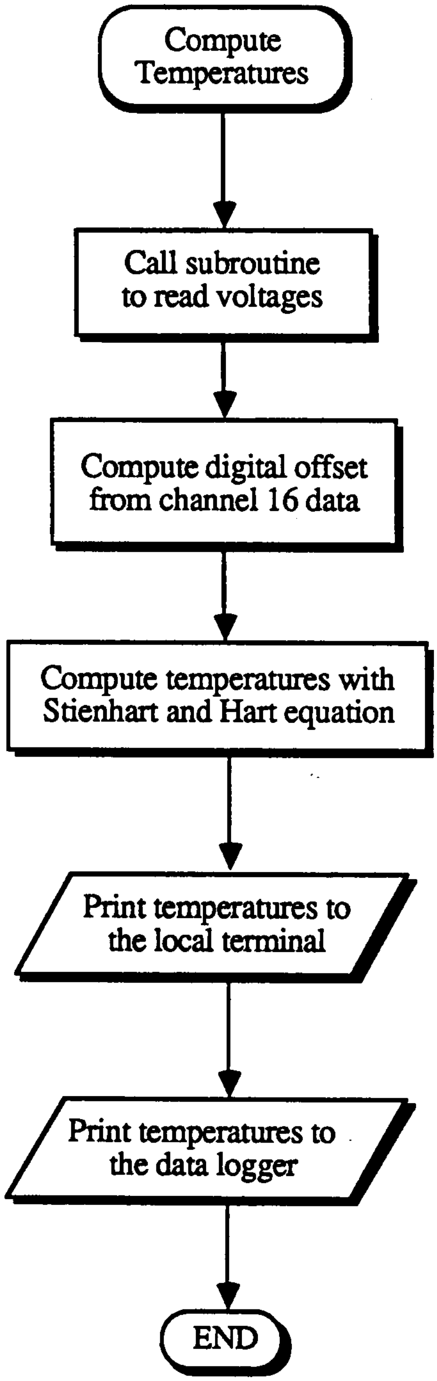

Figure 15. Flowchart of the Routine to Compute and Print Temperatures.

offset becomes excessive, the analog section of the PTS-80B can be recalibrated to compensate.

Figure 16 is a flowchart of the BASIC subroutine that reads the voltages from the A/D converter. The subroutine loops through all sixteen of the analog channels, reading both the voltage across the precision resistor and the voltage across the probe. To select which of the voltages are directed by the analog multiplexer on the driver card to the analog input of the single-board computer, a digital output line is controlled. When this output line is set to a "one", the voltage from the precision resistor is directed to the single-board computer but when the digital line is set to a "zero", the voltage across the temperature probe is selected. After the proper signal is directed to the analog to digital converter, a conversion cycle is initiated by calling an assembly language subroutine. When the conversion is complete, the BASIC program calls a second assembly language subroutine to read the resulting voltage from the A/D converter. This sequence is performed for both the precision resistor and for the thermistor probe. After all sixteen sets of voltages have been read and stored in floating point arrays, execution is returned to the calling program.

Calibration Procedure

The routine that allows thermistor probes to be calibrated initially, periodically checked for drift, and recalibrated if necessary is flowcharted in Figure 17. When the program is in the normal operation mode, the calibration procedure can be entered by pressing a "C" on the keyboard of the locally attached terminal. This aborts the automatic calculation of probe temperatures and enters a mode where the individual probes can be calibrated separately.

To calibrate a probe, the operator is first prompted by the program to select one of the channels (probes) for calibration. If channel number zero is selected, the calibration procedure is terminated and control is passed back to the main routine where the automatic scanning of probe temperatures is resumed. If a valid channel (1-16) is entered, the

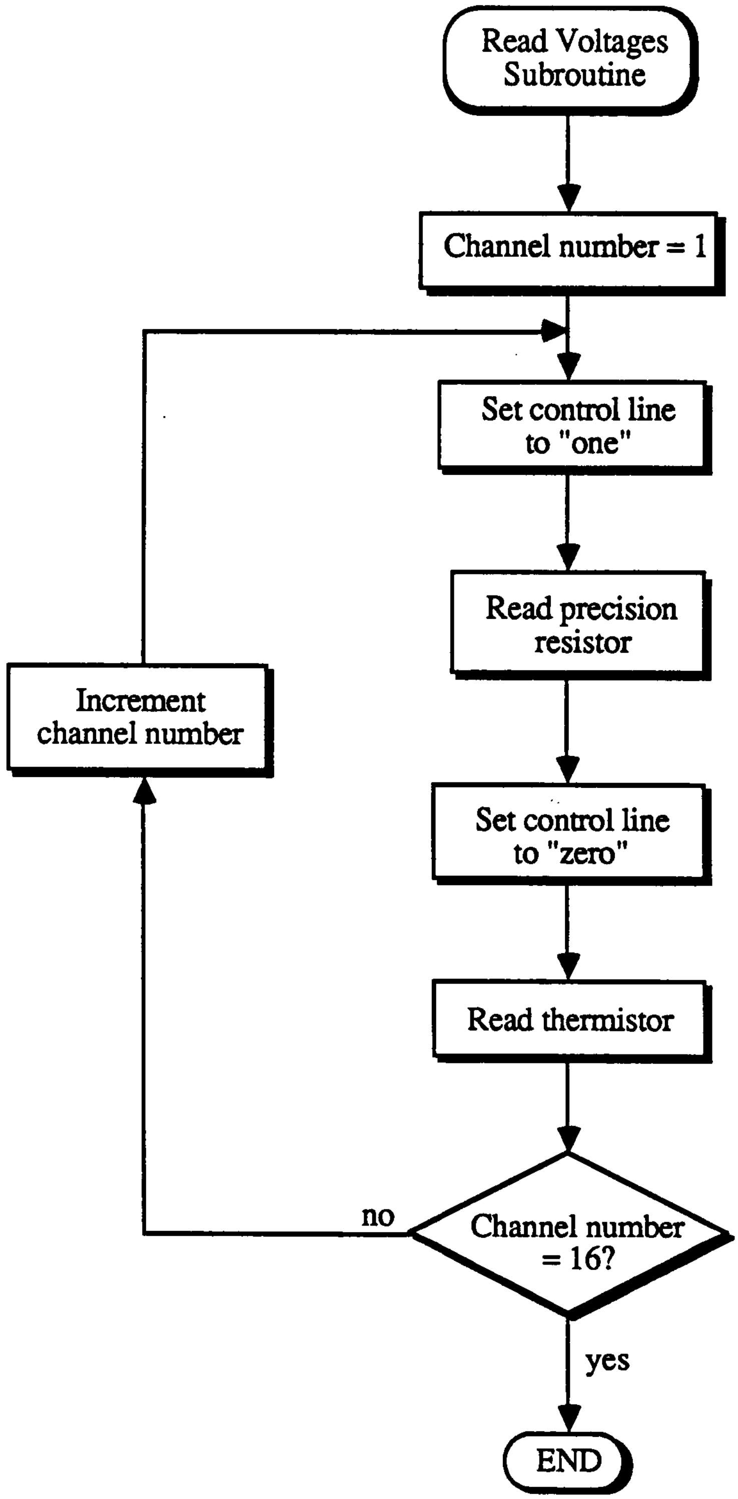

Figure 16. Flowchart of the Subroutine to Read Voltages.

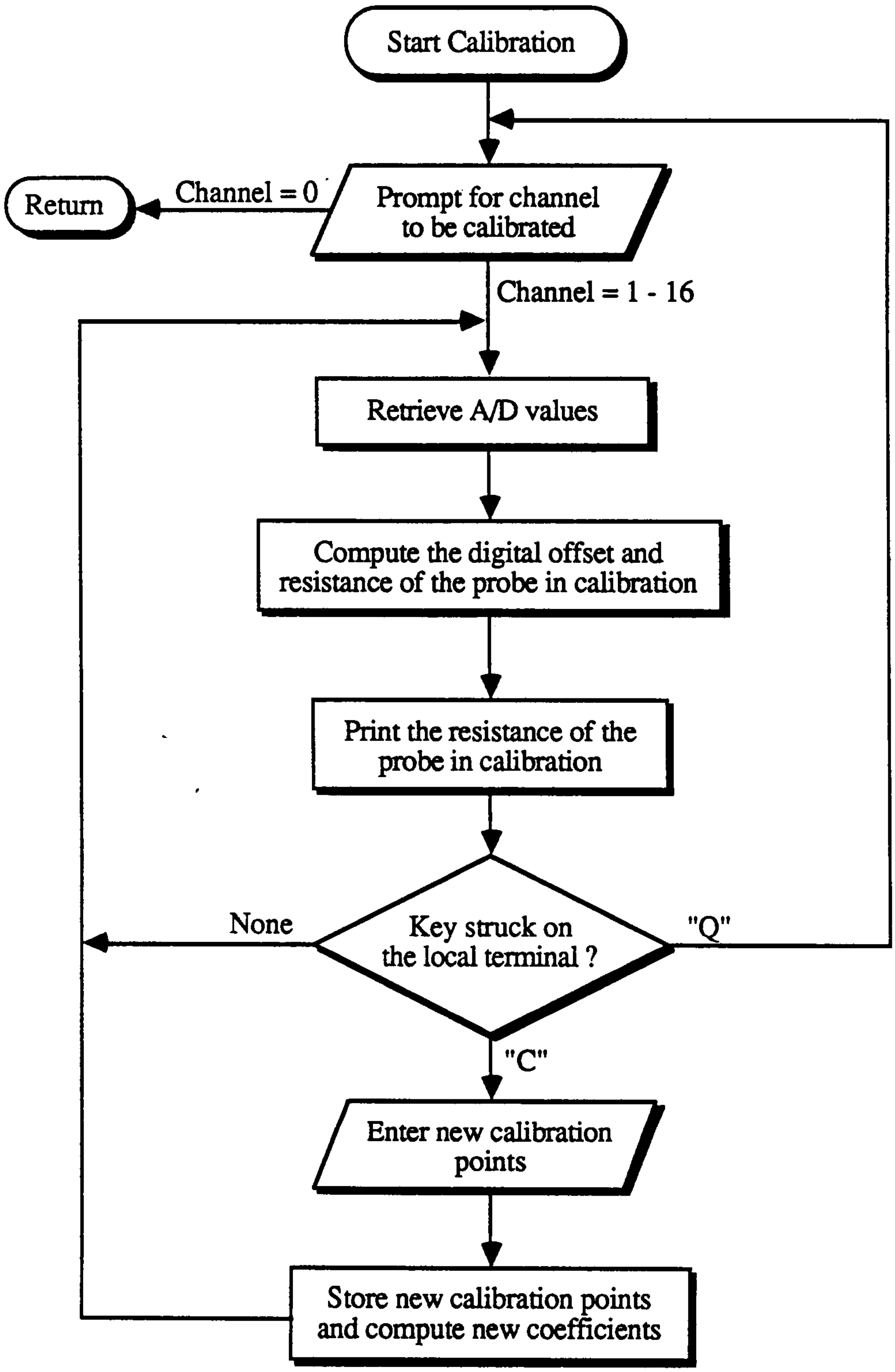

Figure 17. Flowchart of the Calibration Routine.

routine enters a loop that reads and displays the thermistor resistance for the probe selected. At this point, the probe to be calibrated is exposed to a known temperature and allowed to stabilize. The continuous printout of the probe resistance allows the operator to determine when the probe has reached an equilibrium temperature and thus, a stable resistance. Once the probe has stabilized, the operator presses the "C" key on the terminal which directs the program to stop the printout and prompt the operator to enter new calibration points. Each calibration point consists of a known calibration temperature and the corresponding measured probe resistance and the operator has the option of changing any or all of these three points. After the operator modifies the calibration points, the new points are stored in CMOS RAM and a new set of coefficients for the Steinhart and Hart equation are computed. The routine then loops back and again starts to print the resistance of the probe being calibrated. This probe can now be moved to a new temperature and another calibration point can be established. If a "Q" is typed on the terminal when the resistance of the probe in calibration is being printed, then the software branches to the beginning of the calibration routine and prompts the operator to enter a new channel to be calibrated. Entering a valid channel repeats the calibration procedure for the new probe. Again, entering zero for the channel number exits the calibration routine and resumes the automatic calibration of temperatures using the new calibration points and equation coefficients. If channel sixteen is selected, then the digital offset is printed continuously. This can be used to adjust the analog section of the single-board computer if the offset becomes too excessive. Notice that when the program is in the calibration mode, the temperature data are not transmitted over the serial link to the data logger; the operator must exit the calibration mode to resume normal automatic operation.

Transferring Probes

During the development of the PTS-80B, a question surfaced about the ability to move a thermistor probe from one channel to another on the same unit or to move a probe to a channel on a different unit. After performing some calculations and actual testing on a prototype system, it was determined that simply switching the probes would not provide an acceptable transfer. The reasons for this were obvious; not the least of which was the fact that the nominal (25 degree Celsius) value of the thermistors was specified to only a ±20 percent tolerance. A better result was achieved by transferring not only the probe but the calibration points that were associated with that probe as well. The requirement for this approach to work well is for the precision resistor of the original channel to be well matched to the precision resistor of the destination channel. Since the precision resistors are specified as ±0.01 percent, this method provides a transfer that is theoretically accurate to about ±0.03 Kelvin. In practice, this method has been found to be accurate to about ±0.05 Kelvin.

To provide the maximum possible transfer accuracy, a method was developed to transfer the probe characteristics using a set of three precision resistors that can be substituted for the thermistor probe. In this method, the three resistors are substituted one at a time for the thermistor on the original calibrated channel. The "temperature" of each resistor is read using the PTS-80B and recorded. The probe to be transferred, the precision resistors, and the recorded "temperatures" can now be moved to to the new PTS-80B. On the destination channel, the three precision resistors are again substituted one at a time. This time, the resistances as measured on the new channel are noted. The calibration points for the destination channel are then set as the "temperatures" from the original channel combined with the corresponding resistances as measured on the destination channel. This method has resulted in probes that were transferred with inaccuracies as low as the resolution of the system (±0.01 Kelvin).

CHAPTER V

RESULTS

Testing Methods

Four PTS-80B units were constructed during the Summer of 1984. An accuracy of ±0.01 Kelvin was used in all of the design work. Self-heating, voltage measurement errors, and other errors were designed to be less than ±0.01 Kelvin individually but the total, front-to-back accuracy of the system could not be exactly predicted. In order to verify the analog design work, the software, and the actual construction, one unit was calibrated and then tested extensively at several points within the operating range. After this prototype unit was verified, the probes on all of the units were calibrated and then tested at several other mid-range points.

The calibration points that were used for all of the probes were: (1) the melting point of water - 0.00 degrees Celsius; (2) the melting point of gallium metal - 29.77 degrees Celsius; and (3) a stirred oil bath near 60 degrees Celsius. The melting point of water was obtained by mixing crushed ice made from distilled water with liquid distilled water in a bath equipped with an electric stirring mechanism. This provided a very stable known temperature that lasted several hours. The heat transfer capability of this bath was so great that immersed probes quickly reached a stable temperature and consequently, a stable resistance.

The second calibration temperature was the melting point of gallium metal. This temperature was obtained using a gallium temperature standard cell manufactured by Yellow Springs Instrument Company, Incorporated. The cell consisted of 500 grams of 99.9999+ percent pure gallium metal surrounding a thermometer well and inclosed in a polypropylene tube. The cell was inserted in a melt environment that consisted of a precisely controlled temperature module that applied the quantity of heat required to bring the gallium cell to its melt plateau and maintain the plateau for over 12 hours. Pure gallium melts at 29.7714 degrees Celsius (given on the International Practical Temperature Scale of 1968), a temperature known with an uncertainty of less than ±0.002 Kelvin. [7] This temperature was selected for calibration for several reasons: it is near the middle of the operating range of the PTS-80B; it is a constant of nature and thus does not need to be calibrated; and it can be easily produced and reproduced in a laboratory environment. The major drawback of the gallium cell was its low heat transfer capability. A probe that was inserted into the cell at a temperature significantly higher than 29.11 degrees Celsius required an unacceptably long period of time in which to equilibrate. Probes inserted at a temperature lower than the cell temperature required less time to stabilize, but still the time to equilibrium was prohibitively long. The problem was reduced by exposing the probes to a water bath maintained just below the gallium temperature. This reduced the time necessary to calibrate a probe in the gallium cell to acceptable periods. Another problem with the gallium cell was that since only one probe could be calibrated at a time in the cell, it took significantly longer to calibrate several probes at this temperature than at ice point or in the stirred oil bath.

The third temperature at which the thermistors were calibrated was in a bath of stirred oil (Dow Corning 200 Fluid, 10W viscosity). The bath temperatures were maintained by a heating element and a precision thermostat unit (Tronac Model PTC-36 with a temperature stability of ±0.0002 Kelvin). The temperature of the bath was measured by a standard platinum resistance thermometer (Rosemount Model 162-N) which was calibrated by the National Bureau of Standards and verified at both ice point and in the gallium cell. The resistance of the standard platinum resistance thermometer (SPRT) was measured by placing it in series with an NBS-certified 100 ohm resistor and forcing about one milliampere of current through the circuit. A six and one-half digit voltmeter (Hewlett-Packard Model 3490A) with NBS certification was used to measure the forward and reverse voltages across both elements. From these measurements, the resistance of the SPRT could be determined and thus the temperature of the oil bath was computed. The oil bath temperature was the point at which the most uncertainty in the calibration arose. The reliance on the SPRT, precision resistor, and the digital voltmeter made this temperature more uncertain than the other two points. In addition, the high temperature region of the operating range was the area in which the PTS-80B was the most unstable. This instability was due to the fact that the voltage across the probes was at a low value and thus more susceptible to system noise. Also, at the high end of the temperature scale a small error in resistance corresponds to large error in temperature. This is in contrast to a much lower error in temperature for the same percent error in resistance at temperatures near the low end of the scale. The instability resulted in resistance fluctuations as measured by the PTS-80B that made calibration at near 60 degrees Celsius less certain than at the other two calibration points. Due to these fluctuations, it was not always clear when the probe had reached equilibrium and the value of the resistance that corresponded to the temperature of the oil bath was somewhat uncertain.

After the probes on the prototype unit were calibrated, several checks were performed to assure that the PTS-80B would perform as expected. The probes were checked for repeatability back to the calibration points and it was verified that the temperature of one probe did not affect the temperatures of the other probes. Different length cables (up to 1000 feet) were tested and the series resistance of the cables unbalanced up to 100 Ohms with no measurable effect on the measured temperatures. A.C. noise was injected by wrapping the probe cable around an operating induction motor but no difference in the measured temperatures could be detected.

The probes were then checked against the SPRT and a calibrated PTS-80A at several temperatures in the operating range. Temperatures above the gallium cell temperature (29.77 degrees Celsius) were generated using a Kaye furnace (Kaye

Instruments Model HTR-150). This is a device consisting of a thermal block with several thermometer wells and a precision thermostat and heater unit. The temperature of the block can be adjusted from ambient to over 100 degrees Celsius. The only problem with the Kaye furnace was the uncertainty of the temperatures between the thermometer wells. The device is specified to have no more than 0.02 Kelvin difference between wells which is about the accuracy to which the measurements were made. Temperatures below 29.77 degrees Celsius were even more difficult to produce with accuracy. A stirred water bath without heating produced a relatively stable temperature near the ambient air temperature in the laboratory. Temperatures below ambient were generated by adding ice to a stirred water bath. This method produced a low temperature that was never stable; it slowly increased as the bath gained heat from the ambient air. The temperature of the cooled bath was read quickly from the PTS-80A, the SPRT, and the PTS-80B at different times as the temperature increased. These temperatures were somewhat uncertain since the probes never fully equilibrated and the stirred water bath probably contained significant temperature gradients.

Accuracy

Table 2 shows the results of a typical comparison test between the SPRT, a PTS-80A unit, and the new PTS-80B unit. The maximum deviation of the PTS-80A from the SPRT was 0.040 Kelvin while the maximum deviation of the PTS-80B was 0.023 Kelvin. Considering that the SPRT was calibrated by NBS to be no better than ±0.01 Kelvin over this range, then the PTS-80B apparently achieved an accuracy of at least ±0.03 Kelvin. This exceeds the target accuracy of ±0.05 Kelvin and is comparable to the accuracy of the PTS-80A. Since all of the design decisions were based on ±0.01 Kelvin accuracy, then the combined inaccuracy apparently does not accumulate in a way that would cause an unacceptable system accuracy. The tests that were performed on the unit do not absolutely guarantee that the accuracy is ±0.03 Kelvin over the entire temperature

Table 2. Typical Accuracy of the PTS-80B.

Source	SPRT	PTS-80A		PTS-80B	
		temperature	deviation from SPRT	temperature	deviation from SPRT
Ice Bath	00.000° C	00.00° C	0.000 K	00.00° C	0.000 K
Water Bath	05.063° C	05.03° C	- 0.033 K	05.05° C	- 0.013 K
Water Bath	09.494° C	09.47° C	- 0.024 K	09.49° C	- 0.004 K
Water Bath	15.302° C	15.28° C	- 0.022 K	15.29° C	- 0.012 K
Water Bath	19.120° C	19.08° C	- 0.040 K	19.10° C	- 0.020 K
Water Bath	22.439° C	22.42° C	- 0.019 K	22.44° C	+ 0.001 K
Gallium Cell	29.780° C	29.76° C	- 0.020 K	29.78° C	0.000 K
Kaye Furnace	35.067° C	35.04° C	- 0.027 K	35.05° C	- 0.017 K
Kaye Furnace	41.422° C	41.40° C	- 0.022 K	41.40° C	- 0.022 K
Kaye Furnace	46.173° C	46.15° C	- 0.023 K	46.15° C	- 0.023 K
Kaye Furnace	49.949° C	49.93° C	- 0.019 K	49.93° C	- 0.019 K
Kaye Furnace	54.590° C	54.58° C	- 0.010 K	54.58° C	- 0.010 K
Oil Bath	56.327° C	56.32° C	- 0.007 K	56.33° C	+ 0.003 K

range. Especially since the comprehensive tests were not run on all of the PTS-80B systems that were produced and since the tests were only performed with the prototype unit at room temperature. But overall, there is little doubt that the PTS-80B can measure temperatures over a zero to 60 degree Celsius range to well within ±0.05 Kelvin.

CHAPTER VI

SUMMARY AND CONCLUSIONS

An accurate and reliable system for measuring temperatures using thermistors was designed and developed by the author. The PTS-80B system was capable of monitoring fifteen independent points and computing the temperature of each with an accuracy of better than ±0.03 Kelvin. The temperature range of the unit was zero to 60 degrees Celsius and the resolution was 0.01 Kelvin.

Ultra-stable probes and precision resistors were connected in series and driven by a constant current source. The voltage across each probe and across the precision resistors was digitized by a 15-bit analog to digital converter and read by an application program running in BASIC on a commercially available single-board computer. The software performed the necessary calculations to compute the temperature of each probe by using the Steinhart and Hart thermistor equation and the calibration coefficients for each probe. The temperatures were printed on an attached local terminal and transmitted over a serial communications port to a properly programmed intelligent data logger. The logger was capable of storing the temperatures and reporting them to a central computer over dial-up telephone lines on request. Software procedures were developed for the temperature system that allowed convenient calibration of the probes and the computation and storage of the equation coefficients in battery-backed CMOS RAM.

Four of the PTS-80B temperature systems, complete with data loggers and central minicomputer, were constructed by the author's company and installed in September, 1984 at the Vermont Yankee nuclear power plant. Since that time, all of the units have been functioning normally. A fifth unit was delivered and installed during March, 1986.

Further study in several areas would result in improvements in the accuracy and reliability of the PTS-80B. First, a detailed study of the temperature characteristics of the unit should be performed using more sophisticated equipment and methods. The ideal situation would be to have the PTS-80B evaluated by the National Bureau of Standards. Environmental Systems Corporation is presently constructing a spare unit and plans to submit it for evaluation to the NBS. This would establish the absolute accuracy of the device over its full operating range.

A design modification that would improve system accuracy would be to change the analog multiplexers on the thermistor driver circuits in order to reduce the input leakage current. This would allow the use of larger nominal-value thermistors and would result in larger voltages across the thermistors. These larger voltages would be less susceptible to noise. Another design change that would increase the performance of the PTS-80B is decreasing the conversion time of the 15-bit analog to digital converter. This would be a simple change involving increasing the clock rate of the A/D converter and would not require any other hardware or software changes. The resulting increase in sampling rate would allow calibrations to proceed more quickly.

Overall, the project proceeded smoothly and resulted in a useable temperature monitoring system with superior characteristics and functionality to the PTS-80A which it replaced. Environmental Systems Corporation is presently in the process of filing an addendum to their PTS-80A patent (United States Patent #4122719) to include the PTS-80B.

REFERENCES

REFERENCES

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5. J.S. Steinhart and S.R. Hart, "Calibration Curves for Thermistors," Deep-Sea Research, 15 (1968), p. 497.

6. Thermistor Data Catalog, Catalog No. 181-D (Edison, New Jersey: Thermometrics, Incorporated, 1981), p. A-2.

7. Henry E. Sostman, "Melting Point of Gallium as a Temperature Calibration Standard", Review of Scientific Instruments, February 1977, pp.197-206.

APPENDIX

```
10 DIM A0(14),A1(14),A2(14),CR(2,14),CT(2,14)
20 DIM RT(15),DP(15),DT(15),T(15),T$(15)
30 DIM DTM(9,15),DTMCOUNT(15),DTMSUM(15)
40 FOR Q=0 TO 15 :DTMCOUNT(Q)=-1 :DTMSUM(Q)=0 :NEXT Q
50 ADSTART=$3A30 :ADREED=$3AF5
60 ADFLAG=$990E :RMTFLAG=$9903 :CALSAV=$9A00 :SIOEN=$990D
70 PIOC=$15 :PIO=$14 :SIOC=$7
80 POKE SIOEN,1
90 UNTRAP
100 RP= 6810 :RT(15)= 600
110 OUT PIOC,$CF :OUT PIOC,0 :OUT PIOC,0 :OUT PIOC,7
120 PRINT :PRINT "***** PTS-80B APPLICATION PROGRAM *****"
130 PRINT "21-AUGUST-84, ENVIRONMENTAL SYSTEMS CORP." :PRINT
140 FOR I=0 TO 14
150 FOR J=0 TO 2
160 K= CALSAV+I*12+J*4
170 CR(J,I)= PEEK(K) JOIN PEEK(K+1)
180 IF CR(J,I)<0 THEN CR(J,I)= -CR(J,I)/10
190 CT(J,I)= (PEEK(K+2) JOIN PEEK(K+3))/100+273.15
200 NEXT J
210 GOSUB 890
220 NEXT I
230 PRINT "***COEFFICIENTS COMPUTED***" :PRINT
240 G$=GET$:IF G$<>"" THEN 480
250 FOR C=0 TO 15 :IF G$<>"" THEN 280
260 G$=GET$ :IF G$<>"" THEN 280
270 GOSUB 950
280 NEXT C
290 IF G$<>"" THEN 480
300 FOR C=0 TO 15
310 IF G$<>"" THEN 390
320 G$=GET$ :IF G$<>"" THEN 390
330 IF C=15 THEN T(15)=D0*1000 :GOTO 380
340 RT(C)= RP*(DT(C)-D0)/(DP(C)-D0)
350 IF RT(C)<=0 THEN T(C)=99.99 :GOTO 380
360 T(C)= (1/(A0(C)+A1(C)*LOG(RT(C))+A2(C)*LOG(RT(C))^3))-273.15
370 IF T(C)>=100 THEN T$(C)="99.99" :GOTO 390
380 TT=T(C) :GOSUB 1070 :T$(C)=TT$
390 NEXT C
400 IF G$<>"" THEN 480
410 FOR C=0 TO 3 :PRINT T$(C);"     "; :NEXT C :PRINT
420 FOR C=4 TO 7 :PRINT T$(C);"     "; :NEXT C :PRINT
430 FOR C=8 TO 11 :PRINT T$(C);"     "; :NEXT C :PRINT
440 FOR C=12 TO 15 :PRINT T$(C);"     "; :NEXT C :PRINT
450 IF TEST(IN(SIOC),3)=0 THEN PRINT "*"; :GOTO 470
460 POKE RMTFLAG,1 :FOR C=0 TO 15 :PRINT T$(C); :NEXT C :PRINT :POKE RMTFLAG,0
470 PRINT :G$=GET$
480 IF G$="C" THEN 500
490 GOTO 240
500 J=0: SUM=0 :MFLAG=1
510 PRINT :PRINT "ENTER CHANNEL TO BE CALIBRATED" :INPUT "(1-16, 0 TO EXIT)" C
520 IF C=0 THEN 240
530 C$=MID$(STR$(C),2)
540 PRINT :C=C-1 :IF (C<0) OR (C>15) THEN 510
550 IF C=15 THEN GOSUB950:T(15)=D0*1000:PRINT"DIGITAL OFFSET = ";T(15):GOTO 640
560 GOSUB 950
570 RT(C)= RP*(DT(C)-D0)/(DP(C)-D0)
580 IF RT(C)<=0 THEN RT(C)=.1
590 TT=RT(C) :GOSUB 1070
600 IF MFLAG=1 THEN PRINT "CALIBRATION RT(";C$;")= ";TT$:SUM=SUM+RT(C):GOTO 650
610 T(C)= (1/(A0(C)+A1(C)*LOG(RT(C))+A2(C)*LOG(RT(C))^3))-273.15
620 TT=T(C) :GOSUB 1070
630 PRINT "CALIBRATION TEMP(";C$;")= ";TT$;" C"
640 SUM= SUM+T(C)
```

```
650 J=J+1
660 IF J>=10 THEN TT=SUM/J :GOSUB 1070 :PRINT "AVERAGE = ";TT$ :J=0 :SUM=0
670 IF (J=0 AND C<>15) THEN TMP=C :C=15 :DTMCOUNT(15)=-1 :GOSUB 950 :C=TMP
680 G$=GET$ :IF G$="Q" THEN 500
690 IF G$="R" THEN MFLAG=1 :GOTO 550
700 IF G$="T" THEN MFLAG=0 :GOTO 550
710 IF G$<>"C" THEN 550
720 IF C=15 THEN 550
730 PRINT
740 FOR I=0 TO 2
750 PRINT "CALIBRATION POINT #";I+1;"-";CR(I,C);"@";CT(I,C)-273.15;"C"
760 INPUT "RESISTANCE" R
770 IF R=0 THEN 870
780 IF (R<100) OR (R>10000) THEN 750
790 INPUT "TEMPERATURE" TEMP
800 IF (TEMP<-50) OR (TEMP>=100) THEN 750
810 IF (R<1000) THEN CR%= -R*10
820 IF (R>=1000) THEN CR%=R
830 CT%=TEMP*100 :CR(I,C)=R :CT(I,C)=TEMP+273.15
840 J= CALSAV+C*12+I*4
850 POKE J,MSBYTE(CR%) :POKE J+1,LSBYTE(CR%)
860 POKE J+2,MSBYTE(CT%) :POKE J+3,LSBYTE(CT%)
870 NEXT I
880 I=C :GOSUB 890 :J=0 :SUM=0 :MFLAG=0 :PRINT :GOTO 560
890 L1= LOG(CR(2,I)/CR(1,I)) :L2= LOG(CR(1,I)/CR(0,I)) :L3= LOG(CR(2,I)/CR(0,I))
900 M1= LOG(CR(0,I))^3 :M2= LOG(CR(1,I))^3 :M3= LOG(CR(2,I))^3
910 A2(I)= (L1/CT(0,I)+L2/CT(2,I)-L3/CT(1,I))/(L1*M1+L2*M3-L3*M2)
920 A1(I)= (1/CT(1,I)-1/CT(0,I)-(M2-M1)*A2(I))/L2
930 A0(I)= 1/CT(0,I)-LOG(CR(0,I))*A1(I)-M1*A2(I)
940 RETURN
950 CL%=SET(0,C) :C%=C
960 OUT PIO,#FF :POKE ADFLAG,0
970 CALL ADSTART,CL%
980 IF PEEK(ADFLAG)=0 THEN 980
990 CALL ADREED,DP(C%),C%
1000 OUT PIO,0 :POKE ADFLAG,0
1010 CALL ADSTART,CL%
1020 IF PEEK(ADFLAG)=0 THEN 1020
1030 CALL ADREED,DT1,C%
1040 GOSUB 1160
1050 IF C=15 THEN DO= (DT(15)*RP-DP(15)*RT(15))/(RP-RT(15))
1060 RETURN
1070 IF TT<=-9.995 THEN TT$="-9.99" :GOTO 1150
1080 IF TT>=9999.5 THEN TT$="9999" :GOTO 1150
1090 TP=INT(ABS(TT)*100+.5)/100
1100 IF TP=0 THEN TT$="00.00" :GOTO 1150
1110 IF TT<0 THEN TT$="-"+MID$(STR$(TP+10.001),3,4) :GOTO 1150
1120 IF TP>=1000 THEN TT$=MID$(STR$(INT(TP+.5)+10000.1),3,5) :GOTO 1150
1130 IF TP>=100 THEN TT$=MID$(STR$(INT(TP*10+.5)/10+1000.01),3,5) :GOTO 1150
1140 TT$=MID$(STR$(TP+100.001),3,5)
1150 RETURN
1160 IF DTMCOUNT(C%)<>-1 THEN 1220
1170 FOR Q=0 TO 9 :DTM(Q,C%)=DT1 :NEXT Q
1180 DTMSUM(C%)=DT1*10
1190 DT(C%)=DT1
1200 DTMCOUNT(C%)=0
1210 RETURN
1220 DTMSUM(C%)=DTMSUM(C%)-DTM(DTMCOUNT(C%),C%)
1230 DTM(DTMCOUNT(C%),C%)=DT1
1240 DTMSUM(C%)=DTMSUM(C%)+DT1
1250 DT(C%)=DTMSUM(C%)/10
1260 DTMCOUNT(C%)=DTMCOUNT(C%)+1 :IF DTMCOUNT(C%)=10 THEN DTMCOUNT(C%)=0
1270 RETURN
```

```
        .TITLE XYBASIC'S I/O DRIVERS
        .SBTTL BASIC INIT ROUTINE

        .MCALL  RMCDEF
        RMCDEF

        .PSECT  .XYBR,RW
IOBYTE::
        .BLKB   4000                ;BASIC WORKSPACE
TOPRAM::
NVRAM:: .BLKB   1800                ;NON-VOLATILE AREA
        .=.+100
MSTACK::
FAILBF: .BLKW   1
COLD::  .BLKB   1                   ;COLD FLAG
REMFLG::.BLKW   1                   ;REMOTE ACCESS FLAG
CF1::   .BLKW   1                   ;CONFIG WORD FOR SIO1
CF2::   .BLKW   1                   ;CONFIG WORD FOR SIO2
CF3::   .BLKW   1                   ;CONFIG WORD FOR SIO3
CF4::   .BLKW   1                   ;CONFIG WORD FOR SIO4
CONEN:: .BLKB   1                   ;CONSOLE ENABLE FLAG

        .PSECT  ZZZZZY,RW
ENDRAM::

        .PSECT $$XYB1,RO
START:: JP      BINIT               ;JUMP TO INIT ROUTINE
.=START+^H8
        RET
.=START+^H10
        RET
.=START+^H18
        RET
.=START+^H20
        RET
.=START+^H28
        RET
.=START+^H30
        RET
.=START+^H38                        ;SETUP TO LOAD RST7 INSTRUCTIONS
        DI
        JP      START               ;JUMP TO EFFECT GLITCH RECOVERY
.= START + 66
        JP      START

.=START + 78

IVTABL::
S1VEC::
        .WORD   0                   ;SIO2
        .WORD   STCH2
        .WORD   0
        .WORD   0

        .WORD   0                   ;SIO1
        .WORD   STCH1
        .WORD   0
        .WORD   0

S2VEC::
        .WORD   0                   ;SIO4
        .WORD   STCH4
        .WORD   0
        .WORD   0
```

```
        .WORD   0               ;SIO4
        .WORD   STCH3
        .WORD   0
        .WORD   0
CLKVEC::
        .WORD   0
        .WORD   0
        .WORD   CLKSRV
        .WORD   ADSERV          ;CTC 1
EXTVEC::
        .WORD   0
        .WORD   0
        .WORD   0
        .WORD   0
```

```
        .PSECT   $$XYB3,RO

MATCHW= 0A442

BINIT:: DI
        LD      SP,MSTACK               ;SET STACK POINTER
        LD      HL,FAILBF               ;PREP TO CHECK FOR COLD START
        LD      A,(HL)                  ;GET FIRST BYTE
        CP      MATCHW&0FF              ;TEST FOR MATCH
        JR      NZ,1$                   ;JUMP TO COLD START IF NO MATCH
        INC     HL                      ;GET 2ND HALF
        LD      A,(HL)
        CP      <MATCHW&0FF00>/100      ;COMPARE SECOND HALF
        LD      A,-1
        LD      (COLD),A
        JP      Z,WARMST                ;JUMP TO WARM START IF MATCH
1$:     LD      HL,IOBYTE
        LD      DE,IOBYTE + 1
        LD      BC,ENDRAM-IOBYTE
        LD      (HL),0
        LDIR
        LD      HL,8000                 ;INIT CONSOLE TO 300 BAUD
        LD      (CF1),HL
        LD      HL,0801                 ;INIT REMOTE PORT TO 4800 BAUD
        LD      (CF2),HL
        LD      HL,8002                 ;INIT PRINTER PORT TO 300 BAUD
        LD      (CF3),HL
        LD      HL,0403                 ;INIT LINK PORT TO 9600 BAUD
        LD      (CF4),HL

        LD      A,15.                   ;AQUATEC INITIALIZATION STUFF
        LD      DE,9A00
2$:     LD      BC,COEFL
        LD      HL,COEFT
        LDIR
        DEC     A
        JR      NZ,2$
        JR      WARMST

COEFT:  .BYTE   17,55,0,0,7,0D0,9,0C4,0E9,99,17,70
COEFL=  .-COEFT

;       5937 OHMS @ 0 C
;       2000 OHMS @ 25 C
;       573.5 OHMS @ 60 C

WARMST: LD      HL,MATCHW               ;SET FAILBF
        LD      (FAILBF),HL
        IM2
        LD      A,<IVTABL&0FF00>/100    ;LOAD VECTOR TABLE
        LD      I,A
        LD      A,2
        OUT     (SIO2C),A
        OUT     (SIO4C),A
        LD      A,S1VEC
        OUT     (SIO2C),A
        LD      A,S2VEC
        OUT     (SIO4C),A
        LD      A,CLKVEC & OFF          ;SET VECTOR
        OUT     (BAUD1),A
        LD      BC,(CF1)
        CALL    LDCONF                  ;SET UP DART1
        LD      BC,(CF2)
```

```
        CALL    LDCONF              ;SET UP DART2
        LD      BC,(CF3)
        CALL    LDCONF              ;SET UP DART3
        LD      BC,(CF4)
        CALL    LDCONF              ;SET UP DART4
        LD      A,3                 ;SET UP INTERRUPTS
        OUT     (CLKINT),A
        OUT     (ADINT),A
        LD      A,55                ;SET UP INTERRUPTS
        OUT     (CLKINT),A
        OUT     (ADINT),A
        LD      A,1                 ;SET UP INTERRUPTS
        OUT     (CLKINT),A
        OUT     (ADINT),A
        LD      A,0D1               ;SET UP INTERRUPTS
        OUT     (CLKINT),A
        LD      A,0C1
        OUT     (ADINT),A
        LD      A,-1                ;SET UP CLOCK ICR
        OUT     (CICR),A
        IN      A,(CISR)            ;CLEAR ANY INTERRUPTS
        XOR     A
        LD      (REMFLG),A          ;CLEAR REMOTE FLAG
        XOR     A
        LD      (CONEN),A           ;CONSOLE NOT ENABLED
        EI
        JP      BASIC               ;BRING UP BASIC (COLD START)

LDCONF::PUSH    BC                  ;SAVE REGS
        PUSH    DE
        PUSH    HL
        PUSH    AF
        PUSH    BC                  ;SAVE UNIT AND SPEED
        LD      A,C                 ;GET UNIT
        LD      HL,DARTC
        ADD     A,L
        LD      L,A
        JR      NC,1$
        INC     H
1$:     LD      C,(HL)
4$:     LD      A,B                 ;GET SPEED
        CP      175.
        LD      HL,CNFIG1           ;STANDARD CONFIG
        JR      NZ,5$
        LD      HL,CNFIG2           ;110 BAUD
5$:     LD      B,DFCNFL
        OTIR                        ;CONFIGURE SIO
6$:     POP     BC
        LD      A,C                 ;GET UNIT
        LD      HL,BAUDS
        ADD     A,L
        LD      L,A
        JR      NC,2$
        INC     H
2$:     LD      C,(HL)
14$:    LD      A,3
        OUT     (C),A
        LD      A,45
        OUT     (C),A
        OUT     (C),B
16$:    POP     AF                  ;RESTORE REGS
        POP     HL
        POP     DE
        POP     BC
        RET
```

```
DARTC:   .BYTE SIO1C,SIO2C,SIO3C,SIO4C
BAUDS:   .BYTE BAUD1,BAUD2,BAUD3,BAUD4
CNFIG2: .BYTE 18,0,0,14,8C,3,0C1,5,0EA,11,5,0    ;110 BAUD
CNFIG1: .BYTE 18,0,0,14,44,3,0C1,5,0EA,11,5,0    ;>110 BAUD
DFCNFL= .-CNFIG1

.END
```

```
        .TITLE XYBASIC MACHINE LANGUAGE SUBROUTINES
        .SBTTL ADSERV A-D SERVICE ROUTINE

        .MCALL  RMCDEF
        RMCDEF

        .PSECT ADRAM,RW
SCNRDY::.WORD   0
CHNSEL::.BLKW   2
CHANID::.BYTE   0
ADBUF:: .BLKW   64.
GAINTB::.BLKB   32.

        .PSECT ADSERV,RO
ADSERV::DI
        PUSH    AF
        PUSH    BC
        PUSH    DE
        PUSH    HL
        LD      A,(CHANID)              ;GET THE PREVIOUS CHANNEL ADDR.
        OUT     (ADCHAN),A
        LD      HL,ADBUF                ;LOAD ADDRESS OF A-D BUFFER
        ADD     A,A                     ;MULT BY TWO
        ADD     A,A                     ;MULT BY TWO
        ADD     A,L                     ;ADD TO ADDRESS
        LD      L,A
        JR      NC,1$                   ;JUMP IF NO CARRY
        INC     H                       ;BUMP HIGH BYTE
1$:     LD      C,ADL                   ;LOAD LOW BYTE PORT ADDRESS
        IN      E,(C)                   ;GET LOW BYTE
        INC     C                       ;BUMP PORT ADDRESS
        IN      D,(C)                   ;GET HIGH BYTE
        CALL    ADFLT
        LD      A,(CHANID)              ;BUMP POINTER
        INC     A
        LD      (CHANID),A
        CALL    SCANST                  ;GET THINGS ROLLING AGAIN
        POP     HL                      ;GO TO BACKGROUND
        POP     DE
        POP     BC
        POP     AF
        EI
        RETI

ADINIT::CALL    GTPAR                   ;CHECK VARIABLE
        OR      A                       ;ANY THERE?
        JR      NZ,1$                   ;JUMP IF VARIABLE PRESENT
        LD      HL,0
        LD      (CHNSEL),HL             ;CLEAR SELECTED CHANNELS
        LD      (CHNSEL+2),HL
        LD      (CHANID),A              ;CLEAR CHANNEL
        JP      SCANST
1$:     CP      1                       ;SEE IF INTEGER VARIABLE
        JP      NZ,BASERR               ;JUMP OUT IF NOT
        LD      A,C                     ;INSURE NOT ARRAY ELEMENT
        OR      A
        JP      NZ,BASERR               ;JUMP IF ARRAY ELEMENT
        LD      E,(HL)                  ;GET INTEGER
        INC     HL
        LD      D,(HL)
        LD      (CHNSEL),DE             ;STORE 1ST 16 SELECT
        CALL    GTPAR                   ;CHECK FOR SECOND 16 SELECT
        OR      A                       ;MORE?
        JR      NZ,2$                   ;JUMP IF MORE
```

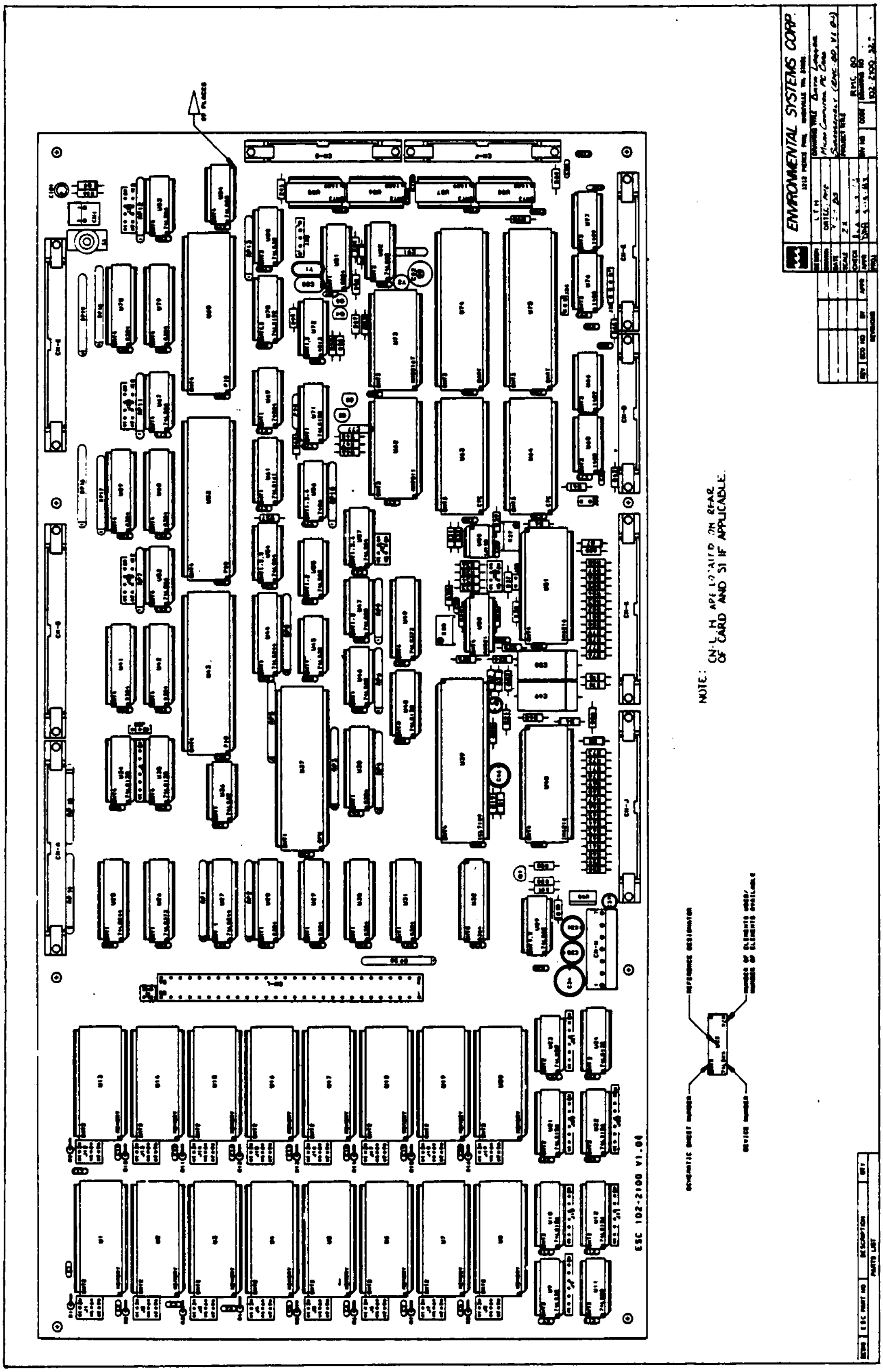
```
         LD      HL,0
         LD      (CHNSEL+2),HL         ;NULL OUT 2ND 16 CHANNEL SELECT
         LD      A,0
         LD      (CHANID),A
         JP      SCANST
2$:      CP      1                     ;SEE IF INTEGER
         JP      NZ,BASERR             ;JUMP IF NOT
         LD      A,C                   ;SEE IF ARRAY ELEMENT
         OR      A
         JP      NZ,BASERR
         LD      E,(HL)
         INC     HL
         LD      D,(HL)
         LD      (CHNSEL+2),DE
         LD      A,0
         LD      (CHANID),A

SCANST::PUSH     AF
         PUSH    BC
         PUSH    DE
         PUSH    HL
4$:      LD      A,(CHANID)            ;GET CHANNEL ID
         LD      HL,(CHNSEL)           ;GET CHANNEL SELECT PATTERN
         LD      DE,(CHNSEL+2)
         CP      32.
         JR      C,2$                  ;KEEP GOING IF NOT A NULL
14$:     XOR     A
         OUT     (ADCHAN),A            ;IF IT WAS A NULL - STOP THE A-D
         CPL
         LD      (SCNRDY),A            ;SET THE SCAN COMPLETE FLAG
         JR      9$                    ;HEAD ON OUT OF HERE
2$:      SRL     D                     ;GET SELECT BIT
         RR      E
         RR      H
         RR      L
         JR      C,3$
         INC     A
         CP      32.
         LD      (CHANID),A            ;STORE NEW CHANNEL ID
         JR      NC,14$
         JR      2$
3$:      LD      (CHNSEL),HL
         LD      (CHNSEL+2),DE
         OUT     (ADCHAN),A            ;SWITCH MUX ADDRESS
         LD      (CHANID),A            ;IT BECOMES THE NEW PREVIOUS ID
         OR      80                    ;ADD THE A-D ENABLE BIT
         OUT     (ADCHAN),A            ;START THE CONVERSION
9$:      POP     HL
         POP     DE
         POP     BC
         POP     AF
         RET

ADFLT:   EX      DE,HL                 ;GET POINTER INTO DE
1$:      LD      A,H
         AND     7F                    ;TEST FOR ZERO (15-BIT A/D)
         OR      L
         JR      NZ,11$
         EX      DE,HL                 ;GET ADDRESS
         LD      (HL),0
         INC     HL
         LD      (HL),0
         INC     HL
         LD      (HL),0
         INC     HL
         LD      (HL),0
```

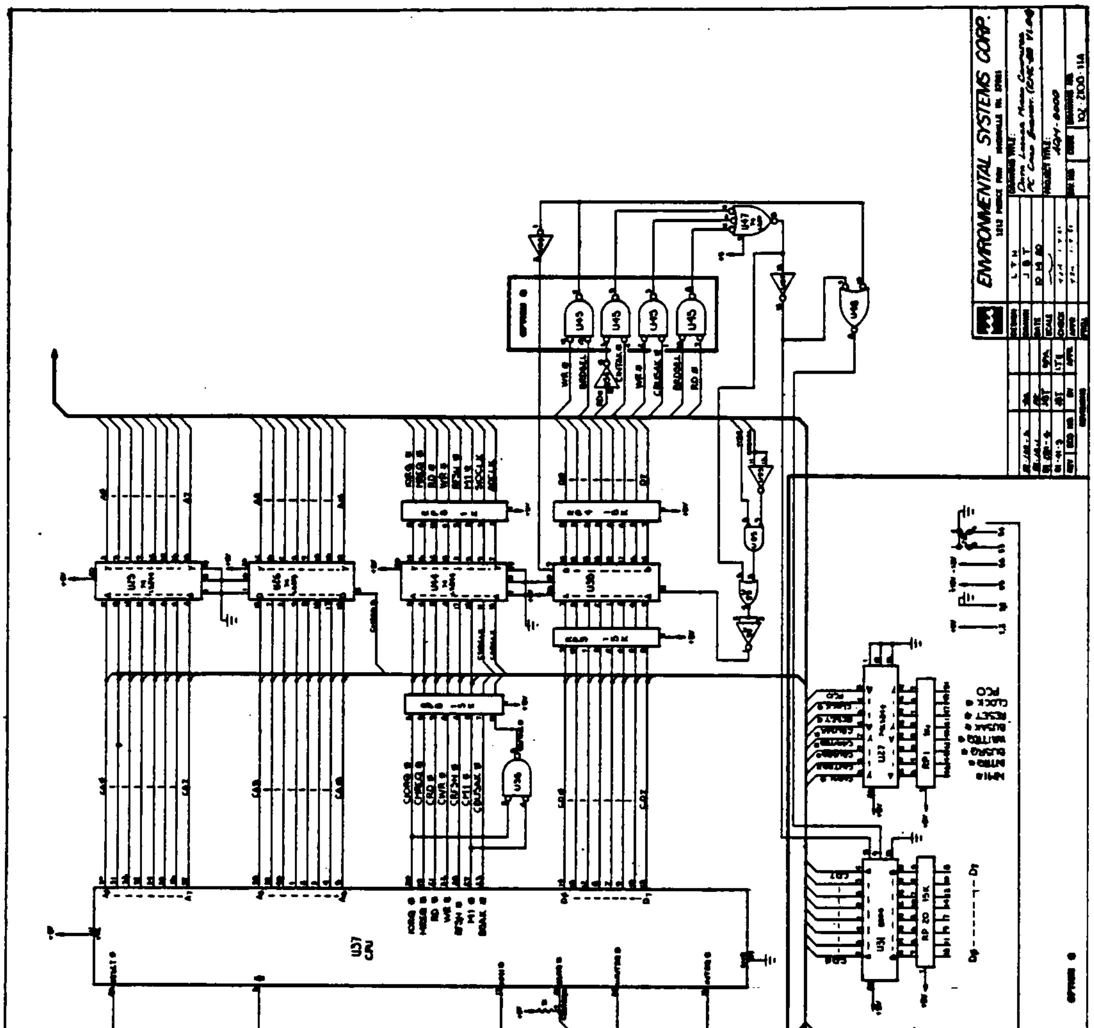
```
        RET
11$:    LD      B,15.                   ;15 BITS
        ADD     HL,HL                   ;SHIFT OUT AND GET SIGN
        PUSH    AF                      ;SAVE SIGN
        LD      C,80                    ;SET EXPONENT
4$:     BIT     7,H                     ;TEST FOR BIT
        JR      NZ,3$                   ;JUMP IF PRESENT
        ADD     HL,HL                   ;SHIFT LEFT
        DEC     C
        DJNZ    4$
3$:     POP     AF                      ;RESTORE SIGN
        JR      NC,5$                   ;JUMP IF NEGATIVE
        RES     7,H
5$:     EX      DE,HL                   ;SWAP ADDRESS,DATA
        LD      (HL),C                  ;MOVE EXPONENT
        INC     HL
        LD      (HL),D                  ;MANTISSA
        INC     HL
        LD      (HL),E
        INC     HL
        LD      (HL),0
        RET

ADREAD::CALL    GTPAR                   ;GET DESTINATION
        OR      A
        JP      Z,BASERR                ;JUMP OUT IF NO PARAMETER
        CP      3                       ;SEE IF FLOATING VARIBLE
        JP      NZ,BASERR
        LD      A,C
        OR      A                       ;TEST FOR SINGLE ELEMENT
        JP      NZ,BASERR
        PUSH    HL                      ;SAVE DESTINATION ADDRESS
        CALL    GTPAR                   ;GET CHANNEL NUMBER
        OR      A
        JP      Z,BASERR                ;JUMP IF NO CHANNEL SELECTED
        CP      1                       ;CHECK FOR INTEGER
        JP      NZ,BASERR               ;JUMP IF NOT INTEGER
        LD      A,(HL)                  ;GET CHANNEL NUMBER
        AND     1F                      ;MOD 32.
        ADD     A,A
        ADD     A,A
        LD      HL,ADBUF                ;LOAD ADDRESS OF AD BUFFER
        ADD     A,L
        LD      L,A
        JR      NC,1$
        INC     H
1$:     POP     DE                      ;RESTORE DESTINATION
        LD      BC,4
        DI
        LDIR
        EI
        RET
```

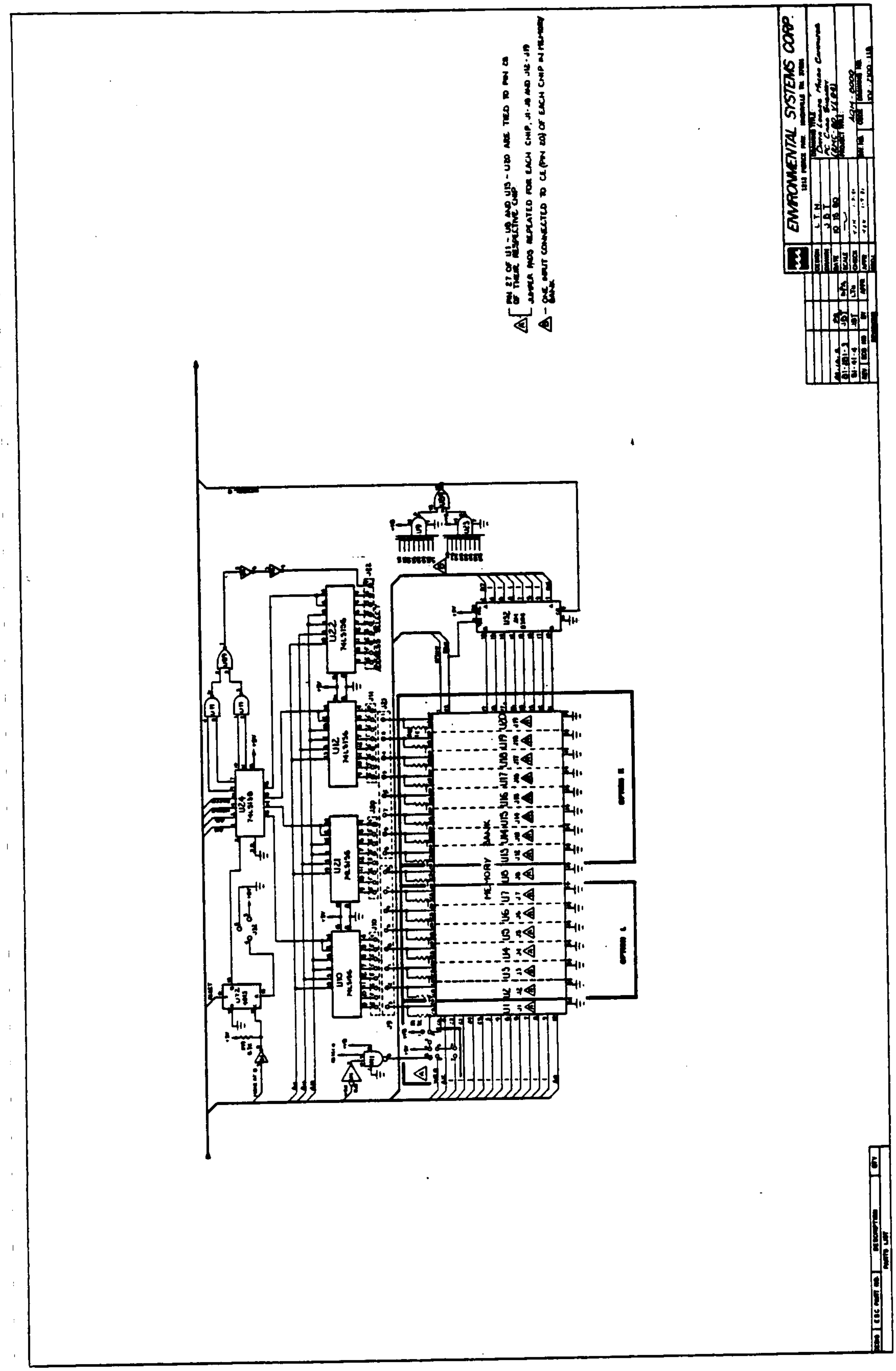
```
        .SBTTL  BASIC SERIAL INTERRUPT ROUTINES
        .PSECT  BSIO,RO

UC0I::          ;USER CONSOLE 0 IN
UC1I::          ;USER CONSOLE 1 IN
UC2I::          ;USER CONSOLE 2 IN
UC3I::          ;USER CONSOLE 3 IN

1$:     LD      A,(REMFLG)
        OR      A
        JR      Z,2$
        IN      A,(SIO2C)               ;SEE IF CARRIER PRESENT
        AND     1
        JR      Z,1$
        IN      A,(SIO2)
        JR      3$

2$:     LD      A,(REMFLG)
        OR      A
        JR      NZ,1$
        IN      A,(SIO1C)
        AND     1
        JR      Z,1$
        IN      A,(SIO1)

3$:     PUSH    AF
        LD      A,(CONEN)
        CP      2
        JR      NZ,4$
        POP     AF              ;CONTROL MODE -- ALL CHARACTERS PASSED
        RET

4$:     POP     AF
        CP      0C              ;CONTROL 'L'?
        JR      NZ,5$
        LD      A,2             ;IF SO, GOTO CONTROL MODE
        LD      (CONEN),A
        LD      A,3
        RET

5$:     CP      20              ;CONTROL CHARACTER?
        JR      NC,6$
        CP      0D              ;IF <CR> THEN OK
        JR      Z,6$
        CP      08              ;<BSP> IS OK TOO
        JR      Z,6$
        XOR     A               ;OTHER CONTROL CHARACTERS NOT SENT
        RET

6$:     PUSH    AF
        LD      A,(CONEN)
        OR      A
        JR      NZ,7$
        POP     AF              ;HERE IF CONSOLE NOT ENABLED
        XOR     A
        RET

7$:     POP     AF              ;HERE IF IN APPLICATION MODE
        RET

UR0I::  ;USER READER 0 IN
UR1I::  ;USER READER 1 IN
UR2I::  ;USER READER 2 IN
```

```
UR3I::  ;USER READER 3 IN

        XOR     A
        SCF
        RET

UC00::  ;USER CONSOLE 0 OUT
UC10::  ;USER CONSOLE 1 OUT
UC20::  ;USER CONSOLE 2 OUT
UC30::  ;USER CONSOLE 3 OUT

        PUSH    AF
        LD      A,(CONEN)
        OR      A
        JR      NZ,1$
        POP     AF              ;GET OUT OF HERE IF CONSOLE NOT ENABLED
        RET

1$:     LD      A,(REMFLG)      ;GET REMOTE FLAG
        OR      A
        JR      NZ,2$
        IN      A,(SIO1C)       ;GET STATUS
        AND     4               ;TRANS. BUFFER EMPTY?
        JR      Z,1$            ;LOOP IF NOT EMPTY
        LD      A,C             ;GET CHAR
        OUT     (SIO1),A        ;OUTPUT CHAR
        POP     AF
        RET

2$:     LD      A,(REMFLG)      ;GET REMOTE FLAG
        OR      A
        JR      Z,1$
        IN      A,(SIO2C)
        AND     4               ;TRANS. BUFFER EMPTY?
        JR      Z,2$            ;LOOP IF NOT EMPTY
        LD      A,C             ;GET CHAR
        OUT     (SIO2),A        ;OUTPUT CHAR
        POP     AF
        RET

UL00::  ;USER LIST 0 OUT
UL10::  ;USER LIST 1 OUT
UL20::  ;USER LIST 2 OUT
UL30::  ;USER LIST 3 OUT

        PUSH    AF
1$:     IN      A,(SIO3C)       ;GET STATUS
        AND     4               ;TRANS. BUFFER EMPTY?
        JR      Z,1$            ;LOOP IF NOT EMPTY
        LD      A,C             ;GET CHAR
        OUT     (SIO3),A        ;OUTPUT CHAR
        POP     AF
        RET

UP00::  ;USER PUNCH 0 OUT
UP10::  ;USER PUNCH 1 OUT
UP20::  ;USER PUNCH 2 OUT
UP30::  ;USER PUNCH 3 OUT

        PUSH    AF
1$:     IN      A,(SIO4C)       ;GET STATUS
        AND     4               ;TRANS. BUFFER EMPTY?
        JR      Z,1$            ;LOOP IF NOT EMPTY
        LD      A,C             ;GET CHAR
        OUT     (SIO4),A        ;OUTPUT CHAR
        POP     AF
```

```
        RET

UC0S::  ;USER CONSOLE 0 STATUS
UC1S::  ;USER CONSOLE 1 STATUS
UC2S::  ;USER CONSOLE 2 STATUS
UC3S::  ;USER CONSOLE 3 STATUS

1$:     LD      A,(REMFLG)
        OR      A
        JR      Z,2$
        IN      A,(SIO2C)
        JR      3$
2$:     IN      A,(SIO1C)
3$:     AND     1
        RET     Z
        LD      A,-1
        RET

STCH1:: EX      AF,AF
        EXX
        LD      BC,SIO1C
        JR      STCH
STCH2:: EX      AF,AF
        EXX
        LD      BC,100+SIO2C
        JR      STCH
STCH3:: EX      AF,AF
        EXX
        LD      BC,200+SIO3C
        JR      STCH
STCH4:: EX      AF,AF
        EXX
        LD      BC,300+SIO4C
        JR      STCH
STCH:   LD      A,10            ;RESET AND READ LATCH
        OUT     (C),A
        IN      D,(C)
        BIT     3,D             ;DCD
        JR      Z,1$
        LD      A,0C1           ;ENABLE RECEIVER
        JR      2$
1$:     LD      A,0C0           ;DISABLE RECEIVER
2$:     LD      E,3             ;SEND COMMAND
        OUT     (C),E
        OUT     (C),A
        LD      A,B
        CP      1
        JR      NZ,10$
        BIT     4,D             ;RING?
        JR      Z,10$
        LD      A,100.
        LD      (REMFLG),A
10$:    EX      AF,AF
        EXX
        EI
        RETI

        .END
```


ENVIRONMENTAL SYSTEMS CORP.
ESC 102-2100 V1.04
NOTE:
OF CARD AND S1 IF APPLICABLE.


ENVIRONMENTAL SYSTEMS CORP.
U37
CPU
CN-L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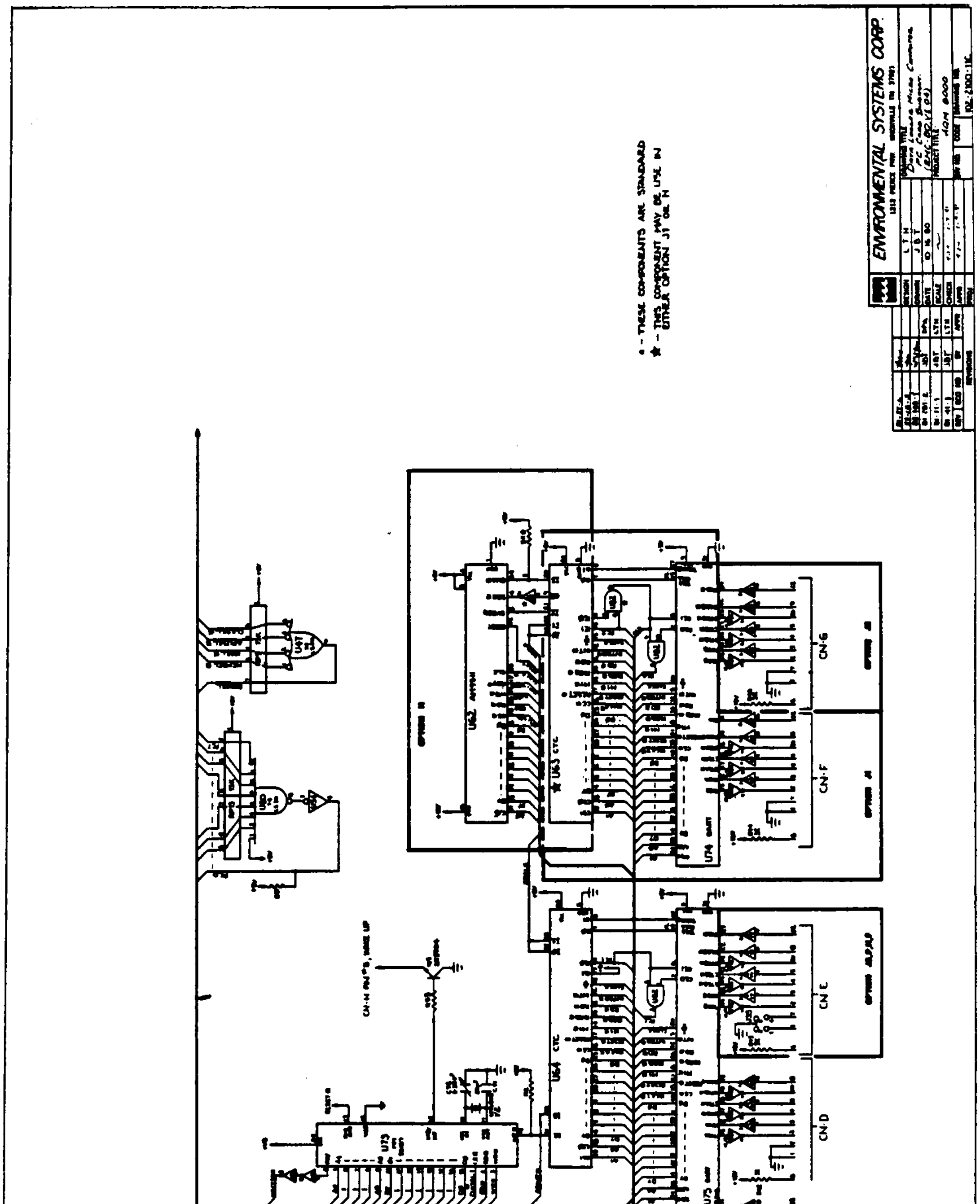
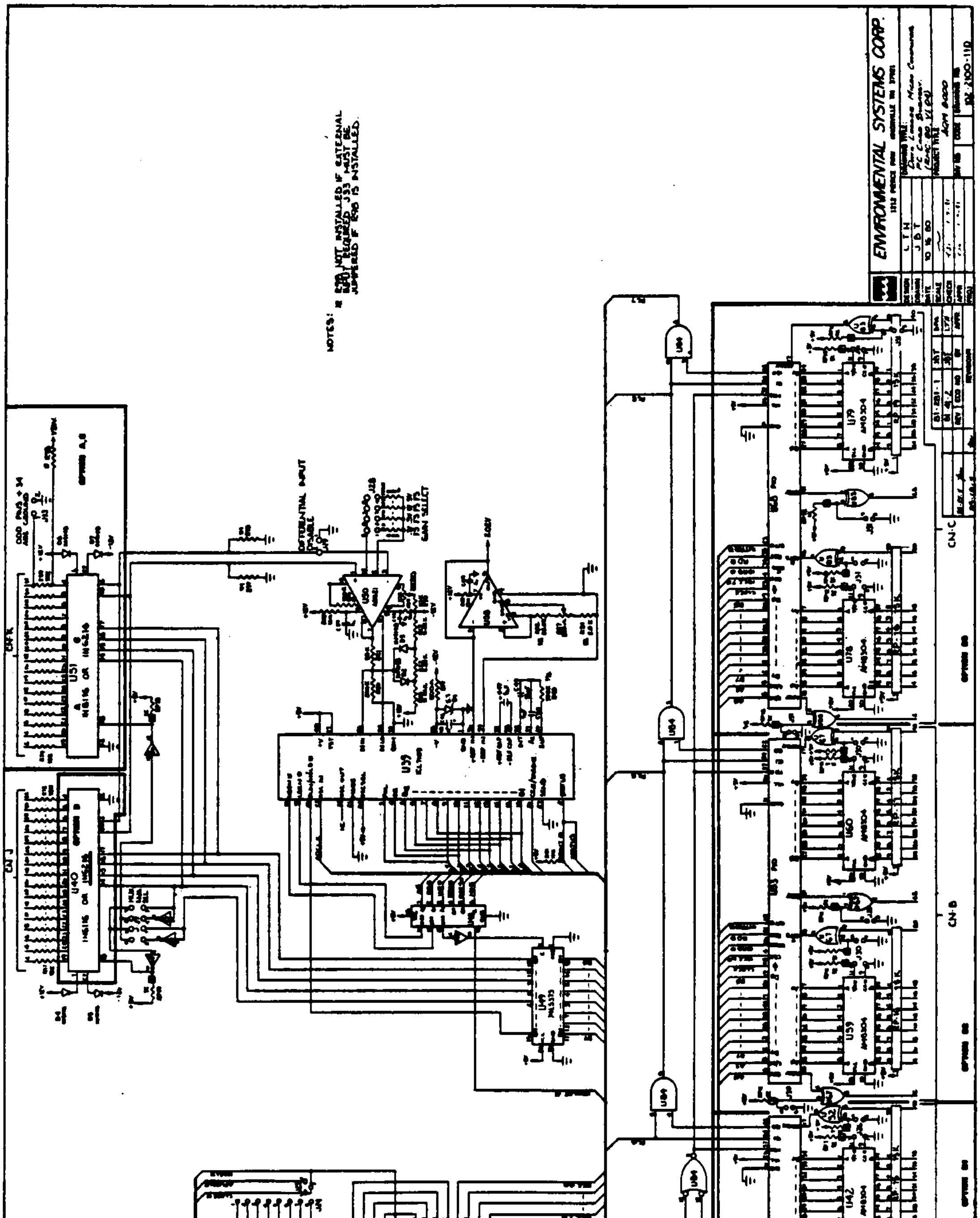
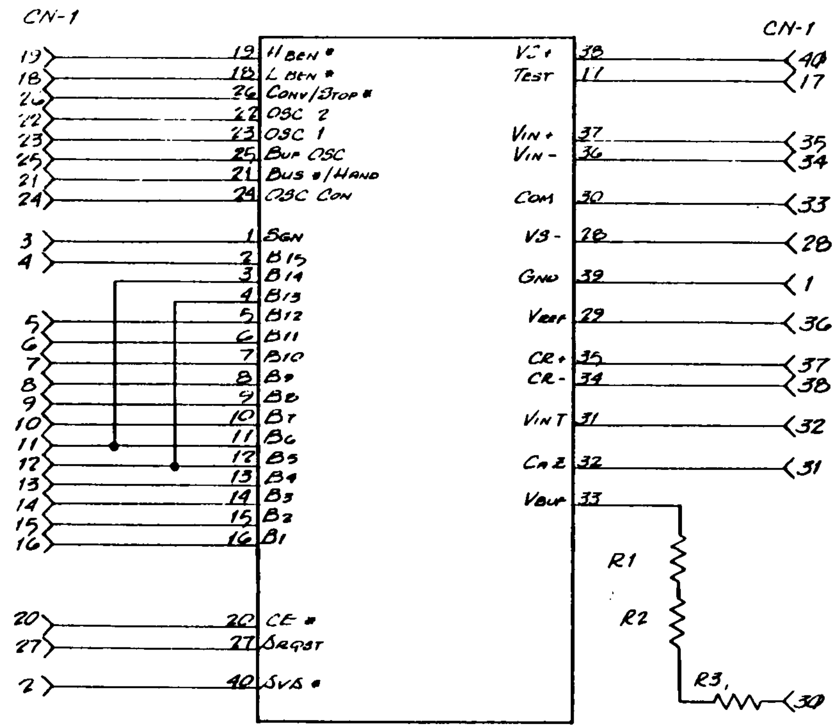


ENVIRONMENTAL SYSTEMS CORP.
CN-G
CN-F
CN-E
CN-D


ENVIRONMENTAL SYSTEMS CORP.
NOTES:
NOT INSTALLED IF EXTERNAL
INPUT REQUIRED J33 MUST BE
JUMPERED IF
IS INSTALLED.
DIFFERENTIAL INPUT
GAIN SELECT
CN-A
CN-B
CN-C
CN-J
CN-K



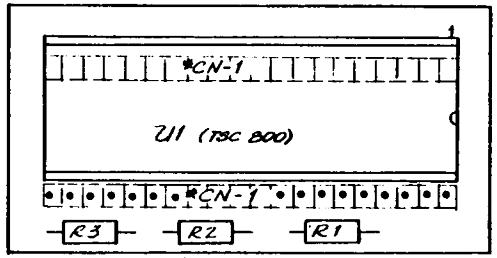
ENVIRONMENTAL SYSTEMS CORPORATION

DESIGN	
DRAWN	
DATE	
SCALE	
CHECK	MS 7/20/89
APPR.	
PROJ.	
DRAWING TITLE	15 BIT A/D ADAPTER PC CARD SUBASSEMBLY
PROJECT TITLE	ETS-30B
DIV. NO.	
DRAWING NO.	102-2120-11

NO	DATE	BY

REVISIONS

NOTES:
1. * CN-1 (INDICATED W/DASHED LINES) ARE MOUNTED ON FOIL SIDE OF PC CARD. THESE SAMTEC CONNECTORS MUST BE MOUNTED FIRST & THEIR LEADS CUT BEFORE SOLDERING. (THESE MUST BE ALIGNED PROPERLY.)

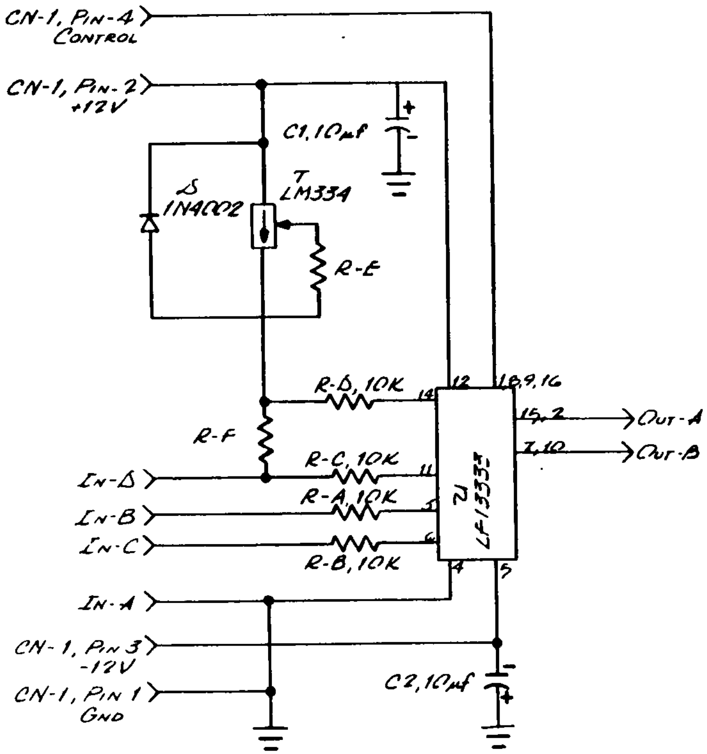


ENVIRONMENTAL SYSTEMS CORPORATION

DESIGN	Mark Shue
DRAWN	[illegible]
DATE	5/17/84
SCALE	2:1
CHECK	MS 7/20/89
APPR.	RER 7/23/84
PROJ	

NO	DATE	BY
REVISIONS		

DRAWING TITLE: 15 BIT A/D ADAPTER PC CARD SUBASSEMBLY
PROJECT TITLE: PT-1-80B
DIV. NO.:
DRAWING NO.: 102-2120-32



Typical Circuit for Channels 1 thru 8

Channel	U	T	S	R-A	R-B	R-C	R-D	R-E	R-F
1	U1	T1	S1	R1	R2	R3	R4	R5	R6
2	U2	T2	S2	R7	R8	R9	R10	R11	R12
3	U3	T3	S3	R13	R14	R15	R16	R17	R18
4	U4	T4	S4	R19	R20	R21	R22	R23	R24
5	U5	T5	S5	R25	R26	R27	R28	R29	R30
6	U6	T6	S6	R31	R32	R33	R34	R35	R36
7	U7	T7	S7	R37	R38	R39	R40	R41	R42
8	U8	T8	S8	R43	R44	R45	R46	R47	R48

Channel	In-A	In-B	In-C	In-D	Out-A	Out-B
1	CN-3, Pin 1	CN-3, Pin 3	CN-3, Pin 5	CN-3, Pin 7	CN-2, Pin 2	CN-2, Pin 18
2	Pin 9	Pin 11	Pin 13	Pin 15	Pin 4	Pin 20
3	Pin 17	Pin 19	Pin 21	Pin 23	Pin 6	Pin 22
4	CN-3, Pin 25	CN-3, Pin 27	CN-3, Pin 29	CN-3, Pin 31	Pin 8	Pin 24
5	CN-4, Pin 1	CN-4, Pin 3	CN-4, Pin 5	CN-4, Pin 7	Pin 10	Pin 26
6	Pin 9	Pin 11	Pin 13	Pin 15	Pin 12	Pin 28
7	Pin 17	Pin 19	Pin 21	Pin 23	Pin 14	Pin 30
8	CN-4, Pin 25	CN-4, Pin 27	CN-4, Pin 29	CN-4, Pin 31	CN-2, Pin 16	CN-2, Pin 32

Odd Pins and Pin-34 on CN-2 are GND.
Even Pins and Pin 33 on CN-3 and CN-4 are GND.

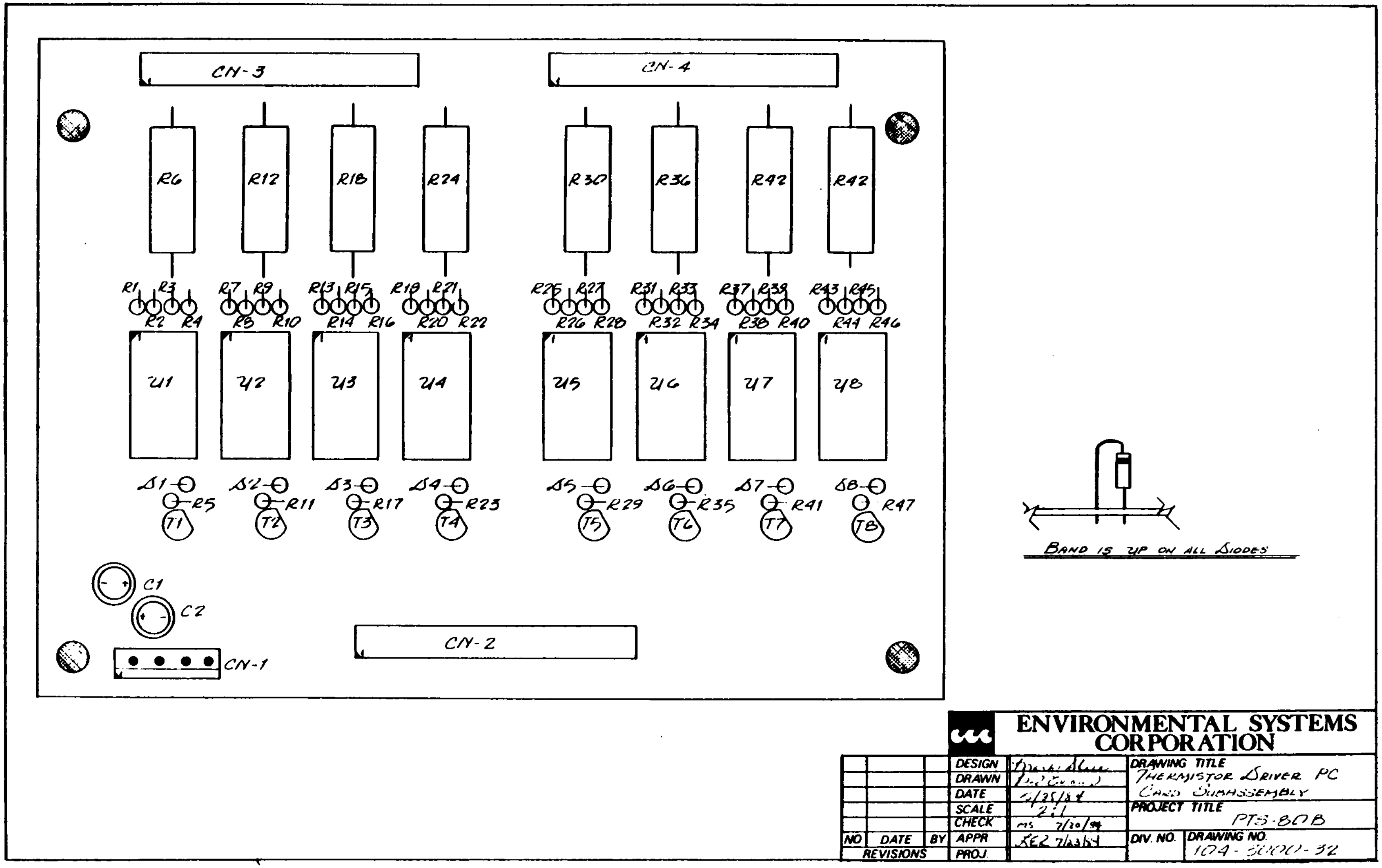
ENVIRONMENTAL SYSTEMS CORPORATION

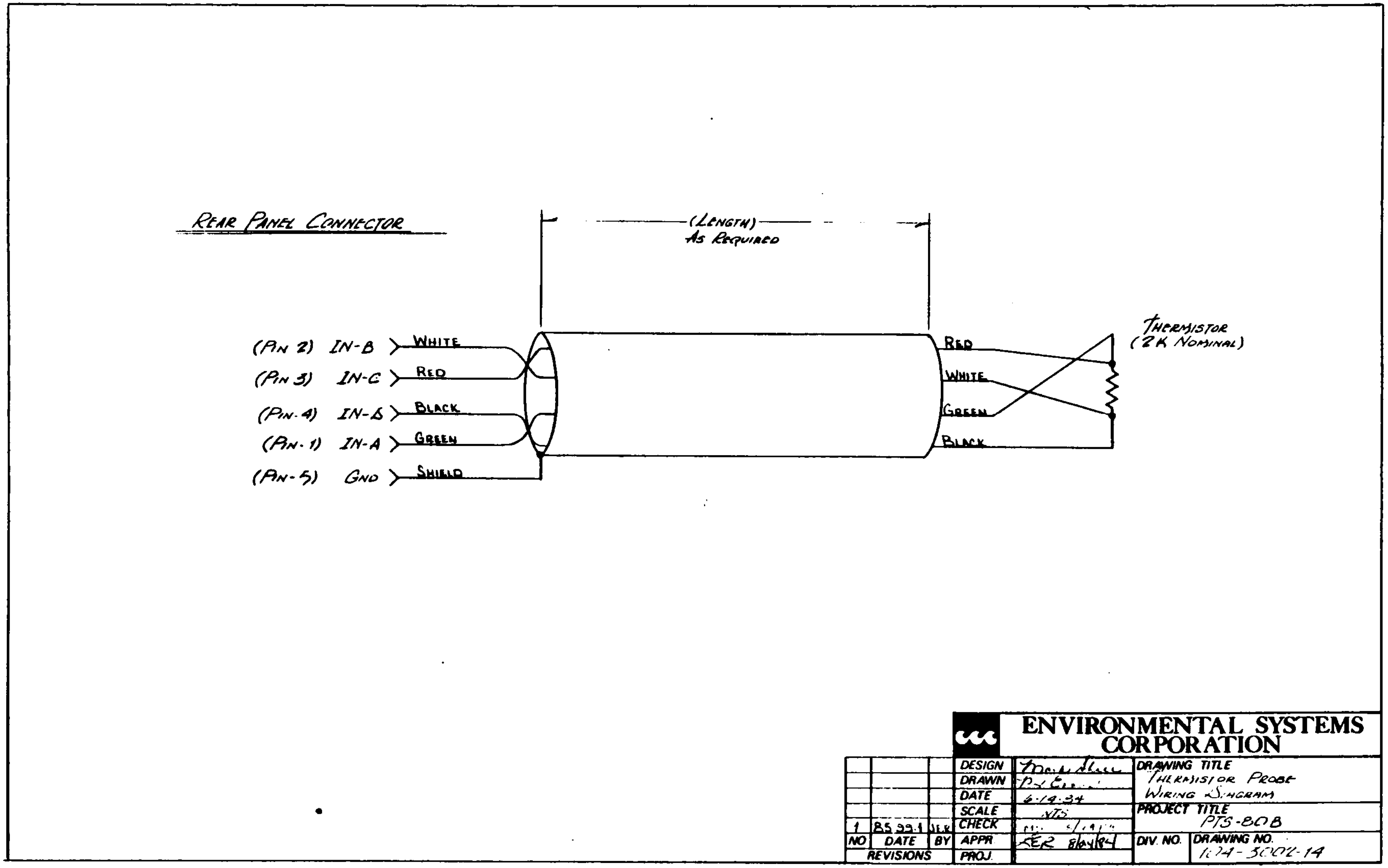
NO	DATE	BY

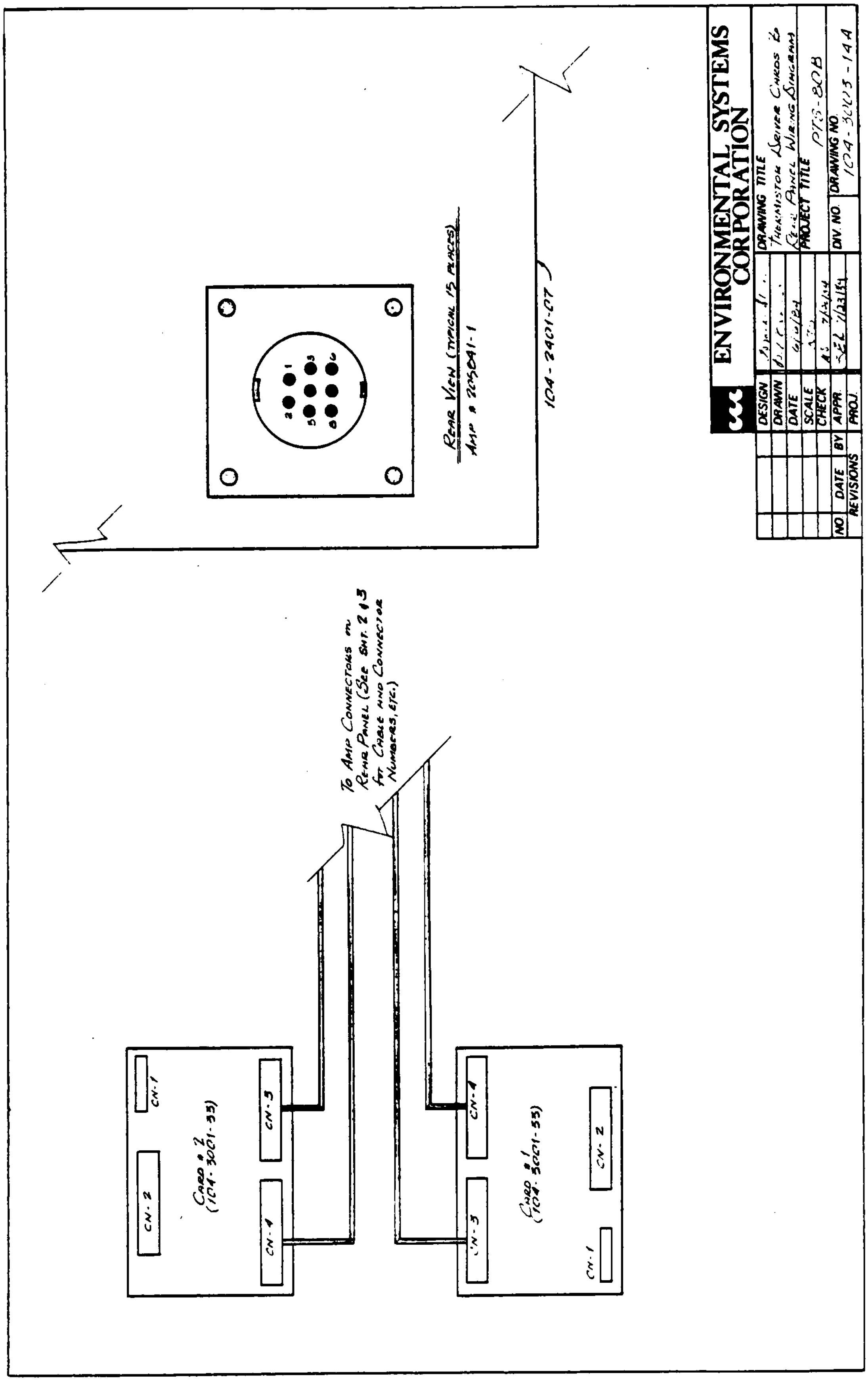
REVISIONS

DESIGN: [illegible]
DRAWN: [illegible]
DATE: 5-25-84
SCALE: [illegible]
CHECK: MS 7/20/84
APPR: REP 7/23/84
PROJ:

DRAWING TITLE: Thermistor Driver PC [illegible] Subassembly
PROJECT TITLE: PTS-30B
DIV. NO.
DRAWING NO. [illegible] 3000-11


CN-3
CN-4
R6
R12
R18
R24
R30
R36
R42
R42
R1 R3 R2 R4
R7 R9 R8 R10
R13 R15 R14 R16
R19 R21 R20 R22
R25 R27 R26 R28
R31 R33 R32 R34
R37 R39 R38 R40
R43 R45 R44 R46
U1
U2
U3
U4
U5
U6
U7
U8
D1 R5 T1
D2 R11 T2
D3 R17 T3
D4 R23 T4
D5 R29 T5
D6 R35 T6
D7 R41 T7
D8 R47 T8
C1
C2
CN-1
CN-2
BAND IS UP ON ALL DIODES
ENVIRONMENTAL SYSTEMS CORPORATION
DESIGN
DRAWN
DATE
SCALE 2:1
CHECK 7/20/84
APPR 7/23/84
PROJ.
DRAWING TITLE
THERMISTOR DRIVER PC CARD SUBASSEMBLY
PROJECT TITLE
DIV. NO.
DRAWING NO.
NO
DATE
BY
REVISIONS


REAR PANEL CONNECTOR
(LENGTH) AS REQUIRED
(PIN 2) IN-B WHITE
(PIN 3) IN-C RED
(PIN-4) IN-D BLACK
(PIN-1) IN-A GREEN
(PIN-5) GND SHIELD
RED
WHITE
GREEN
BLACK
THERMISTOR (2K NOMINAL)
ENVIRONMENTAL SYSTEMS CORPORATION
DESIGN
DRAWN
DATE 6-14-84
SCALE NTS
CHECK
APPR
PROJ.
DRAWING TITLE
THERMISTOR PROBE WIRING DIAGRAM
PROJECT TITLE
PTS-80B
DIV. NO.
DRAWING NO.
104-3002-14
NO DATE BY
REVISIONS


ENVIRONMENTAL SYSTEMS CORPORATION
DESIGN
DRAWN
DATE
SCALE
CHECK
APPR.
PROJ.
NO
DATE
BY
REVISIONS
DRAWING TITLE
Thermistor Driver Cards to Rear Panel Wiring Diagram
PROJECT TITLE
PTS-80B
DIV. NO.
DRAWING NO.
104-3003-14A
Rear View (Typical 15 places)
Amp # 205041-1
104-2401-07
To Amp Connectors on Rear Panel (See Sht. 2 & 3 for Cable and Connector Numbers, etc.)
Card # 2 (104-3001-55)
Card # 1 (104-3001-55)
CN-1
CN-2
CN-3
CN-4

Thermistor Sensor Card #1 (104-3001-33)

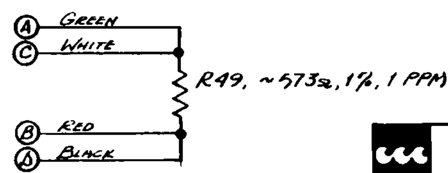
Card Conn. #	Conn. Pin #, Wire Color	Signal Name	Rear Panel Conn. #	Rear Panel Conn. Pin #
CN-3,	Pin-1, Brown	IN-A	1	Pin-1
	Pin-3, Orange	IN-B	1	Pin-2
	Pin-5, Green	IN-C	1	Pin-3
	Pin-7, Violet	IN-Δ	1	Pin-4
	Pin-2, Red	GND	1	Pin-5
	Pin-4, Yellow	GND	1	Pin-5
	Pin-6, Blue	GND	1	Pin-5
	Pin-8, Gray	GND	1	Pin-5
	Pin-9, White	IN-A	2	Pin-1
	Pin-11, Brown	IN-B	2	Pin-2
	Pin-13, Orange	IN-C	2	Pin-3
	Pin-15, Green	IN-Δ	2	Pin-4
	Pin-10, Black	GND	2	Pin-5
	Pin-12, Red	GND	2	Pin-5
	Pin-14, Yellow	GND	2	Pin-5
	Pin-16, Blue	GND	2	Pin-5
	Pin-17, Violet	IN-A	3	Pin-1
	Pin-19, White	IN-B	3	Pin-2
	Pin-21, Brown	IN-C	3	Pin-3
	Pin-23, Orange	IN-Δ	3	Pin-4
	Pin-18, Gray	GND	3	Pin-5
	Pin-20, Black	GND	3	Pin-5
	Pin-22, Red	GND	3	Pin-5
	Pin-24, Yellow	GND	3	Pin-5
	Pin-25, Green	IN-A	4	Pin-1
	Pin-27, Violet	IN-B	4	Pin-2
	Pin-29, White	IN-C	4	Pin-3
	Pin-31, Brown	IN-Δ	4	Pin-4
	Pin-26, Blue	GND	4	Pin-5
	Pin-28, Gray	GND	4	Pin-5
	Pin-30, Black	GND	4	Pin-5
	Pin-32, Red	GND	4	Pin-5
CN-3,	Pin-33, Orange	GND	4	Pin-5
CN-4,	Pin-1, Brown	IN-A	5	Pin-1
	Pin-3, Orange	IN-B	5	Pin-2
	Pin-5, Green	IN-C	5	Pin-3
	Pin-7, Violet	IN-Δ	5	Pin-4
	Pin-2, Red	GND	5	Pin-5
CN-4,	Pin-4, Yellow	GND	5	Pin-5

CN-4,	Pin-6, Blue	GND	5	Pin-5
	Pin-8, Gray	GND	5	Pin-5
	Pin-9, White	IN-A	6	Pin-1
	Pin-11, Brown	IN-B	6	Pin-2
	Pin-13, Orange	IN-C	6	Pin-3
	Pin-15, Green	IN-Δ	6	Pin-4
	Pin-10, Black	GND	6	Pin-5
	Pin-12, Red	GND	6	Pin-5
	Pin-14, Yellow	GND	6	Pin-5
	Pin-16, Blue	GND	6	Pin-5
	Pin-17, Violet	IN-A	7	Pin-1
	Pin-19, White	IN-B	7	Pin-2
	Pin-21, Brown	IN-C	7	Pin-3
	Pin-23, Orange	IN-Δ	7	Pin-4
	Pin-18, Gray	GND	7	Pin-5
	Pin-20, Black	GND	7	Pin-5
	Pin-22, Red	GND	7	Pin-5
	Pin-24, Yellow	GND	7	Pin-5
	Pin-25, Green	IN-A	8	Pin-1
	Pin-27, Violet	IN-B	8	Pin-2
	Pin-29, White	IN-C	8	Pin-3
	Pin-31, Brown	IN-Δ	8	Pin-4
	Pin-26, Blue	GND	8	Pin-5
	Pin-28, Gray	GND	8	Pin-5
	Pin-30, Black	GND	8	Pin-5
	Pin-32, Red	GND	8	Pin-5
CN-4,	Pin-33, Orange	GND	8	Pin-5

ENVIRONMENTAL SYSTEMS CORPORATION

NO	DATE	BY			
			DESIGN	[illegible]	DRAWING TITLE Thermistor Sensor Cards to Rear Panel Wiring Diagram (Card #1)
			DRAWN	[illegible]	
			DATE	[illegible]	
			SCALE		PROJECT TITLE PTS-80B
			CHECK	[illegible]	
REVISIONS			APPR.	[illegible]	DIV. NO. / DRAWING NO. 104-3003-14B
			PROJ.		

Thermistor Driver Card #2 (104-5001-35)				
Card Conn #	Drv Pin # / Wire Color	Signal Name	Rear Panel Conn #	Rear Panel Pin #
CN-3	Pin-1, Brown	In-A	9	Pin-1
	Pin-3, Orange	In-B	9	Pin-2
	Pin-5, Green	In-C	9	Pin-3
	Pin 7, Violet	In-D	9	Pin-4
	Pin-2, Red	Gnd	9	Pin-5
	Pin-4, Yellow	Gnd	9	Pin-5
	Pin-6, Blue	Gnd	9	Pin-5
	Pin-8, Gray	Gnd	9	Pin-5
	Pin 9, White	In-A	10	Pin-1
	Pin 11, Brown	In-B	10	Pin-2
	Pin 13, Orange	In-C	10	Pin-3
	Pin-15, Green	In-D	10	Pin-4
	Pin-10, Black	Gnd	10	Pin-5
	Pin-12, Red	Gnd	10	Pin-5
	Pin-14, Yellow	Gnd	10	Pin-5
	Pin-16, Blue	Gnd	10	Pin-5
	Pin-17, Violet	In-A	11	Pin-1
	Pin-19, White	In-B	11	Pin-2
	Pin-21, Brown	In-C	11	Pin-3
	Pin-23, Orange	In-D	11	Pin-4
	Pin-18, Gray	Gnd	11	Pin-5
	Pin-20, Black	Gnd	11	Pin-5
	Pin-22, Red	Gnd	11	Pin-5
	Pin-24, Yellow	Gnd	11	Pin-5
	Pin-25, Green	In-A	12	Pin-1
	Pin-27, Violet	In-B	12	Pin-2
	Pin 29, White	In-C	12	Pin-3
	Pin 31, Brown	In-D	12	Pin-4
	Pin 26, Blue	Gnd	12	Pin-5
	Pin 28, Gray	Gnd	12	Pin-5
	Pin 30, Black	Gnd	12	Pin-5
	Pin 32, Red	Gnd	12	Pin-5
CN-3	Pin 33, Orange	Gnd	12	Pin-5
CN-4	Pin-1, Brown	In-A	13	Pin-1
	Pin-3, Orange	In B	13	Pin-2
	Pin 5, Green	In-C	13	Pin-3
	Pin-7, Violet	In-D	13	Pin-4
CN-4	Pin-2, Red	Gnd	13	Pin-5
CN-4	Pin 4, Yellow	Gnd	13	Pin-5
	Pin-6, Blue	Gnd	13	Pin-5
	Pin-8, Gray	Gnd	13	Pin-5
	Pin-9, White	In-A	14	Pin-1
	Pin-11, Brown	In-B	14	Pin-2
	Pin-13, Orange	In-C	14	Pin-3
	Pin-15, Green	In-D	14	Pin-4
	Pin-10, Black	Gnd	14	Pin-5
	Pin-12, Red	Gnd	14	Pin-5
	Pin-14, Yellow	Gnd	14	Pin-5
	Pin-16, Blue	Gnd	14	Pin-5
	Pin-17, Violet	In-A	15	Pin-1
	Pin-19, White	In-B	15	Pin-2
	Pin-21, Brown	In-C	15	Pin-3
	Pin-23, Orange	In-D	15	Pin-4
	Pin-18, Gray	Gnd	15	Pin-5
	Pin-20, Black	Gnd	15	Pin-5
	Pin-22, Red	Gnd	15	Pin-5
	Pin-24, Yellow	Gnd	15	Pin-5
	Pin-25, Green	In-A		(A)
	Pin-27, Violet	In-B		(B)
	Pin-29, White	In-C		(C)
	Pin-31, Brown	In-D		(D)
	Pin-26, Blue	Gnd		N.C
	Pin-28, Gray	Gnd		N.C
	Pin-30, Black	Gnd		N.C.
	Pin-32, Red	Gnd		N.C.
CN-4	Pin-33, Orange	Gnd		N.C.



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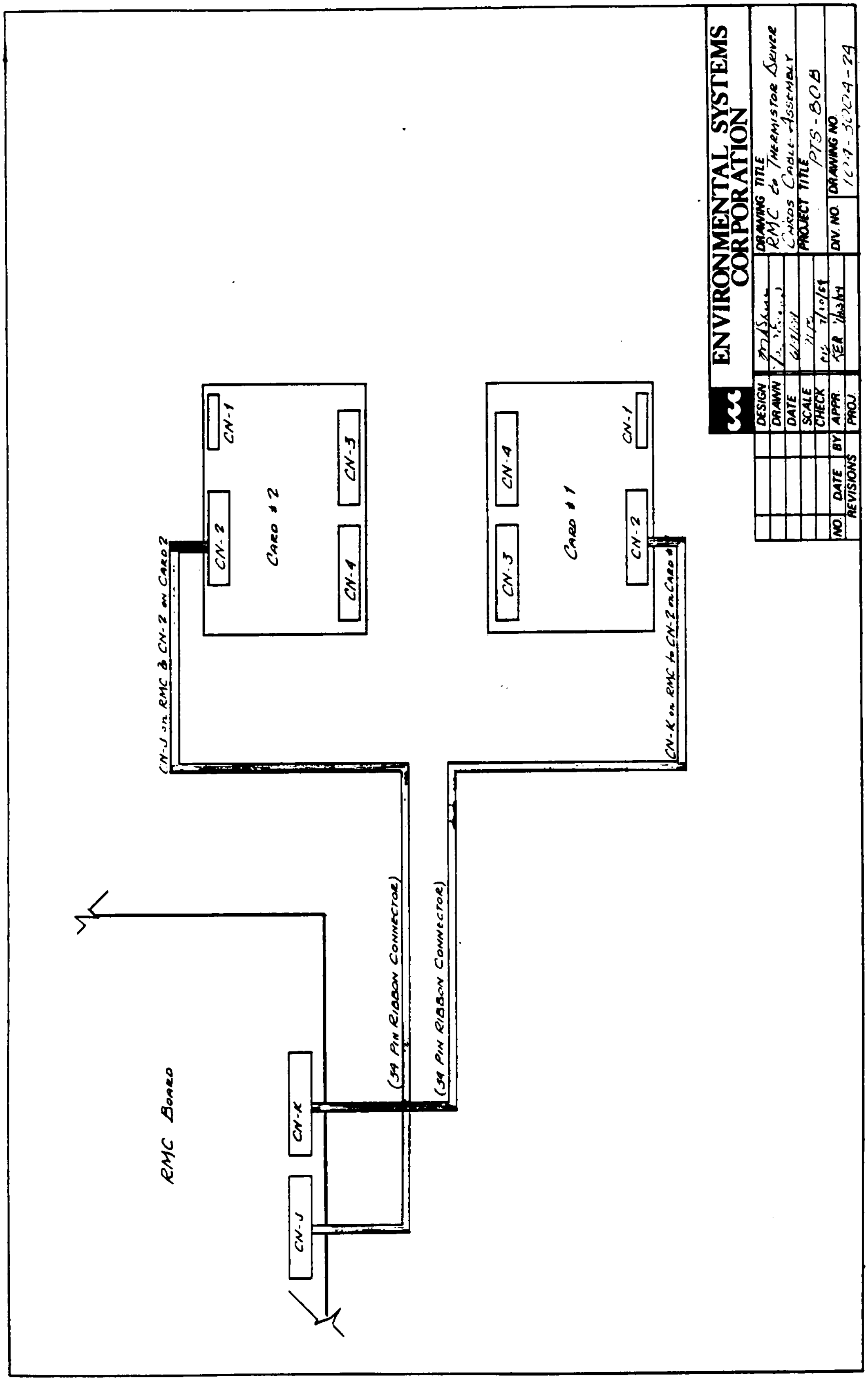
NO	DATE	BY		
REVISIONS			DESIGN	[illegible]
			DRAWN	[illegible]
			DATE	6-6-84
			SCALE	[illegible]
			CHECK	MS 7/20/84
			APPR.	KEP 7/23/84
			PROJ.	

DRAWING TITLE: Thermistor Driver Cards to Rear Panel Wiring Schematic (Card #2)

PROJECT TITLE: PTS-80B

DIV. NO.

DRAWING NO. 104-5003-14C


ENVIRONMENTAL SYSTEMS CORPORATION
DRAWING TITLE
RMC to Thermistor Driver Cards Cable Assembly
PROJECT TITLE
PTS-80B
DIV. NO.
DRAWING NO.
DESIGN
DRAWN
DATE
SCALE
CHECK
APPR.
PROJ.
NO.
DATE
BY
REVISIONS
Card # 2
CN-1
CN-2
CN-3
CN-4
Card # 1
CN-1
CN-2
CN-3
CN-4
CN-J on RMC to CN-2 on Card 2
CN-K on RMC to CN-2 on Card 1
(34 Pin Ribbon Connector)
(34 Pin Ribbon Connector)
RMC Board
CN-K
CN-J

VITA

Mark Allen Shell was born in Camden, Tennessee on August 26, 1960. After graduating in June 1978 as salutatorian from Farrragut High School in Knoxville, Tennessee, he enrolled in the College of Engineering at the Knoxville campus of the University of Tennessee. While at the University, he participated in the Cooperative Engineering Education program and worked as an electrical engineering assistant for five quarters with the National Security Agency in Fort Meade, Maryland. He was graduated with a Bachelor of Science Degree in Electrical Engineering with highest honors in August 1982.

During February 1982, he began work part-time with Environmental Systems Corporation as an engineering assistant. After receiving his B.S. in August 1982, he was promoted to the title of microprocessor engineer at ESC and he enrolled in the graduate program in Electrical Engineering at the University of Tennessee. He began working full time in June 1983 after completing his course work for the Master of Science Degree. In June of 1985, he received a promotion at ESC to project engineer.

The author has been responsible for designing, writing, and maintaining the microprocessor assembly language software in the ESC Model AQM-8000B data loggers since his employment. During this time, the code has been expanded from less than six thousand lines of code to over twenty thousand lines with over thirty different versions in the field. In addition to his software duties, he has designed hardware improvements to the AQM-8000B, designed and tested the PTS-80B, and has recently designed a new generation data logger, the ESC8040.

He has been married to Tammy Denise Shell since 1982 and is the father of a one-year-old daughter, Elizabeth Ann.