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I am submitting herewith a dissertation written by Majed Nasr Natour entitled "Development of a Smart Temperature Measurement System Based on the Multilead Thermocouple Concept." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Nuclear Engineering.

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DEVELOPMENT OF A SMART TEMPERATURE MEASUREMENT SYSTEM BASED ON THE MULTI-LEAD THERMOCOUPLE CONCEPT

A Dissertation

Presented for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

Majed N. Natour

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ABSTRACT

A smart temperature measurement system (STMS) based on the concept of multi-lead thermocouples (MTC) was developed and tested. The system consists of a MTC, an interface, and a knowledge base. The MTC is comprised of five thermo-elements sharing a single measuring junction that provides up to ten estimates of the temperature. The interface is controlled by a microprocessor. It facilitates signal transmission between the MTC and the microprocessor and provides the reference junction temperature. The knowledge base is interactive, user friendly, and menu driven. It is equipped with on-line signal validation methods that represents the core of the STMS and allows the system to perform the "intelligent" duties of communication, computation, and self-checking.

The system worked, but two of the ten possible measurements were not useful because the corresponding wire pairs showed low sensitivity to temperature. Long term drift tests were performed on five groups of MTCs. The MTCs in each group were made of a unique set of five thermo-elements. Effects of exposure to high temperatures, calibration temperature, type of environment, and frequency of sensor removal from the process for testing purposes on the sensor drift rates were investigated. All the groups showed typical thermocouple behavior (no excess drifts due

to the close proximity of several wires in the same sheath). A set of weight factors were developed that drastically reduced the average error, resulting in high overall system accuracy.

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CHAPTER 1.

INTRODUCTION

1.1 Statement of the Problem

Measurement instruments are a necessity in almost every aspect of our lives. They represent our senses, watching over processes to let us know, understand, and control those processes. Air-conditioning, refrigeration, automotive, and more complex systems such as chemical and nuclear plants and space vehicles require some form of control systems. The proper and optimal control of those processes leads to economically sound and safe industries and vice versa. Our ability to control those processes, however, depends on our ability to measure the variables in those processes.

There is always the question of the quality of the measurements indicated by the sensors. Those measurements do not always reflect accurate and correct values of the measured variables. To overcome this problem, engineers typically implement redundant sensors, signal validation methods, and recommend periodic calibration of the sensors. Furthermore, sensor manufacturers, universities and research laboratories are involved in testing, studying, developing, and improving the measurement systems for better instrumentation and control of processes.

Signal validation is concerned with increasing the engineer's confidence in the measurements by detecting and

isolating faulty sensors. The most commonly used signal validation methods in the nuclear industry are the following (Meijer, 1981):

1. Like-sensor comparison
2. Limit checking
3. Auctioneering
4. Instrument-loop-integrity checking
5. Calibration checking
6. Parity space
7. Analytic redundancy.

The signal validation methods that involve analysis of the outputs of several diverse and like sensors are referred to as Array Processing methods.

Sensors fail unpredictably leading to economical drain on the industries. As a demonstration, the instrument performance in nuclear plants was studied by analyzing data published by the International Atomic Agency (International, 1985). It was calculated that the average number of hours of yearly full-outages of 63 nuclear generating units in the USA within the ten year period from 1975 to 1985, due to reactor instrumentation and control failure (i.e. failure in control and safety rods and drives, neutron monitoring (in core plus external), reactor instrumentation (except neutron), reactor control logic, reactor protection logic, and process computer) was 7,232 hours or 301 plant days. This represents an average shutdown of five days per

generating unit. Assuming that there is a cost of half a million dollars to the utility per day of shutdown, the total annual cost to the nuclear industry was $150.5 million. In 1985 alone, the cost rose to $185.5 million. This does not include full outages due to instrumentation and control failure in other systems such as post-LOCA (Loss of Coolant Accident) instrumentation, health and safety monitoring, pressurizer, and steam generator instrumentation and control. According to another study (Meijer, 1981), instrument failure alone (i.e. excluding control failure) is responsible for an average of 1 percent of the overall nuclear plants unavailability per year, at a cost of $500,000/year/plant.

Recent developments in the nuclear power plant industry made it necessary to increase the sensors self-diagnostic and signal validation capabilities to reduce the frequency of the sensor calibration. During the refueling period, typically every eighteen months, plant maintenance and sensor re-calibration, based upon nuclear regulatory guides, are carried out. Current trends in the nuclear industry are increasing the length of the fuel cycle to twenty four months in order to reduce plant cost due to outages. Therefore, the sensors are expected to perform reliably for an extra six months. This calls for the development of "calibration reduction methods." Such methods may include sensors with on-line enhanced diagnostic capabilities

similar to the one developed in this research project.

In summary, unpredictable and undetectable sensor failure cannot be tolerated for economic and safety concerns. Signal validation can be instrumental in detecting and isolating failing sensors. However, this generally occurs after the fact, and after the failure has occurred. Furthermore, new emphasis on sensor calibration reduction techniques has increased in the nuclear industry. Therefore, there is a definite need for the development of on-line qualitative and quantitative sensor performance evaluation methods.

1.2 An Approach to Solving the Problem

It is desired to develop sensor/readout devices that are capable of digitally indicating the value of the desired measurand and the confidence factor in the value. The computations are performed at the sensor level rather than in the plant's central computer in order to free the central computer for other important tasks. The sensors will diagnose, and provide information about themselves. They may also provide maintenance, repair, and/or replacement information to the maintenance engineers. When the instrument system is in error or in route to exceeding the process operating limits, a warning sound or light is activated. Furthermore, if the sensor is not indicating the correct values of the measurand, but it responds properly to

the process changes (such as the case with out-of-calibration sensors), it may be necessary to continue to use such sensor until the next planned plant shutdown. This ideal sensor can be developed by utilizing today's powerful microprocessors in combination with new sensor designs. Such sensors are Intelligent/Smart Sensors/Instruments. Intelligent instrumentation has become one of the latest and most advanced methods of improving our ability to measure variables and keep track of the sensor performance and increasing confidence in the measurement system. The smart sensor technology may focus on current sensor designs or it may focus on new sensors designed explicitly to provide enhanced diagnostic possibilities. This new area is not yet fully developed: future micro-processors will be thousands of times more powerful, less expensive, and smaller than the present microprocessors; there is great promise for the intelligent sensor research community.

Future industrial plants will rely heavily on distributed networks of digitally intercommunicating, self checking, and performance tracking smart sensors. The individual validated signals from the smart sensors will be the inputs to digital controllers, which in turn will supervise the plant's actuators.

1.3 Project Description

The problem described above is universal. It occurs in all kinds of industrial factories, power plants, research and highly technical laboratories and with all kinds of sensors, such as temperature, pressure, flow, etc.. Smart sensor technology can be applied to all kinds of sensors.

In this research a smart temperature measurement system that can operate from 0 °C to 482 °C (32 °F to 900 °F) using existing thermocouple (TC) technology, a uniquely designed interface, and a data acquisition board in a microcomputer is developed and tested in the Nuclear Engineering Department of The University of Tennessee at Knoxville. The new self-checking smart temperature system, is enhanced with computation, communication, and diagnostic capabilities.

1.3.1 New Sensor Designs for Enhanced Diagnostics: Multi-Junction Thermocouples

New fabrication capability (mainly ultra-small, high reliability thermocouples and very small platinum resistance thermometers (PRT)) provides new possibilities for manufacturing process sensors with enhanced diagnostic capability. Some of these have reached the early commercial stage and others are still speculative. Such sensors combined with powerful microprocessors and data acquisition devices pave the way for the development of smart sensors.

Reed (1982) has investigated the enhanced diagnostic

potential of multilead thermocouples (MTC). The advantage of the MTC is that the number of redundant measurements increases rapidly as the number of dissimilar wires increases (three measurements with three wires, six measurements with four wires, etc).

In a smart setting, the MTC can provide the operator with the temperature indication and the corresponding confidence factor based on the weighted averages of the simultaneous measurements. The weights themselves may be adjusted as needed or based on the collective sensor performance.

1.3.2 Project Objectives

Based on the desirability to realize the potential of smart sensors in the process industry and to advance their technology, a smart temperature measurement system (STMS) based on the MTC technology is to be constructed and tested in the Nuclear Engineering Department. The following tasks and goals have been set for achievement in this project:

TASK A: Select the MTC wires.

TASK B: Fabricate and test the MTC

a. to prove the principle,

b. to develop tables and polynomials for all candidate wire pairs (especially the nonstandard wire pairs).

TASK C: Develop methods for decision making and develop the accompanying software.

Task D: Develop computer/sensor interface.

TASK E: Develop an interactive and menu driven knowledge base to control the operation of the devices; the data acquisition, conditioning, analyses, and display; and other intelligent functions such as communications, self-tracking, moving status window display, maintenance assistance, and parameter modification.

TASK F: Perform drift and thermal cycling tests on groups of immersion type MTCs over a three month period.

TASK G: Document all the procedures and results obtained in the development and testing of this device, and make recommendations regarding the commercial development of the system.

1.4 Relevance of the Project to Nuclear Power Plants

1.4.1 Introduction

The main function of nuclear power plants is to generate electrical energy for commercial use. In the plant, the reactor core houses the nuclear fuel elements

which, under highly controlled environment, are used to produce heat by nuclear fission (i.e. splitting certain heavy atoms, such as uranium, into two or more lighter fission products, which results in generating about 200 MeV per fission). The tremendous amount of heat generated in the core is then used to generate high pressure steam that drives conventional turbo-generators to produce electricity.

There are several types of commercial nuclear power plants, depending on the type of coolant used to remove the core heat. Those are the light water reactors (LWR), the heavy water reactors (HWR), and the gas cooled reactors. The LWR, the most common reactors in the United States, consist of pressurized water reactors (PWR), and boiling water reactors (BWR). The HWRs, a type of which is called the "Canadian deuterium-uranium" (CANDU) reactors, are common in Canada. The high-temperature gas-cooled reactor (HTGR) utilizes helium gas to cool the reactor. All these reactors require accurate temperature measurement to properly control and safeguard the plant. To provide specific details on the importance of temperature sensors in nuclear power plants, the operation of PWRs is described as a study case.

A typical primary coolant system of a PWR is shown in Figure 1.1 (Nero, 1979). This system consists of four primary coolant loops, a single pressurizer, and the pressure vessel where the reactor core is located as shown

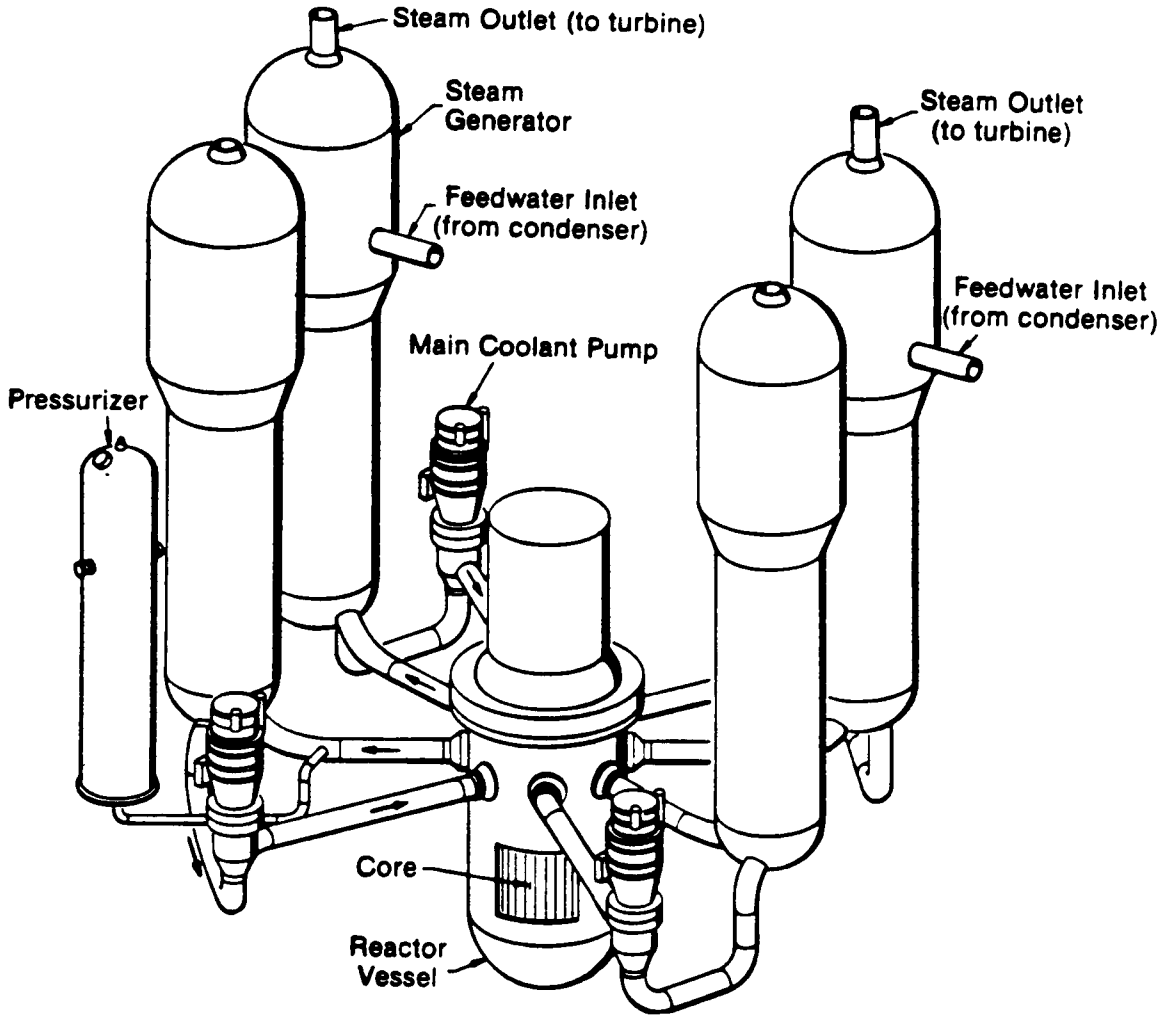


Figure 1.1 A Schematic of the Nuclear Steam Supply System of a Typical PWR (Nero, 1979).

in Figure 1.2 (Nero, 1979). Each primary coolant loop consists of a steam generator, a reactor coolant pump, and piping. The reactor coolant, at a temperature of 289 °C (Nero, 1979), enters the reactor pressure vessel through inlet nozzles (one inlet nozzle for each primary loop). The coolant then flows down between the core barrel and the vessel wall and enters the core from the bottom, then flows up through flow channels at a speed of 4.7 m/s where it cools the fuel elements. The coolant exits the pressure vessel through outlet nozzles, with a temperature of 325 °C (Nero, 1979). The hot coolant flows, through a pipe called the "hot leg," to the steam generator (SG). There are two types of SGs that are commercially used, the U-tube SG and the once-through SG. In both types the "hot" primary coolant flows through thousands of small tubes, then out of the SG through a pipe called the "cold leg." A pump is used to pump the coolant back to the reactor pressure vessel, and to maintain the coolant circulation process. In the SG, heat is transferred from the primary coolant through the walls of the small pipes, and to surrounding secondary feedwater. As the feedwater is heated by the primary coolant, steam is generated, and passed through a moisture separator to increase the quality of the steam by removing water droplets. The steam, with quality of 99.75%, is transmitted to the turbo-generator at a high speed to generate electricity. The steam is then condensed and

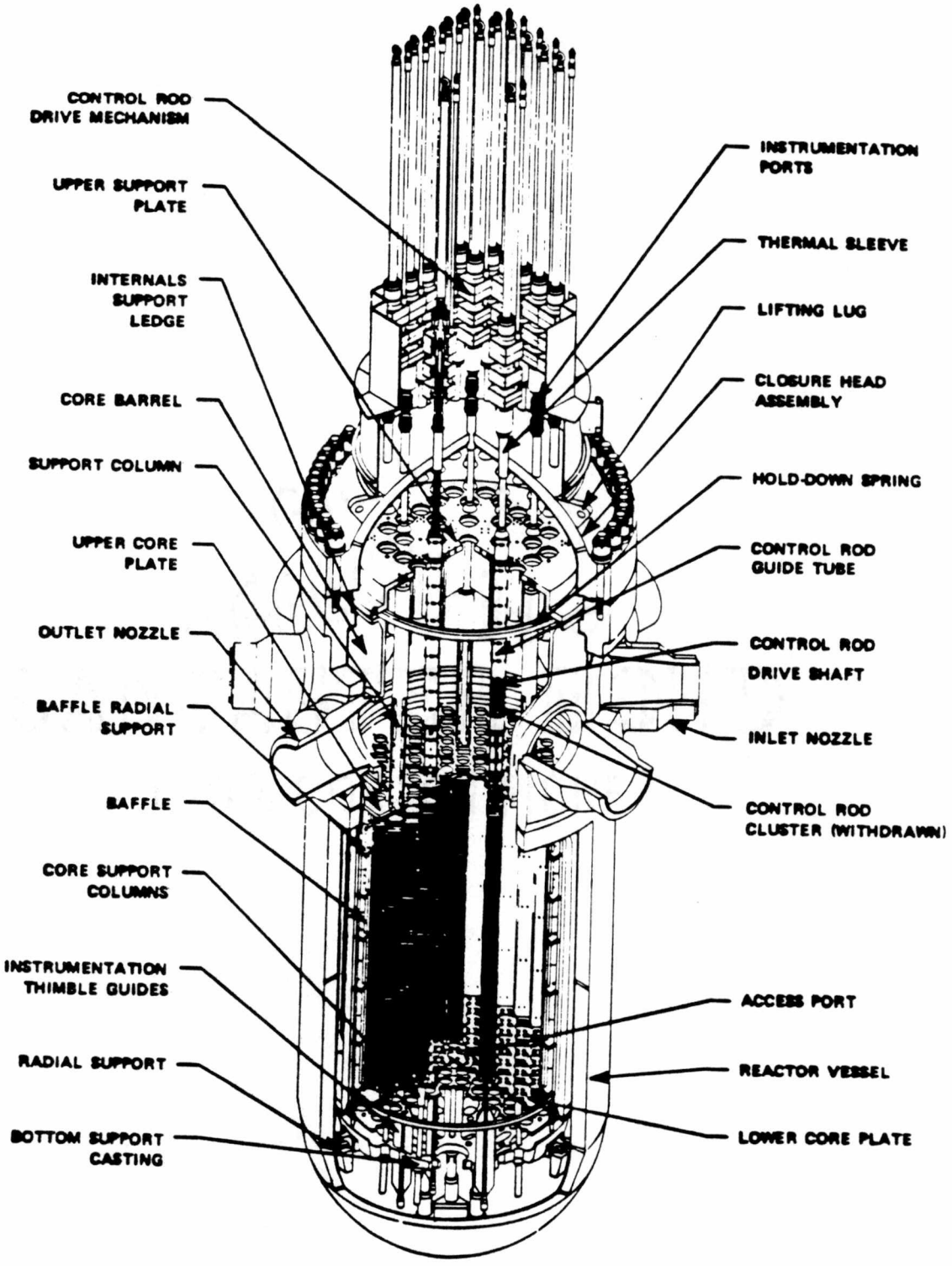


Figure 1.2 A Schematic of the Pressure Vessel of a Typical PWR (Nero, 1979).

recirculated back to the SG.

Since the primary coolant side has to be maintained at a pressure of about 2250 pisa, a pressurizer is attached to the hot leg of one of the primary loops. The high pressure is needed to prevent boiling in, and hence, uncovering of the core. The pressurizer is the hottest and highest point in the reactor coolant system (NRC, 1981). Therefore, it is the only location where a steam void is allowed. Its volume is occupied by coolant fluid and steam. To increase the system pressure, the power to heaters located in the bottom of the pressurizer is turned up. To reduce the system pressure, a sprayer located at the top of the pressurizer is activated whereby coolant is drawn from the cold leg, sprayed onto the steam, resulting in condensing the steam and reducing the pressure. Such action is needed for "large" pressure reductions. For "small" pressure reductions, the heater power is reduced from its normal output.

It is clear from this description that a huge amount of heat transfer occurs in the various component subsystems of the plant. Therefore, reliable temperature measurements are essential. To maintain the delicate heat balance within the safe and economical range of operation of the plant, several safety and control actions are based on the temperature measurement of those subsystems.

1.4.2 Temperature Measurement for Control of Power Plants

One of the most important control actions taken by the automatic and/or manual controllers of the nuclear power plant is based on the average temperature, T_{avg}, of the cold temperature, T_c, measured at the reactor coolant pump discharge, and the hot leg temperature, T_h, measured at the inlet of the steam generator. T_{avg} is found for each loop, then passed through auctioneering unit where the highest T_{avg} is used for the desired control action. The control action may be explained by considering the action following a load increase. The demand on the turbine is increased, resulting in decreasing the T_{avg}. The automatic control rod system senses the decrease in T_{avg}, and withdraws certain control rods to increase the power, and thus, increase T_{avg} because the T_{avg} has to be maintained to within ±1.9 °C (±3.5 °F) during steady state operation (NRC, 1981; Rust, et. al., 1976).

T_{avg} is also used in the steam dump control system, pressurizer level control system, and rod insertion limit computer as indicated in Figure 1.3 (NRC, 1981).

1.4.3 Temperature Measurement for Safety of Power Plants

Safety instrumentation channels are separate from the control instrument channels. A number of protective actions can be taken by the reactor protection system whenever signals received from the reactor sensors indicate an

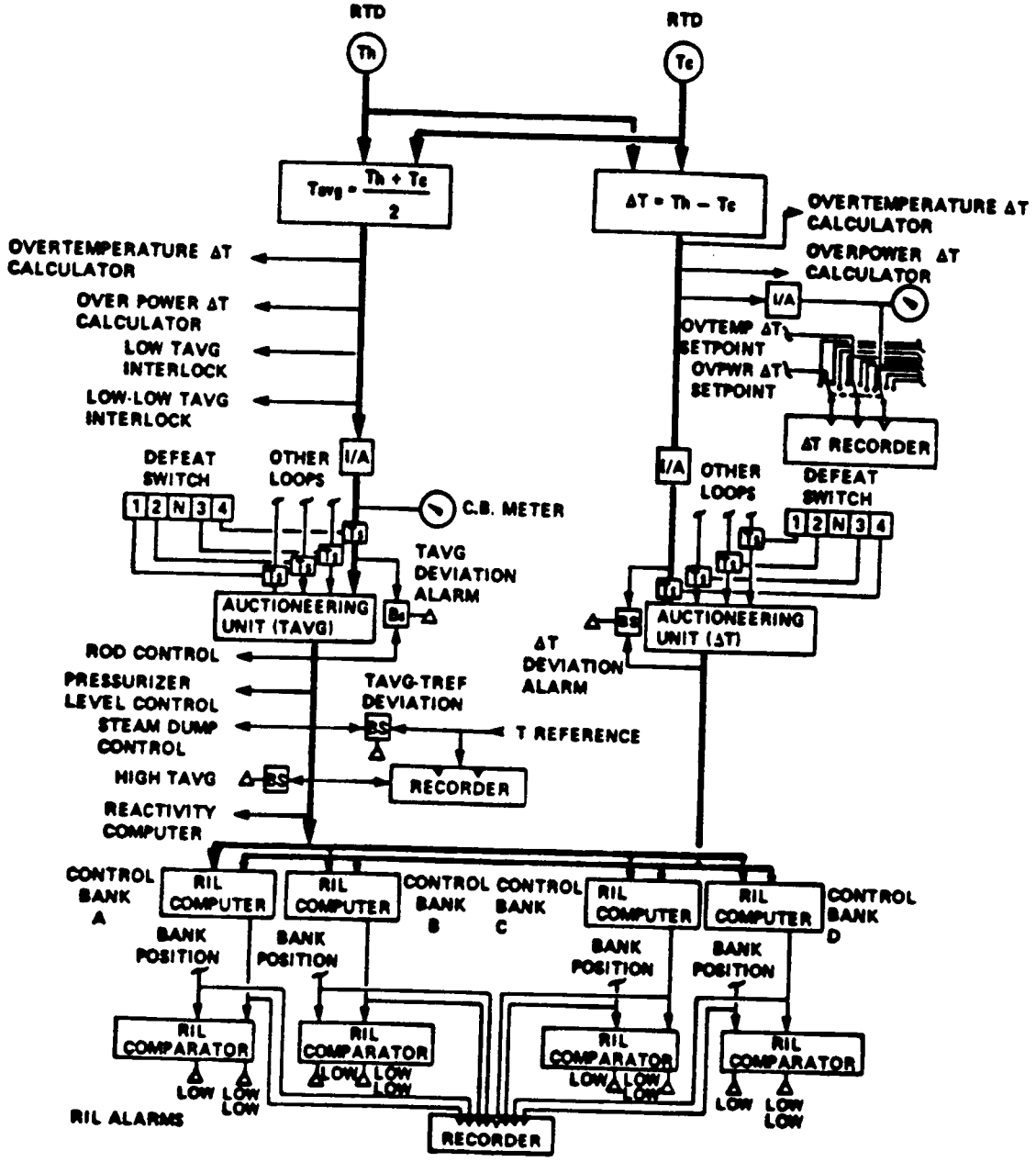


Figure 1.3 A Schematic of the Reactor Coolant System Instrumentation and Control Rod Insertion Limit Circuit (NRC, 1981).

approach to violation of the safety limits. For example, the protection system may activate alarms, prevent control rod withdrawal, initiate load cutback, or scram (rapid shutdown) the reactor depending on the severity of the incident (Harrer, 1974). The reactor operating region is defined such that with all the reactor coolant pumps operating; no combination of power, pressure, and temperatures could result in a departure from nucleate boiling ratio (DNBR) that is less than 1.3 (Harrer, 1974; NRC, 1981).

There are two reactor trips that occur based on the T_{avg} and ΔT (where $\Delta T = T_h - T_c$). Those are the overtemperature ΔT, and the overpower ΔT trips (Harrer, 1974; NRC, 1974). The overtemperature ΔT scram occurs to protect the cladding against overheating by ensuring that the DNBR is greater than 1.3. This is accomplished by comparing ΔT with a ΔT set point (ΔT_{sp}). Where, ΔT_{sp} is constantly being recalculated based on T_{avg}, pressurizer pressure, localized flux peaking, coolant temperature, and constants. The overpower ΔT scram occurs whenever $\Delta T \geq \Delta T_{sp}$ to protect the fuel elements from melting. ΔT_{sp} is continuously calculated for each loop based on T_{avg}, rate of change of T_{avg}, and constants representing three or four-loop operation (NRC, 1981).

1.4.4 Other Uses for Temperature Measurement in PWRs

Typically, 65 in-core thermocouples of Type K are used to provide the operator with a rough approximation of the core status. They are inserted into guide tubes that penetrate the head of the reactor vessel and end at the flow exits above the fuel assembly as shown in Figure 1.4 (NRC, 1981). Specifically, they are used to periodically calculate the time average of all the thermocouples, the enthalpy rise at each TC location, the relative fuel assembly powers, and the core radial tilting factor (NRC, 1981).

Other temperature sensors are located in the reactor drain tank (which initiates a high temperature alarm whenever a leak occurs), the pressurizer spray line (which initiates a low alarm if insufficient bypass flow occurs), and the pressurizer relief tank.

The importance of reliable temperature measurements for safe and proper operation of the plant is very clear. The economical gains received by increasing the efficiency of the plant (by using accurate sensors which allow for optimal operation of the plant), protecting the structure and integrity of the expensive plant components, and ensuring the staff and public safety are huge.

The STMS developed in this project is suitable for temperature measurements in power plants although it is not limited to them. The system's ability to provide constantly

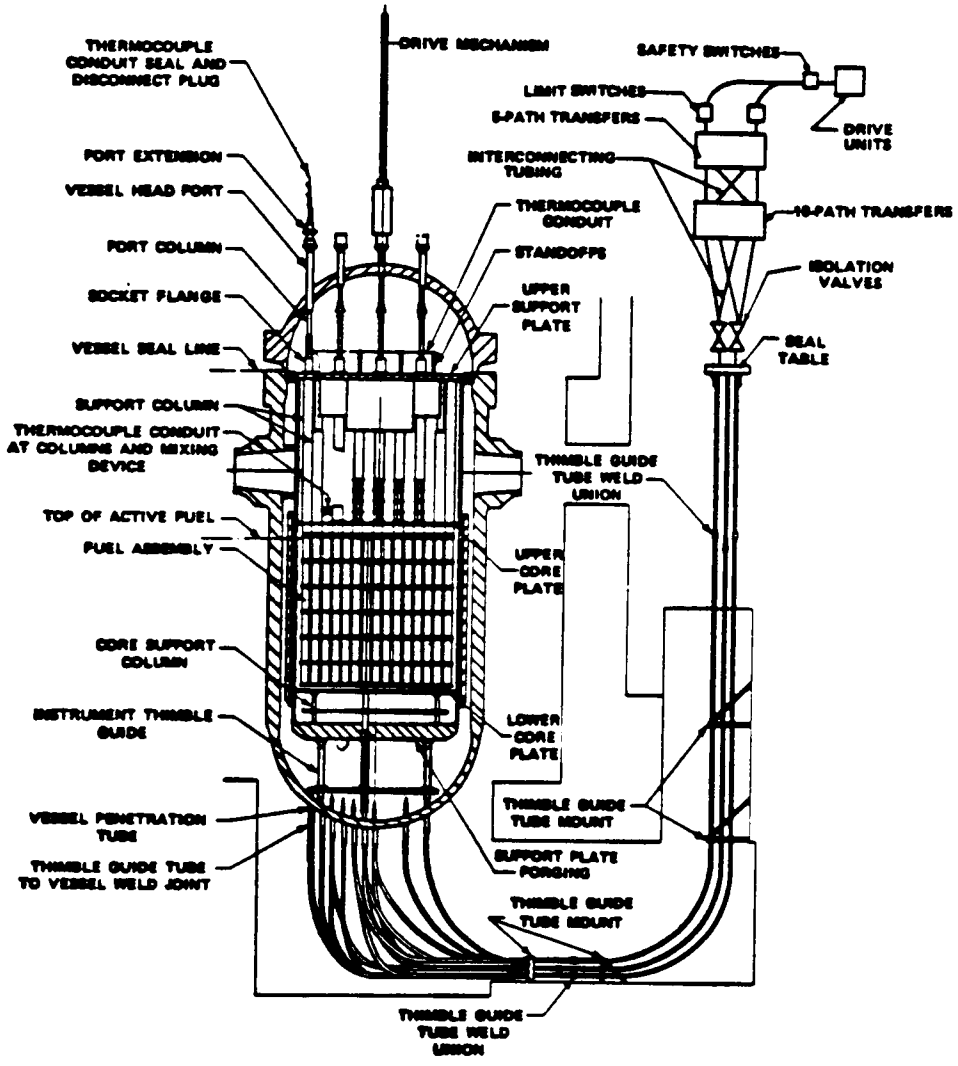


Figure 1.4 In-Core Instrumentation (NRC, 1981).

validated, reliable, and converted measurements will improve the temperature measurement reliability of power plants.

1.5 Outline of the Remaining Chapters

In Chapter 2, the state of the art of smart sensors is described. Several products, available on the market, are claimed to be smart by their manufacturers, yet they do not conform to some of the basic characteristics of smart sensors that are described in Chapter 2. Hence, Chapter 2 is provided to provide the reader with guidelines regarding what may or may not be considered a smart sensor.

A general introduction to the principles of thermocouples, laws of thermometry, types and styles of TCs, and MTCs are presented in Chapter 3. The signal validation methods used in the STMS are described in Chapter 4.

Chapters 2, 3, and 4 are written to help the reader develop an understanding of the theory, concerns, pros and cons of the STMS. The STMS itself is described in detail in Chapter 5. The MTC thermoelements selection process, the MTC fabrication, the unique interface designed to facilitate the data transmission between the sensor and the data acquisition system, as well as the 43000 byte computer code that controls the whole system are all described in this Chapter.

In Chapter 6, description of the testing procedures and facilities used in the drift and thermal cycling analysis of

the MTCs are presented. The results and conclusions regarding the sensor performance during the testing period are also presented in this Chapter.

The operational experience with the STMS is provided in Chapter 7.

Chapter 8 presents recommendations and future work.

CHAPTER 2.

STATE OF THE ART OF SMART SENSORS

2.1 Introduction

Instrumentation and controls (I&C) constitute the backbone of industrial processes. Since controls are driven by data that are generated by sensors, it is of utmost importance that sensors in industrial plants are reliable and accurate. The safety of plant equipment, and of the public, the proper and optimal control of the process, and the reduction of the plant's downtime due to sensor failure are factors behind the intense interest in sensor research. In the next ten years (Jordan, 1985), it is predicted that the need for all types of sensors will have a 10-15 percent annual growth rate. In addition, it is expected that the availability of enhanced and reliable sensors will lead to vast savings.

The major recent improvement in the I&C industry was the invention of the microprocessor around 1970. Microprocessors permitted the measurand to be converted into a digital electronic signal, as opposed to traditional hydraulic or pneumatic signals (Middelhoek, 1987). Digital electronics laid the foundation for building sensors that were more accurate and 'smarter'.

At present, the following are the main areas of research in sensor technologies (Jordan, 1985):

1. Resonator sensors (frequency based devices such as mass flow, density, viscosity, and pressure devices).
2. Microelectronic sensors (crystal quartz or single crystal based devices such as pressure and force devices).
3. Optical sensors (fiber optics and opto-electronic devices).
4. Integrated sensors (silicon based sensors such as integrated smart sensors).

Another factor that is fueling the huge interest in smart sensor technology is the new computational approaches brought by the artificial intelligence (AI) research community. A definition of AI is "a growing set of computer problem-solving techniques that are being developed to imitate human thought or decision-making processes or to produce the same results as those processes." (Scown, 1985) There are many other definitions of AI but all share the basic premises expressed above.

Active areas of research and applications in AI are (Scown, 1985):

1. Expert systems
2. Natural language systems
3. Robotics, vision, and smart sensing systems
4. Automatic programming.

Expert systems have been successfully utilized for

economical gains in the industrial world (Jasany, 1986). Smart sensor research is an integrated part of AI research throughout the world, which is mainly utilized to add intelligence to robots (Stauffer, 1987; Ogorek, 1985).

Smart sensor technology benefits from the flexibility of new AI languages such as LISP, PROLOG, OPS5, and object oriented programming, which deal with data in symbolic fashion in addition to the conventional numeric algorithmic approach of traditional programming languages. The process of symbol manipulation emulates the human thinking process by representing objects with symbols. Hence, AI languages are ideal to be used in intelligent communication between sensors and controllers/operators.

Besides robotics, smart sensor technology is being used in other applications such as combustion control in fossil plants (Gouldin, 1987), automotive industry (Wolff, 1985; Giachino, 1987), biomedical applications (Van der Piegel, 1985; Boomkamp, 1985), weather monitoring (Garcia, 1986), and space exploration (Dapeng, 1986).

2.2 Definition of Smart Sensors

There is no unique definition of the term 'smart' / 'intelligent' sensor / instrument. One definition is "the use of a measurement system to evaluate a physical variable usually employing a digital computer to perform all (or nearly all) the signal/information processing." (Barney, 1985) This definition is broad and it doesn't indicate what

kind of signal/information processing is considered intelligent. Some researchers believe that if a sensor has the circuitry, the signal amplification and processing capability, and the sensing element integrated into the same physical entity, then the sensor is smart. Others believe that the sensor has to make some kind of decision regarding its own performance (by utilizing a microprocessor) to be considered smart (Giachino, 1986).

2.3 Characteristics of Smart Sensors

Several researchers seemed to agree on the following three basic characteristics of smart sensors (Favennec, 1987; Giachino, 1986; Brignell, 1986):

1. **Communication** (a two-way communication with a network or central computer).
2. **Computation** performed at the sensor level to generate the physical magnitude of the measured variable free from defects and parasitic influences.
3. **Self-diagnosis** and calibration.

Favennec (1987) has cited the following additional characteristics of smart sensors:

4. The signals are **digital** instead of analog.
5. All of the additional functions are **integrated into the transmitter** part of the sensor. This characteristic, however, is subject for debate

since the intelligence in the integrated smart sensors is located in the sensor device itself rather than the transmitter.

6. **Maintenance assistance,** which may be considered an added feature of smart sensors.

Brignell (1986) cited yet another characteristic which is:

7. The main configuration of the subsystem is performed using **software.**

2.4 Types of Smart Sensors

Smart sensors can be divided into two main categories:

a. Integrated Smart Sensors

b. Hybrid Smart Sensors.

Following is a detailed description of each type.

2.4.1 Integrated Smart Sensors (ISS)

Universities and research laboratories in countries such as Japan, USA, Great Britain, and the Netherlands have done a great deal of work in the area of ISS. As mentioned earlier, the term, integrated smart sensor, implies that the knowledge and data processing circuitry are located within the same sensor housing.

It is important to realize that not every integrated sensor is smart and vice versa. Typically, any material that shows sufficient sensitivity to external environmental variables such as temperature and pressure can be utilized as a sensing element in a sensor. The material has to show

systematic dimensional, vibrational, optical, or electrical characteristic changes caused by changes in the external variables. Silicon shows sensitivities to many measurands. It is also the major component of microprocessor chips. Silicon can be used as a sensing element by itself or combined with other sensing elements by techniques such as thick film hybrid technology, which produces devices that are compact, versatile, robust and economic (Brignell, 1987). Thus, silicon based sensors have become an important part of integrated smart sensor research.

Silicon based sensors have been built in all five signal domains which are (Middelhoek, 1987)

1. Radiant: light detection, nuclear radiation.
2. Mechanical: flow, pressure, position, displacement.
3. Thermal: temperature.
4. Magnetic: Magnetic field direction and magnitude.
5. Chemical: PH, composition.

Reviews of the existing integrated sensors are available (Middelhoek, 1987; Jordan, 1985; Brignell, 1985).

Integrated sensors offer the following advantages:

1. On the spot amplification reduces the signal to noise ratios since much of the noise comes from transmitting the signal through long wires (Giachino, 1986; Middelhoek, 1987).
2. The size and area needed for electronic equipment

is reduced along with a reduction in wiring (Giachino, 1986; Layman, 1987).

3. Improvement of characteristics, such as cross sensitivity, offset, etc., may be handled best in an on-chip basis.

Other advantages cited by Middelhoek (1985) are not unique to integrated sensors and will be discussed in the 'Hybrid Smart Sensors' section.

Considering that the integrated sensors technology is relatively new and still in the development stages, some apparent disadvantages have been identified (Giachino, 1986):

1. Electronic circuits are very susceptible to damage or degradation in severe environmental conditions such as high temperatures and radiation fields.
2. Integrated sensors require careful packaging and housing if they are to be used in processes such as chemical plants.

Most of the existing integrated sensors utilize simple circuitry. It is difficult to build integrated sensors with digital processing and filtering based on semiconductor technology alone because of design and implementation complexities (Jordan, 1985).

2.4.2 Hybrid Smart Sensors (HSS)

The term hybrid used in conjunction with integrated sensors implies that the sensor consists of silicon and some other material. In this section, however, the term 'hybrid' implies that the sensor itself is physically separated from the 'intelligence' circuitry. This is an advantage of the hybrid smart sensors since electronic circuits can be removed from the process thereby reducing the effects of damaging factors (i.e., heat and radiation) on them. Another advantage is that the 'intelligence' can be added to existing sensors with present technology. Other advantages are minimizing calibration times by correcting for imperfections, self checking to enhance reliability, reducing the wiring cost due to use of external buses, and reducing work load on the central computer (Favennec, 1987).

Favennec (1987) had divided the hybrid smart sensors into the two categories:

a. Sensor part, where the sensing element, sensor identification, and sensor specifications are located.

b. Transmitter part, where the power supply, computation, and communication functions are performed.

This configuration, however, still utilizes electronic circuits in the sensor part. This, again, imposes the disadvantage of exposing electronic circuits to severe

environmental conditions. Favennec (1987) claims that the sensor's PROM, Programmable Read Only Memory, "should be physically indissociable from the sensor part to forestall any risk of inversion of the transducers and their associated PROM." This is a drawback that may not be necessary, especially in sensors that are to be used in environments that are inherently hostile to electronic circuits. Furthermore, the functions performed by the PROM do not require that the PROM be close to the sensor.

Most of the smart sensors presently available on the market are smart pressure transducers. A new pressure transducer consisting of a hybrid circuit, a sensing element, and an NMOS operational amplifier has recently been developed (Stefanides, 1986). The circuit consists of a microcomputer, ROM, EEPROM, elements for filtering, A/D conversion, buffering address recognition, and serial communication. The circuit is less than one inch cube in size. The sensing element consists of a quartz diaphragm with a silicon layer etched to give four stress and four temperature sensitive resistors. Hence, an increase in the deflection of the diaphragm results in an increase in the resistance of two of stress resistors, while the other two resistors (oriented at 90° from the first two resistors, and connected in a Wheatstone Bridge fashion) show a decrease in resistance. The output is proportional to the diaphragm stress, and hence, the applied pressure. The temperature

sensitive resistors provide the bridge's temperature which is used for compensating the pressure. This device performs its own calculations, and communications. The device needs to be "characterized" to be properly used. The characterization process consists of exposing the device to pressure cycles at -55 to +125 °C, then fitting the pressure-temperature data to a third order polynomial. Other parameters are stored in the EEPROM. The transducer performs self-diagnostics upon power up and recalibrates itself based on the characterization data which eliminates long term drift. The device is capable of detecting up to 800 psi and operates in -55 to 125 °C temperature range. The sensor's on the spot amplification, conversion, and fewer wires increase its reliability, reduce the signal noise, and cost. The device is well suited for computer controlled jet engines and other aerospace equipment.

A smart sensor, as used in this project, can be defined as a microprocessor based device that employs a conventional (or new) sensor (or set of sensors) equipped with software that controls the sequence of events of computation, communication, and self-checking; and used in conjunction with hardware that facilitates signal acquisition, conditioning, and self diagnostics. The details of a new smart temperature measurement system that utilizes the hybrid approach are presented in the remaining Chapters.

CHAPTER 3

THEORY AND DESIGN OF THERMOCOUPLES

3.1 Introduction

In 1821, T. J. Seebeck discovered the thermoelectricity phenomenon (Finch, 1961). That is, if two dissimilar metals are joined together at one end, then a voltage is created in the wires when they are placed in a thermal gradient. The voltage is a function of the temperature difference between the joint end and the open end. Thermocouples (TC) were then developed by making use of this "effect."

A TC is constructed by mechanically joining, welding or brazing, two dissimilar wires, wire A with Seebeck coefficient S_a and wire B with Seebeck coefficient S_b, as shown in Figure 3.1. The Seebeck coefficient of a material is defined as "the potential difference established along a wire of that material by the application of a unit temperature difference" (Kerlin, 1982). This coefficient has the units of volts/°C and it is called the Thermoelectric Power of the material. The joint end is called the Measuring Junction (MJ), while the open end is called the Reference Junction (RJ). As the TC is placed in a temperature difference, (i.e., there exists a temperature difference between the MJ and the RJ) an electromotive force (emf) is generated and can be measured at the RJ. This emf is roughly proportional to the temperature difference.

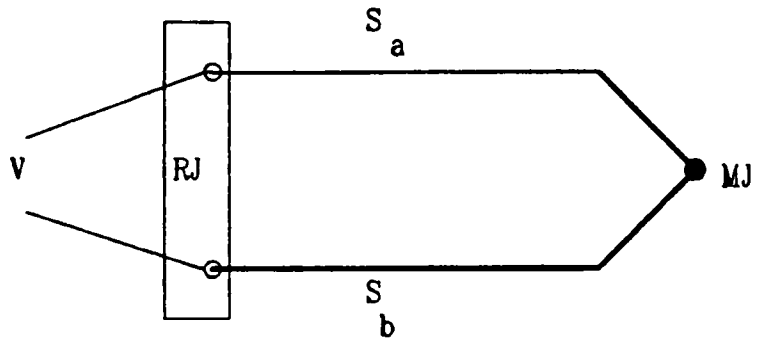


Figure 3.1 A Schematic of a TC.

It can be calculated in terms of the difference in Seebeck coefficients of both wires, and the temperatures difference as

$$V = (S_a - S_b)*(T_m - T_r) \qquad (3.1)$$

where

V = The emf generated at the open end, volts

T_m = The MJ temperature, °C

T_r = The RJ temperature, °C.

It must be noted that V depends only on S_a, S_b, and the temperature difference. Two types of Seebeck coefficients are usually used. The first is the absolute Seebeck coefficient, which is a property of the material. It is denoted by S_a for material A. The second is the relative Seebeck coefficient (S_{ab}) defined as $S_{ab} = S_a - S_b$. Hence, Equation 3.1 can be rewritten as

$$V = S_{ab} * (T_m - T_r) \qquad (3.2)$$

Equations 3.1 and 3.2 are true only if S_a and S_b are constants between T_m and T_r. Typical thermocouples, however, do not behave in such a linear fashion. Hence, researchers and developers have resorted to devising high order polynomials based on fitting high precision experimental temperature-emf data points to describe the true relationship between the emf and temperature.

The wires are usually electrically and thermally insulated by cement or powder. The most commonly used powders are aluminum oxide (Al_2O_3) or magnesium oxide (MgO).

The sensing wires and insulator are usually protected by a stainless steel sheath. The most commonly used types of stainless steel are 304, 316, and 446 (Natour, 1985). Figure 3.2 shows a typical multilayered structure of a sheathed thermocouple.

TCs are characterized as being simple, inexpensive, versatile, durable, and accurate. They can cover ranges of temperatures between -183 °C (cryogenic thermocouples) to 2500 °C (refractory thermocouples) (Kerlin, 1982).

3.2 Laws of Thermoelectric Circuits

There are three basic laws governing the behavior of thermoelectric circuits. Even though these laws have been formulated based only on experimental evaluation of TC circuits, they have never been disproved (ASTM 1981).

These laws provide the basis for precautions to be taken during sensors fabrication. They can also be used to explain the sources of certain measurement errors, and sensor degradation.

3.2.1 Law of Homogeneous Metals

"A thermoelectric current cannot be sustained in a circuit of a single homogeneous material, however, varying in cross section by the application of heat alone" (ASTM, 1981). Hence, the only source of emf generated in a single wire exposed to temperature difference is local

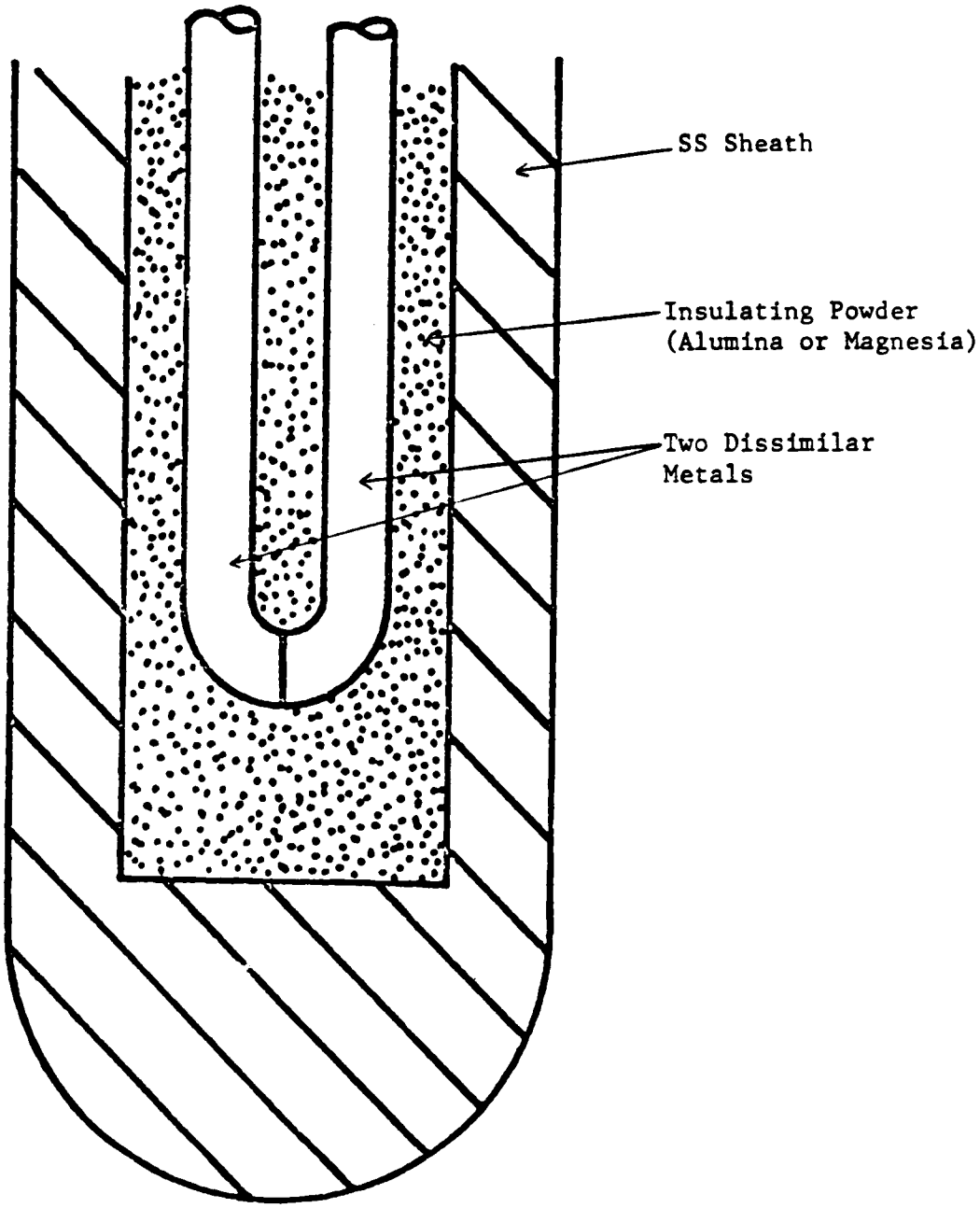


Figure 3.2 A Schematic of a Typical Multilayered (Industrial) TC.

inhomogeneities. Therefore, extreme caution should be exercised while fabricating the wires to avoid contaminating them with mechanical or chemical inhomogeneities. Such contamination will lead to the generation of unwanted emfs, degradation of the TC, and ultimately the failure of the sensor.

3.2.2 Law of Intermediate Metals

"The algebraic sum of the thermoelectromotive forces in a circuit composed of any number of dissimilar materials is zero if all of the circuits are at a uniform temperature" (ASTM, 1981). This implies that any inhomogeneities created at the measuring junction (by welding or twisting wire, atomic diffusion, etc.) will not result in changes in the generated emf as long as the inhomogeneous region is at constant temperature. Furthermore, an emf measuring device may be added to the circuit as long as the contact nodes are maintained at uniform temperature. Consider the case illustrated in Figure 3.3. In this case the measured voltage, E, is given by:

$$\begin{aligned} E &= S_c*(T_3 - T_1) + S_a*(T_1 - T_2) + S_b*(T_2 - T_1) \\ &\quad + S_c*(T_1 - T_3) \\ &= S_a*(T_1 - T_2) - S_b*(T_1 - T_2) \\ &= (S_a - S_b)*(T_1 - T_2) \\ &= S_{ab}*(T_1 - T_2). \end{aligned} \tag{3.3}$$

Therefore, adding wire C, such as a copper lead wire, will

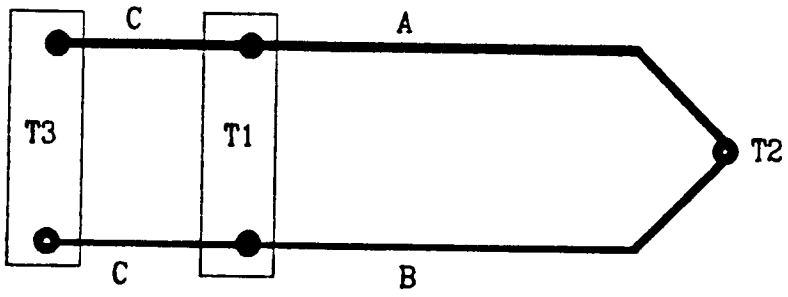


Figure 3.3 A Schematic of a TC Circuit When the Added Wire C Has no Effects on the Measured EMF According to the Second Law.

not have any effect on the E value except to change the reference temperature from T_3 to T_1.

This law further implies that if the emf values of two dissimilar wires, A and B, with respect to a third wire, C, (i.e. E_{ac} and E_{bc}) are known, then the emf created by wires A and B, E_{ab}, is given by:

$$E_{ab} = E_{ac} + E_{cb} \tag{3.4}$$

In this case, wire C may be considered as a reference wire such as Pt-67. (Pt-67 is high purity platinum wire that was selected and characterized by the National Institute of Standards and Technology (NIST) (formerly known as the National Bureau of Standards (NBS)), Office of Standard Reference Materials as the thermo-electric reference standard in 1967 (Monograph 125, 1974)). This consequence is the basis for theoretically determining the relationship between the temperature and the measured emf of the non-standard TC wire combinations used in this project since the relationships of individual wires with respect to Pt-67 are known. This is explained further in Chapter 5.

3.2.3 Law of Intermediate or Successive Temperatures

"If two dissimilar homogeneous metals produce a thermal emf of E_1, when the junctions are at temperatures T_1 and T_2, and a thermal emf of E_2, when the junctions are at T_2 and T_3, the emf generated when the junctions are at T_1 and T_3 will be $E_1 + E_2$" (ASTM, 1981). This law is important for it

facilitates the compensation process as described below.

Consider the case illustrated in Figure 3.4.a. This represents a TC with its reference junction at 0 °C. By measuring E_{m1}, one can find T_1 from the Relationship

$$E_{m1} = S_{ab}*(T_1 - 0). \quad (3.5)$$

In the thermometry industry Reference Tables that indicate T_1 for a measured E_{m1} for all Types of TCs with reference junction temperature of 0 °C, have been established. On the other hand, Figure 3.4.b shows a schematic of a TC with its reference junction at a non-zero temperature such as room temperature. In this case the measured emf, E_{m2}, is given by

$$E_{m2} = S_{ab}*(T_1 - T_2) \quad (3.6)$$

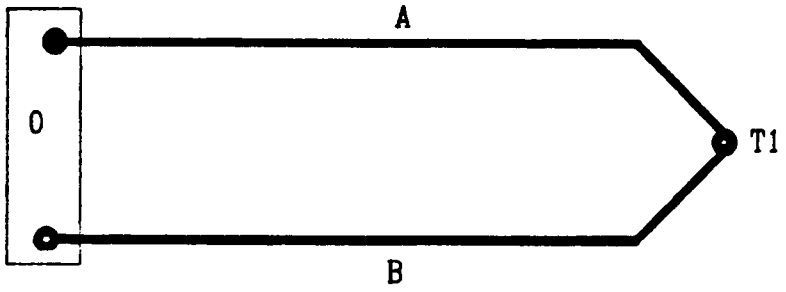
If a similar TC with its reference junction at 0 °C is used to measure the reference temperature T_2, then

$$E_r = S_{ab}*(T_2 - 0) \quad (3.7)$$

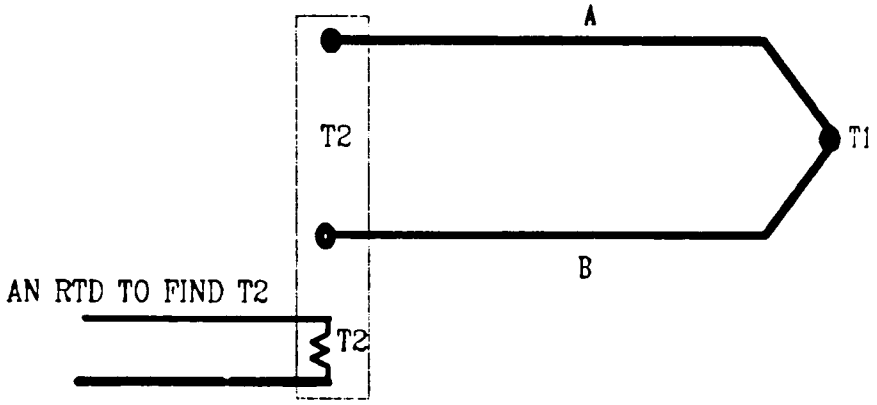
According to the Third Law,

$$E_{m1} = E_{m2} + E_r \quad (3.8)$$

Therefore, the Reference Tables may be used to determine the process temperature by first determining E_r by looking up the emf value which corresponds to T_2. Next, E_r is added to the measured E_{m1}. Finally, the temperature which corresponds to the total emf, E_{m1}, is determined from the Reference Table. Commonly, T_2 is measured with another kind of temperature sensor, such as a resistance temperature detector (RTD), and the corresponding E_r is found from the



a) A Schematic of a TC with Its RJ at 0 °C.



b) A Schematic of a TC with Its RJ at T_r. The RTD is Used to Find T_r or T_j.

Figure 3.4 A Schematic of a TC with the RJ at Different Temperatures.

Reference Tables. It must be noted that the accuracy of the TC depends on the accuracy with which the RJ temperature is determined.

3.3 Types of Thermocouples

It is obvious that the properties of a thermocouple depend on the two metals forming the sensing element. Such metals are chosen on the basis of their stability, ductility, and sensitivity (Kerlin, 1982). TCs that have relatively large Seebeck coefficients and, hence, large emf's are preferred especially if this emf follows an approximately linear relationship with temperature.

There are numerous TC Types in existence. Seven of them have been assigned letter designations by the Instrument Society of America (ISA) and later adopted as an American Standard in ANSI MC 96.1 (ASTM, 1981). Those are

Type K (Chromel/Alumel),

Type T (Copper/Constantan),

Type J (Iron/Constantan),

Type E (Chromel/Constantan),

Type S (Platinum-10%Rhodium/Platinum),

Type R (Platinum-13%Rhodium/Platinum), and

Type B (Platinum-30%Rhodium/Platinum-6%Rhodium).

Recently, Type N (Nicrosil/Nisil) has been approved (Kerlin, 1990).

The NIST among other sources has published Reference

Tables and polynomials that describe the relationships between the emf and temperatures while the RJ maintained at 0 °C for those thermocouples. It must be noticed that neither the ISA nor the NIST recognize the Type J TC as standard.

Thermocouples may be classified into three classes depending on the sensing metals (Kerlin, 1982):

1. Base-metal thermocouples,
2. Noble metal thermocouples, and
3. Refractory metal thermocouples.

Table 3.1 contains a list of the different types of TCs and their properties.

3.4 Thermocouple Styles and Special Designs

The most commonly manufactured TCs are those which employ one MJ and one RJ. The MJ can be insulated or grounded. Both cases are shown in Figures 3.2 and 3.5. The grounded sensors are usually faster than an insulated one of the same diameter.

Other thermocouple styles include the differential and thermopile thermocouples. Differential TCs are used to measure the difference in temperature between the measuring junctions as shown in Figure 3.6. The thermopile TCs employ several measuring junctions that are all exposed to one temperature. They are connected in the manner shown in Figure 3.7. The advantage of such thermocouples is that

Table 3.1 List of the TC Types Used in the Industry.

TC TYPE	+ LEAD	- LEAD	MAXIMUM USEFUL TEMPERATURE RANGE (C)	EMF (mV) OVER USEFUL TEMPERATURE RANGE	LIMITS OF ERROR (STANDARD) (WHICHEVER IS GREATER)
J	Iron Fe	Constantan Copper-Nickel Cu-Ni	0 - 750	0 - 42.283	2.2 C or 0.75%
K	Chromel Nickel-Chromium Ni-Cr	Alumel Nickel-Alumel Ni-Al	-200 - 1250	-5.973 - 50.633	2.2 or 0.75% above 0 C 2.2 or 2.0% below 0 C
T	Copper Cu	Constantan Copper-Nickel Cu-Ni	-200 - 350	-5.802 - 17.816	1.0 or 0.75% above 0 C 1.0 or 1.5% below 0 C
E	Chromel Ni-Cr	Constantan Cu-Ni	-200 - 900	-8.824 - 68.783	1.7 or 0.75% above 0 C 1.7 or 1.0% below 0 C
N	Nicrosil Ni-Cr-Si	Nisil Ni-Si-Mg	-270 - 1300	-4.345 - 47.502	2.2 or 0.75% above 0 C 1.7 or 1.0% below 0 C
R	Platinum 13% Rhodium Pt-13%Rh	Platinum Pt	0 - 1450	0 - 16.741	1.5 or 0.25%
S	Platinum 10% Rhodium Pt-10%Rh	Platinum Pt	0 - 1450	0 - 14.973	1.5 or 0.25%
B	Platinum 30% Rhodium Pt-30%Rh	Platinum 6% Rhodium Pt-6%Rh	0 - 1700	0 - 12.426	0.5 over 800 C
G	Tungsten W	Tungsten 26% Rhenium W-26%Re	0 - 2320	0 - 38.564	4.5 C to 450 C 1.0% to 2320 C
C	Tungsten 5% Rhenium W-5%Re	Tungsten 26% Rhenium W-26%Re	0 - 2320	0 - 37.066	4.5 C to 425 C 1.0% to 2320 C

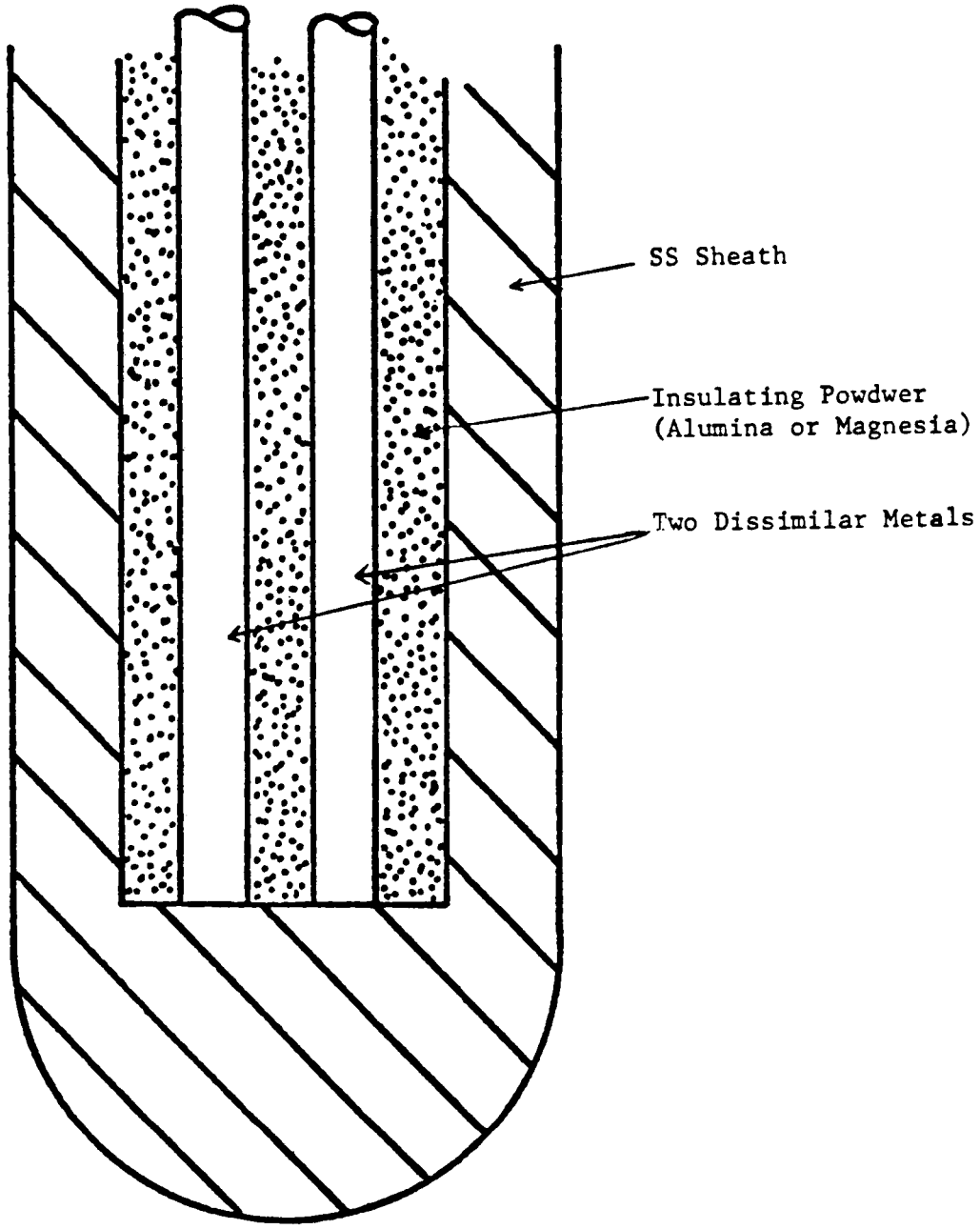


Figure 3.5 A Typical Grounded TC.

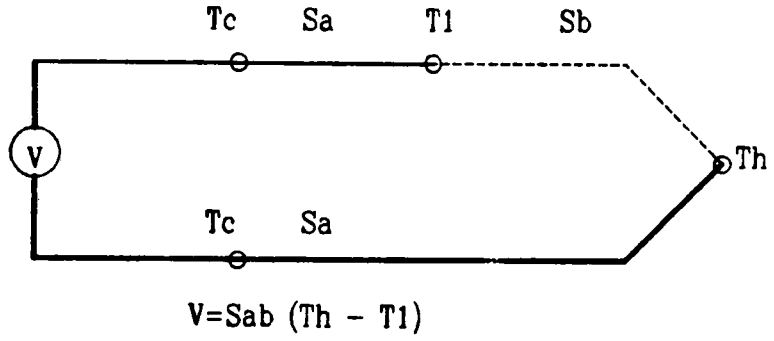


Figure 3.6 A Typical Differential TC.

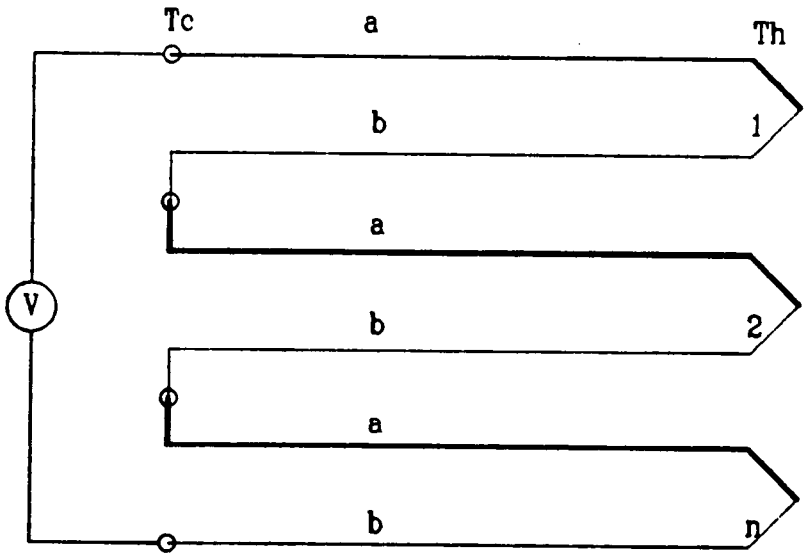


Figure 3.7 A Typical Thermopile.

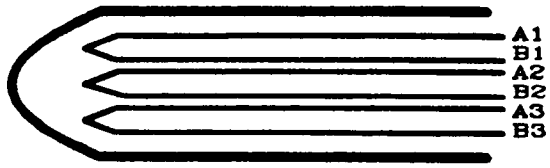
they increase the output voltage by as many times as there are measuring junctions.

3.5 Multilead Thermocouples (MTC)

MTCs typically consist of two or more TCs housed in a single device. The device may be insulated or bare. The basic advantage offered by the MTC is an increase in the number of simultaneous temperature measurements. Signal validation methods, designed specifically for redundant signals, can then be used to provide sensor performance evaluation. Such evaluations, if performed continuously and on-line, become a strong foundation for a smart temperature measurement system (STMS).

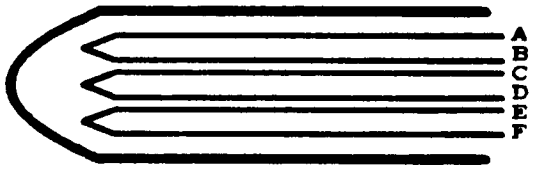
Present day MTC's typically consist of two or three thermocouples housed in a single sheath. There are several ways an MTC can be fabricated as shown in Figure 3.8.

1. Two (or more) TCs of the same type, with two (or more) junctions (see Figure 3.8.a).
2. Two (or more) different TC types, with two (or more) junctions (see Figure 3.8.b).
3. Two (or more) similar TCs sharing a single junction (see Figure 3.8.c).
4. Two (or more) different TCs sharing a single junction (see Figure 3.8.d).
5. Three (or more) thermoelements sharing a single junction (see Figure 3.8.e).



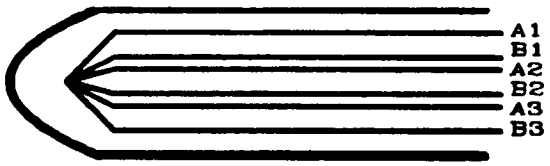
3 MEASUREMENTS
A1–B1, A2–B2, A3–B3

a)



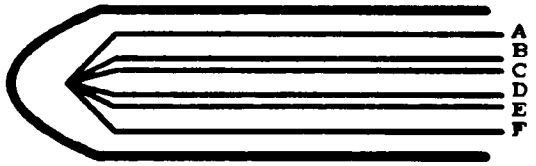
3 MEASUREMENTS
A–B, C–D, E–F

b)



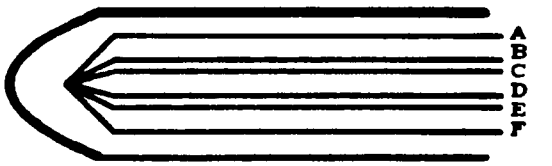
3 MEASUREMENTS
A1–B1, A2–B2, A3–B3

c)



3 MEASUREMENTS
A–B, C–D, E–F

d)



12 MEASUREMENTS
A–B, A–C, A–D,
A–E, A–F, B–C,
B–D, B–E, B–F,
C–D, C–E, C–F,
D–E, D–F, E–F.

e)

Figure 3.8 Various Styles of MTCs.

Each method has advantages and disadvantages. The first method simplifies comparison analysis and measurement methods, but it is susceptible to common mode failure. The second method reduces the chances for common mode failure, but complicates the signal conditioning requirements and analysis time. Both methods produce a number of redundant signals that are equivalent to the number of sensors. The third method produces a number of measurements, M, given by

$$M = NP^2 \tag{3.9}$$

where

M = Number of possible measurements

NP = Number of similar pairs.

Hence, the number of possible redundant measurements increases. However, the measurement circuit (or interface) becomes more complex to allow for switching between the various pairs. The analysis and reference junction compensation is simpler than in the forth method. The fourth and fifth methods provide more redundant signals than the previous three methods. The number of possible redundant measurements is given by:

$$M = N * (N-1)/2 \tag{3.10}$$

where

M = the maximum number of possible redundant measurements

N = the number of thermocouple wires used.

The main problems with these methods are material and

chemical compatibility, increase in drift rates due to encasing several wires in a close proximity, fabrication complexity, and interface and analyses complexity. These problems are discussed in detail in Chapter 5.

The MTCs in all their forms offer several advantages over placing several redundant sensors adjacent to each other in a process. These advantages include:

1. measuring temperature at a single location, thus reducing errors due to variations in process temperature
2. more compact
3. less expensive
4. less wiring and cabling involved.

Present MTCs lack the proper readout devices that can take advantage of all the possible redundant signals (including the non-standard ones), and the vast amount of information and analysis that can be extracted from such sensors. In this project, this problem is solved by developing a smart temperature measurement system. The system entails the development and testing of a five lead MTC that utilizes dissimilar thermoelements, and also the development and testing of variations of this sensor. An interface, which utilizes relays that are switched on and off via a computer controlled electronic circuit, has been designed to facilitate communications between the sensor and the data acquisition system. A computer code acting as the

brain of the smart system has also been developed.

A smart system, like a human, may vary in its intelligence. The STMS takes full advantage of the PC microprocessor to enhance its 'smartness'. For example, all the calculations that are necessary to convert the measured raw signals (including the reference temperature compensation) into meaningful temperature values are all done in double precision to improve the accuracy of the estimate. The on-line signal validation method has the capability of eliminating the inconsistent signals from the estimate of the process temperature. The system provides a 'good' estimate of the process temperature even if only two signals are consistent. The system utilizes a set of weight factors to be used in calculating a weighted average of the process temperature. Such weight factors have been shown to drastically reduce the inaccuracies of the measurements as discussed in Chapter 6. The system is flexible to the point where the user will always be in control, yet the system is equipped with the 'smartness' to function intelligently without outside input. For example, the weight factors, just mentioned, may be determined by the user based on actual laboratory experience with the MTC, in which case those weight factors will be constant; yet the system itself can dynamically determine a set of weight factors that are based on the actual behavior of the STMS over a period of time, in which case the weight factors are variables.

However, the user still can alter the constant weight values and other parameters as needed.

The STMS is enhanced with smart features such as maintenance assistance and moving window whereby graphs of important events such as maximum and minimum temperatures that occur every hour in the previous month can be easily accessed by the user. The system is capable of displaying a statistical account of its status upon the user's request. other features include visual displays of colors and text to reflect the overall performance of the system and to alarm the user if the process temperature is about to be exceeded.

The system is designed to operate in two modes; the fast mode and the normal mode. In the fast mode, the system measures and displays the temperature as indicated by a single user selected channel. This process is interrupted at user specified frequencies for overall consistency checkup. This mode is suited for tracking fast process transients. In the normal mode, the system collects temperature signals from all the channels, collects the reference temperature, performs consistency checking, performs the necessary bookkeeping, and displays the process temperature and the standard deviation. This mode is suited for steady state operations. During the fast mode, if major inconsistencies occur between the channel used and the remaining channels, then the system automatically switches to the normal mode.

The speed at which the system performs the bookkeeping and data analyses in the normal mode is of obvious concern, especially if safety actions are to be taken based on the indicated temperatures. When a dedicated microprocessor is used in the commercial STMS, the analyses will be performed at much faster rate. Furthermore, future microprocessors will be much faster and more powerful than present microprocessors. The actual performance of the STMS will be discussed in Chapters 5 and 7.

CHAPTER 4

SIGNAL VALIDATION

4.1 Introduction

Signal validation is "a technique delivering on information, representing a physical parameter, which can be considered as reliable for further uses in the protection, control and computerized operator aid systems." (Zwinglestein, 1983) The extra effort involved in applying signal validation techniques to industrial processes such as nuclear plants and aerospace industries, is justified by the potential for economic savings by early detection and identification of failed sensors, and by increased safety to the public, employees, and equipment of such industries.

The new STMS relies on the availability of eight redundant temperature measurements to provide a reliable estimate of the process temperature and the corresponding tolerance. The signal validation methods utilized by the STMS, then, are those concerned with redundant signals.

Redundant measurements can be obtained directly, and/or analytically (Ray, 1983). Direct redundancy is achieved by utilizing two or more sensors measuring the same process variable. Analytic redundancy is achieved by utilizing mathematical models of the process which in turn utilize other process variables measured by other kinds of sensors to estimate the variable of interest. For example, the

steam flow out of the steam generator may be analytically evaluated by utilizing estimates of the feedwater flow, feed water temperature, steam drum pressure, drum water level, and primary heat input rate from the primary coolant loop (Meijer, 1981). This method is particularly important in detecting common mode failure.

The STMS utilizes the direct redundancy approach. The most common method used in this case is the Consistency Checking (CC) method. This method, among others, has been successfully utilized in the nuclear and aerospace industries (Upadhyaya, 1987).

4.2 Consistency Checking Method

Ideally, a plant operator is interested in obtaining a good estimate of the process variable as well as information about the sensor performance. The objective of the consistency checking method is to provide both services.

This method, referred to as Parity Space Method by some authors (Meijer, 1981; Upadhyaya, 1987; Ray, 1983; Zwinglestein, 1983) depends on comparing each sensor with the remaining redundant sensors as described below.

Suppose there are n redundant sensors (S), producing n redundant measurements (M). Each sensor has a pre-specified tolerance or error bound (ERB). Then a pair of sensors, S_i and S_j, are said to be consistent if the absolute difference between their simultaneous measurements M_i and M_j is less

than or equal to the sum of their error bounds. That is,

$$|M_i - M_j| \leq ERB_i + ERB_j \qquad (4.1)$$

Where i is not equal to j

If the relationship is not satisfied, then both sensors are said to be inconsistent with each other. In this case a present inconsistency index, PINC, for sensors i and j are increased by 1. That is, the PINC(i) is a counter of the total number of signals in a single data set with which signal S_i has been inconsistent. Similar steps are followed to compare S_i with the remaining sensors. This can be represented as

$$PINC(i) = \sum_{j=1} F_{ij}(R) \quad , \text{ i not equal to j} \qquad (4.2)$$

where

R is the Relationship $|M_i - M_j| \leq (ERB(i) + ERB(j))$

$$F_{ij}(R) = \begin{cases} 0 \text{ if R is True} \\ 1 \text{ if R is False} \end{cases} \qquad (4.3)$$

Next, sensor S_{i+1} is compared with the remaining sensors. The total number of comparisons that are made before an estimate of the variable is made is given by:

$$\text{Total number of comparisons} = n*(n - 1)/2 \qquad (4.4)$$

Where n is the total number of redundant signals or sensors.

The reading from the sensor with the maximum PINC(i) value

is excluded from the measurand estimation.

Other important parameters utilized in this method are

MAXINC = Maximum inconsistency index value of the PINC(i) set. i.e.

$$MAXINC = MAX\ (PINC(1), PINC(2), \ldots, PINC(n)) \qquad (4.5)$$

MININC = Minimum inconsistency index value of the PINC(i) set. i.e.,

$$MININC = MIN\ (PINC(1), PINC(2), \ldots, PINC(n)) \qquad (4.6)$$

NMAX = Number of signals with MAXINC values.

These parameters are used in the CC logic which is described shortly.

4.2.1 Temperature Estimation

Typically, the estimate, T, is given by

$$T = \frac{\Sigma\ M(i)}{n} \qquad (4.7)$$

In this case all the signals, bad or good, are treated equally. A different and more appropriate approach to estimating the temperature may be based on taking the weighted average of the signals in the data set. This approach is used in the CC method.

It begins by finding the PINC(i)'s for all the signals. IF all indexes are zero then all the signals are consistent, and the weighted average of all the signals is used in determining the estimate of the temperature, T, as follows:

$$T = \frac{\sum_{i=1}^{n} W(i)*(n-1-PINC(i))*M(i)}{\sum_{i=1}^{n} W(i)*(n-1-PINC(i))} \qquad (4.8)$$

where

W(i) is the weighting constant of the ith signal

Hence, the estimate, T, is weighted in two ways:

1. using W(i), and
2. using (n-1-PINC(i)).

These weighting methods are described below.

First, all consistent measurements, M(i), are multiplied by a weighting factor W(i). In the STMS, W(i) is determined based on the overall performance of the individual sensors (wire pairs or channels) over a user specified number of samples (cycle length) or by experience. In the first case, the W(i)s are updated at the end of each cycle based on a cumulative inconsistency index, CINC(i), which will be discussed shortly. In the second case, the user (or developer) assigns constant W(i)s that are based on the actual sensor performance under controlled laboratory conditions. Once the "good" and "bad" channels are identified in the laboratory, weighting constants are assigned to each one. The "good" channels are assigned "higher" weights while the "bad" channels are assigned lower weights. For example, noisy signals are assigned lower weights and vice versa. Signals that reproduce the true

measurement with high accuracy are assigned higher weights. Actual experience with each sensor's behavior, such as drift rates, sensitivities, and reliability, may also be incorporated in their weight assignments.

Second, the measurement, M(i), is updated based on the performance of the measurement in the present data set by multiplying M(i) by the factor (n - 1 - PINC(i)) according to Equation (4.7). Therefore, signals with a higher PINC(i) will have a lower effect on the estimate. More details on this subject will be presented in the next Chapter.

The MTC provides eight (i.e. n = 8) redundant temperature signals at a given time instant. Once the eight signals are collected and compensated for the reference junction temperature, twenty-eight comparisons, according to Relationship 4.4, are made by the STMS. At the end of these comparisons, the values of PINC(i) for all signals, MAXINC, MININC, and NMAX are determined. Based on those values, a CC logic is followed to arrive at an estimate of the temperature. The logic is shown schematically in Figure 4.1. It must be noted, that a parameter k, representing the total number of signals that are under investigation, is substituted for n since some of the original signals may be excluded from the data set as necessary (See Figure 4.1). Furthermore, if there are no consistent measurements, the system will simply display a "No Estimate" message.

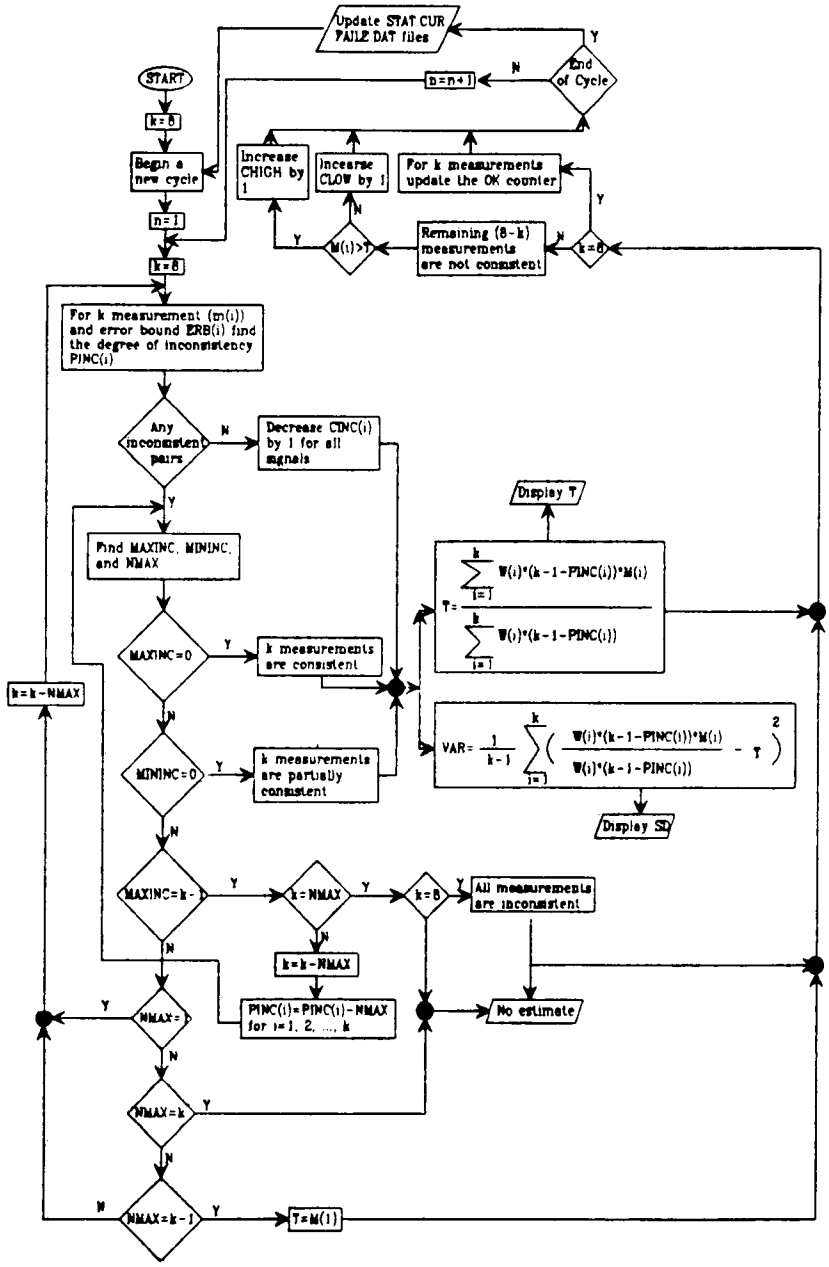


Figure 4.1 A Schematic of the CC Method.

4.2.2 Variance Estimation

The variance of all the consistent and weighted measurements is determined as follows:

$$\text{VARIANCE} = \frac{1}{k-1} \sum_{i=1}^{k} \left(\frac{(W(i)*(k-1-PINC(i))*M(i)}{(W(i)*(k-1-PINC(i))} - T \right)^2. \quad (4.9)$$

The standard deviation, SD, is given by

$$SD = (\text{VARIANCE})^{1/2}. \quad (4.10)$$

If the number of consistent signals is 1, (i.e., k = 1) then no SD is determined. The STMS, in this case, will warn (by changing the screen color) the operator as to the severity of the inconsistency problem as will be discussed in the next Chapter.

4.2.3 The Cumulative Inconsistency Index

The PINC(i) provides information about the status of the various channels for a given data set (eight simultaneous signals from the eight wire pairs (channels)) at a given time instant. A "good" channel may be subjected to a spurious effect, such as random electrical spikes, that may result in an increase in its inconsistency value. Therefore, it is important to utilize another parameter that encompasses the sensor performance over a period of time to determine the true overall MTC performance. One such parameter is the cumulative inconsistency index, CINC(i), for each channel. The CINC(i) is updated after the PINC(i) for the data set is determined for sensor S_i. The CINC(i)

is increased by 1 each time the ith signal is inconsistent with another signal, and decreased by 1 each time the ith signal is consistent with another signal. This process is repeated for all the data sets within a cycle. At the end of each cycle, the CINC(i) values are analyzed. A decision regarding updating the W(i)s values is made. This procedure will be described in the next Chapter.

To illustrate the CC method, an actual data set collected by the STMS is presented in Figure 4.2.

Given the actual temperature measurements M_i and weight factors W_i, and error bounds ERB(i):

$M_1 = 81.95$ $M_2 = 79.22$ $M_3 = 168.47$ $M_4 = 82.10$
$M_5 = 85.10$ $M_6 = 60.22$ $M_7 = 78.54$ $M_8 = 37.71$

W(1) = 1 W(2) = 1 W(3) = 1 W(4) = 1
W(5) = 1 W(6) = 1 W(7) = 1 W(8) = 1

ERB(1) = 2 ERB(2) = 2 ERB(3) = 2 ERB(4) = 2
ERB(5) = 2 ERB(6) = 2 ERB(7) = 2 ERB(8) = 2

Assume

CINC(1) = -1 CINC(2)= 1 CINC(3) = 7 CINC(4) = -1
CINC(5) = 3 CINC(6)= 7 CINC(7) = 1 CINC(8) = 7

Then

First sweep:
PINC(1) = 3 PINC(2) = 4 PINC(3) = 7 PINC(4) = 3
PINC(5) = 5 PINC(6) = 7 PINC(7) = 4 PINC(8) = 7

MAXINC = 7 MININC = 3 NMAX = 3 k = 8

Get rid of the 3 signals with MAXINC = 7
Make MAXINC = 7-3 = 4
Perform a second sweep

Second sweep
PINC(1) = 0 PINC(2) = 1 PINC(3) = 4 PINC(4) = 0
PINC(5) = 2 PINC(6) = 4 PINC(7) = 1 PINC(8) = 4

MAXINC = 4 MININC = 0 NMAX = 3 k = 5

Since MAXINC > 0, but MININC= 0
Then the remaining five measurements are partially consistent
the usable measurements are:

$M_1 = 81.95$ $M_2 = 79.22$ M_3 = not used $M_4 = 82.10$
$M_5 = 85.10$ M_6 = not used $M_7 = 78.54$ M_8 = not used

The average temperature = 81.38 °C
The standard deviation = 2.38 °C

Figure 4.2 A Typical Calculation Made by the STMS Utilizing the CC Method.

CHAPTER 5

THE SMART TEMPERATURE MEASUREMENT SYSTEM DESIGN

5.1 Introduction

The smart temperature measurement system (STMS) current design consists of the following components:

1. The multi-lead thermocouple (MTC) sensor device which utilizes five dissimilar standard TC wires to provide up to ten redundant temperature measurements (only eight are actually used).
2. An interface that transmits the MTC signals to the data acquisition system and provides it with the reference junction temperature.
3. The data acquisition, microprocessor, and software system that represents the center of intelligence of the system. It controls the sequence by which signals are acquired from the interface, performs all the computations, and communications, tracks the sensor performance, and makes decisions regarding the status of the system.

Two linear amplifiers are also used to amplify the MTC and interface temperature signals before they are fed to the data acquisition system. The amplification factor is manually set based on the maximum operating range of the sensor, and the maximum sensitivity available. The three devices comprising the STMS as well as some peripherals are

shown schematically in Figure 5.1.

5.2 MTC Device

Extensive research was conducted to select a set of "Good" MTC wires. Since five wires are to be selected, welded at one end, inserted into a ceramic insulator, and encased in a protective sheath, several potential problems and concerns need to be addressed. The most important concern is the metallurgical and chemical compatibility of those wires which in turn affect the manufacturability, and reliability of the MTC. Other concerns had to do with the temperature sensitivity of the various combinations of thermoelements, cost of production, and operating temperature range. After the selection was made, and the sensors were fabricated, comprehensive drift and thermal cycling tests were performed on those MTCs to ensure the reliability of the selection process, and to provide a more solid foundation for commercializing the STMS. The testing procedure and results are presented in the next Chapter. The material selection and sensor fabrication is described in the following Section.

5.2.1 Material Selection

Selecting the five metals to be used as part of the multilead TC was not an easy task from a metallurgical or chemical point of view. There were two major concerns with

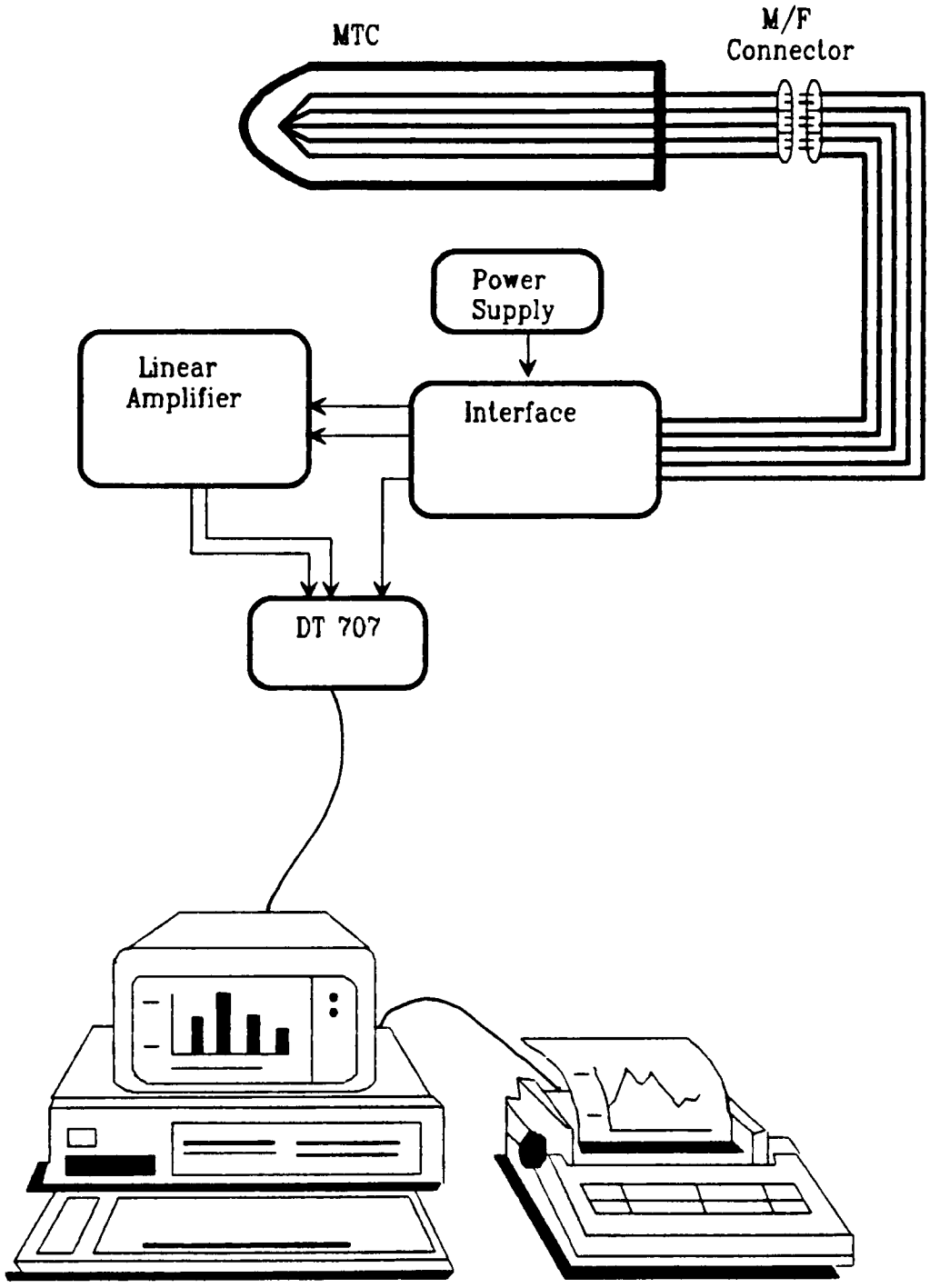


Figure 5.1 A Schematic of the STMS.

regard to the compatibility of the thermoelements. The first had to do with whether a measuring junction can be formed by welding the five different thermoelements. If it could, would the measuring junction function reliably for a suitable period of time (i.e. at least for the same duration of time standard TCs are useful)? Would there be chemical reactions at the measuring junction that would lead to a total deterioration of the junction and eventually the failure of the MTC? The second concern was with the wires themselves. They have to maintain their homogeneity. It is important to understand, evaluate, and minimize the mechanisms with which those wires may be contaminated.

A literature search was conducted to find solutions to the material compatibility problem to aid in the MTC wire selection. However, the literature primarily discusses the chemical and metallurgical compatibility of wire use in particular types of TCs and discloses little regarding the effects of combining several metals in close proximity on the thermoelectric behaviors of those wires, sensor manufacturability, and long term reliability of the thermocouple. Furthermore, phase diagrams that describe the behavior of four or five element alloys of interest to this research were not available. Phase diagrams are experimentally determined to provide the effects of temperature and alloy composition on the phases present under stable conditions, and the means of determining the

chemical composition and relative amounts of different phases present in an alloy of a given composition at a given temperature (Tweeddale, 1962). Such diagrams would have simplified the selection process by providing crucial information such as the solubility of metals and the melting point of the alloy as a function of the alloy contents. Under these circumstances, qualitative analysis was conducted in the material selection phase, while the quantitative analysis was conducted after the MTCs were tested comprehensively.

The literature search and personal discussions with thermometry experts resulted in the identification of the common metallurgical and chemical problems of TCs. Those problems were studied, their severity or magnitude in the case of MTC was put in perspective, and precautions were taken against them both in the material selection phase and in the MTC fabrication phase.

5.2.1.1 Identification of Factors Affecting the Emf of TCs

One of the earliest and most comprehensive studies performed in the area of identifying factors causing TC degradation was conducted by Potts and McElroy (1961) with the help of Professor E.E. Stansbury of the University of Tennessee at Knoxville. They identified factors that lead to changes in the Seebeck coefficients of TCs; some of which are:

A. Oxidation

B. Cold working and annealing

C. Precipitation of a new phase

D. Grain growth

E. Composition conversion caused by thermal neutron irradiation.

Composition conversion (Factor E) will not be discussed since TCs are irradiated only in very specialized and limited cases. Grain growth is a phenomena that occurs when a strain free metal or alloy is heated at a sufficiently high temperature causing the grain boundaries to migrate and increase in the size (Guy, et.al., 1974). Another cause of grain growth is the annealing of cold worked metals which could cause motion of subgrain boundaries, growth of primary recrystallized grains, and grain growth during the secondary recrystallization (Guy, et.al., 1974). It determines the strength and usefulness of the metal (Tweeddale, 1962). Typically the larger the grain size of a metal is, the lower its strength is. Fortunately, the grain growth problem has negligible effects on the Seebeck coefficients of sensors (Potts and McElroy, 1961). Therefore, they will not be discussed in this work.

5.2.1.1.A. Oxidation

Oxidation of thermoelements is one of the main causes of the "isothermal drift of thermal emf and the ultimate

failure of nickel-base thermocouples" (Potts, 1961). Potts and McElroy performed extensive tests on commercial and laboratory samples of nickel-base alloys and studied changes in alloy composition on the reaction rates. Furthermore, they studied the changes in diameter, microstructure, and thermal emfs of alloys due to oxidation. The subject of metal oxidation is crucial to predict the behavior of new alloys such as the one created at the measuring junction of the MTC. If the specific volume of the oxide is greater than or equal to the specific volume of the metal (ASM, 1948) i.e.,

$$\frac{M*d}{m*D} > 1 \qquad (5.1)$$

where

M = Molecular weight of the oxide

D = Molecular density of the oxide

m = Molecular weight of the metal

d = Molecular density of the metal

then the oxide is a protective one. This property would prevent further oxidation of the alloy. The ratio for nickel, Ni, is 1.52. Other favorable alloys are the ones that have low electrical conductivity since this indicates a low rate of diffusion of metal ions. Such oxides typically have high melting points.

Effects of oxidation on the diameter of alloys placed in 900 °C to 1000 °C environments for up to 500 hours indicate that highly alloyed material show the least diameter change (less than 1%) while pure nickel and Alumel

have the most diameter change of 15% - 50% (Potts and McElroy, 1961, 1962).

The main findings of Potts and McElroy can be summarized:

1. Minimum oxidation was observed at lower temperatures.
2. Reduced oxidation rates were observed when iron was reduced, when manganese was removed, when the grain size was refined, and when niobium was added to chromel-P.
3. Increasing the chromium content of alloys from 9 - 10% to 18 - 20% reduced their oxidation rate by a factor of 10 due to formation of $NiO-Cr_2O_3$, which improves the alloy's resistance to oxidation: Cr_2O_3 is a protective oxide and is more refractory than NiO. Cr_2O_3 is created when there is more than 10% Cr content.
4. Alumel oxidizes three times faster than chromel-P, presumably due to formation of nonprotective oxides. Therefore, it is the weaker leg of type K TC. Figure 5.2 shows a comparison between Alumel and other thermoelements. The addition of silicon decreased the oxidation rate.
5. When constantan is used with either Fe or copper, Cu, at 800 °C it oxidizes at a slower rate than

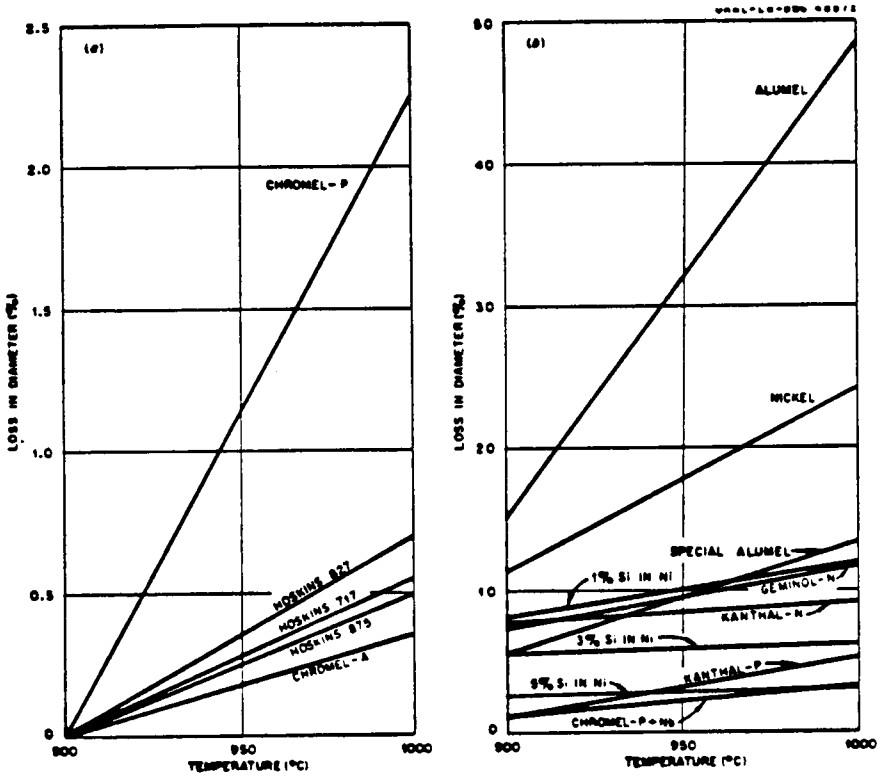


Figure 5.2 Comparison of the Change of Diameter of Alumel and Other Thermoelements Tested at 1000 °C (McElroy, 1961).

either of the other metals. Cu oxidizes faster than iron and is completely consumed in 300 hours.

5.2.1.1.B. Cold Working and Annealing

In Chapter 3, the term "homogeneous metals" was used in conjunction with the laws of thermometry. In this section, further details on what constitutes homogeneity are presented.

There are two types of metallic homogeneity properties. Those are the mechanically homogeneous metals and the chemically homogeneous metals. If a metal wire is fully or partially mechanically and/or chemically inhomogeneous, it will produce erroneous emfs if placed in a temperature gradient. The homogeneous mechanical state is defined as "that state which exists when no change in physical properties occurs after subjecting a chemically homogenous wire to any temperature in the range over which it is used" (Potts, 1961). Wires that are perfectly annealed (i.e., that have not been cold worked) are characterized as mechanically homogeneous. (Annealing or heat treatment of wires is "an operation or a combination of operations involving the heating and cooling of a metal or an alloy in a solid state for the purpose of obtaining certain desirable conditions" such as release of internal stresses, change of structure, and change in the nature, form, size or distribution of the structural constituents (ASM 1936).

Cold work is defined as "permanent deformation of a metal below its recrystallization temperature," (ASM, 1936)). Such mechanical homogeneity can be produced by recovery or recrystallization of the cold worked wire. Recovery is characterized by a "restoration of the electrical and magnetic properties of the cold worked metal to those of an annealed metal, with no observed change in the metal microstructure or other mechanical properties" (Potts, 1961).

Recrystallization takes place at higher temperature than recovery. It is characterized by the "growth of new strain free grains in partially recovered metal with a restoration of the mechanical properties characteristic of the annealed metal" (Potts, 1961). Recrystallization is time, temperature, and original cold work state dependant because of its growth nature.

The homogeneous chemical composition is defined as "that state of the wire which exists when all portions of the wire are chemically identical" (Potts, 1961).

McElroy and Potts (1961 and 1962) concluded that changes in Seebeck coefficients of materials occur due to changes in the physical state of the metal by cold working, recovery, and recrystallization. Some of their results indicate that:

1. TC wires are typically less than 5% cold worked.
2. The recrystallization temperature range of nickel

base alloys is between 500 and 750 °C depending on their cold work and the time at that temperature. Their recovery temperature range is 250 to 450 °C.

3. Heat treatment (annealing) leads to recovering 90% of the error induced by cold working in Chromel-P. The recovery in Alumel is lower than 90%.
4. Cold work may cause up to 10 °C shifts in the calibration of nickel-base TCs.

Potts and McElroy studied the effect of the method used in TC preparation on the TC's performance. They prepared some of the TC samples with extra care to avoid cold working and contaminating the wires(by washing the insulators with acetone and ether, baked in air at 1000 °C, then stored in sealed glass bottles; the thermo-elements were wiped with clean lint-free acetone soaked cloth; the technicians wore clean white cotton gloves; and the measuring junctions were a-c welded in a mercury-pool argon-atmosphere device), while they prepared other samples without the use of special handling methods. Comparison between the methods indicated that to within ± 2 °C there is no difference between either method of fabrication up to 700 °C.

5.2.1.1.C Precipitation of a New Phase

The precipitation of a new phase due to the presence of chromium carbide, which leads to the depletion of the solid solution of Cr, is blamed for the 10 to 15 °F of positive

drift noticed after Type K TC wires were exposed to a temperature range of 800 to 1200 °F for 2 to 8 hours. McElroy and Potts (1961) conducted extensive tests to study this phenomenon. Their conclusion was that the carbide precipitation may occur and cause serious sensor drifts only if carbon was available for the sensor from an external source. There is insufficient carbon in Type K TC to cause carbide precipitation.

5.2.1.2 Additional Considerations in the Material Selection

Additional criteria were considered while selecting the MTC wires:

1. Useful operating temperature range of the process. McElroy and Potts performed extensive drift analysis to qualitatively correlate the drift rates with the isolated physical and corrosion resistant properties of the alloys. One of the pertinent findings was that "to within 1 °C there was no evidenced advantage of any one of the base-metal thermocouples to 390 °C." For best results the STMS will be limited to low to medium temperature range. This limitation should reduce the problematic oxidation rate and increase the useful life span of the device.
2. Sensitivity, in mV/ °C, of the corresponding type of TC along with the various wire combinations. Generally, wires with higher overall sensitivities have a better chance of being selected than wires of low overall sensitivities.

3. Minimum number of different elements in the sensor. Keeping the number of various materials inside the sensor to a minimum to reduce the chances of chemical attacks and material diffusion was considered.

4. Cost/performance tradeoffs. If the performance of a less expensive wire is only slightly lower than a more expensive wire, then the inexpensive wire is selected.

5. Past experience with the wire. If a wire is known to degrade faster than other wires that wire is rejected.

6. Sensor gage. The useful operating range of a thermocouple is dependant on the gage of the wires. Generally, the finer the diameter (higher gage) the lower the useful temperature operating range.

With these criteria in mind, the search for the right wire combinations was performed. In Table 3.1, the maximum useful temperature ranges of various TC types were shown. Type T with a maximum useful range of 350 °C (662 °F) was eliminated from the selection process because it does not meet criterion 1.

Type K thermocouples were found to exhibit a peculiar behavior at elevated temperatures (600 °C). They have a short range ordering problem whereby their cell structure is reordered if they are maintained at about 600 °C for a short period of time. This alters their Seebeck coefficient, and they become incapable of reproducing the same output at the same temperature (i.e., a hysteresis problem occurs)

(Anderson, 1982). Potts and McElroy (1961 and 1962) and Anderson (1982) verified that the problem is more severe in the Alumel (Kn) leg. Therefore, Kn wire was removed from the initial list of possible TC wires based on criterion 5. However, since the sensor is to be operated at temperatures below 500 °C, Kn was retained in the variations of the MTC as will be explained in Chapter 6.

TC types E, J, K, N have the highest sensitivities in descending order as can be seen in Figure 5.3. The average sensitivity for E, J, and K was found to be (Omega Catalog) 67.9, 52.6, and 38.8 μV/°C. Notice that these sensitivity figures represent the Seebeck coefficient for those types and provide only a starting point, since they represent only a single signal out of ten possible signals. A highly sensitive pair of thermoelements does not necessarily imply that either thermoelement will be highly sensitive in conjunction with other thermoelements. Therefore, a more detailed analysis was performed. The sensitivity of each wire relative to platinum, as shown in Figure 5.4, was studied. Figure 5.4 was obtained by adding plots of nicrosil (Np) and the nisil (Nn) legs of the type N TC to an existing Figure obtained from Kerlin (1982). Equations of a 14 gage (although emf-T Relationships are not dependant on the gage of the wires, two different sets of relationships were developed for type N TC by Burley (1974)) Np and Nn leads of type N TC were used to generate and plot the emf

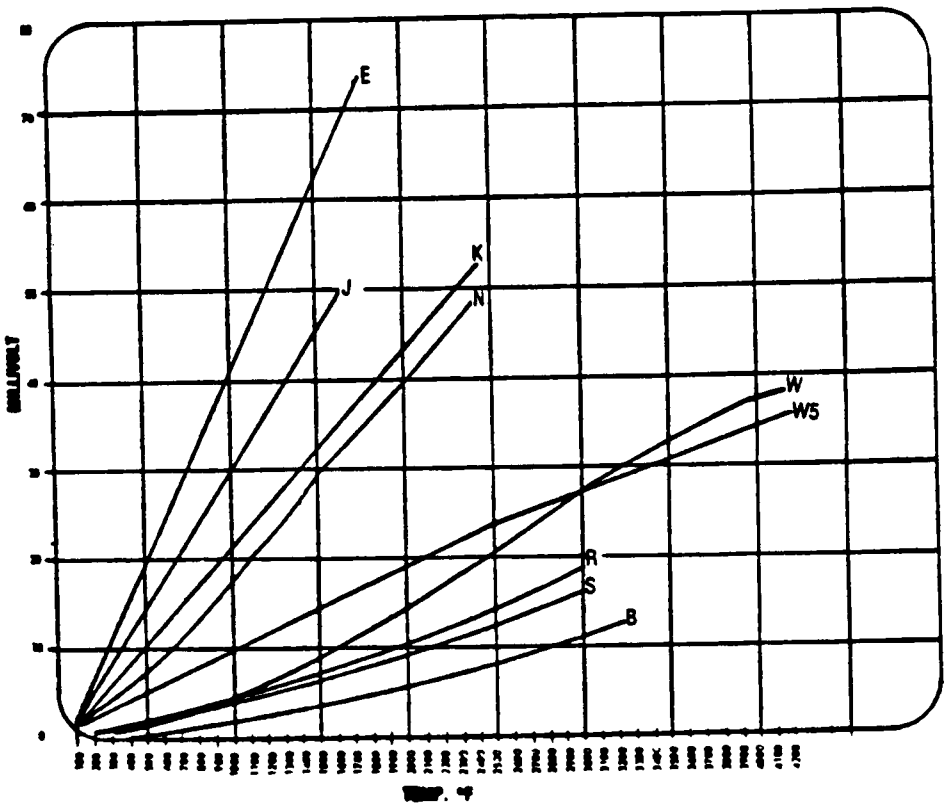


Figure 5.3 Relationship between Temperature and emf for the Various Types of TCs.

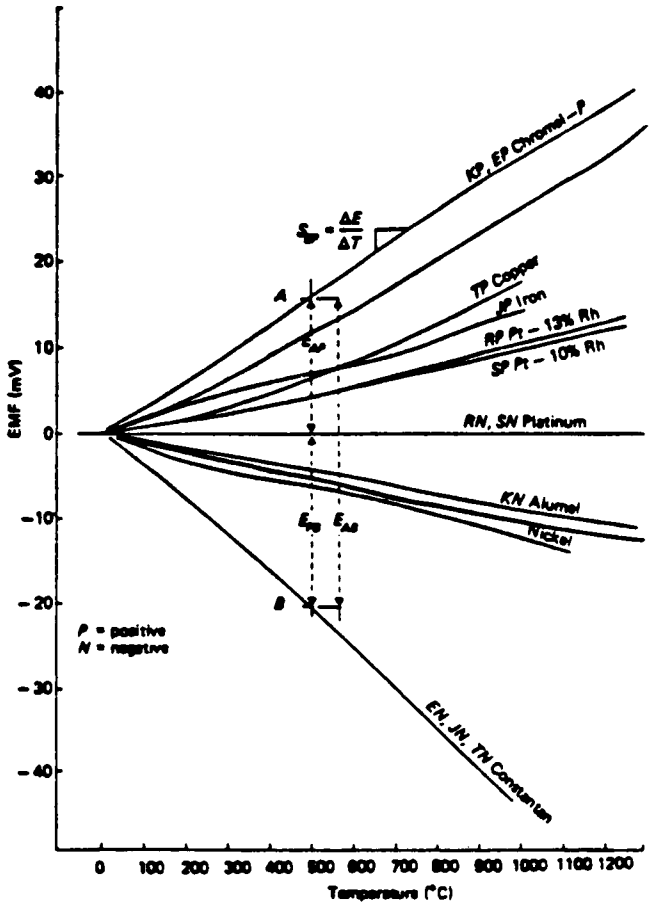


Figure 5.4 Relationship between Temperature and emf for the Various TC Thermoelements (Kerlin, 1982).

values relative to platinum as a function of temperature. The sensitivity analysis was continued by utilizing Figure 5.4 to obtain the absolute abscissa on the plot representing the sensitivities, among the wires and the other pertinent wires, at 500 °C. The results of the measurements are shown in Table 5.1. The sum of all the pertinent emfs for each wire was found and used as an index of selectness of the wire. The same data are also represented graphically in Figure 5.5. By examining Table 5.1 and Figure 5.5, it can be seen that En, the wire with the highest selectness index, is the best choice. Ep, Nn, and Np were also selected for their higher-than-the-rest index values.

The remaining wires iron (Jp), Pt-13%Rh (Rp), Pt-10%Rh (Sp), Pt (Rn, and Sn) have comparable indexes. All wires except Jp contain platinum; an expensive element. In this case Jp was selected because it is less expensive. (By analyzing the price list in the OMEGA Catalog, Jp was found to be an average of 85 times less expensive than the platinum wires.)

By consulting Table 5.2, which describes the constituents of the various pertinent TC wires, copper (Cu), nickel (Ni), chromium (Cr), and iron (Fe) are found to be the main constituents of En, Ep, Jp. Np and Nn contain two extra materials: silicon (Si) and magnesium (Mg). A combination of wires Ep, En, Np, Nn, and Jp welded at the measuring junction will have the overall material

Table 5.1 The Absolute Emf Values for the Various TC Wires at 500 °C.

A Ref. Wire	B Wire	$\lvert A-B \rvert$ Abs. emf between A and B (mV)	Total (mV)
EP	EN	35.3	
	SN, RN	15.3	
	SP	11.2	
	NN	21.1	
	NP	3.9	
	JP	8.6	95.4
EN	RN, SN	20.0	
	SP	24.1	
	JP	26.7	
	EP	35.3	
	NP	31.7	
	NN	14.7	152.5
JP	EP	8.6	
	RP, SP	2.6	
	RN, SN	6.7	
	EN	26.7	
	NP	4.4	
	NN	11.9	60.9
NP	EP	3.9	
	JP	4.4	
	RP, SP	7.2	
	RN, SN	11.6	
	NN	16.4	
	EN	31.4	74.9
NN	EN	15.0	
	RN, SN	5.0	
	RP, SP	9.2	
	JP	11.9	
	NP	16.4	
	EP	17.9	75.4
RP, SP	EP	11.7	
	NP	7.5	
	JP	2.2	
	NN	9.2	
	RN, SN	3.9	
	EN	23.9	58.4
RN, SN	EP	15.8	
	NP	11.7	
	JP	6.3	
	RP, SP	3.9	
	NN	5.0	
	EN	20.0	62.7

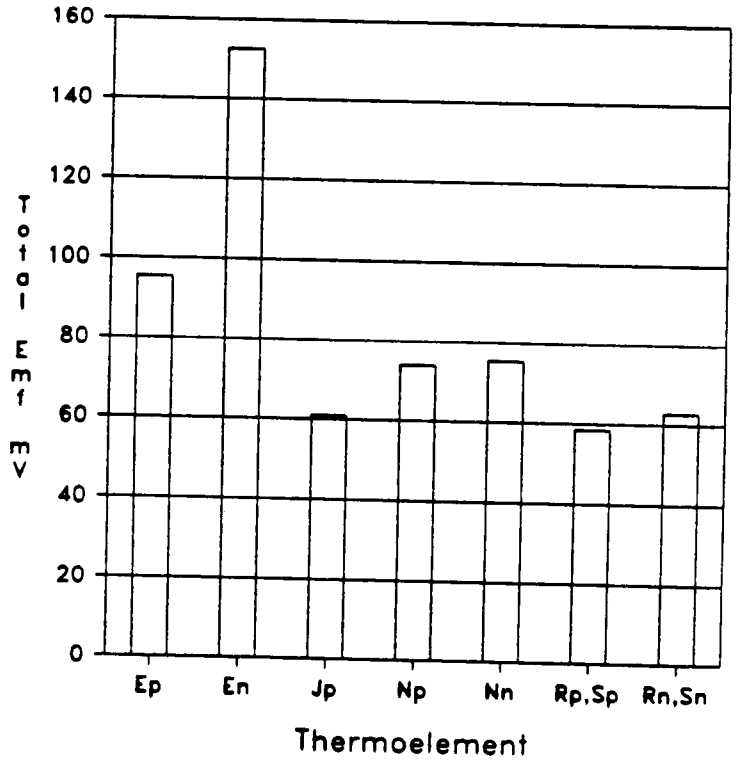


Figure 5.5 Graphical Representation of the Absolute emf Values for the Various Combinations of Wires.

Table 5.2 Constituents of Various TC Thermoelements.

Thermoelements		Constituents
Letter	Name	
Ep, Kp	Chromel	90% Ni, 10% Cr
En, Tn, Jn	Constantan	55% Cu, 45% Ni
Jp	Iron	99.5% Fe
Kn	Alumel	95% Ni, 2% Al, 2% Mn, 1% Si
Np	Nicrosil	84.4% Ni, 14.2% Cr, 1.4% Si
Nn	Nisil	95.5% Ni, 4.4% Si, 0.1% Mg

concentrations shown in Table 5.3. These figures are approximate, and they do not include impurities. Notice that the Mg concentration is virtually nonexistent in comparison with the rest of the materials. This is good since reduction of Mg concentration results in reduced oxidation rates (Potts, 1961). Increased amounts of Si should also have a favorable effect in reducing drift of the MTC.

When these wires are welded, they essentially become a five metal alloy with some impurities. It becomes extremely difficult to predict the chemical and metallurgical behavior of the measuring junction. However, studies in the area of "alloys" revealed some important facts that increased our confidence in the selected material.

An alloy is defined as a "substance with metallic properties containing two or more elements, at least one of which is a metal" (Bowen, 1967). Two useful rules presented by Hume-Rothery apply to alloys. They are (Bowen, 1967)

"1. Two metals will not dissolve appreciably in one another if their atomic radii differ by more than 15 percent.

2. Corresponding phases of similar alloys have similar numbers of valency electrons per atom."

Table 5.3 Material Concentration in the Measuring Junction of the MTC.

Element	Concentration
Ni	63.04% by weight
Fe	19.92%
Cu	11.01%
Cr	04.85%
Si	01.16%
Mg	0.02%
Total	100.0%

The first rule may be of value in determining whether the selected MTC wires are compatible or not.

Alloys containing Ni, Fe, and Cr have been discussed in several references such as Lancaster (1980) and Staehle (1971). They can be found naturally as nickel-copper-iron sulfides (Sproule, 1961). Ni-Cr-Fe alloys have good strength and they resist atmospheric oxygen attacks at high temperature as mentioned in the **Handbook of Metals** (1936): "this combination of slow oxidation and good high temperature strength makes these materials almost indispensable in the various chemical industries." Therefore, Fe-Cr-Ni alloys are reliably used for applications where corrosion resistance is required. When forming a nickel alloy, however, precautions must be taken not to contaminate the metal with sulphur, a material that is present in cutting oil used in machinery of metals, lead, or phosphorus. The presence of such contaminants results in the formation of intergranular films which lead to severe embrittlement at high temperatures (Lancaster, 1980). When a contaminated metal is welded, a hot cracking problem occurs in the heated area of the weld caused by intergranular penetration of the contaminants (Lancaster, 1981). Therefore, extreme caution was exercised when welding the various MTC thermoelements which contain Ni or Ni alloys. Ni-Cr-Fe may suffer from porosity if the weld metal doesn't contain nitride forming and deoxidizing

elements such as aluminum, titanium, or niobium. These elements form stable compounds with nitrogen and oxygen. Such elements may be provided in the filler rods used in the arc welding of the Ni alloys. Furthermore, the Ni alloys may be welded using most of the welding methods (Lancaster, 1980).

Increasing Ni content in Ni-Cr-Fe alloys results in decreasing the alloy's susceptibility to transgranular stress corrosion cracking (SCC) and in increasing the susceptibility to intergranular attack.

Copper should not be considered as a threat to the weldability of the MJ since TC types E, T, and J all contain a combination of Cu, Ni, and at least one of the Fe and Cr elements in their MJ. Furthermore, "Alloy development work in recent years has improved basic copper nickel alloy composition. For example, they are more corrosion resistant and withstand impingement attack better if they combine a small amount of iron" (ASM, 1979).

As mentioned earlier, the concern at the measuring junction centers around its weldabiltiy and long term reliability. The previous discussion showed that it is possible to weld the five selected MTC elements, and that they should have desirable corrosion resistant properties. On the other hand, having all five wires joined at the measuring junction forms an inhomogeneous alloy. But, as long as the MJ region is at constant temperature, which is

usually the case, no erroneous emfs will be generated according to the second law of thermometry. (See Chapter 3.) However, inhomogeneities in the remaining parts of the thermoelements cannot be tolerated because they alter the Seebeck Coefficient of the thermoelements resulting in erroneous emfs if they happen to be in a temperature gradient. One of the important mechanisms that leads to wire contamination inside the TC is the creation of gases, such as SiO_2, due to inserting the sensor in low partial pressure locations, such as in deep wells. Such gases could move freely in the voids inside the sensor. Hence, they could contaminate the thermoelements by depositing Si alongside them. It is possible to reduce or eliminate these gases by inserting oxygen absorbing elements, such as titanium, inside the sensor (Potts and McElroy, 1961).

The literature search and discussion presented in this section answers the question of compatibility between the various selected metals to some extent. There are other factors, however, that must be considered such as the insulator and sheath effects on the atomic diffusion of metals and oxidation, and the possibility of having gases created inside the MTC. Since these factors and others make it extremely difficult to predict the compatibility question, the ultimate evaluation was left to experimentation and drift analysis as will be discussed in Chapter 6.

5.2.2 MTC Fabrication

Bare MTCs were adequate to prove the principles and to establish the interpolation polynomials. To study the performance of the MTCs in an industrial setting, immersion type MTCs were constructed.

5.2.2.1 Bare MTCs

Five, 90 cm long, standard MTC wires of types Ep, En, Np, Nn, Jp were inserted inside a multi-hole, 12 inch long, ceramic Alumina. The reference junction was formed by using pliers to twist the five wires tightly, but gently, around each other. The wires were insulated with color coded Teflon at the open end. It is typical to use red as a standard color for negative TC wires. However, since more than one negative wire is used in the MTC, a non-standard coloring system was adopted as shown in Table 5.4.

The five wires were then inserted inside flexible heat shrink tubing. A hot air blower was used to shrink the tube around the MTC wires.

Ideally, a single multi-pin connector was used to plug the sensor to the interface. However, type Np and Nn pins and sockets are not available commercially. Therefore, three standard connectors of type J (Black), E (Purple), and N (Orange) are joined together (using a long screw and four washers) to create a single and fool proof connector. Figure 5.6 shows the details of the bare MTC.

Table 5.4 The Teflon Insulator Colors Used with the Bare MTC

Wire type	color
EP	Purple
En	Red
Np	Blue
Nn	Black
Jp	White
Kn	White

*Either Jp or Ku would be found in a sensor--never together in one sensor

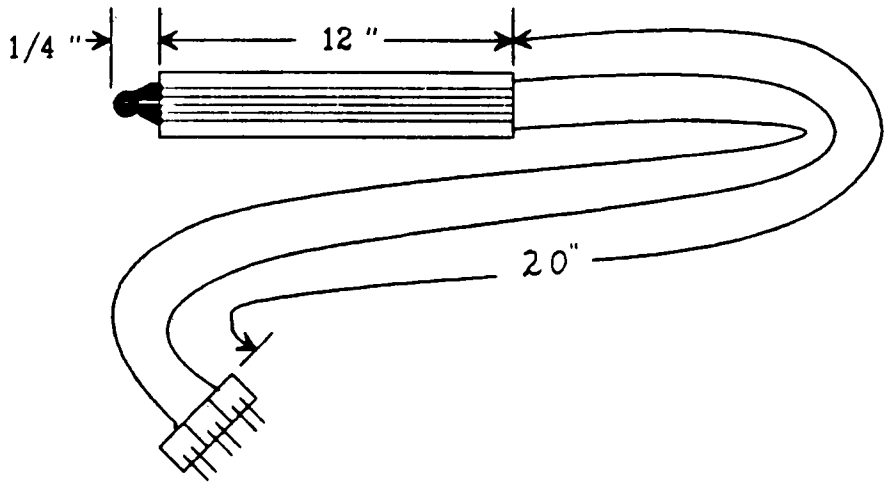


Figure 5.6 Details of the Bare MTC Used in the Analysis.

5.2.2.2 Immersion MTC

Twenty six immersion type MTCs, classified into five groups, were prepared at JMS Southeastern Company in Statesville, North Carolina. The procedure for building those sensors was as follows:

1. Five fifteen inch, 24-Gage (0.02" diameter) bare TC wires were inserted into a 12 inch long, 0.24 inch diameter multi-hole ceramic insulator.
2. For best results, it was decided to use a combination of twisting the wires then welding them to create the measuring junction. The twisted wires were 3/8 inch long. After welding, their length was reduced to 1/4 inch. A Miller 50-ampere straight DC welder was used. Argon gas was used to prevent metal oxidation in the hot phase and to cool the junction to room temperature. The current was set for 20 amperes. Iron and chromel tended to split from the rest and not bond, possibly due to their high melting points, which necessitated twisting the wires together. Figure 5.7 is a photo of the wire-insulator assemblies after their measuring junctions were welded, and before they were inserted into the metal sheaths.
3. Long stainless steel (SS 316) tubes were cut to twelve and a half inches. They were polished around the open ends and high pressure air was used to clean the inside of the tubes.

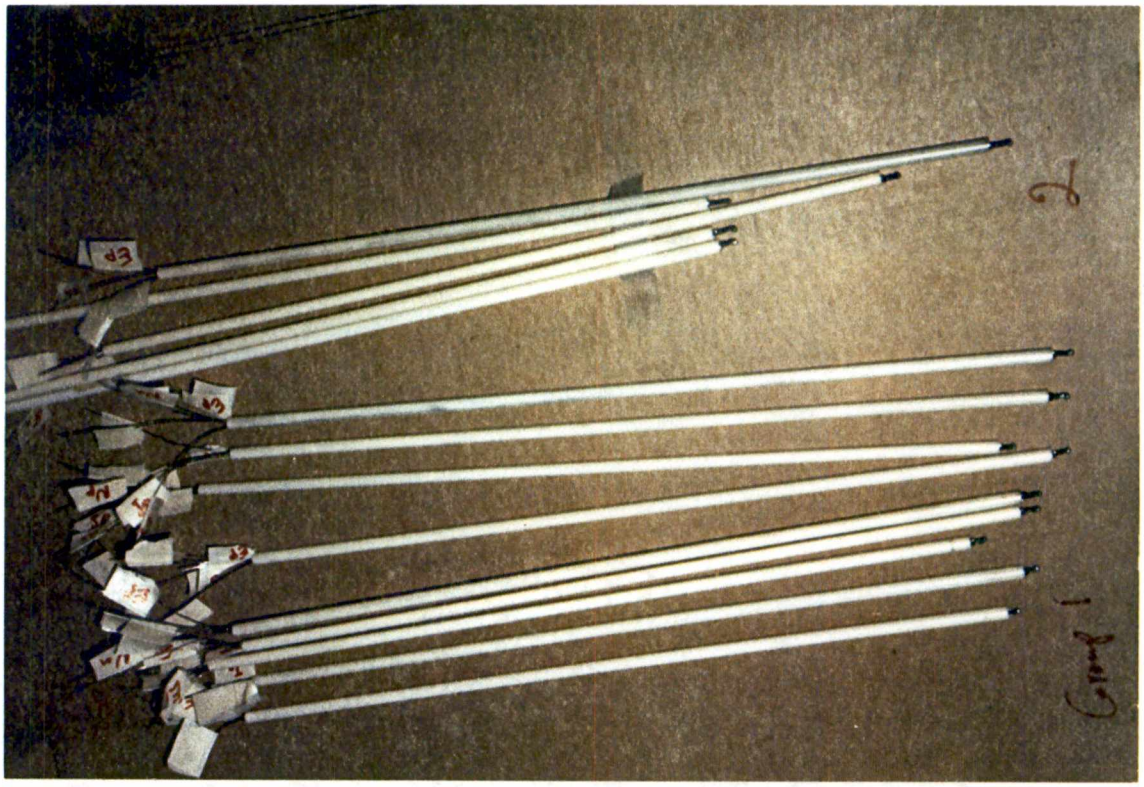


Figure 5.7 The MTC Assembly before Insertion into the Sheath.

4. Each ceramic insulator and wire assembly was fully inserted into the sheath. This configuration kept the welded measuring junction at a distance of 1/4 inch inside the sheath.

5. The measuring junction end was packed with MgO (Magnesia) to enhance the response time of the sensor.

6. The measuring junction end was blow torched using a TIG (tungsten inert gas) welder to remove impurities. The MgO level tended to expand beyond the edge of the sheath, so the extra MgO was removed with a knife-like sharp object.

7. The edge of the sheath was wiped clean, until no visible MgO powder residue were noticed, to facilitate the "capping," or closure, of the sheath. Capping was accomplished by welding a 316 SS, 3/16 inch diameter, wire on top of the sheath end. A red 1/4 inch half sphere of molten melted metal at the end of the sheath completely covered the sheath. It was allowed to cool and solidify. A photo of the welding and capping process is shown in Figure 5.8.

8. The "capped" end was then polished using a table top grinder with an abrasive wheel on one side and a cloth buffer wheel on the other side.

9. The MTC assembly was placed inside a warm (about 110 °C) oven for about 20 minutes to remove moisture.

10. Epoxy was placed at the sensor head to seal the interior. The MTCs were placed in the warm oven for 5



Figure 5.8 The "Capping" Process.

minutes to quicken the hardening of the sealant. When the sensors were removed from the oven, they were resealed with epoxy since epoxy tended to seep through the ceramic holes. This process was repeated until the epoxy hardened without any visible holes.

11. During the resealing process, quality checks were performed on the sensor to ensure that the capacitance between the MTC wires and the sheath was unmeasurably large.

12. After the sealant hardened, each wire was insulated with Teflon insulators of various colors as previously mentioned (See Table 5.2).

13. The wires were connected to three miniature connectors. A photo of some completed sensors is shown in Figure 5.9.

5.2.2.3 Extension Wires

Extension cables, 90 cm long, were constructed from 24 gage wires of types Ep, En, Nn, Np, Kn, and Jp. The wires were insulated with heat shrink tubing. Type Ep and En wires were fit with a type E female connector, Nn and Np with a type N connector. The single Jp and Kn wires were fit with type J and K connectors respectively.

Then, three 15 cm wires of type Ep were twisted together and welded to the free end of wire Ep to facilitate the signal acquisition process as will be discussed in Chapter 6. A 250 Watt Second welder (Model Number 1-180-02) developed by UNITEK Corporation was used. It uses a Force

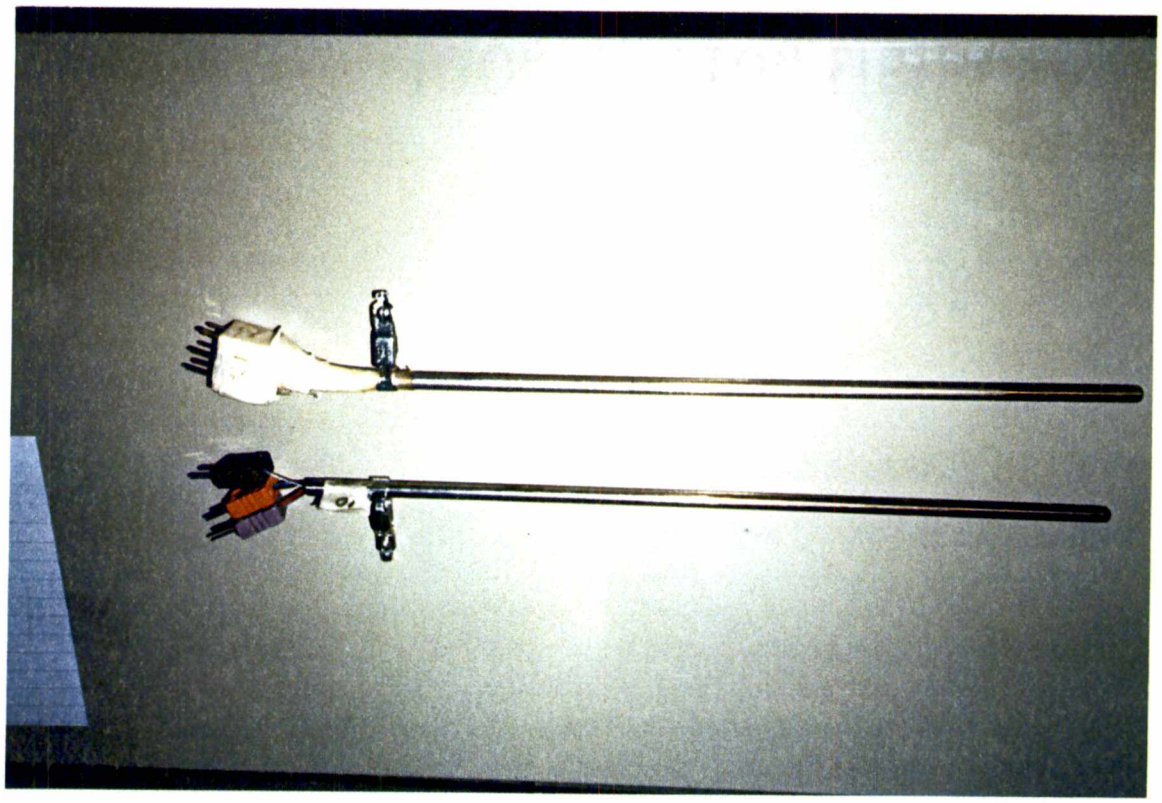


Figure 5.9 The Finished Immersion Type MTCs.

Actuated Probe (Model Number 1150) by AILTECH. This procedure was followed for all the extension wires. The details are shown in Figure 5.10.

5.3 Development of the Interface

5.3.1 Introduction

The five MTC wires will provide up to ten simultaneous temperature signals. To develop a commercial product, signal acquisition and analysis has to be performed automatically. This is accomplished by converting the analog signals to digital signals using an Analog to Digital (A/D) converter. The digital signals may then be easily analyzed by a Personal Computer (PC) or a dedicated microprocessor. The question of how to facilitate and control the signal collection process in the most efficient and economical manner was addressed. The solution was to design a new, unique, and affordable device to act as an interface between the MTC and the rest of the data acquisition system.

5.3.2 Interface Components

The prototype interface uses two input and one output channels of a data acquisition board in a Zenith/AT personal computer. The data acquisition board (Model Number DT 2801-A) has multiple input/output, analog/digital channels with a

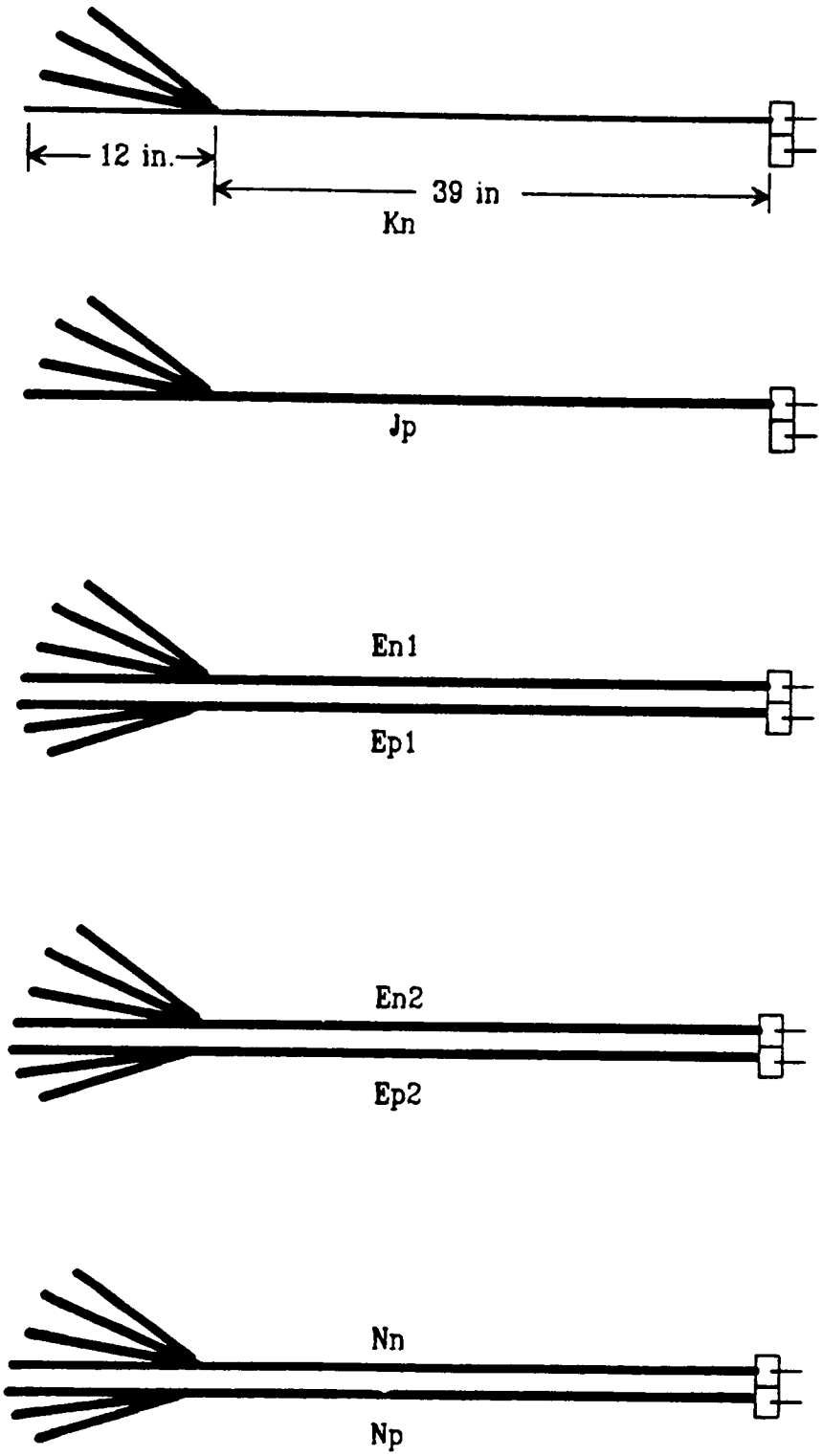


Figure 5.10 Extension Cables.

twelve bit resolution, developed by Data Translation. The main data acquisition software used with the board is Data Translation's PCLAB in conjunction with BASICA as will be discussed in Section 5.4. A Data Translation screw terminal panel (Model Number DT-707) was connected to the DT2801-A board (see Figure 5.1).

The interface consists of the following parts:

1. a set of eight relays
2. relay control logic
3. an AD590 solid state temperature measuring circuit (for reference junction compensation)
4. counter reset circuit
5. power supply
6. case and insulation

1. Relays

A set of eight double pole double throw relays, (Model Number W171 DIP-21) developed by Magnecraft, driven by a +5 volt power supply, is used to obtain measurements from all the MTC wire pairs. The positive and the negative legs of each MTC wire pair are connected to a relay as shown in Figure 5.11. The positive output of all the relays share a single line while the negative output of all the relays share another line. (Only one relay will be closed at a time, the rest are left open.) Both lines are connected to input Channel 0 of the DT-707. A diode (Model Number

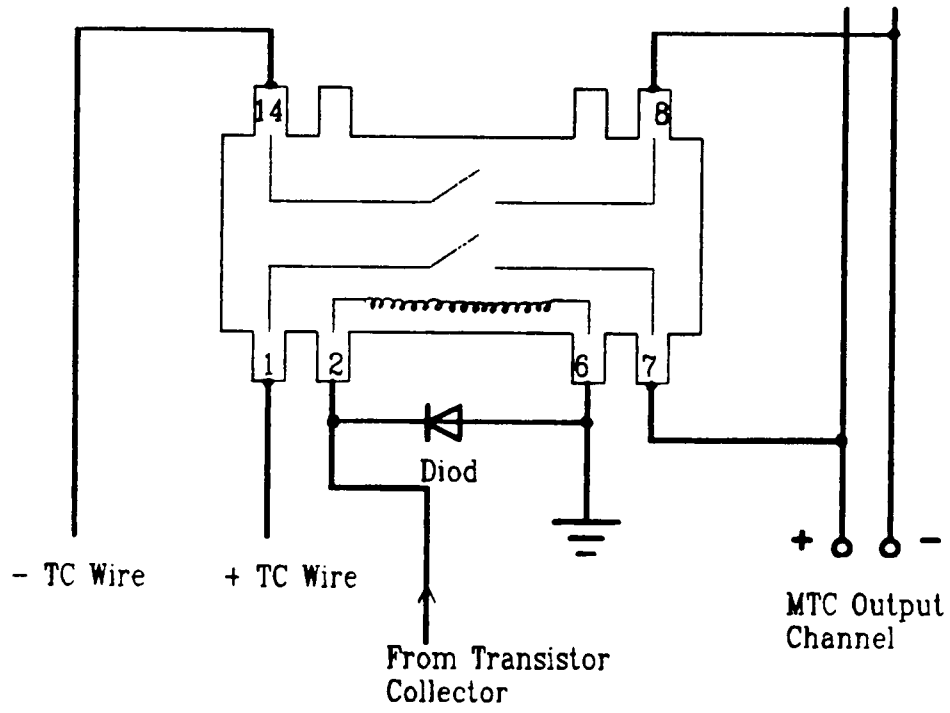


Figure 5.11 A Typical Relay Connection in the Interface.

IN4001) was connected to the legs of the activating coil of the relay, pins 2 and 6, to provide protection (from the inductive effects of the relay coil) for the circuit after a sudden power cut-off. (Diodes act as a one way valve to allow the current to pass in one direction and not the other. Typically, a damaging reverse current passes through the relay's coil after a sudden power cut off in the absence of the diode.)

2. Relay Control Logic

A logic circuit consisting of the following items regulates the sequence in which each relay is activated:

1. A counter 74193 driven by +5 volts supply
2. A decoder (BCD-to-Decimal 7442) decoder driven by a +5v supply
3. A set of eight positive negative positive transistor-resistor circuits driven by a +5 volt power supply, which provides enough current to drive the relays since the decoder signals alone are too weak. Each set contains:
    a. a 10k Ohm resistor between the +5v line and the corresponding pin on the output of the decoder (i.e., one of pins 0 through 7, and 9);
    b. a 4.7k Ohm resistor between the decoder and the Base of the PNP transistor;

c. a PNP transistor (Model Number ECG 150 PNP-Is) with the Base connected to the 4.7k Ohm resistor, the Emitter connected to the +5v supply, and the Collector connected to the relay's pin 2.

The connections from a single channel to a sample relay are shown in Figure 5.12.

3. The Board Temperature Circuit

To determine the reference junction temperature at the place of initial contact between the MTC extension wires and measuring circuit, the following circuit is used:

1. a solid state temperature device (Omega Model Number AD590);
2. a 100 Ohm variable resistor;
3. a 910 Ohm resister; and
4. a +5v power source.

The output of this circuit is amplified and fed to channel 1 of the input of the DT2801-A board. A schematic of this circuit is shown in Figure 5.13.

4. Counter Reset Circuit

The counter reset circuit is designed to ensure that Relay 1 is closed whenever the interface is powered up. This provides the PC with a reference starting point. Furthermore, this circuit is responsible for resetting the

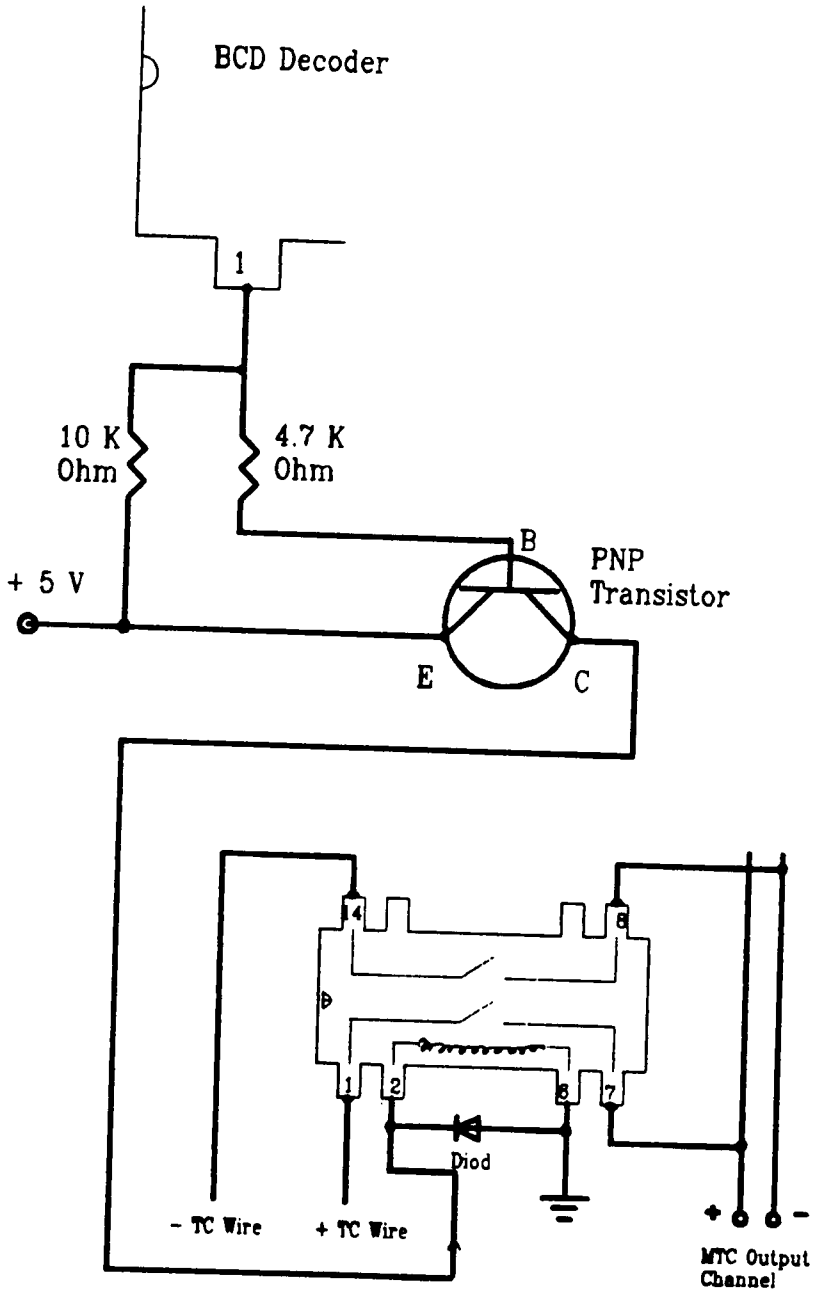


Figure 5.12 Connections from a Single Decoder Channel to a Single Relay.

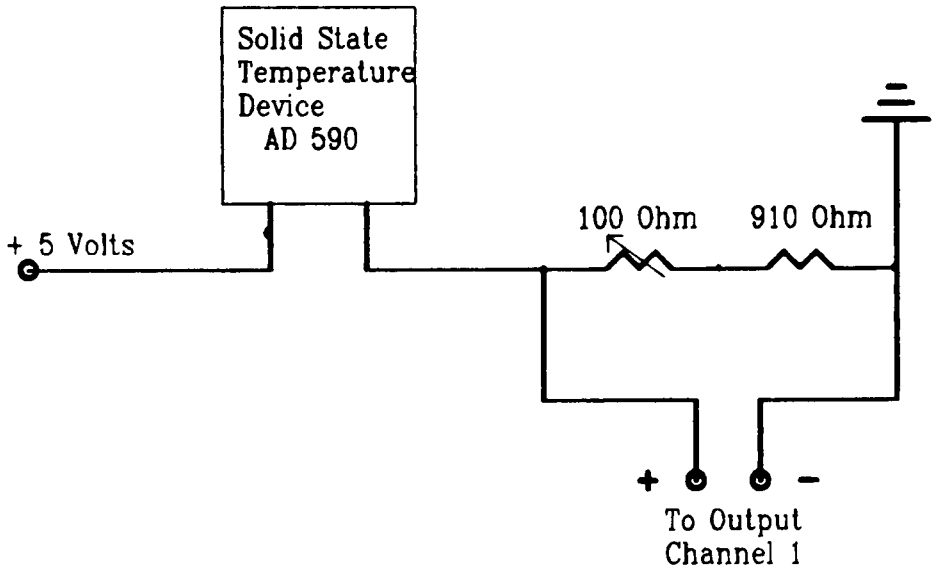


Figure 5.13 Board Temperature Measurement Circuit.

counter to the initial state after the eighth relay is deactivated. The circuit consists of

1. 4232 positive OR Gate chip
2. a +5v supply;
3. a 10 micro farad capacitor; and
4. a 1k Ohm resistor.

The main connections to and from the Positive OR Gate are shown in Figure 5.14.

5. Case and Insulation

It is important to keep the set of relays at a uniform, constant temperature, reference junction temperature. Therefore, the circuit board has been encased in fiberglass insulation. The assembly is then encased in 1/8 inch aluminum casing.

6. Power Supply

A single power supply is used to provide all the components in the interface with 5 volts. It is a 5 V - 15 AMPS, 115 - 230 VAC power supply (Part Number 001-192-0Y) developed by Computer Products, Inc.

A schematic of the interface is shown in Figure 5.15.

5.3.3 Functional Description of the Interface

In addition to the resetting circuit, the interface is controlled by the software and the PC's DT2801-A board. The main controlling components of the interface are the

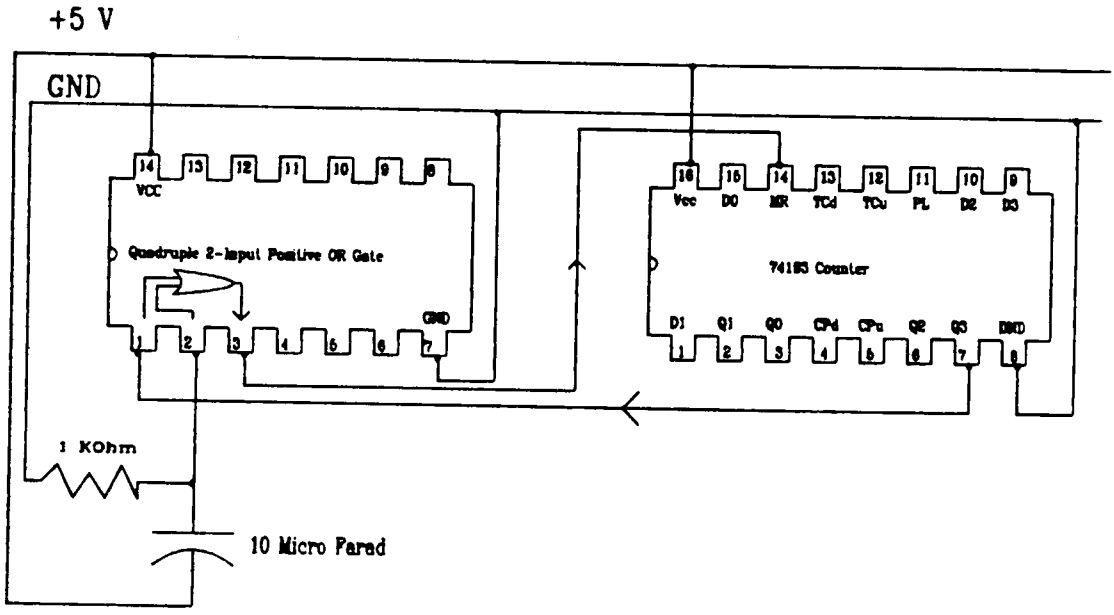


Figure 5.14 The Counter Reseting Circuit.

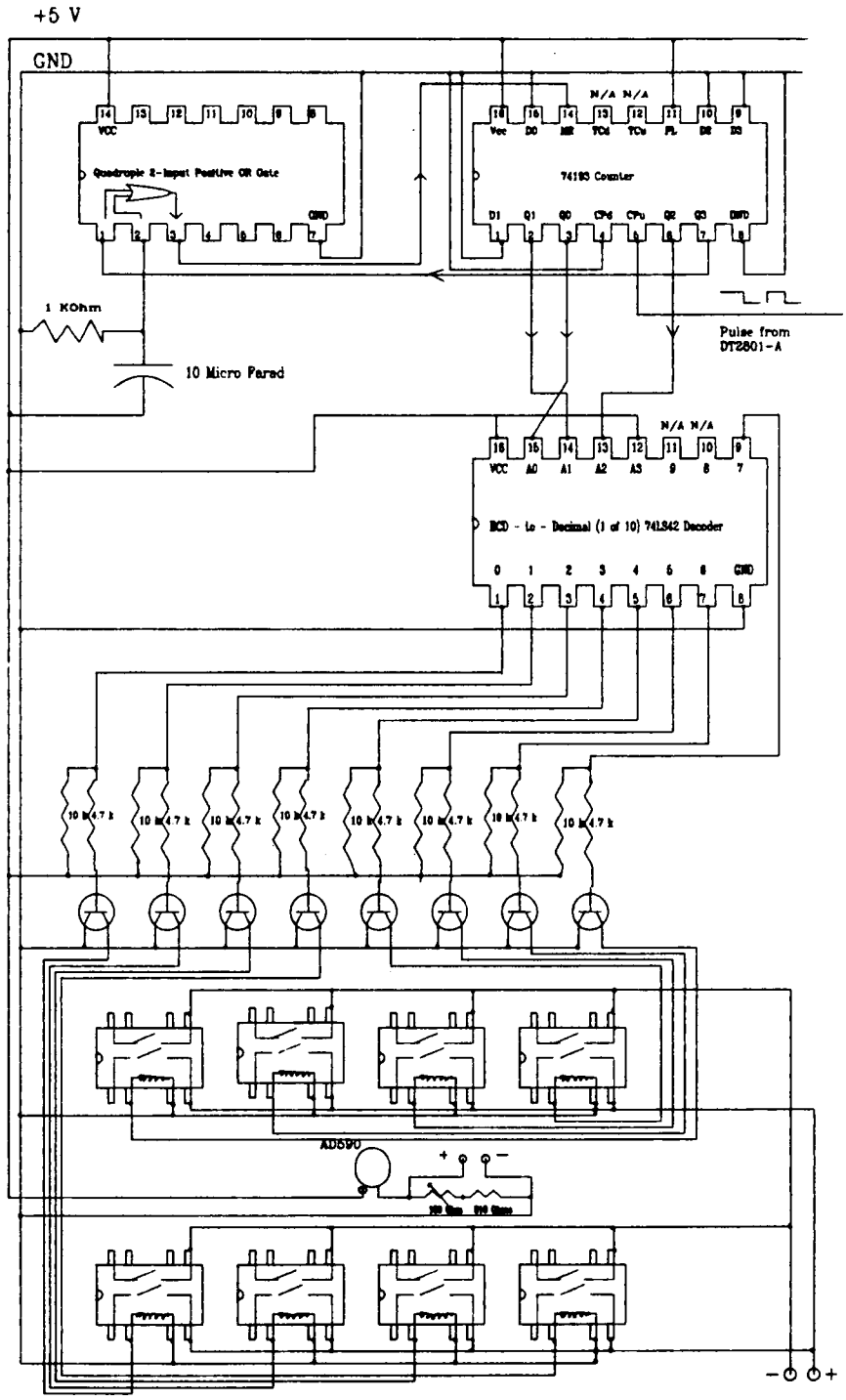


Figure 5.15 A Schematic of the Interface.

counter, the decoder, and the resetting circuit (See Section 5.3.2). These components and their connections are shown in Figure 5.16.

The counter sends output signals to the decoder through its pins 3, 2, 6, and 7 which correspond to Q_0, Q_1, Q_2, and Q_3, respectively. Q_0 represents the least significant bit while Q_3 is the most significant bit. The signals at those pins can be characterized by 0's or 1's depending on whether they are active (High) or inactive (Low). That is, if pin 6 shows about +5 volts (High) then it is represented by a 1. If the output is about zero volts (Low), then it is assigned a 0. A typical state of the counter would be 0, 0, 0, and 0 at pins 7, 6, 2, and 3 simultaneously. If a pulse, a +5 volt rising edge in the input signal, is introduced to the counter from an external source at its input (pin 5), the counter state would change to 0, 0, 0, 1 for Q_3, Q_2, Q_1, and Q_0 respectively. That is, all the Q's are zeros (Low) except for Q_0, which is High. If another pulse is sent to the counter, the state would change to 0, 0, 1, 0. The third pulse would change the counter state to 0, 0, 1, 1. The correspondence between the pulses and the counter state is shown in Table 5.5. It must be noted that, although this counter can count up to 16 (decimal), it is used only in the range of zero to eight. Therefore, the counter is reset to the initial state of 0, 0, 0, 0, as soon as Q_3 becomes active (High) by the reset circuit.

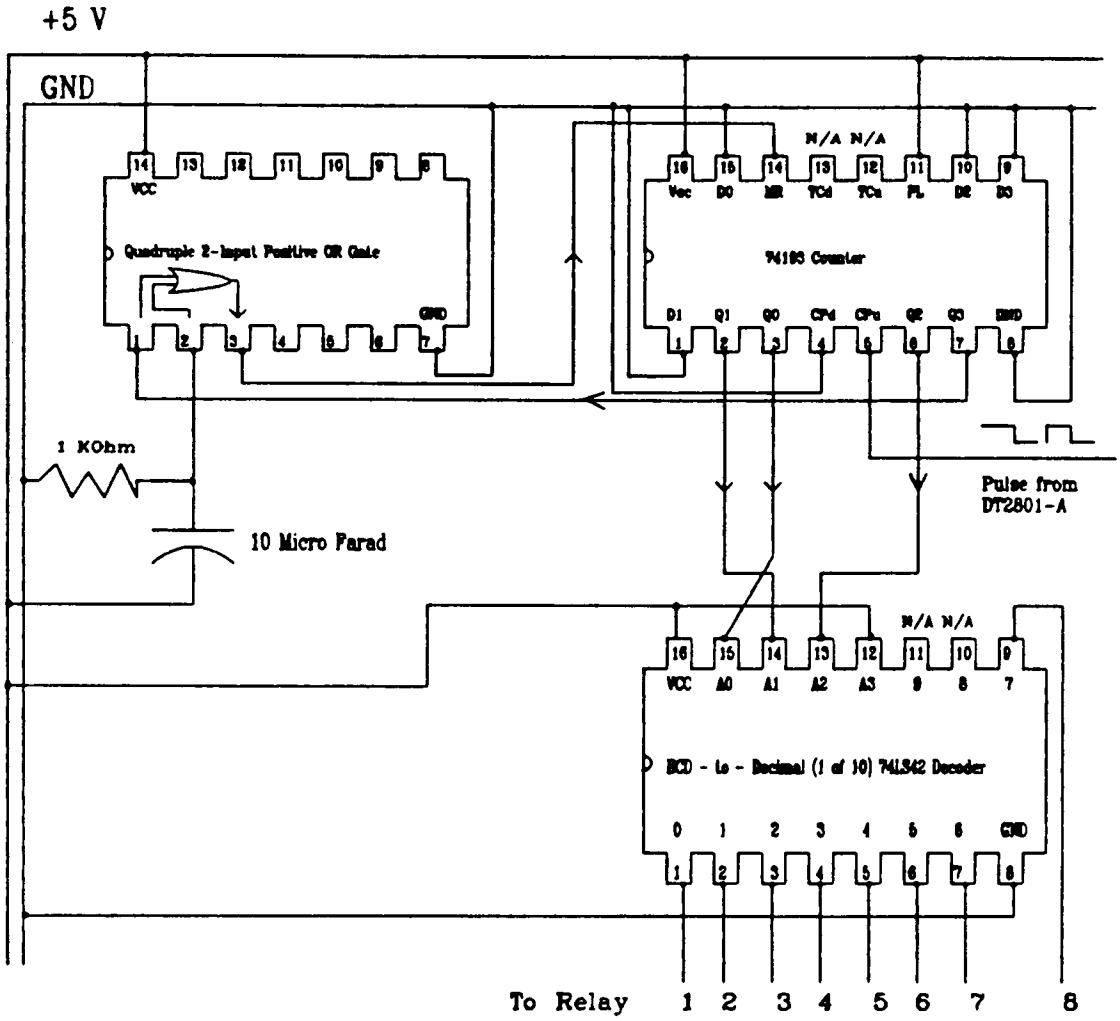


Figure 5.16 A Schematic of the Counter, Decoder, and Resetting Circuit of the Interface.

Table 5.5 Representation of the Pulses and the Corresponding State of the Counter's Output

PULSE #	COUNTER PIN			
	Q_3	Q_2	Q_1	Q_0
	7	6	2	3
1	0	0	0	0
2	0	0	0	1
3	0	0	1	0
4	0	0	1	1
5	0	1	0	0
6	0	1	0	1
7	0	1	1	0
8	0	1	1	1

At the heart of the reset circuit is the Positive OR Gate chip, consisting of four OR Gates with only one needed in this interface (See Figure 5.4 and Figure 5.16). The Truth Table for this circuit is shown in Table 5.6: when one or both inputs (at pins 1 and 2) is 1 (High), the output (at pin 3) is High. This output feeds directly to the Master Reset (MR) pin of the Counter (Pin 14). Notice that pin 2 of the OR Gate is connected to pin 7 of the counter. Therefore, as soon as pin 7 becomes High (after the eighth pulse), the output of the OR Gate becomes High: the MR receives a pulse from the OR Gate's output and resets the output to 0, 0, 0, and 0 state.

The third piece of equipment in Figure 5.16 is the decoder, with inputs pins 12, 13, 14, and 15. (Note that pin 12 is not used since only eight signals are needed.) The decoder's outputs are pins 1, 2, 3, 4, 5, 6, 7, and 9 (10 and 11 are not used). The default state for those pins is High. A pin may be switched to the Low state by changing the input state. The correspondence between the input states and the output states is represented in Table 5.7. The circuit is arranged such that the current needed to activate the relay's coil is drawn from the power supply when the decoder's output, at a specific pin, is switched to Low. Therefore, when pin 1 is Low, a current is drawn from the power supply to turn on relay 1 while the remaining

Table 5.6 The Positive OR Gate Truth Table.

INPUT		OUTPUT
PIN # 1	2	PIN # 3
0	0	0
1	0	1
0	1	1
1	1	1

Table 5.7 The Relationship between the Input and the Output States of the Decoder.

COUNTER				DECODER									
OUTPUT COUNTER PIN #				INPUT DECODER PIN #			OUTPUT DECODER PIN #						
Q_3	Q_2	Q_1	Q_0	A_2	A_1	A_0	0	1	2	3	4	5	6	7
7	6	2	3	13	14	15	1	2	3	4	5	6	7	9
0	0	0	0	L	L	L	L	H	H	H	H	H	H	H
0	0	0	1	L	L	H	H	L	H	H	H	H	H	H
0	0	1	0	L	H	L	H	H	L	H	H	H	H	H
0	0	1	1	L	H	H	H	H	H	L	H	H	H	H
0	1	0	0	H	L	L	H	H	H	H	L	H	H	H
0	1	0	1	H	L	H	H	H	H	H	H	L	H	H
0	1	1	0	H	H	L	H	H	H	H	H	H	L	H
0	1	1	1	H	H	H	H	H	H	H	H	H	H	L

decoder output pins remain High, and the remaining relays stay in the off position.

The description of the functions of the individual interface components simplifies the description of the interface operation.

When the power is turned on, pin 1 of the OR Gate reads High due to the immediate effect of the capacitor. Regardless of what pin 2 indicates, the output of the OR Gate is High, which causes the MR of the counter to reset the counter to 0, 0, 0, 0 state. This results in changing the state of pin 1 of the decoder from High to Low. This, in turn, leads to switching on relay 1. That is, upon power up, relay 1 is turned on. This is important to provide a reference starting point.

After the power up, pin 1 of the OR Gate becomes zero (since the capacitor is an open circuit at steady state); and remains zero until the next power up. Pin 2 of the OR Gate is also zero since the counter was reset to the initial state. Hence, the OR Gate has no effect on the circuit until pin 7 of the counter becomes High.

The software proceeds to acquire the signal from relay 1 by reading channel 0 of the DT-707. Then, the software commands the DT2801-A Board to send a digital output pulse to channel 0 of the DT-707's output. This pulse is fed to the counter input (Pin 5), changing the decoder state to 0, 0, 0, 1 state, forcing the decoder to deactivate pin 2

(i.e., turns it Low). Pin 1 is automatically reactivated. Therefore, relay 2 is closed and relay 1 is turned off while the rest of the relays stay open. Next the signal at relay 2 is measured. The process is repeated until the eighth pulse. The eighth relay is closed when the counter state is 0, 1, 1, 1 (See Table 5.5). After the measurement is taken, a pulse is sent to the counter resulting in a 1, 1, 1, 1 state. That is, Q_3 becomes High. In this case, the High signal is transmitted to pin #2 of the OR Gate which leads to a High signal on its output (pin 3). The High output results in resetting the counter to 0, 0, 0, 0 state and hence, relay 1 is turned on again.

After the eighth measurement is taken, the computer switches to Channel 1, to collect a signal from the board temperature circuit. That signal is conditioned so that the output of the AD590 is 1 °K/mV absolute. Therefore, the board temperature, BT, in °C, is given as:

$$BT = \frac{M*1000}{G} - 273.16 \qquad (5.2)$$

where

M = the measured value in volts

G = the amplification factor

The eight MTC signals and the board temperature are processed and analyzed by the software, then the process of pulsing the counter and collecting the signals is repeated.

The interface design is versatile and dependable. It is built from components that are readily and inexpensively

available. The relays allow the entire MTC signals to be transmitted since they use mechanical switches. Furthermore, small degradations (drifts) in the counter, OR Gate, and/or decoder will not affect the integrity of the MTC signals. All this is possible because the relays draw their current from the power supply instead of the decoder.

5.4 Software Development

A menu driven, user friendly, flexible BASIC code was developed to perform the duties of computation, communication, and self-checking in an intelligent and efficient fashion. Most of the 1000 lines of code include multiple commands, and occupies 43000 bytes of memory. There are 13 auxiliary files, occupying 10000 bytes of memory, which the code uses to store, retrieve, and update needed information. A list of file names and comments about them are presented in Table 5.8. The code and the auxiliary files are listed in the Appendix.

The program incorporated some of the commands and libraries of PCLAB software that are designed to facilitate interaction with the DT2801-A board. Loading the program is done within the PCLAB Loader File PCLCDR.EXE by executing the following command at the DOS prompt:

PCLLDR STMS

where

STMS is the code's name with extension .BAS. It

Table 5.8 A List of the Auxiliary Files Used in Conjunction with the STMS.BAS Code.

No	File Name	Comments
1.	INSTRUCT.TXT	A text material describing the code's menu and other aspects of the code.
2.	COEFF.DAT	A data file containing the E(T) coefficients' values.
3.	FAIL.CH	A data file containing the number of the channels that fail along with time, and date of failure.
4.	WEIGHT.VAR	A data file containing the variable weights as determined at the end of each cycle.
5.	STAT.CUR	A data file containing the values of PERINC(i), PERH(i), PERL(i), and PEROK(i) for each channel.
6.	WIND.DAT	A data file containing the maximum and minimum process temperature values for up to one month period. The file is updated every hour.
7.	MAINT1.TXT	Describes the sensor assembly.
8.	MAINT2.ASC	A file that describes the interface.
9.	MAINT3.ASC	A text file that describes synchronization between the program and the interface.
10.	PARM.DAT	A data file containing the values of ID$, VLOC$, MOT, SL, GS, GT, and DT$.
11.	GCCPARM.DAT	A data file containing the values of ERB(i), BIAS(i), VAR0(i), VAR1(i) for each channel, and AVETIME.
12.	WEIGHT.DAT	A data file containing the constant weights as determined based on experiments and experience.
13.	P.DAT	A data file containing values of P, MAXT MINT, and F(i) updated whenever the main menu is displayed, hence, the buffer of is cleared.

must be located in the PCLAB directory.

This will allow BASIC to understand the special PCLAB commands.

A title screen is displayed as soon as the above command is issued. The user is prompted to press any key to exit from the title screen, after which a menu is displayed. Selection from the menu is accomplished by pressing the number corresponding to the menu item of interest or by pressing "U" or "D" buttons for Up or Down in which case an arrow pointing to the menu item is also toggled up or down. Then the "Enter" key is pressed to make the selection.

The main selections on the menu are:

1. Instructions
2. Start Temperature Measurement
3. Moving Window
4. Maintenance Assistance
5. Status Report
6. Update Sensor Parameters.

These menu options are described in detail in Sections 5.4.1 through 5.4.6.

The user also has the option to interrupt the execution of any part of the code simply by pressing F1, F2, or F10 function keys, where

F1 = Displays the main menu for the user to make a new selection.

F2 = Asks "Do you want to exit to DOS (Y/N)?"

F10 = Displays a Help screen where the user is reminded of the functions of F1 or F2 buttons.

5.4.1 Instructions

When this option is selected, general information describing the purpose of the code, the main menu items, the F1, F2, and F10 buttons, and some reminders are displayed. The prompt "Press any key to continue.." is displayed at the end of each screen. The user may push any key, except F1, F2, or F10 buttons, to scroll to the next screen. When the end of the instruction set is reached, the main menu is displayed. To exit from this mode before the last instructions are displayed, simply push the F1 button. The main menu is displayed, and another selection can be made.

The instructions are saved in a file, called INSTRUCT.TXT, in a special format. This file may be modified using any PC text editor since it is in ASCII characters. However the "B" flag, found in a line by itself with no space before or after it, represents the beginning of a screen while the "E" flag represents the end of that screen. That is, the text between the B and E characters is displayed on a single screen. If this file is to be modified, then special attention should be paid to these flags. A listing of this file can be found in the Appendix.

5.4.2 Start Temperature Measurement

The option "2. Start Temperature Measurement" represents the heart of the code. When it is selected, the following sequence begins.

1. The PCLAB variables are assigned their proper values.
2. The code evaluates the coefficients of all the interpolation polynomials used to convert the measured voltages to temperature (i.e T = f(E)) and vice versa. The coefficient value of the voltage as a function of temperature (i.e. E = f(T)) are stored in a file called "COEFF.DAT"
3. The code asks the following questions:
   a. Do you wish to obtain a hard copy of the data? (Y/N)
   b. How many samples per cycle do you wish to have?
   c. What mode do you wish the system to operate in?

      Fast mode ---> Type F

      Normal mode ---> Type N

   In the fast mode data is collected from a user selected single channel, C, for a specified number of samples, X. When X samples are collected, the code collects a set of signals from all eight channels and performs signal validation based on the Consistency Checking Method discussed in Chapter 4. Next, another X samples are collected from channel C. This is repeated until one of two events occur:

i. The difference between measurement obtained and the validated estimate exceeds the specified error bound (or tolerance) on that channel.

ii. The specified number of samples per cycle is reached.

If either event occurs, the code switches to the normal mode. In the normal mode, the code collects data from all eight channels and performs the signal validation and bookkeeping for the duration of the cycle.

d. Do you want the system to use variable or constant weights? (V/C)

The weight factors are used in estimating the true temperature (See Chapter 4.) The constant weights are weights assigned to the various channels based on operating experience with the STMS under laboratory conditions. The variable weights are weights that the STMS determines independently, based on the actual performance of the various channels during each cycle.

4. The code sets up the screen where the date, time, the operating mode, the temperature, and the standard deviation headings are displayed.

5. When the system is operating in the normal mode, eight MTC signals and one board (reference junction) temperature are collected. Reference junction

compensation is performed on all the channels by convertingthe signals from amplified measured voltages to the actual emf in mV. The board temperature is calculated based on Equation 5.2. The emfs representing the board temperature, measured by each pair of the MTC wires are calculated. (In order to accomplish this, it was necessary to find the emf as a function of temperature (V(T)), for each MTC channel. Since, the coefficients of all the interpolation polynomials producing T(V), are known, it was possible to find the coefficients of V(T) from the equations in Table 5.9.) Each calculated emf is then added to the measured emf of the corresponding channel to find V_T. Finally, the process temperature is calculated using the $T(V_T)$ equation of each channel.

6. Signal validation by consistency checking is performed as described in Chapter 4. A weighted average estimate and the corresponding standard deviation are displayed.
7. Several checks are performed and more parameters are evaluated to monitor sensor performance. These include
   a. Find the cumulative inconsistency index for each channel
   b. Update the high or low (CHIGH or CLOW) counters of the inconsistent signals; if the measured T is greater then the estimate, AVE, then CHIGH is increased by 1, otherwise, CLOW is increased by 1

Table 5.9 Equations* Used to Find V(T) Given T(V).

Given $T(V) = a*V + b*V^2 + c*V^3 + d*V^4 + e*V^5 + f*V^6 + \ldots\ldots$; a is not equal to zero

Then, the coefficients of:

$$V(T) = A*T + B*T^2 + C*T^3 + D*T^4 + E*T^5 + F*T^6 + \ldots\ldots ;$$

are given by:

$$A = 1/a$$

$$B = -b/a^3$$

$$C = (2*b^2 - a*c)/a^5$$

$$D = (5*a*b*c - a^2*d - 5*b^3)/a^7$$

$$E = (6*a^2*b*d + 3*a^2*c^2 + 14*b^4 - a^3*e - 21*a*b^2*c)/a^9$$

$$F = (7*a^3*b*e + 7*a^3*c*d + 84*a*b^3*c - a^4*f - 28*a^2*b^2*d - 28*a^2*b*c^2 - 42*b^5)/a^{11}$$

* Ref. Hedrick

c. Check for end of the cycle; several "bookkeeping" actions and decisions are made when the system reaches the end of a cycle: Those are:

i. A decision is made regarding the weights and the failure status of all the channels based on the CINC values as follows:

$$\text{If } \frac{CINC(i)}{CL*NC} > .95$$

Then
Channel i has failed. Update the FAIL.CH file by adding the newly failed channel to it.

where
CL = Cycle length
NC = Number of usable signals

$$\text{If } \frac{CINC(i)}{CL*NC} > .5$$

Then
update the variable weights as follows:

$$W(i) = 1 - \frac{CINC(i)}{CL * NC}$$

Otherwise, keep the old weights.
The new set of weights are saved in a file called "WEIGHT.VAR."

ii. The following parameters are calculated:

PERINC(i) = Percent of the time during which channel, i, was inconsistent

PERH(i) = Percent of the time during which channel, i, was higher than the estimate

PERL(i) = Percent of the time during which channel, i, was lower than the estimate.

PEROK(i) = Percent of the time during which

The current status file, called "STAT.CUR", is then updated.

d. The estimated temperature is compared to the present sensor operating range and the process temperature limits. Warning messages are provided when those limits are exceeded:

i. If the maximum operating temperature (MOT) is less than or equal to the estimated temperature, then the following warning is displayed:

"MAX.OP.T. has been Exceeded,"

ii. If T ≥ (MOT-15) then the message

"Current T. is within 15C from Max.Op.T."

is flashed on the screen,

iii. If the sensor limit (SL) ≤ T then the message

"Sensor limit has been exceeded"

is displayed.

iv. If T ≥ (SL-50) then the following message

"Current T. is within 50 C of sensor limit"

is displayed.

v. Dotted lines appear in place of the warning messages when operation is normal

e. The code produces another indication of the system status by changing the screen colors based on the number of signals (k) used in the temperature estimate as follows:

If $k \leq 4$ the screen color is Red,
indicating poor performance of system;

If $k \leq 6$ then the screen color is Green
indicating good performance.
Otherwise, the screen is blue, indicating
that the system is functioning properly.

f. The system records the minimum and maximum temperatures (MINT and MAXT) each hour. The file "WIND.DAT" is designed to track the MINT and MAXT for up to one month (720 hours). Therefore, this file is updated by deleting the oldest data points and appending the new data points (MAXT, MINT) to the end of the file hourly.

Listings of the files mentioned in this section can be found in the Appendix.

5.4.3 Moving Window

When the third option is selected, the following sub-menu appears:

1. See last month's important events
2. See last weeks important events
3. See the third weeks important events

4. See the second weeks important events

5. See the first weeks important events.

When a selection is made, a graph of temperature versus time, in days, is displayed. Two plots representing the MAXT (Cyan) and MINT (Red) are displayed. A line representing the process maximum operating temperature is also drawn.

If the first item on the sub-menu is selected, extra calculations are performed before the graph is displayed: a representative data set is formed from the 720 data points to facilitate drawing by finding and plotting the maximum and the minimum temperature for every five hour interval.

The moving windows may provide easy and fast information that explain why certain channels failed. Furthermore, the moving windows provide valuable and independent information about the process behavior over a month period.

5.4.4 Maintenance Assistance

This menu option provides the operator with on-line maintenance information about the system hardware, identification of possible sources of error, and how to fix them

1. Sensor Assembly Description

2. Interface Description

3. Program Interface Coordination.

The information pertaining to each item is saved in separate files: MAINT1.TXT, MAINT2.ASC, and MAINT3.ASC. These files can easily be modified externally to the code using any PC text editor. If such modifications are necessary, the same methodology discussed in modifying the instructions text (See Section 5.4.1) should be used in modifying the maintenance files.

5.4.5 Status Report

This is an important menu option since it provides the operator with up-to-date information about the sensor status. With this option, two other sub-menu options appear on the screen:

1. Simple Sensor Status Report
2. Detailed Sensor Status Report.

When either option is selected, the user is asked if he wishes to obtain a hard copy of the report. If option 1 is selected, the code opens the STAT.CUR file (See Section 5.4.2, Item 7.c.ii). The up-to-date information is read and displayed, including time and date, channel number, the error bound for that channel, the weighting factor, the percent of time during which the channel was inconsistent, the percent of time during which the temperature indicated by the channel was higher than the estimate, and the percent of time during which the channel read lower than the

estimate. The "failed" channel numbers are also displayed. A sample current status screen is shown in Figure 5.17.

The detailed sensor status report includes details, such as the sensor identification number, location, and limit of operation. It is produced by combining information from the PARM.DAT, STAT.CUR, and FAIL.CH files. A sample listing of this report is shown in Figure 5.18.

5.4.6 Updating Sensor Parameters

This option represents the main communication between the system and the outside world. Several important sensor and environment specific parameters can be altered by invoking this module.

A dialogue with the user begins by a display of the current information and value of a specific parameter. The user is asked if that value should be changed. If yes, the user is prompted to change the value of the parameter. If no, the code keeps the current value in memory and proceeds to evaluate the next parameter.

The parameters that may be altered are:

a. Sensor identification number (ID$): ID$ value may need to be altered in cases where the MTC part is replaced with a new device.
b. The sensor location (VLOC$).
c. The maximum process operating temperature in °C (MOT).
d. The maximum sensor operating temperature °C (SL).

Simple Sensor Status Reprot

Date: 04-26-1990 TIME: 10:20:14

Channel #	Error Bound (C)	Weight Factor	%Inconsistency	%High	%Low	%OK
1	2	1	21.875	0	3.125	96.875
2	2	1	21.875	0	0	100
3	2	1	21.875	0	3.125	96.875
4	2	1	21.875	0	3.125	96.875
5	2	1	21.875	0	3.125	96.875
6	2	1	21.875	0	3.125	96.875
7	2	1	21.875	0	3.125	96.875
8	2	1	21.875	0	0	100

The following channels have failed:
NONE

Figure 5.17 A Sample Listing of a Simple Sensor Status Report.

Detailed Sensor Status Report

Date: 04-26-1990 TIME: 10:24:11

Sensor Identification Number MTC1-1

Sensor location ..... cold leg

Sensor maximum operating temperature ..... 200 C

Amplifier's gain setting for the sensor 222

Amplifier's gain setting for board T. 30

Channel #	Error Bound (C)	Weight Factor	%Inconsistency	%High	%Low	%OK
1	2	1	21.875	0	3.125	96.875
2	2	1	21.875	0	0	100
3	2	1	21.875	0	3.125	96.875
4	2	1	21.875	0	3.125	96.875
5	2	1	21.875	0	3.125	96.875
6	2	1	21.875	0	3.125	96.875
7	2	1	21.875	0	3.125	96.875
8	2	1	21.875	0	0	100

The following channels have failed:
NONE

Figure 5.18 A Sample Listing of a Detailed Sensor Status Report.

e. The MTC signal amplification factor (GS) based on the current linear amplifier setting.

f. The interface temperature signal amplification factor (GT).

g. The Consistency Checking parameters: For each channel the user may change the error bound (ERB(i)). At the end of this loop, the file "GCCPARM.DAT" is updated.

h. The constant weight factor of each channel, W(i): At the end of this procedure, the "WEIGHT.DAT" file is updated.

i. The latest date of maintenance parameter (DT$).

When the module is finished updating parameters, it saves the new values as well as the unaltered values in "PARM.DAT."

5.5 Software/Hardware Synchronization

This program was developed to be user friendly and flexible. The software tracks sensor performance by storing and retrieving information in auxiliary files. So, most of the system information will not be lost in case of power failure. However, it is important for the software to recognize which relay is closed. Therefore, the most important parameter to track is P, corresponding to the active relay, with values from 1 to 8. The value of P is updated every time the counter is pulsed. If for any reason, such as a random electrical spike that triggers the

counter, the software seems to display erratic temperatures, simply

a. turn off the power to the interface
b. discontinue the current program execution
c. reconnect the power supply to the interface, and
d. run the program by typing "start"

By cutting the power off to the interface, the special resetting circuit on the interface will insure that relay 1 is on. Because the program starts with P equal to 1, this process insures that the program and interface are coordinated.

5.6 Commercial STMSs

The STMS, in its present form, utilizes a personal computer (PC) to control the operation of system. This is adequate for analysis and demonstration purposes. However, it is unrealistic to utilize PCs in future commercial STMSs since the size and the cost of the system would be impractical. Ideally, a commercial STMS should consist of two parts, the sensor part, and the transmitter part as shown in Figure 5.19. No special design modifications are required of the sensor part. The extension wires need to be long enough to reach the location of the transmitter part.

The transmitter should contain the following devices in a single case:

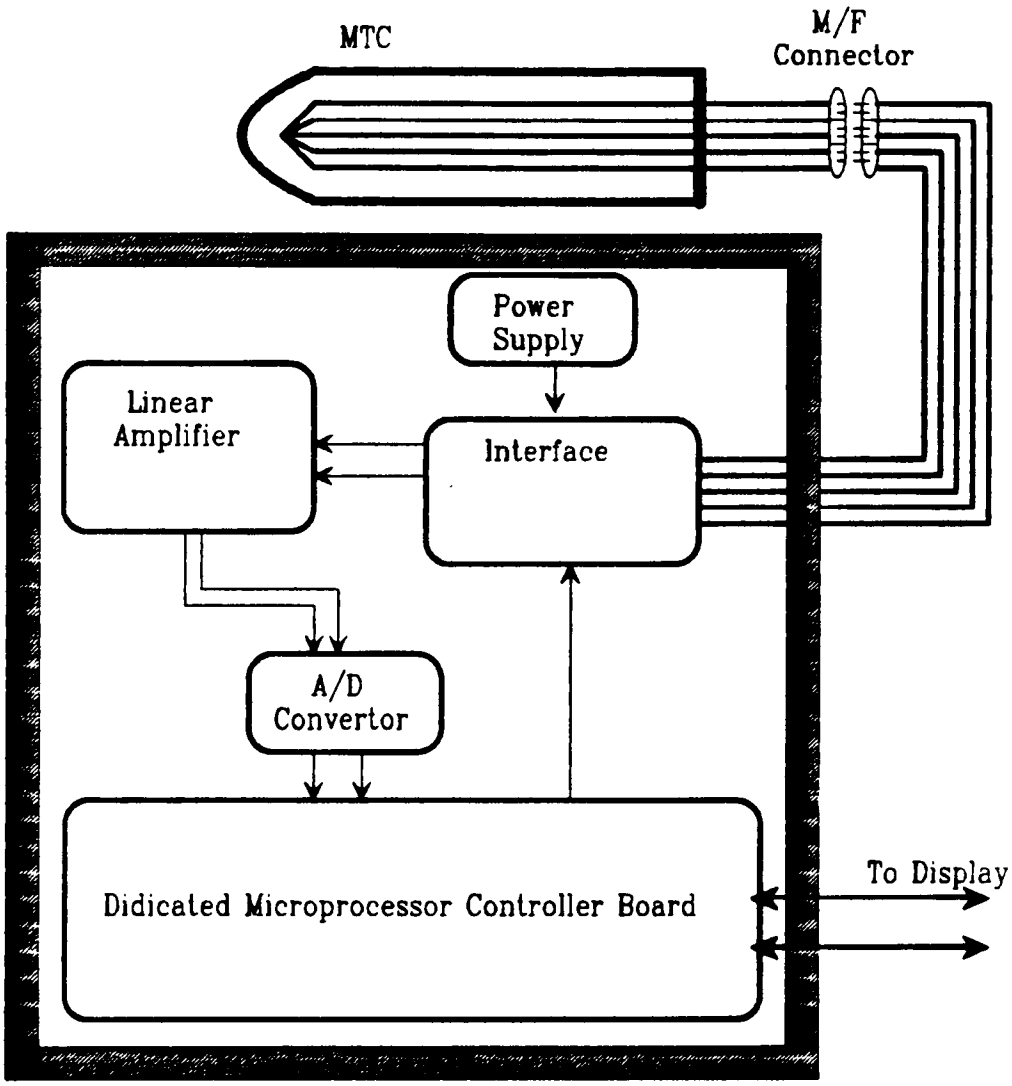


Figure 5.19 A Schematic of Potential Commercial STMS.

A. Interface:

The interface's basic method of switching between the various channels by means of relays can still be used. An alternative design, that simplifies the interface circuitry and make it less expensive, replaces the eight relays with two eight channel multiplexers. Multiplexers are commonly used in data acquisition boards for multi-input signal transmission. However, signals transmitted by the multiplexers are dependant on the quality and reliability of the multiplexer. A degraded multiplexer results in partial transmission of the signal, and hence, to erroneous measurements. Therefore, the subject of altering the interface design should be left for future investigation.

B. Analog to Digital Convertors:

The second device to be used is the analog to digital convertor (A/D). Two A/Ds are needed to convert the MTC and the reference temperature signals to digital signals accessible by the microprocessor described below. 12 bit A/D chips are available and are relatively inexpensive. However, pre-amplification of MTC signals is required to enhance the resolution of the system. As 16 (or higher) bit A/D chips become more readily available, there will be little or no amplification needed.

C. Amplifiers:

The two outputs of the interface (i.e. the MTC signals and the reference temperature signal should be fed to a

linear amplifier circuit. The linear amplifier may be a readily available device, for high accuracy, or designed from discrete components, for adequate use. It must be noted that since the STMS is a microprocessor based device, provisions can be made to account for the non-linearities of the amplifiers in the form of characteristic curves. The curves describe the relationship between the amplifier's input and output signals at each gain setting and for the entire range of the input signals. The curve may then be used to determine the true input based on the measured output voltage. Hence, the on-board amplifiers may be designed simply and inexpensively using op-amp chips, but rigorously tested to determine the characteristic curves.

The output of the amplifiers is fed to the A/D convertors.

D. Dedicated Microprocessor:

The most important device in the transmitter is the dedicated microprocessor-based controller board. This board contains the software that controls the entire communication, computation, and self-checking processes of the STMS. The software program would be burned in an erasable programmable read only memory (EPROM) that can be inserted in a dedicated socket in the board. There would be a need to modify the software based on the method of display of temperature and tolerance as well as the alarm messages,

and the control commands needed to communicate with the data acquisition hardware (i.e. to replace the PCLAB commands).

E. Power Supply:

The interface, A/D, and the linear amplifiers, and the microprocessor board require a well regulated and switchable power supply.

F. Other Devices:

Additional devices and cables may be needed. For example, if the signals proved to be noisy, then filters may be needed. If the transmitter is located in a convenient place, then an alpha-numeric liquid crystal display (LCD) may be added to act as the systems visual display. If the transmitter is to communicate with the central computer or controller, then a serial link cable and a bus controller will be needed. Provisions should also be made to facilitate the manual adjustment of the amplifier gain and the variable resistor of the AD 590.

Future STMSs may not be limited to the MTC types selected in this project. The MTCs may vary in number of leads needed. The interface may then be altered to collect two, four, eight, or sixteen redundant signals. The AD 590 circuit may be replaced with an RTD and a Wheatsone bridge circuit for reference temperature determination if the operating temperature range of the AD 590 is deemed a limiting factor.

CHAPTER 6

MTC TESTING AND RESULTS

6.1 Introduction

A crucial part of the development of a new measurement device is to put it to rigorous testing to prove its commercial viability and to solve problems not foreseen by application of theory alone. Therefore, the MTCs were tested comprehensively in a short term phase and a long term phase, with different objectives in each phase.

The overall objectives of the short term tests are to

A. prove the principle of operation of the sensor,

B. obtain the calibration curves and the corresponding polynomials for the standard and non-standard pairs of measurements to be used in the signal processing,

C. develop the best methods and procedures of testing the MTCs in the long term tests phase, and

D. help debug the STMS.

Bare type MTCs were used in this phase.

The objectives of the long term tests are to

A. perform drift and thermal cycling analysis on the immersion type MTCs,

B. compare the original design of the MTC with different types of MTCs, and

C. use the results of these tests in assigning the weight factors as discussed in Chapter 5.

Ultimately, these tests proved that the STMS is commercially viable.

The testing and calibration of the MTC devices in both phases were conducted in conformity with, and in some cases improved over, the guidelines presented by Roeser and Lonberger in the NBS Circular 591, 1958, titled "Methods of Testing Thermocouples and Thermocouple Materials." The pertinent guidelines are summarized below:

A. "The most accurate calibration in the range -190° to 300° C are made by comparing the thermocouples directly with a standard platinum resistance thermometer in a stirred liquid bath" (Roeser, 1958).

B. The ice-water reference junction should have the following:

1. the ice should be shaved, not crushed, and saturated with water.
2. glass tubes containing a few drops of mercury (Hg) should be inserted in an ice-water mixture to form the electrical connection between the TC wires and the Cu lead wires.
3. the tubes should be inserted to a depth of 10 cm.
4. the Cu lead wires should be insulated.

5. the insulator should be submerged into the Hg although this is not required of the insulators of the TC thermoelements.
6. dirt, water, and moisture should be kept away from the Hg tubes.

C. 100, 200, and 300 °C were the temperatures recommended for testing TCs for the low to med temperature ranges. For example, Type T and K may be calibrated at 100, 200, and 300 °C for applications in the ranges of -190 to 300 °C, and 0 to 1300 °C respectively. The recommended least square fit utilizes a polynomial of the form:

$$E = at + bt^2 + ct^3 \qquad (6.1)$$

Where,

E = Emf in μV

t = Temperature in °C.

For Type K, such polynomial may result in an error of 1 °C at 50 °C, 0.5 °C at 150 °C, and 0.2 °C between 200 and 300 °C. That is, the errors are smallest within the calibration range.

D. It is important to bring the reference resistance temperature detector (RTD) and the TC to the same temperature. One of the ways this is accomplished is by "inserting the thermocouples ... into holes drilled in a large metal block" (Roeser, 1958). The block may be heated in one of several ways, for

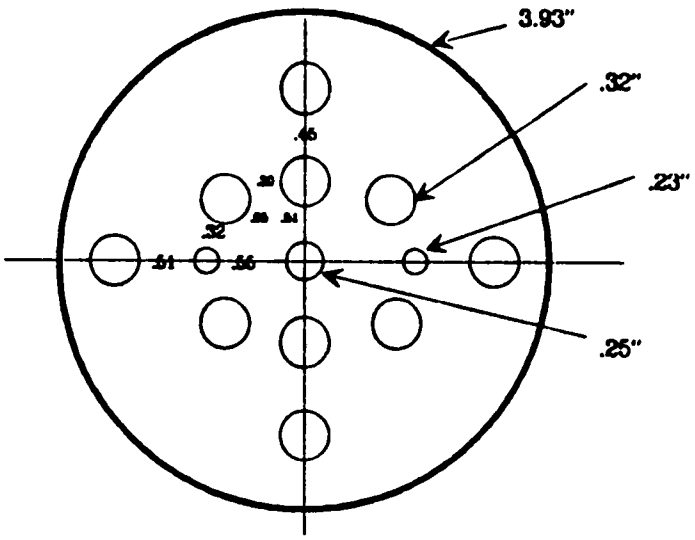
example in a furnace or electrically.

6.2 Description of the Experimental Setup

The MTC was tested in a temperature controlled, hot, and isothermal oil bath while the reference junction was maintained at the 0 °C temperature of an ice water bath.

6.2.1 Hot Oil Bath Description

The hot oil bath, developed by NESLAB Co., consists of two basic devices. The first device is a high temperature bath controller/readout, model EXACAL. The second device is an EXACAL high temperature bath with a flow controller (not used in this setup) and an EX-250HT basic container with multiple holes of various sizes for sensor insertion. To ensure temperature uniformity inside the oil bath a 6 inch long and 3 inch diameter copper block is placed in the center of the oil bath while the oil is circulated around it by means of a small pump. Therteen symmetrically distributed holes are drilled in the cylindrical copper block, as shown in the Figure below, to house the sensors during calibration. The holes are 5.5 inch deep. Typically, the oil surface is 1 to 3 inches above the block's top surface. Therefore, each sensor is submerged to depths of 6.5 to 9.5 inch.



The oil temperature can be set by manipulating the fine and the coarse tuning knobs, while pressing the "SET" button. The controller's readout digital display indicates the set temperature. Once the SET button is released the controller turns the power on to the heating elements (if the set point is higher than the oil temperature). As the temperature of the oil approaches the set point, the power to the heaters is turned on and off rapidly until the set point is reached. The controller continues to rapidly turn the power to the heating elements "on" and "off" to maintain the oil temperature at the set point.

Although the oil bath relies on a four-lead RTD to determine the oil temperature, this RTD is not standard. Furthermore, it may indicate an erroneous copper block temperature since it is located near the heating elements

and far from the copper block. Furthermore, having several holes at the top of the oil bath with sensors in them may result in axial heat conduction which alters the copper block temperature. A standard precision Rosemount RTD (model 162CE), certified by the NIST, was used to determine the true calibration temperature. The reference RTD was inserted in the center of the copper block. The copper block temperature determined by the reference RTD and the temperature indicated by the oil bath readout differed by about 0.7 °C.

6.2.2 Ice Water Bath Description

The ice water bath consists of

A. A 13 inch diameter and 15.5 inch high plastic barrel, with a 1 inch thick wall, and equipped with a faucet.

B. A 7 inch diameter and 12 inch high cylinder. The outer wall is stainless steel, while the inner wall is glass; similar to the common coffee thermos.

C. Shaved ice made from distilled water.

D. 1/4 inch diameter and 12 inch long glass tubes.

E. Mercury.

The smaller cylinder is placed inside the barrel. Both are filled completely with the wetted ice. Excess water can then be poured from the inner cylinder to the outer cylinder

as needed.

Mercury is poured into the glass tubes until it reaches a height of 1 to 2 inch. The mercury ensures temperature uniformity, electrical circuit continuity, and easy handling of the wires. The glass tubes are inserted into multi-hole rubber stoppers for support. The tubes and the rubber stoppers are then submerged in the ice-water in the inner cylinder.

6.2.3 Measurement Equipment Description

The equipment used to collect the signals from the MTCs consists of

A. A high quality Hewlet Packard digital multi-meter model number 3457A. The six and a half digit accuracy of the device is ± (%0.0040 of the reading + 365 count error) for a DC voltage input range of 0 to 30 mV. The resolution for the same DC voltage range and number of digits is 10 ηV.

B. A 10 channel switch with insulated and color coded Cu wires. There is a total of twenty input Cu wires. Ten of those are positive (i.e. they are connected to the positive contacts of each channel of the switch). The other ten are labeled as negative. Each wire is labeled by its sign and the corresponding channel number (i.e. +1, -1; +2, -2; etc.). The signals are transmitted via two

output Cu wires one of which is labeled as negative. The output of the switch is connected to the input of the digital voltmeter.

6.3 Short Term Tests

6.3.1 Initial Setup and Test Procedure

To test the MTC using its various wire combinations the arrangement shown in Figure 6.1 was used. In this arrangement the five TC leads, Ep, En, Jp, Np, and Nn, are inserted into five mercury glass tubes. Five positive copper wires corresponding to channels 1 through 5 of the switch were also inserted into the same mercury tubes. The five negative copper wires were inserted into a sixth 1/2 inch diameter, 12 inch long, glass tube half filled with mercury was marked as negative. All six tubes are inserted into the ice water mixture.

The MTC is placed in the oil bath with the oil temperature set for the desired value. Four of the MTC wires are inserted into four of the positive mercury tubes, while the fifth wire is inserted into the negative tube.

When the oil and ice-water baths each reach thermal equilibrium, a resistance measurement, representing the true oil temperature at the "beginning" is taken using the reference RTD and the HP 3457A digital voltmeter. Next, emf measurements, in mV, are taken from the switches's output at

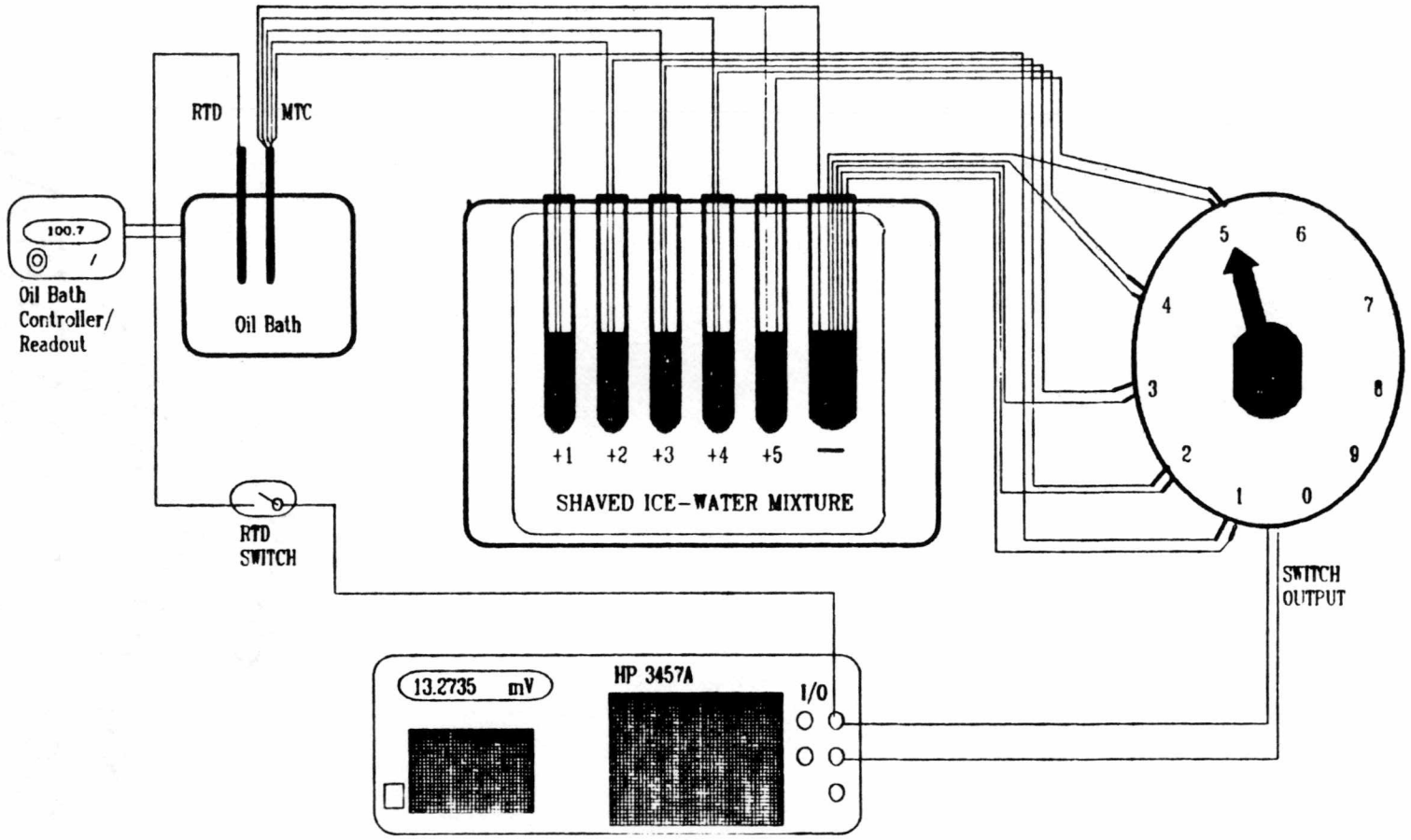


Figure 6.1 Initial Experimental Setup.

a given channel. Then, the output of the next channel is recorded, and so on. After the output of the fourth channel is recorded, the process is repeated until five signals are collected from each channel. The waiting period between signals from the same channel (while collecting the signals from the rest of the channels) is crucial to determine whether the system is at equilibrium. If drift in temperatures were noticed, data are discarded and the system is given time to reach equilibrium. After all the signals are satisfactorily collected, another reference RTD resistance is recorded to determine the oil temperature at the "end" of the data set. Then, the thermo-element is removed from the negative tube and reinserted in its original place among the positive Hg tubes. A different MTC wire is removed from its original place in the positive Hg tube, and placed into the negative Hg tube. Then, the process of waiting for the system to stabilize, and collecting a new set of data points is repeated. After all the MTC wires have been placed in the negative tube once, the measurements at that particular temperature are concluded. A new calibration temperature is set, and the process is repeated.

The advantages of the arrangement shown in Figure 6.1 are that it is optimal, accurate, and requires few wires (17 wires including two switch output wires) and few channels (five channels). The disadvantages include the long waits

for thermal equilibrium when a wire is switched, and the fact that it does not simulate or reflect the state of the MTC's extension wires in the STMS. Therefore, a second experimental setup was developed to correct these deficiencies.

6.3.2 The Second Experimental Setup and Procedure

The new experimental setup utilizes the same oil bath as in the initial setup. However, it is designed to eliminate the need for removing the MTC wires from their original positive tubes and inserting them into the negative tube, by utilizing twenty Hg tubes, and splitting the MTC signals among ten channels. Figure 6.2 shows the details of the new setup.

The basic difference between the experimental setup shown in Figure 6.2 and the one shown in Figure 6.1 is that each MTC lead is welded to four extra wires of its kind at the open end. For example, four wires of type Ep are welded to the MTC wire of type Ep. Figure 6.3 shows a schematic of the MTC used in this setup. Since each five wire set is of the same type, there is no emf generated in the added wires even if they are at different temperature. This allows the same emf values to be transmitted in each set of four wires of the same kind.

Twenty Hg tubes are placed in the ice-water bath. Ten positive Cu wires, corresponding to the positive contacts of

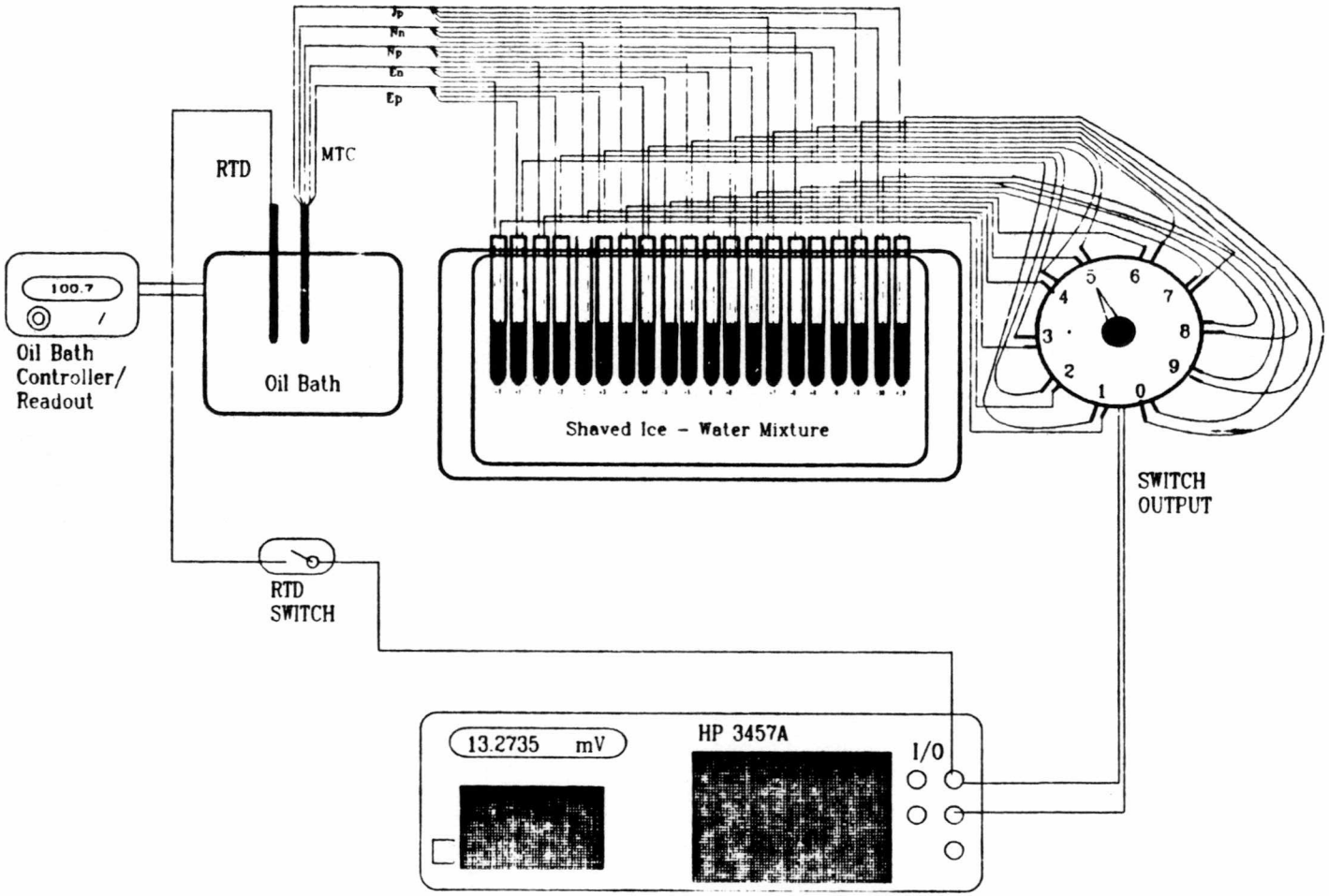


Figure 6.2 A Schematic of a New Experimental Setup that Speeds up the Calibration Process.

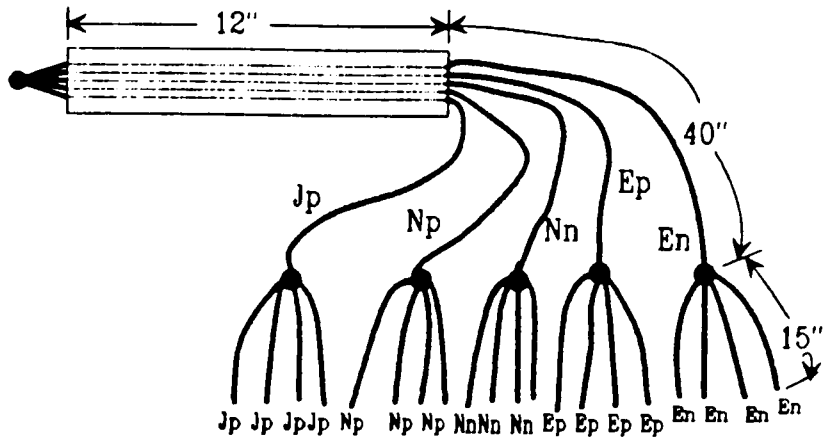


Figure 6.3 A Schematic of the Bare MTC Used in Conjunction with the New Experimental Setup.

the ten channels of the switch, are submerged into ten of the mercury tubes. The other ten negative leads are inserted into the remaining tubes. The positive tubes are identified as +1, +2, ..., +10, while the negative tubes are identified as -1, -2, ..., -10. Tubes +1 and -1 represent channel 1 of the switch; tubes +2 and -2 represent channel 2; and so on. The MTC lead wires are inserted into the mercury tubes so that the signals are positive; a crucial factor when A/D convertors are used in the final MTC design. For example, wire Ep1 - the subscript 1 is needed to distinguish between wires of the same kind - is inserted into tube +1, and wire En1 is inserted into tube -1. The output of channel 1 will then correspond to the emf value created by the wire combination Ep-En. If an arrangement produced a negative emf value, the wires in the corresponding positive and negative tubes are switched to produce the desired positive signals. The arrangement of wires, tubes, and channels that produce positive emfs are presented in Table 6.1.

By eliminating the handling of the MTC wires, the configuration shown in Figure 6.2 becomes practical and speeds the calibration process significantly. The initial reference junction configuration should reach equilibrium regardless of the oil temperature. The wires in the mercury tubes are not handled for the duration of the calibration process. The facility is one step closer to the final

Table 6.1 Arrangement of Thermoelements in the Ten Channels.

Channel Number	Positive Lead	Negative Lead
1	Ep	En
2	Ep	Np
3	Ep	Nn
4	Ep	Jp
5	Np	En
6	Nn	En
7	Jp	En
8	Np	Nn
9	Jp	Np
10	Jp	Nn

commercial STMS since the extension wires of the STMS must be split as discussed in Section 5.3.

The disadvantages of the arrangement in Figure 6.2 are that it requires more wires (47 wires), more mercury tubes (ten tubes), and more channels (ten) than the previous arrangement. The disadvantages, however, are far outweighed by the advantages.

A typical calibration procedure utilizing this experimental setup is as follows:

1. The system is configured as described in this Section, and the oil and ice water baths are allowed to reach equilibrium. The reference RTD's resistance is monitored to find out if the system has reached thermal equilibrium.
2. The reference RTD's resistance is determined to find the true oil temperature before collecting data from the sensor.
3. Emf (mV) measurements from channels 1 through 10 are taken and recorded simultaneously.
4. Step 3 is repeated five times.
5. The reference RTD's resistance is determined again to determine the calibration temperature at the end of the data set.
6. For another calibration temperature set the oil bath for that temperature. The system requires one to two hours to reach equilibrium at the new

temperature. Then steps 2 through 6 are followed again.

6.3.3 Analysis and Results

Several preliminary tests ensured that the MTC works in principle and also ensured that the changes imposed on and method of construction of the MTC do not alter its signals. That is, these tests showed that the transition from the experimental setup shown in Figure 6.1 to the one in Figure 6.2 had no effect on the measured signals. The addition of three extra leads to each MTC thermoelement has no adverse effects. Hence, the experimental setup of Figure 6.2 was adopted throughout the remainder of this research for calibrating the MTC. Also, the interface was designed based on this fact (See Chapter 5).

6.3.3.1 Interpolation Polynomials Based on the Experiments

For better accuracy determining the interpolation polynomials of the various channels of the MTC, tests were performed at 100, 150, 200, 250, and 300 °C, instead of the recommended 100, 200, and 300 °C.

Typically 5 data points are collected from each channel at each temperature. Furthermore, the resistance of the reference RTD is determined before and after each data set. In most cases, there was no difference in the resistance measurements. In some cases, there was a difference of

0.001 Ohm (equivalent to 0.01 °C). If the difference exceeded 0.001 Ohms, then the collected data set would be discarded. Each data set was averaged, and its standard deviation was determined. To find the true process temperature, the average of the measured resistances at the "beginning" and "ending" of the data set is calculated. Then, the corresponding true oil bath temperature was interpolated using a table of resistance, Ohms, versus temperature, °C, that was developed based on the Calendar Van Dusen Equation (Kerlin, 1982). This table was generated in 0.001 Ohm increments. Hence, the oil temperature would be known to within 0.01 °C.

The average emf versus temperature for each channel was fit to a fifth order polynomial of the form

$$T(E) = a + bE + cE^2 + dE^3 + eE^4 + fE^5 \qquad (6.2)$$

where

T = temperature, °C

E = emf, mV.

The coefficients a, b, c, d, e, and f for each wire pair were determined based on the least square fit method in double precision. A program was developed to generate the elements of the desired matrixes, and the code $MATRIX_x$ was used to invert those matrixes in double precision. The coefficients of the polynomials for all the MTC channels are shown in Table 6.2. Plots of channels 1 through 10, excluding channels 2 and 9 for reasons that will be

Table 6.2 The Interpolation Coefficients of T(E) as Determined by the Least Square Fit Method of the Experimental Data.

Thermoelement	Coefficients	
Ep-En	a	$-5.172285158550949 \times 10^{-03}$
	b	$1.706493667399991 \times 10^{+01}$
	c	$-2.346318024160610 \times 10^{-01}$
	d	$6.918500330641564 \times 10^{-03}$
	e	$-1.181054119490099 \times 10^{-04}$
	f	$8.761570584742140 \times 10^{-07}$
Ep-Np	a	$-2.764153878160869 \times 10^{-02}$
	b	$9.638442228810163 \times 10^{+01}$
	c	$6.857515465235338 \times 10^{-01}$
	d	$2.695454404165503 \times 10^{-01}$
	e	$-4.784010965522612 \times 10^{-02}$
	f	$1.730120401543900 \times 10^{-02}$
Ep-Nn	a	$-2.732943065529980 \times 10^{-02}$
	b	$2.760827767558658 \times 10^{+01}$
	c	$-3.862178819254041 \times 10^{-01}$
	d	$1.042302478685997 \times 10^{-02}$
	e	$3.945916986936027 \times 10^{-06}$
	f	$-3.648670092726292 \times 10^{-06}$
Ep-Jp	a	$1.553016505591586 \times 10^{+00}$
	b	$1.141889828162748 \times 10^{+02}$
	c	$-2.209275594451901 \times 10^{+01}$
	d	$3.699050096081919 \times 10^{+00}$
	e	$-3.232329297995875 \times 10^{-01}$
	f	$1.122770519955196 \times 10^{-02}$
Np-En	a	$4.337818470776256 \times 10^{-02}$
	b	$2.066649943155062 \times 10^{+01}$
	c	$-4.033156315140332 \times 10^{-01}$
	d	$1.453676531156134 \times 10^{-02}$
	e	$-3.066151109081261 \times 10^{-04}$
	f	$2.728883574276697 \times 10^{-06}$
Nn-En	a	$1.437387905589276 \times 10^{-01}$
	b	$4.427579467661417 \times 10^{+01}$
	c	$-2.238432529582496 \times 10^{+00}$
	d	$1.968485762349701 \times 10^{-01}$
	e	$-9.770471180672757 \times 10^{-03}$
	f	$1.998689799167508 \times 10^{-04}$

Table 6.2 (Continued)

Thermoelement	Coefficients	
Jp-En	a	$-1.766695429250831 \times 10^{-02}$
	b	$1.975671839805000 \times 10^{+01}$
	c	$-2.028284495409025 \times 10^{-01}$
	d	$9.728538676881726 \times 10^{-03}$
	e	$-1.827932131774901 \times 10^{-04}$
	f	$8.061770438438920 \times 10^{-07}$
Np-Nn	a	$-3.014612255356042 \times 10^{-02}$
	b	$3.869200167225790 \times 10^{+01}$
	c	$-1.106879476217728 \times 10^{+00}$
	d	$5.605095979854013 \times 10^{-02}$
	e	$-1.529365552215722 \times 10^{-03}$
	f	$1.449802895026053 \times 10^{-05}$
Jp-Nn	a	$1.035948769531387 \times 10^{-01}$
	b	$3.471882401542098 \times 10^{+01}$
	c	$6.684963632505969 \times 10^{-01}$
	d	$-1.098967950729275 \times 10^{-01}$
	e	$1.906409339392212 \times 10^{-02}$
	f	$-8.498296876631173 \times 10^{-04}$

described, based on these data fit polynomials are shown in Figure 6.4.

Fifth order polynomials representing E as a function of T were also determined

$$E(T) = a + bT + cT^2 + dT^3 + eT^4 + fT^5 \qquad (6.3)$$

where

T = temperature, °C

E = emf, mV.

The corresponding coefficients are shown in Table 6.3.

It is necessary to determine how closely the data and the interpolation polynomials reflect the true temperature and how consistent they were. Two methods were used. The first is based on the Graph Theory. The second is a theoretical determination of the interpolation polynomials for the standard and non-standard channels.

6.3.3.2 Graph Theory

Graph Theory represents a convenient method for checking the consistency of the raw signals without elaborate calculations. As used in this research, it can be described as follows: an emf measurement, A, is determined by a wire combination a and b; another measurement, B, is determined using wires b and c; then an emf, C, based on wires c and a, may be found as

$$C = A + B. \qquad (6.4)$$

This is shown schematically in Figure 6.5.

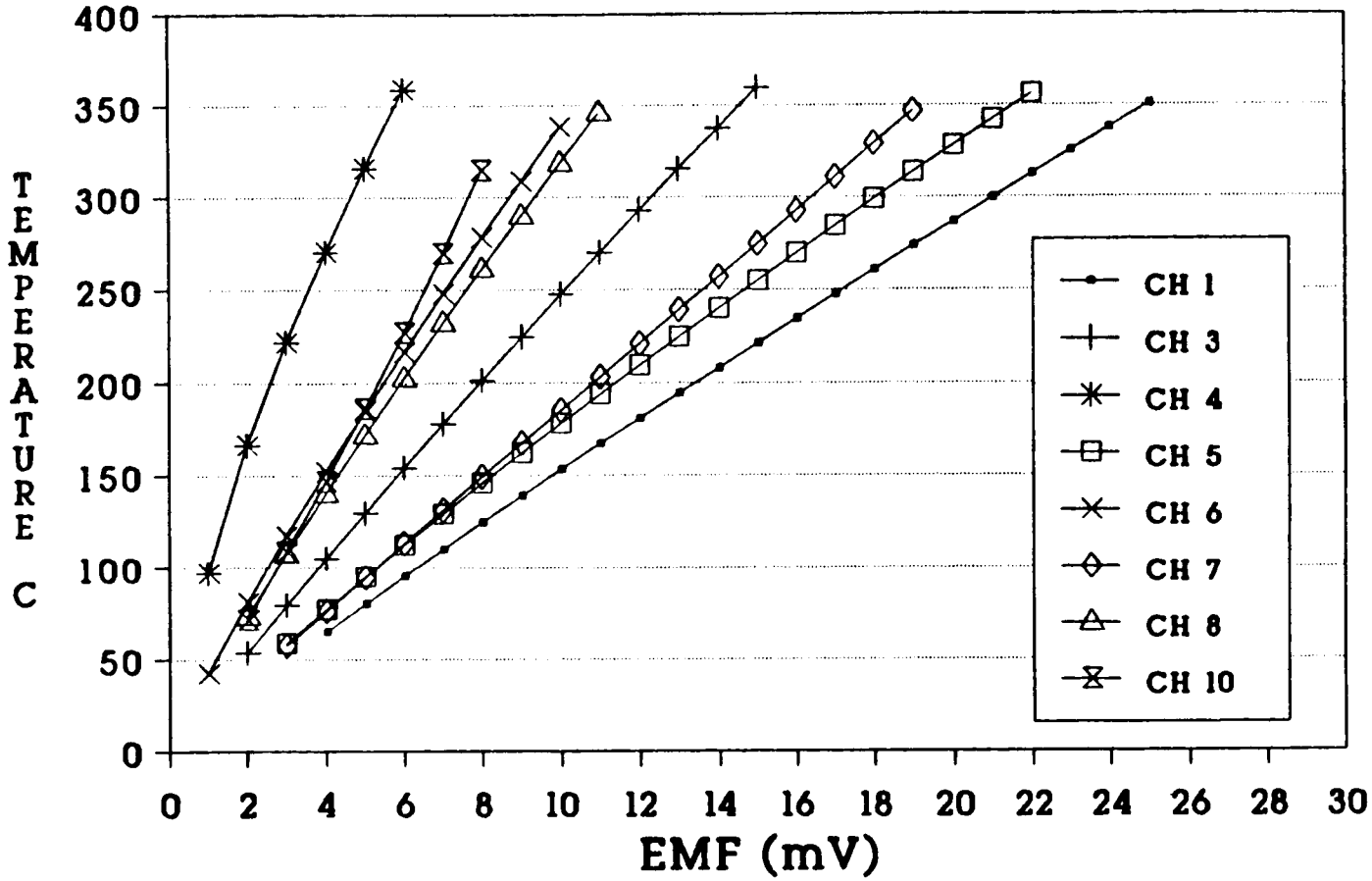


Figure 6.4 Plots of the Experimental Interpolation Polynomials, T(E), of Channels 1 Through 10 Excluding Channels 2 and 9.

Table 6.3 The Interpolation Coefficients of E(T) as Determined by the Least Square Fit Method of the Experimental Data.

Thermoelement	Coefficients	
Ep-En	a	$9.350456559332088 \times 10^{-02}$
	b	$5.515077583550010 \times 10^{-02}$
	c	$1.001668105686804 \times 10^{-04}$
	d	$-3.455889155956626 \times 10^{-07}$
	e	$8.662774100484660 \times 10^{-10}$
	f	$-9.318390741088676 \times 10^{-13}$
Ep-Np	a	$2.378423550399020 \times 10^{-01}$
	b	$7.804759859709520 \times 10^{-03}$
	c	$1.355635516375742 \times 10^{-05}$
	d	$-3.083922813952000 \times 10^{-08}$
	e	$1.510389770610458 \times 10^{-11}$
	f	$-1.181219896895914 \times 10^{-15}$
Ep-Nn	a	$9.052586005418561 \times 10^{-02}$
	b	$3.340042077707039 \times 10^{-02}$
	c	$5.888184870173063 \times 10^{-05}$
	d	$-2.381695254349836 \times 10^{-07}$
	e	$6.227667220890659 \times 10^{-10}$
	f	$-6.762171930289274 \times 10^{-13}$
Ep-Jp	a	$-1.702292722620768 \times 10^{-02}$
	b	$7.844377593301033 \times 10^{-03}$
	c	$2.224889177426803 \times 10^{-05}$
	d	$2.116600722468220 \times 10^{-08}$
	e	$-2.796230879221345 \times 10^{-11}$
	f	$-3.551020412293336 \times 10^{-14}$
Np-En	a	$7.659120406606235 \times 10^{-02}$
	b	$4.547025069314259 \times 10^{-02}$
	c	$8.555934664400411 \times 10^{-05}$
	d	$-2.480630060253119 \times 10^{-07}$
	e	$6.045904595106816 \times 10^{-10}$
	f	$-6.617311890840514 \times 10^{-13}$
Nn-En	a	$9.475864481646568 \times 10^{-02}$
	b	$2.076539696781765 \times 10^{-02}$
	c	$3.975514520959678 \times 10^{-05}$
	d	$-4.364041711335531 \times 10^{-08}$
	e	$-4.461397505768627 \times 10^{-11}$
	f	$1.370900784275006 \times 10^{-13}$

Table 6.3 (Continued)

Thermoelement	Coefficients	
Jp-En	a	$1.046549732564017 \times 10^{-01}$
	b	$4.739645908648527 \times 10^{-02}$
	c	$7.807417333083322 \times 10^{-05}$
	d	$-3.738220915594503 \times 10^{-07}$
	e	$9.271151465897048 \times 10^{-10}$
	f	$-9.420350398761711 \times 10^{-13}$
Np-Nn	a	$6.583889706234913 \times 10^{-02}$
	b	$2.383338550498593 \times 10^{-02}$
	c	$4.427468813616997 \times 10^{-05}$
	d	$-1.452452828565320 \times 10^{-07}$
	e	$3.780634723468332 \times 10^{-10}$
	f	$-4.230178303074201 \times 10^{-13}$
Jp-Nn	a	$1.033693552453769 \times 10^{-01}$
	b	$2.561225868612382 \times 10^{-02}$
	c	$3.674201031600433 \times 10^{-05}$
	d	$-2.638910529262350 \times 10^{-07}$
	e	$6.721569398076763 \times 10^{-10}$
	f	$-6.709122941840634 \times 10^{-13}$

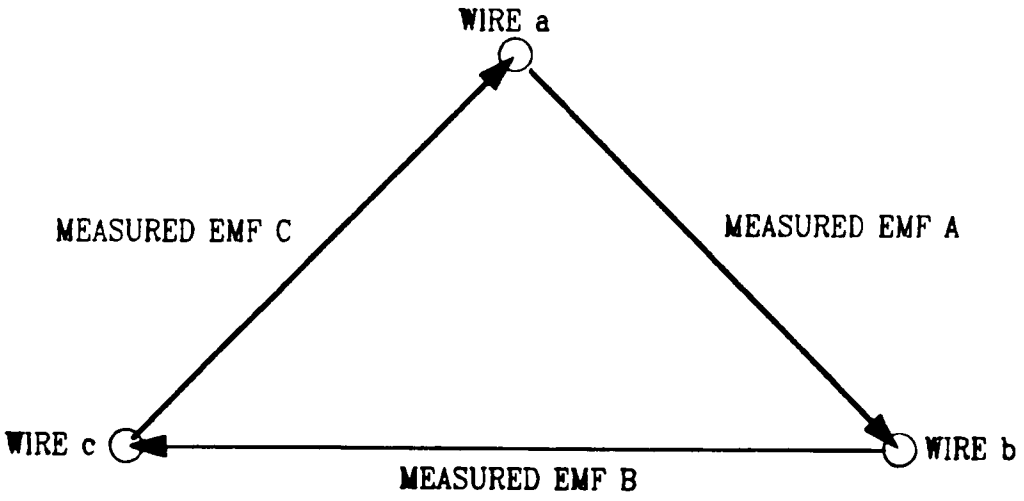


Figure 6.5 A Simple Application of the Graph Theory.

A schematic representation of the Graph Theory as it applies to the MTC is shown in Figure 6.6 where the circles represent the MTC thermoelements. The arrows indicate the negative element of the wire pair. The values reflect the actual theoretical values calculated at one of the calibration points (100 °C) for each channel. Utilizing Figure 6.6, it is possible to arrive at a single measurement in several ways. For example, the measurement using Ep-En wire pairs can be arrived at as follows:

1. Directly = 6.3144
2. Adding ch4 + ch7: 1.0338 + 5.2806 = 6.3144
3. Adding ch2 + ch5: 1.0271 + 5.2873 = 6.3144
4. Adding ch3 + ch6: 3.8025 + 2.5119 = 6.3144
5. Adding ch2 + ch8 + ch6:
   1.0271 + 2.7754 + 2.5119 = 6.3144
6. Adding ch3 - ch10 + ch7:
   3.8025 - 2.7687 + 5.2806 = 6.3144
7. Adding ch2 - ch9 + ch7:
   1.0271 - (-.0067) + 5.2806 = 6.3144
8. Adding ch2 + ch8 - ch10 + ch7:
   1.0271 + 2.7754 - 2.7687 + 5.2806 = 6.3144

Obviously, actual data will not be so perfect. The following example used actual emf measurements at 100 °C. Data and possible paths, except for channels 2 and 9, are presented in Figure 6.7. The measurement made using Jp-En wire pairs (channel 7), selected at random, can be arrived

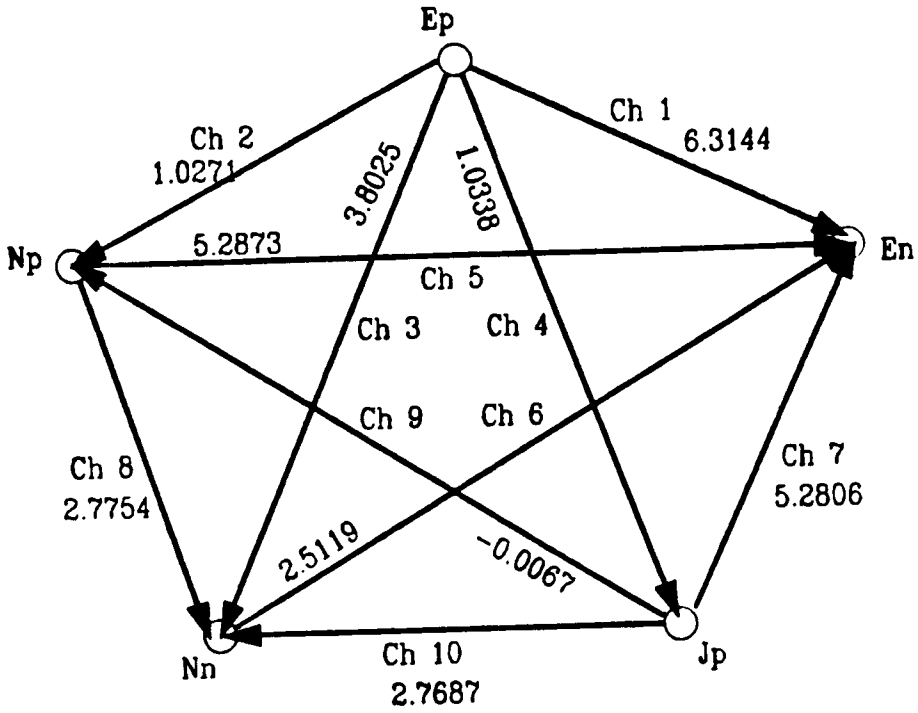


Figure 6.6 A Representation of the MTC from the Graph Theory Perspective Using Theoretical Measurements.

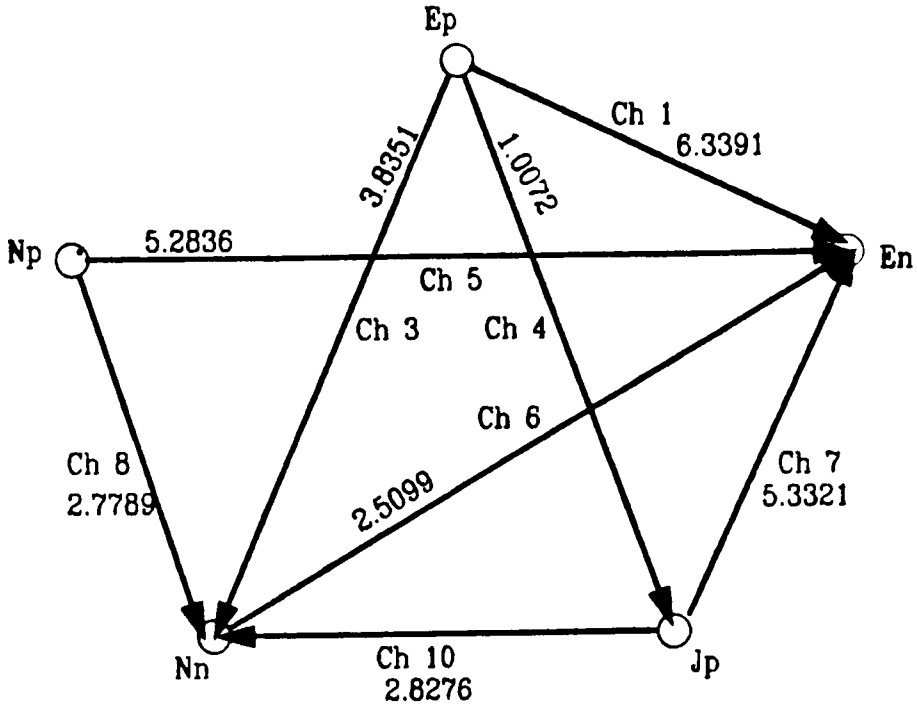


Figure 6.7 A Representation of the MTC from the Graph Theory Perspective Using Actual Measurements.

at as follows:

1. Directly: = 5.3321
2. Adding ch10 + ch6: 2.8276 + 2.5099 = 5.3375
3. Adding ch1 - ch4: 6.3391 - 1.0072 = 5.3319
4. Adding ch10 - ch8 + ch5:

   2.8276 - 2.7789 + 5.2836 = 5.3323
5. Adding ch10 - ch3 + ch1:

   2.8276 - 3.8351 + 6.3391 = 5.3316

Then, to estimate the emf, $E_{ch7}(100)$, utilizing the direct measurement, and the other indirect paths, one may use:

$$E_{ch7}(100) = [3*ch7 + 2*(ch10 + ch6) + 2*(ch1 - ch4) + (ch10 - ch8 + ch5)]/8 \quad (6.5)$$

or,

$$E_{ch7}(100) = (3*5.3321 + 2*5.3375 + 2*5.3319 + 5.3323)/8 = 5.3334 \text{ mV}$$

The weights are assigned based on the number of paths used to arrive at the estimate; the smaller the number of paths, the higher the weight. The advantage of this method of calculating an estimate are (Burley, et. at, 1978)

1. it randomizes spurious voltages in the lead wires.
2. if a potentiometer is used, this method randomizes the potentiometer errors due to resetting the dial for the different measurements.

The Graph Theory was used to compare the measurements utilizing paths other than the direct path, with the values from the direct path. All the direct measurements were

verified, except channels 2 and 9, within small tolerances attributable to measurement errors. Confidence was increased in the experimental setup, procedure, and the MTC principle. A more detailed analysis, however, was carried out.

6.3.3.3 Interpolation Polynomials Based on Theory

The theoretical interpolation polynomials of the widely used TC types (i.e., K, T, E, J, R, S, N) that allow users to find the temperature at a given measured emf are published in the literature. (It must be mentioned that the published polynomials are themselves based on experimental data. Since they are accepted as "standards," they are referred to as "theoretical" in this work.) Two of the measurements produced by the MTCs, Ep-En (i.e., type E, channel 1) and Np-Nn (i.e., type N, Channel 6) are standard. The remaining channels do not have published polynomials. Therefore, it was necessary to establish those polynomials by other means. The interpolation polynomials of individual thermoelements versus Pt-67 are found in the literature. Such polynomials can be used to construct the nonstandard polynomials by application of the second law of thermometry (See Chapter 3, Section 3.2.2). That is, it is possible to find the emf values of various wire combination by simple subtraction of their combined emfs versus Pt-67:

$$E_{AB} = E_{A\text{-}Pt\text{-}67} - E_{B\text{-}Pt\text{-}67} \qquad (6.6)$$

where

E_{AB} = emf of thermoelement A versus Thermoelement B

$E_{A\text{-}Pt\text{-}67}$ = emf of A versus Pt-67,

$E_{B\text{-}Pt\text{-}67}$ = emf of B versus Pt-67.

Attention should be paid to the sign of wires E_A and E_B. For illustration, consider the hypothetical emf - temperature relationships of elements A, B, C, and D versus Pt-67 as shown in Figure 6.8

$$E_{AB} = (+a) - (+b).$$

Since both a and b are positive wires with respect to Pt-67. Therefore,

$$E_{AB} = a - b$$

Similarly,

$$E_{BA} = (+b) - (+a)$$
$$= - (a - b)$$
$$= - E_{AB}$$

Notice that E_{AB} and E_{BA} are equal in magnitude, but different in sign. In another case,

$$E_{AC} = (+a) - (-c)$$

since wire C is negative with respect to Pt-67. Therefore,

$$E_{AC} = a + |c|$$

and,

$$E_{CA} = (-c) - (+a)$$
$$= -c - a = - (|c| + a)$$
$$= - E_{AC}$$

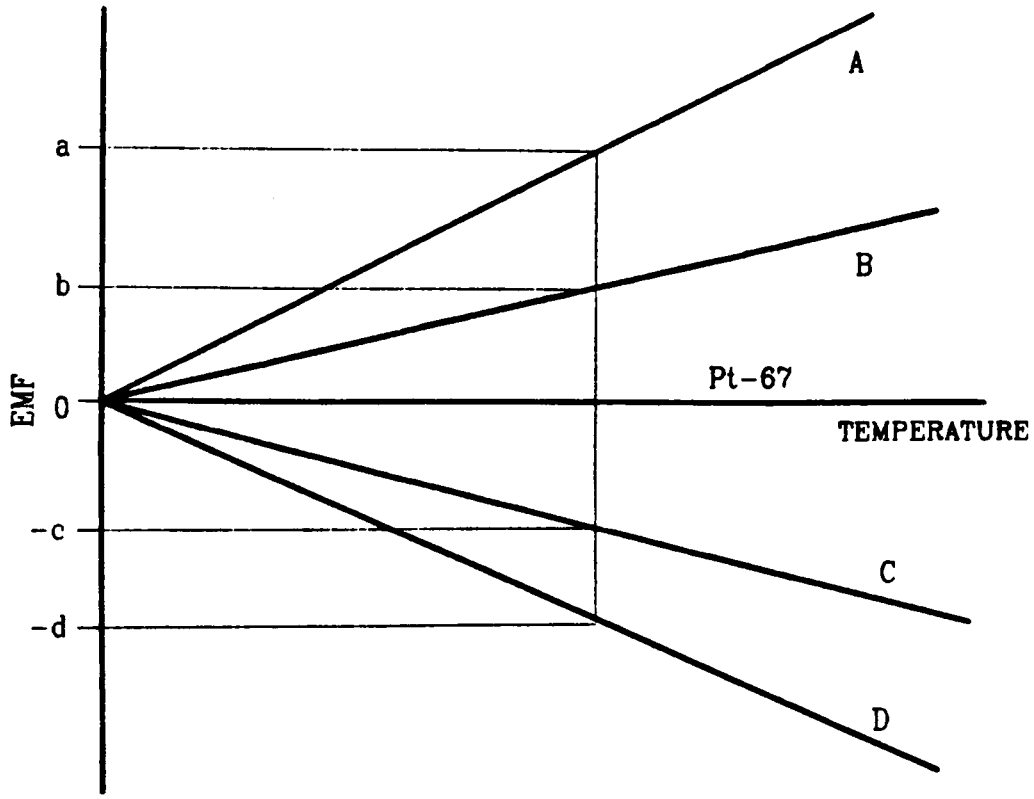


Figure 6.8 An Emf Versus Temperature Plots of the Hypothetical Thermoelements A, B, C, and D Versus Pt-67.

The last case to consider is

$$E_{CD} = (-c) - (-d),$$

where both c and d are negative with respect to Pt-67. Therefore,

$$E_{CD} = (-c) + |d|$$

Notice that $E_{CD} > 0$ since $|d| > |c|$

and

$$E_{DC} = (-d) - (-c)$$
$$= -d + |c|$$
$$= - E_{CD}.$$

The coefficients of the E(T) interpolation polynomials (See Equation 6.3) of Ep, En, Jp, Nn, Np versus Pt-67 can be found in the NBS Monograph 125 (1971) and Burly (1978). Two sets of coefficients were defined for Nn and two set for Np based on Gages 14 and 28. Therefore, to find the E(T) for Nn and Np wires of some Gage, G, interpolation is used as follows: if wire Np of Gage GP is used in the MTC,

$$E_{NpG} = [(GP - 14)/(28 - 14) * (E_{Np28} - E_{Np14})] + E_{Np14} \quad (6.7)$$

where

E_{NpG} = emf of wire Np of Gage GP versus Pt-67

E_{Np28} = emf of wire Np of Gage 28 versus Pt-67

E_{Np14} = emf of wire Np of Gage 14 versus Pt-67

where

$$E_{NnG} = [(GN - 14)/(28 - 14) * (E_{Nn28} - E_{Nn14})] + E_{Nn14} \quad (6.8)$$

Where

E_{NnG} = emf of wire Nn of Gage GN versus Pt-67

E_{Nn28} = emf of wire Nn of Gage 28 versus Pt-67

E_{Nn14} = emf of wire Nn of Gage 14 versus Pt-67

GN = Gage of wire Nn used in the test.

The emf-temperature relationships of various thermoelements versus Pt-67 is shown in Figure 5.4.

If the emf-temperature relationships of the various thermoelements Ep, En, Jp, Nn, and Np versus Pt-67 are denoted as $E_{Ep}(T)$, $E_{En}(T)$, $E_{Jp}(T)$, $E_{NnG}(T)$, and $E_{NpG}(T)$ respectively, then, the responses of all ten channels are constructed as:

Channel 1: $E_{Ep}(T) + E_{En}(T)$

Channel 2: $E_{Ep}(T) - E_{NpG}(T)$

Channel 3: $E_{Ep}(T) + E_{NnG}(T)$

Channel 4: $E_{Ep}(T) - E_{Jp}(T)$

Channel 5: $E_{NpG}(T) + E_{En}(T)$

Channel 6: $-E_{Nn}(T) + E_{En}(T)$

Channel 7: $E_{Jp}(T) + E_{En}(T)$

Channel 8: $E_{NpG}(T) + E_{NnG}(T)$

Channel 9: $E_{Jp}(T) - E_{NpG}(T)$

Channel 10: $E_{Jp}(T) + E_{NnG}(T)$

Plots of E(T) for channels 1 through 5 and channels 6 through 10 are shown in Figure 6.9 and Figure 6.10 respectively. Notice, that Channels 2, 9 had very low sensitivity to temperature which explains the inaccurate

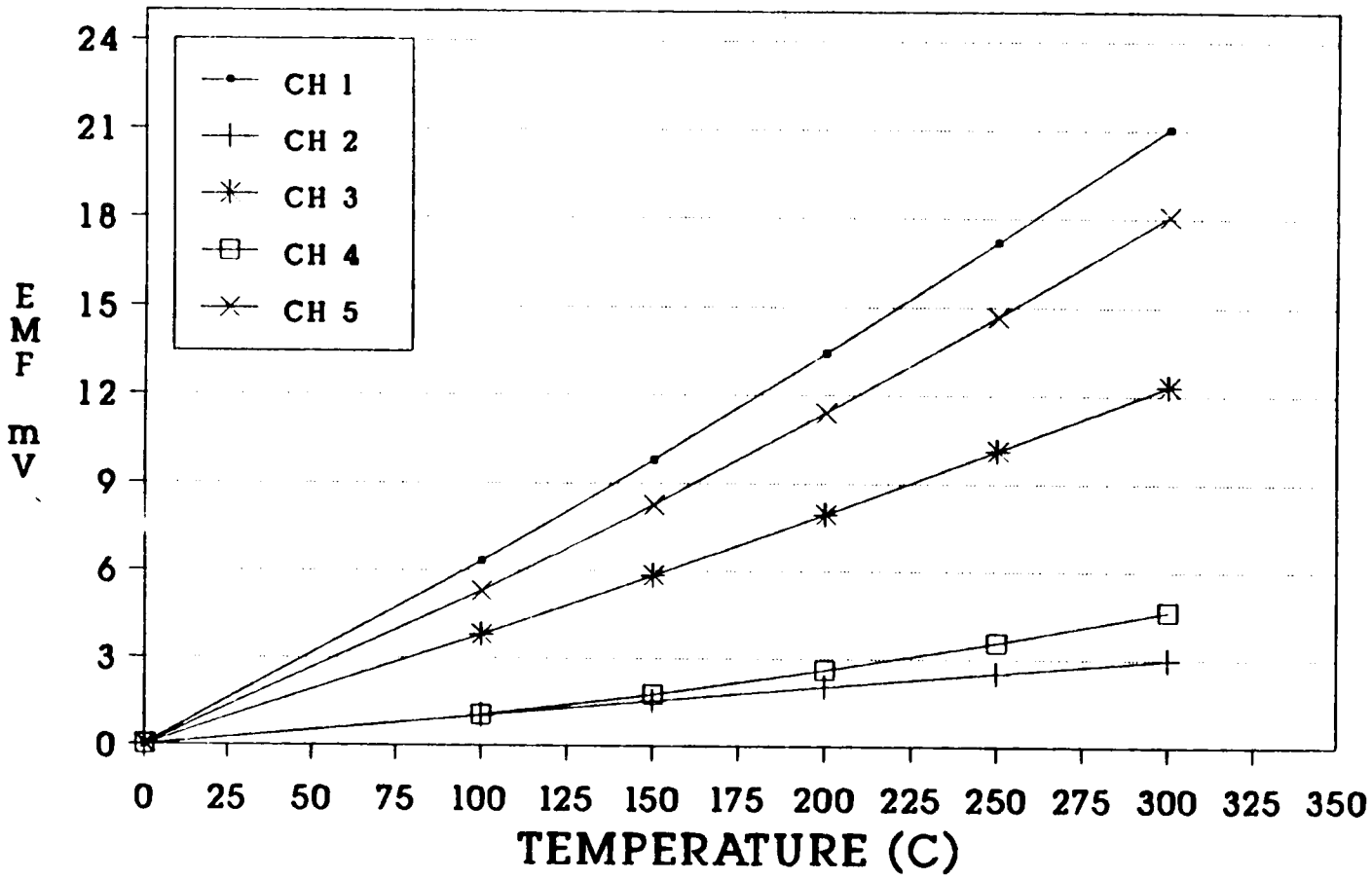


Figure 6.9 Plots of the Theoretical E(T) of Channels 1 Through 5.

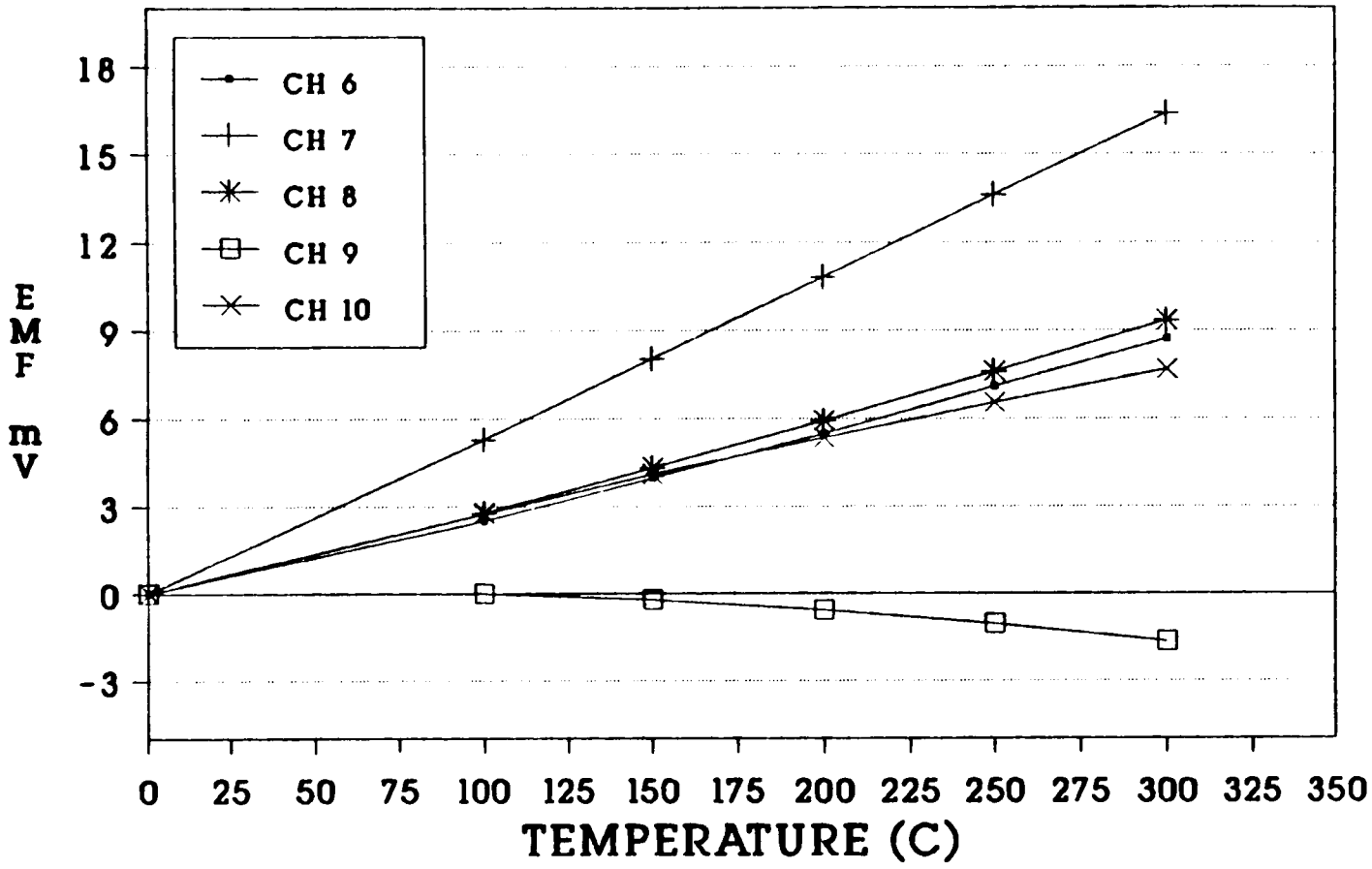


Figure 6.10 Plots of the Theoretical E(T) of Channels 6 Through 10.

response of those channels under experimental situation. Hence, channels 2 and 9 were eliminated from further analyses and the efforts were directed toward the remaining eight channels, renamed as

Channel 1: $E_{Ep}(T) + E_{En}(T)$

Channel 2: $E_{Ep}(T) + E_{NnG}(T)$

Channel 3: $E_{Ep}(T) - E_{Jp}(T)$

Channel 4: $E_{NpG}(T) + E_{En}(T)$

Channel 5: $-E_{Nn}(T) + E_{En}(T)$

Channel 6: $E_{Jp}(T) + E_{En}(T)$

Channel 7: $E_{NpG}(T) + E_{NnG}(T)$

Channel 8: $E_{Jp}(T) + E_{NnG}(T)$

Since both the theoretical E(T) and the experimental T(E) and E(T) were developed, further analysis is carried out to compare the two. Plots of the theoretical emf-Temperature relations and those based on experiments of the channels 1 through 4 and channels 5 through 8 are shown in Figure 6.11, and Figure 6.12 respectively. These Figures show that the experimental polynomials agree well with theory.

To quantify these results, the differences (errors) between the true oil temperature and the temperature predicted by the experimental polynomials at the five test temperatures were calculated. Next, the sensitivity of the channels based on the theoretical interpolation polynomials were determined as:

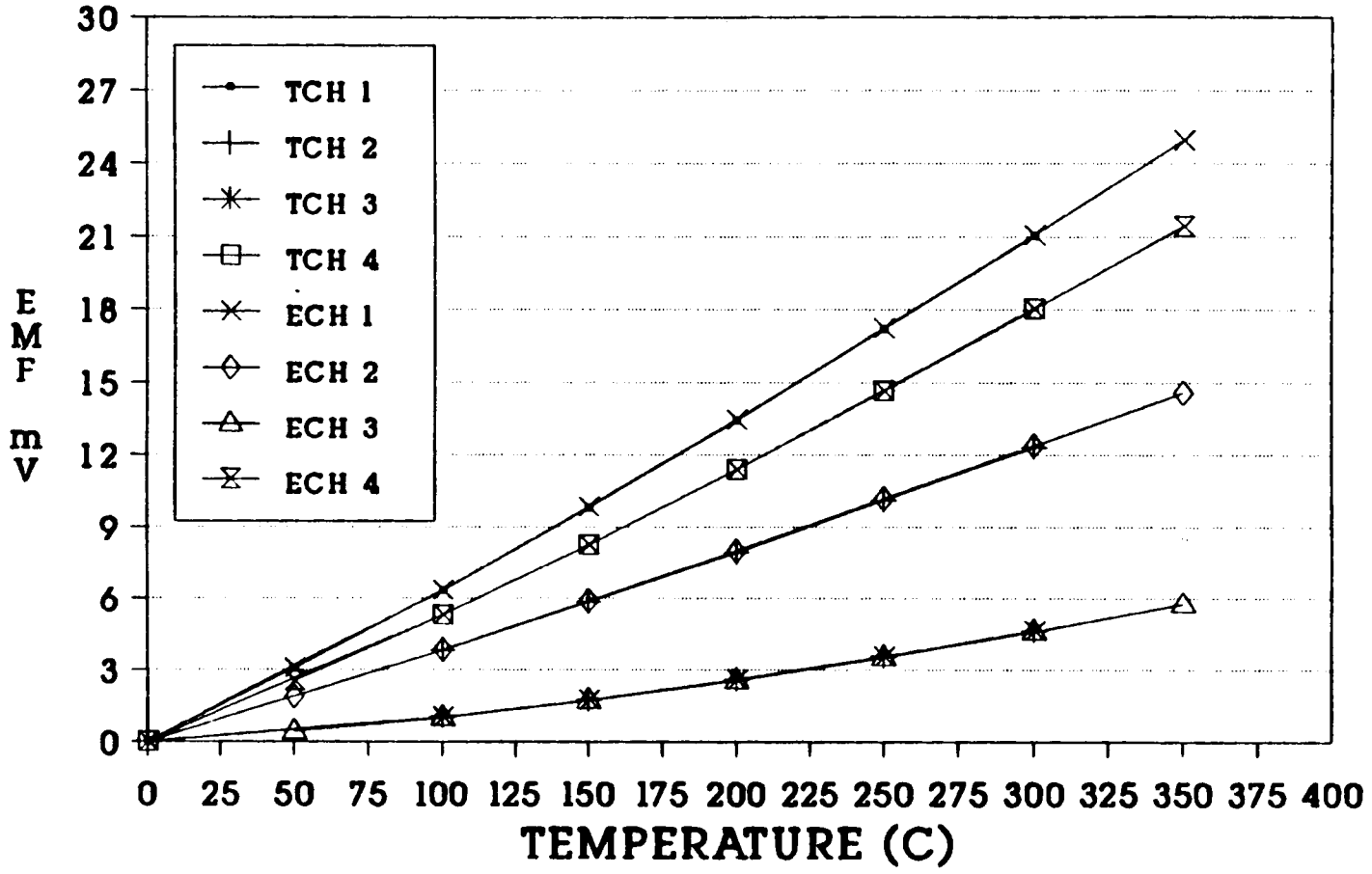


Figure 6.11 Relationship between the Experimental and the Theoretical E(T) for Channels 1 Through 4.

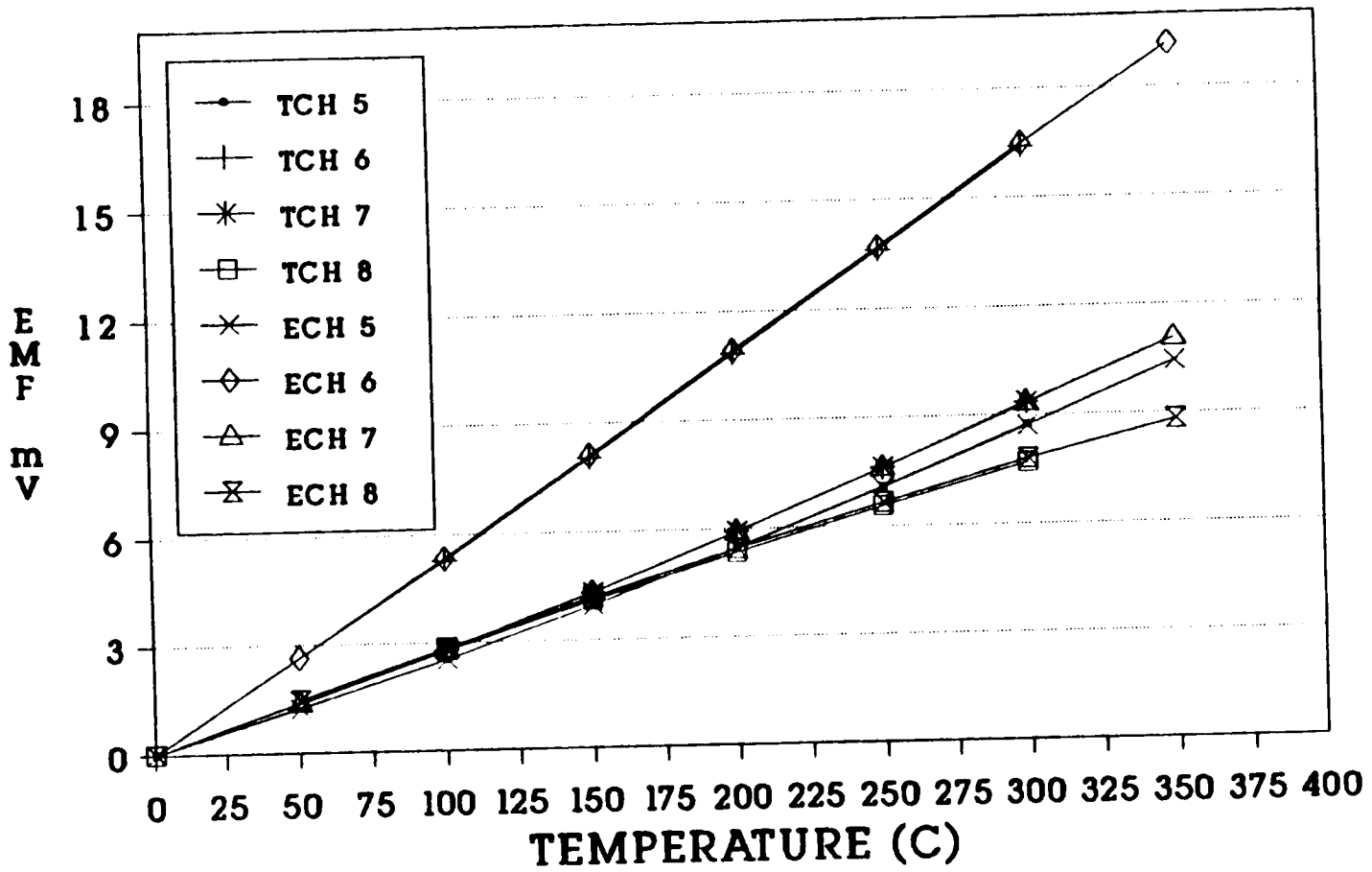


Figure 6.12 Relationship between the Experimental and the Theoretical E(T) for Channels 5 Through 8.

$$Sen = \frac{T_h - T_l}{E(T_h) - E(T_l)} \qquad (6.9)$$

where,

Sen = measure of the sensitivity in $\mu V/^{\circ}C$

T_h = Temperature of interest plus 5 °C

T_l = Temperature of interest less 5 °C.

Table 6.4 shows the results of these calculations. As expected, there are variations in the error depending on the wire combinations. These errors may be attributed to the small amount of data used in deriving the interpolation polynomials, cold work introduced inadvertently while constructing the bare MTC, the inaccuracies of the measuring devices, absence of thermal equilibrium, and possible temperature variations in the copper block. Several observations can be made.

1. Channels 1, 4, 5, and 7 agree to within 0.6 °C with theory. Channels 2 and 6 agree to within 1.5 °C with theory. Channel 3 agrees to within 2.2 °C with theory. Channel 8 agrees to within 4.7 °C with theory at the maximum calibration temperature. These variations may be attributed to variations in the chemical composition of those wires from the ones used in the published information, cold work, oxidation (since the sensing element of the MTC is exposed to the test and surrounding environment). Another possible explanation for this behavior is the relative channel sensitivity to

Table 6.4 Error Analysis.

	Ch 1	Ch 2	Ch 3	Ch4	Ch 5	Ch 6	Ch 7	Ch 8	Average
True Temperature (°C)	99.960	99.960	99.960	99.960	99.960	99.960	99.960	99.960	
Measured Temperature (°C)	100.32	100.76	97.61	99.89	99.91	100.89	100.06	102.20	
Error (°C)	0.36	0.80	-2.35	-0.07	-0.05	0.93	0.10	2.24	0.245
Standard Deviation (Micro-v)	0.1	0.1	0.1	0.1	0.1	0.1	0.6	0.2	
Sensitivity (Micro-v/°C)	67.5	39.8	12.9	57.4	27.7	54.6	29.6	26.9	
True Temperature (°C)	150.063	150.063	150.063	150.063	150.063	150.063	150.063	150.063	
Measured Temperature (°C)	150.56	151.24	148.49	149.85	149.94	151.30	150.09	153.31	
Error (°C)	0.49	1.18	-1.57	-0.21	-0.12	1.23	0.02	3.24	0.53
Standard Deviation (Micro-v)	0.1	0.1	0.1	0.1	0.2	0.1	0.3	0.1	
Sensitivity (Micro-v/°C)	71.1	41.4	15.6	61.1	29.7	55.5	31.2	25.8	
True Temperature (°C)	199.941	199.941	199.941	199.941	199.941	199.941	199.941	199.941	
Measured Temperature (°C)	200.44	201.32	198.20	199.51	199.68	201.31	199.77	203.86	
Error (°C)	0.50	1.38	-1.75	-0.43	-0.26	1.37	-0.17	3.93	0.57
Standard Deviation (Micro-v)	0.3	0.3	0.1	0.3	0.2	0.2	0.2	0.2	
Sensitivity (Micro-v/°C)	74.0	42.8	18.2	64.2	31.2	55.8	32.1	24.6	
True Temperature (°C)	250.101	250.101	250.101	250.101	250.101	250.101	250.101	250.101	
Measured Temperature (°C)	250.59	251.55	247.71	249.49	249.43	251.53	249.65	254.55	
Error (°C)	0.49	1.14	-2.39	-0.61	-0.67	1.43	-0.45	4.45	0.46
Standard Deviation (Micro-v)	0.1	0.2	0.1	0.1	0.2	0.1	0.1	0.3	
Sensitivity (Micro-v/°C)	76.2	43.8	20.5	66.7	32.4	55.7	32.2	23.3	
True Temperature (°C)	300.115	300.115	300.115	300.115	300.115	300.115	300.115	300.115	
Measured Temperature (°C)	300.64	301.51	297.78	299.36	299.51	301.59	299.23	306.81	
Error (°C)	0.53	1.39	-2.34	-0.75	-0.60	1.48	-0.89	6.70	0.44
Standard Deviation (Micro-v)	0.3	0.2	0.2	0.2	0.3	0.3	0.2	0.3	
Sensitivity (Micro-v/°C)	71.1	41.4	15.6	61.1	29.7	55.5	31.2	25.8	

temperature. A plot of the absolute value of the errors versus the sensitivity of each channel is shown in Figure 6.13. This Figure must be used with caution since the sensitivities of different channels (i.e. different wire pairs) are used. Hence, other factors dependant on the type of wires used may affect the error values. In general, it can be concluded, however, that the higher the sensitivity, the lower the errors.

2. On the average, maximum errors occurred at 300 °C while minimum errors occurred at 100 °C as shown in Figure 6.14. This was expected. The T-emf relationships may be approximated by straight lines with positive slopes. Since the slopes are positive, the effects of slight errors become amplified as the temperature increases. Notice that the error itself represents a change in the slope of the line from the published T-emf lines. Other temperature-dependant effects such as atomic reordering, magnetic transformation, and electric resistivity also take place. These internal factors could explain the increase in error with temperature. Furthermore, it was more difficult to stabilize the oil bath at 300 °C than at 100 °C. This is also reflected in the fluctuations in the measured emfs, as indicated by the standard deviation of the measurements, which increased with temperature. Notice that the increase in error may be in the positive or negative directions (i.e. the

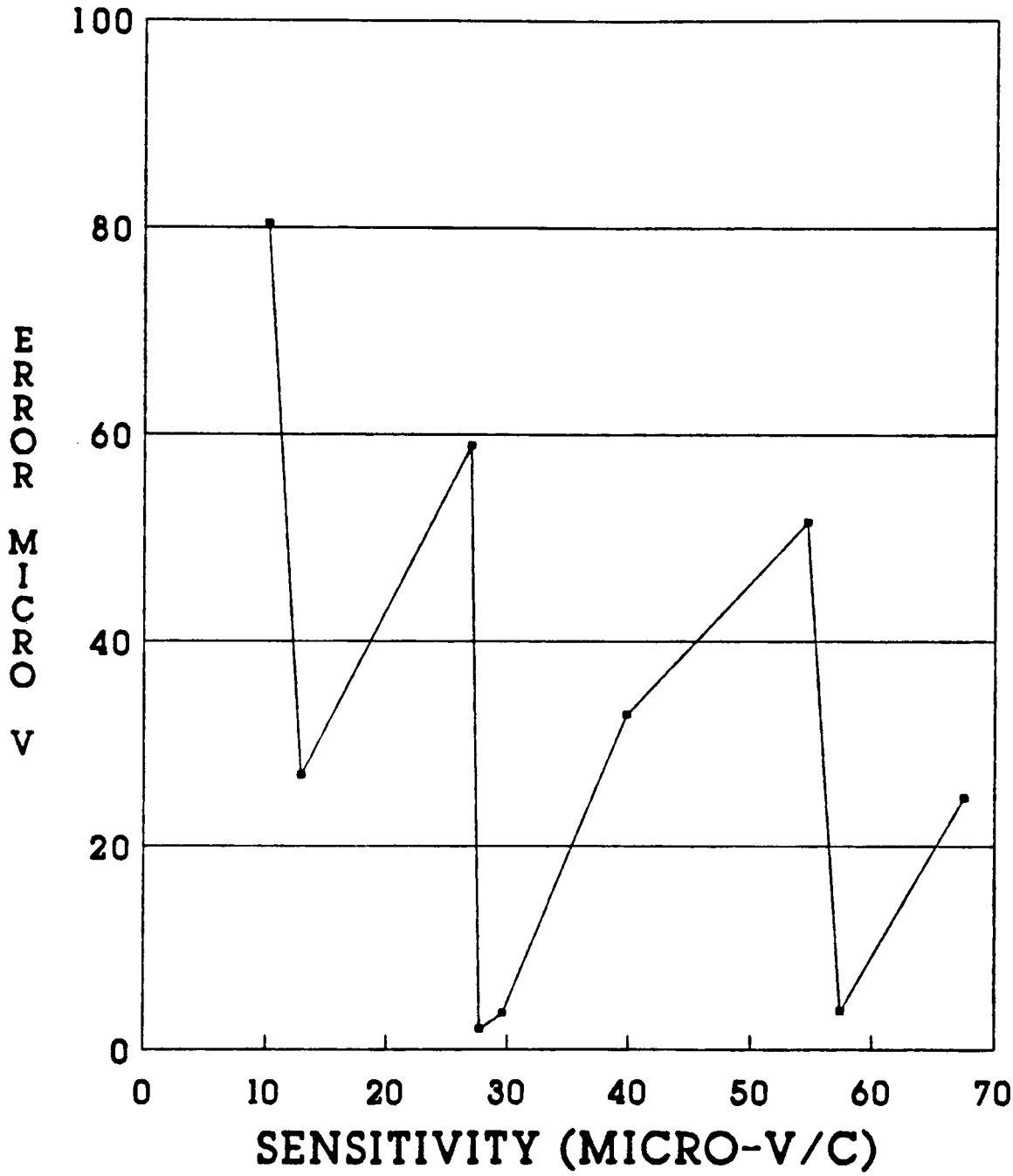


Figure 6.13 Relationship between the Errors and Channel Sensitivities at Calibration Temperatures of 100 and 300 ^{0}C.

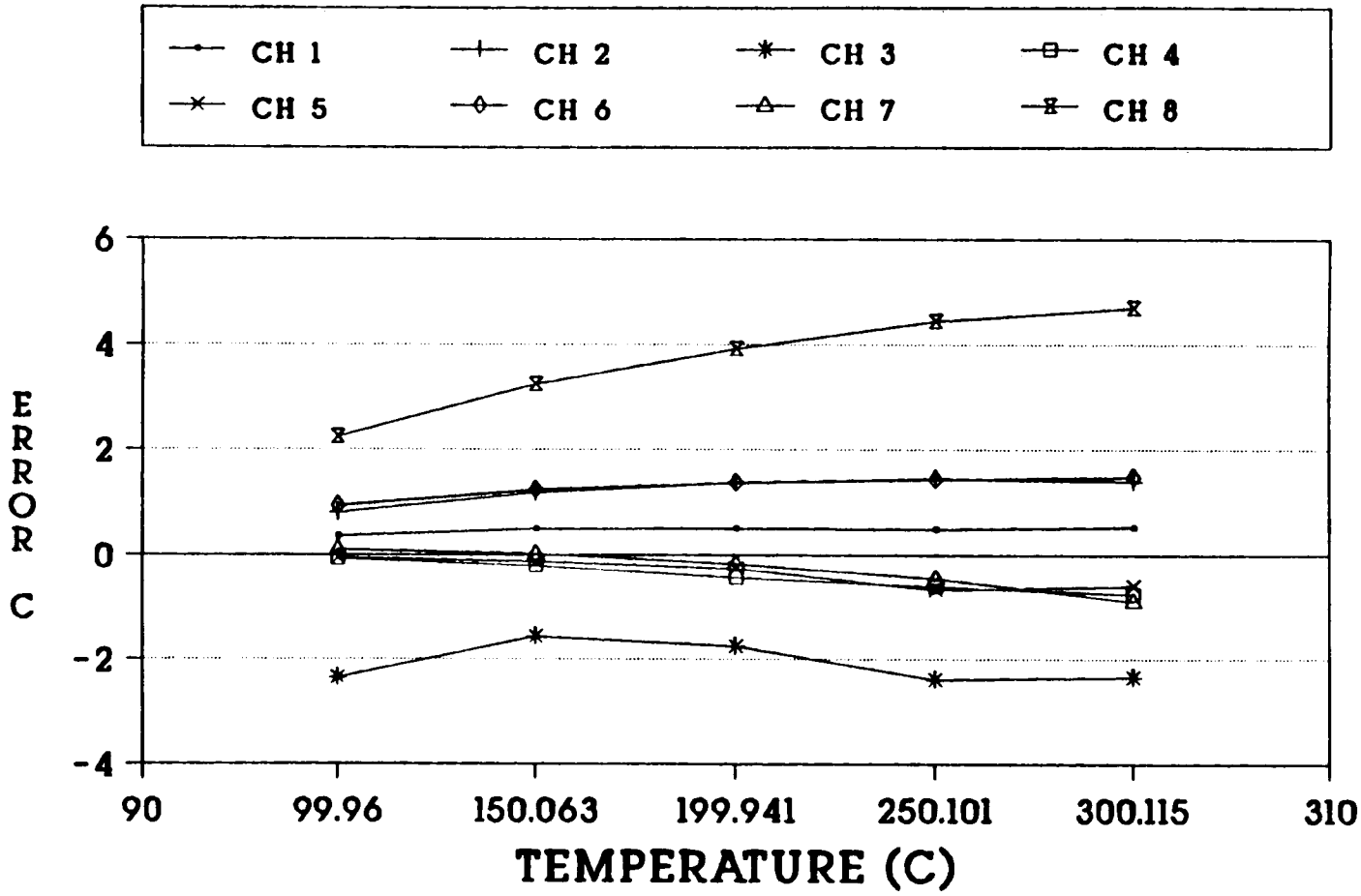


Figure 6.14 Relationship between the Errors and the Calibration Temperatures.

absolute value of the errors generally increase with the calibration temperature.

3. Channels containing En and types E and N performed better than the rest.
4. Channel 8, Jp-Nn pair, showed the highest error 2 °C at 100 °C increasing to more than 4 °C above 200 °C. This may be attributed to iron impurities and rust since the test MTC is bare. Furthermore, iron undergoes magnetic transformation near 760 °C (for AWG 8 wires) and alpha-gamma crystal transformation near 910 °C (Powell, et. al, 1974) which seriously affects the emf of iron. For wires of Gages 24 or 28 the magnetic transformation occurs at 371 °C. It must be mentioned that the combined behavior of both thermoelements of the channel determines the error. Channels 3 and 6, which utilized iron, Ep, and En, showed less than half the error shown by channel 8.

The question remains, "are we better off using individual TCs instead of a single MTC as far as accuracy is concerned?" To answer this question, one must look at the collective behavior of the MTC. This is best described by the following example: The temperature measurements of channels 1 through 8, when the true oil temperature was 99.96 °C, were 100.32, 100.76, 97.61, 99.89, 99.91, 100.89, 100.06, and 102.20 °C respectively. The average of these values is 100.205 °C. Hence, the error is

Error = 100.205 - 99.60 = 0.245 °C.

This error represents an overall improvement of results since it is generally lower than most of the individual errors. If weight factors are used to find the weighted average, then the error is expected to be even less. For example, the average error at 150.063 °C is 0.53 °C (See Table 6.4). If channels 1 through 8 are assigned the weights: 8, 7, 8, 8, 10, 5, 10, and 1 respectively, then the error in the weighted average is reduced to 0.11 °C as shown in Figure 6.15. (These weights are used for illustrative purposes only. The actual weight factors used in the STMS are presented in Section 6.4.4.) It is this capability of the STMS to manipulate the data to reflect as closely as possible the true process temperature, in addition to all the other smart features, that makes this system worthwhile and beneficial to all industries.

6.4 Long Term Tests

6.4.1 Procedures and Events

An industrial temperature sensor is expected to provide years of continuous and reliable service. The useful life of TCs and RTDs depend on many factors such as operating temperature, environment conditions, initial construction and state of thermoelements, and Type of TC used. Theoretically, sensors begin to degrade immediately after

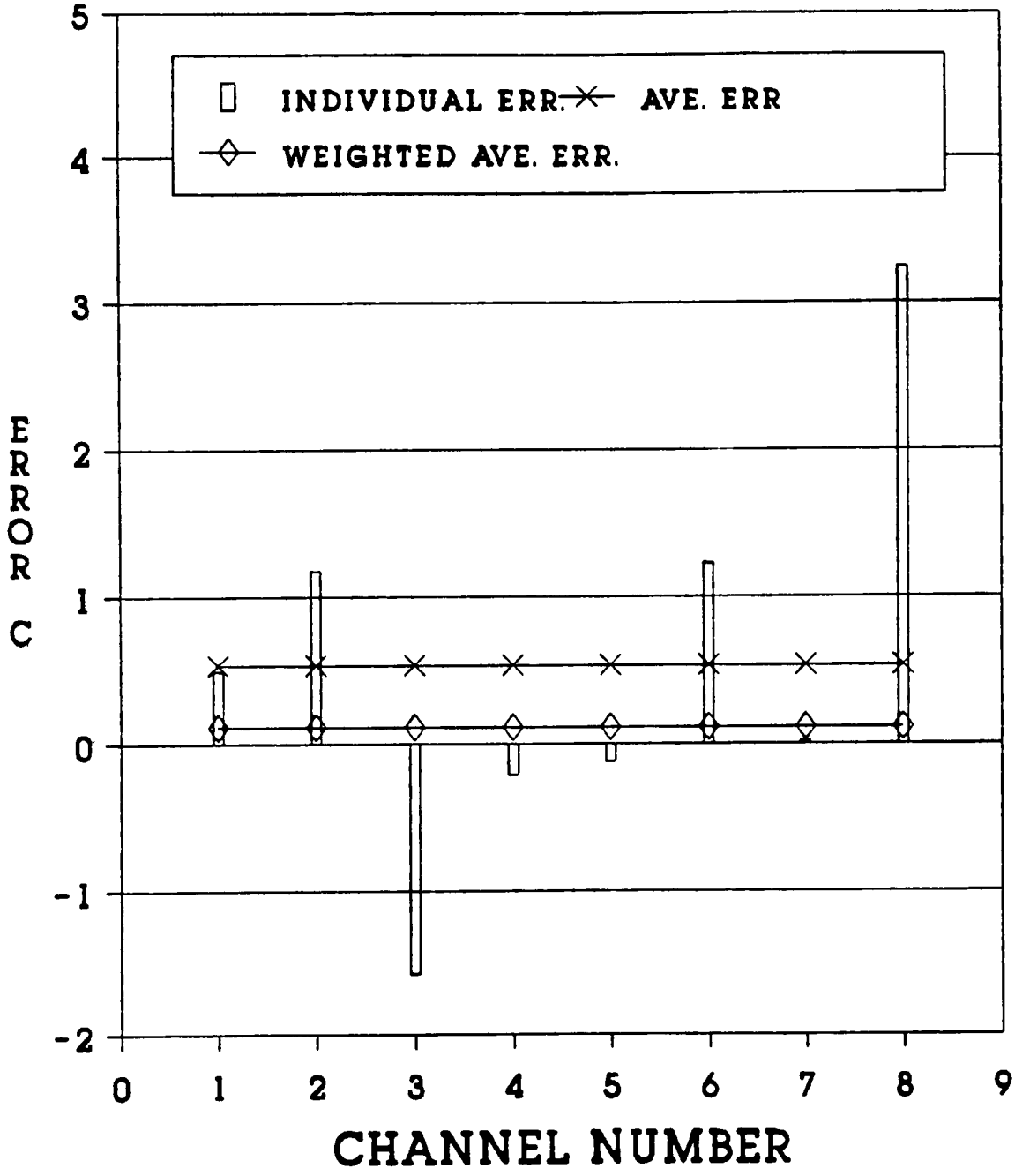


Figure 6.15 A Representation of the Errors of the Individual Channels at 99.96 °C.

fabrication. The rate of degradation may vary from one Type to another, and from one sensor to another of the same Type. Since the MTC is a new device that is expected to be commercially produced for the nuclear and other industries, it is necessary to study its long term behavior under simulated industrial conditions. These tests will help quantify the sensor's drift rates, provide a basis for determining weight constants to be used in the STMS, and verify the commercial viability of the STMS. So it was necessary to fabricate immersion type MTCs (i.e. sensors with metallic sheath for protection) since they are the most likely type of MTCs to be used industrially. The MTC's fabrication process was discussed in Chapter 5.

In addition to constructing a group of MTCs consisting of Ep, En, Np, Nn, and Jp, four new groups were fabricated. These MTCs consisted mainly of the same thermoelements used in the original MTC with the exception of adding an Alumel (Kn) thermoelement and excluding iron (Jp). The arrangement of thermoelements in these groups was based on the conclusion reached at the end of the short term tests that only eight measurements are usable, and the consequent development of an eight-channel interface. Hence, it was possible to select wire combinations that could provide maximum overall sensitivities to temperature and minimum number of dissimilar thermoelements - by using multiple wires of the same type in the same sensor - since the number

of required signals was reduced. A description of the five groups as well as the wire combinations that constitute all eight channels of each group are found in Table 6.5. The theoretical emf of each channel at 300 °C is also shown. The sum of these emfs provides a measure of the overall sensitivity of these MTC groups. Greater emphasis was placed on type E wires since they provide maximum output. As a precaution, iron was eliminated due to its high affinity to oxygen and its high purity (99.5 percent). Any moisture penetrating the sensor may result in altering the Seebeck coefficient. Moreover, high purity metal is easily contaminated and affected by impurities while highly alloyed metals are less susceptible to contamination (Powel, et. al., 1974).

The objectives of testing the new groups of MTCs as well as the original design are

1. to provide a solid foundation for describing the performance of the original design by comparing its long term behavior with the new designs,
2. to obtain a basis for defining the weight factors to be used in the STMS, and
3. to select the group of sensors that exhibit the best performance as the most likely candidate to be used commercially.

The sensors were subjected to two different environments for about 2000 hours:

Table 6.5 The Thermoelements and The emf at 300 °C of Each Channel of the Five MTC Groups.

Group Number	Ch 1	Ch 2	Ch 3	Ch 4	Ch5	Ch 6	Ch7	Ch 8
1								
+lead	Ep	Ep	Ep	Np	Nn	Jp	Np	Jp
-lead	En	Nn	Jp	En	En	En	Nn	Nn
Emf (300)	21.033	12.317	4.638	18.059	8.716	16.395	9.344	7.679
Total emf 98.181								
2								
+lead	Ep_1	Ep_1	Ep_2	Ep_2	Ep_1	Ep_2	Nn	Nn
-lead	En_1	En_2	En_1	En_2	Nn	Nn	En_1	En_2
Emf (300)	21.033	21.033	21.033	21.033	12.317	12.317	8.716	8.716
Total emf 126.198								
3								
+lead	Ep_1	Ep_1	Ep_2	Ep_2	Ep_1	Ep_2	Kn	Kn
-lead	En_1	En_2	En_1	En_2	Kn	Kn	En_1	En_2
Emf (300)	21.033	21.033	21.033	21.033	12.207	12.207	8.826	8.826
Total emf 126.198								
4								
+lead	Ep	Ep	Ep	Np	Np	Np	Kn	Nn
-lead	En	Nn	Kn	En	Nn	Kn	En	En
Emf (300)	21.033	12.317	12.207	18.059	9.344	9.234	8.826	8.716
Total emf 99.737								
5								
+lead	Ep	Ep	Ep	Np	Np	Np	Nn	Nn
-lead	En_1	Nn	En_2	En_1	Nn	En_2	En_2	En_1
Emf (300)	21.033	12.317	21.033	18.059	18.059	9.344	8.716	8.716
Total emf 117.279								

1. An isothermal oven maintained at 300 °C, and
2. A cycling oven that cycles between 200 and 300 °C every 6 hours. A typical temperature cycle is shown in Figure 6.16.

Sensors 1, 2, 3, 4, and 5 of group 1 were placed in the isothermal oven, and the remaining sensors of that group, (i.e. sensors 6, 7, 8, 9, and 10) were placed in the thermal cycling oven. Sensors 11, 12, and 13 of group 2 and 16, 17, and 18 of group 3 were placed in the isothermal oven while sensors 14 and 15 of group 2 and 19 and 20 of group 3 were placed in the thermal cycling oven. All the sensors of groups 4 and 5 were placed in the thermal cycling oven since only three sensors of each group were available for testing. In order to avoid having an overlapping calibration schedule, groups 2 and 3 were placed in the ovens eight days after the placement of group 1. Eight days later, Groups 4 and 5 were placed in the ovens.

Since most of the rapid changes that the sensors undergo occur typically within the first few hours of exposure to the elevated temperatures, the calibration tests were conducted frequently (hours) initially, then less frequently (weeks) later. The calibration schedule is presented in Table 6.6. The inconsistencies in the schedule were caused by an accident, which will be described shortly, and to a power outage.

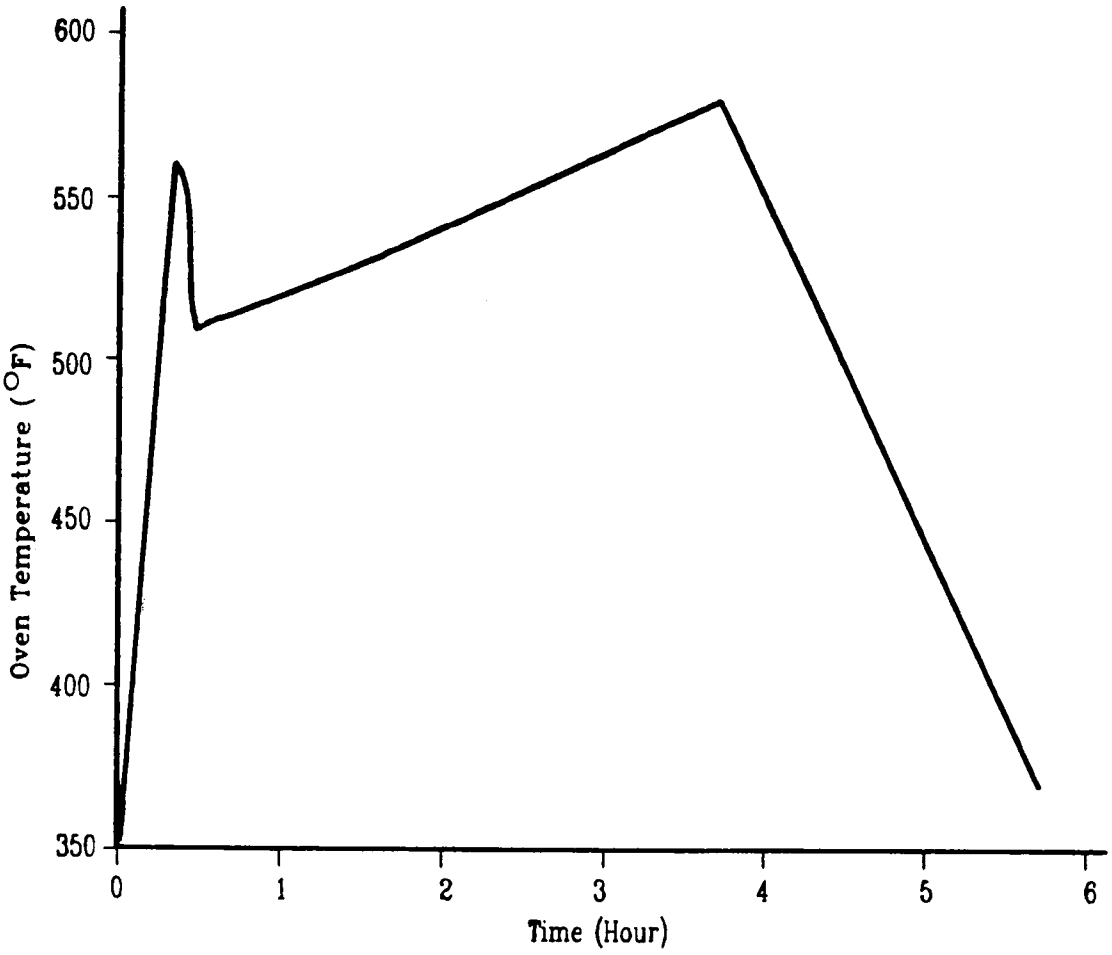


Figure 6.16 A Typical Temperature Cycle of the Thermal Cycling Oven

Table 6.6 Calibration Tests Schedule.

Group Number	Time (Hour)	Sensors Tested	st Temperature (°C)
1	0	All	100, 200, 250
	6	1; 6	100
	24	1, 2; 6, 7	100
	48	1, 2, 3; 6, 7, 8	100
	72	1, 2, 3; 6, 7, 8	100
	168	1, 2, 3; 6, 7, 8	100, 200, 250
	432	1, 2, 3; 6, 7, 8	100
	672	1, 2, 3, 4; 6, 7, 8, 9	100, 200, 250
	1176	1, 2, 3, 4; 6, 7, 8, 9	100
	1992	1, 2, 3, 4, 5; 6, 7, 8, 9, 10	100, 200, 250
2	0	All	100, 200, 250
	6	11; 14	100
	24	11; 14	100
	48	11; 14	100
	72	11; 14	100
	264	11; 14	100, 200, 250
	336	11; 14	100
	672	11, 12; 14	100, 200, 250
	1176	11, 12; 14	100
	2016	11, 12, 13; 14, 15	100, 200, 250
3	0	All	100, 200, 250
	6	16; 19	100
	24	16; 19	100
	48	16; 19	100
	72	16; 19	100
	264	16; 19	100, 200, 250
	336	16; 19	100
	672	16, 17; 19	100, 200, 250
	1176	16, 17; 19	100
	2016	16, 17, 18; 19, 20	100, 200, 250
4; 5	0	All	100, 200, 250
	6	21; 24	100
	24	21; 24	100
	48	21; 24	100
	72	21; 24	100
	168	21, 22; 24, 25	100, 200, 250
	336	21, 22; 24, 25	100
	672	21, 22; 24, 25	100, 200, 250
	1176	21, 22; 24, 25	100
	2016	21, 22, 23; 24, 25, 26	100, 200, 250

Unpublished work conducted at the Nuclear Engineering Department of the University of Tennessee at Knoxville, showed that sensors exposed to the same environment experience different drift patterns when calibrated at different temperatures. So, it was decided to calibrate the MTCs at 100 °C frequently, and at 200, and 250 °C with less frequency (See Table 6.6). (300 °C was avoided because it was difficult to stabilize the oil bath for extended periods of time at this temperature because that is its maximum operating temperature.)

Certain sensors of each group were calibrated frequently while others remained practically untouched until the last calibration was performed. This was necessary to investigate the effects of removing the sensors from the ovens and placing them in the oil bath on the calibration drift. This concern was clearly stated in the NBS circular 590 as follows: "It is difficult if not impossible to determine how much the calibrations are in error by removing them (the sensors) from an installation and testing in a laboratory furnace."

The experimental setup described in Section 6.3.2 was used in the long term tests with a few modifications such as using extension wires as was shown in Figure 5.10. Testing a group of sensors was accomplished by inserting the batch of sensors into the oil bath with one of the sensors connected to the extension wires with miniature connectors.

The branched wires at the free end of the extension wires were placed in the mercury tubes. When both the oil bath and the cold junction setup reached their respective thermal equilibrium, data collection was started. Typically, five data points were collected from each channel. Then, the sensor would be disconnected from the extension wires, but kept in the oil bath, and another sensor was connected to the extension wires. No waiting period was necessary since neither the cold junction bath nor the oil bath was disturbed. The practice of obtaining the reference RTD measurements before and after each data set was carried out to ensure that the oil bath and cold junction remained at their respective temperatures. Since the extension wires were the same thermoelements used in the MTCs, no extraneous or erroneous emfs are generated at the connector site.

Two events during the exposure period of the sensors need to be mentioned. The first was an increase of the temperature of the isothermal oven 580 °C for at least 15 hours due to the failure of the controller. This occurred approximately 264 hours after sensors of group 1 (i.e. sensors 1, 2, 3, 4, and 5) were placed in this oven. Similarly, sensors of groups 2 and 3 (i.e., sensors 11, 12, and 13 of group 2, and sensors 16, 17 and 18 of group 3) were exposed to the elevated temperature 72 hours after their initial placement in the oven. The effects of this incident will be discussed shortly.

The second event was that the type J connector of sensor 1 was found cut from the sensor immediately after the above incident. Hence, measurements involving Jp element (i.e., measurements that involved channels 3, 6, and 8) were not available for the remainder of the long term tests.

6.4.2 Analyses of the Long Term Tests

The raw data representing the measured emf of each channel and the true process temperature were stored in files in a personal computer for further analysis. The average and the standard deviation of the data collected from each channel of each sensor at a single temperature were calculated and stored. A computer program utilizing the Bisection Method (Chapra, 1988) was developed to calculate the temperature corresponding to the measured emf indicated by each channel based on the published interpolation polynomials. This method was needed because the emf as a function of temperature (i.e. E(T)) of each channel is known instead of T(E) (see Section 6.3.3.3). The differences between the temperatures indicated by each channel and the true process temperature were calculated to quantitatively evaluate the errors (drift) of each sensor.

6.4.3 Performance of Group 1

The results of the error calculations for group 1 are presented in Table 6.7. Plots of the errors obtained at the

Table 6.7 Drift Results of Group 1.

Sensor ID	Time Hours	Ch 1			Ch 2			Ch 3			Ch 4			Ch 5			Ch 6			Ch 7			Ch 8		
		100	200	250	100	200	250	100	200	250	100	200	250	100	200	250	100	200	250	100	200	250	100	200	250
1	0	0.25	0.11	0.03	0.43	0.75	0.79	-0.46	-1.40	-1.94	0.12	-0.25	-0.39	-0.08	-0.81	-1.04	0.32	0.61	0.73	0.31	0.28	0.22	0.91	2.43	3.23
	6	0.46			0.53			-0.01			0.16			0.21			0.51			0.01			0.74		
	24	0.53			0.59			0.46			0.12			0.35			0.54			-0.16			0.68		
	48	0.64			0.66			0.63			0.15			0.50			0.58			-0.24			0.68		
	72	0.62			0.68			0.58			0.10			0.44			0.51			-0.30			0.66		
	168	0.64	1.24	1.33	0.71	1.62	1.79	1.12	1.08	0.62	0.08	-0.05	-0.5	0.38	0.56	0.60	0.08	1.05	1.53	-0.27	-0.78	-0.94	0.58	2.04	2.81
	432	0.31			0.95						-0.37			-0.73						-0.11					
	672	0.40	0.70	0.82	1.00	2.24	2.82				-0.39	-0.96	-1.27	-0.60	-1.54	-2.01				-0.15	-0.41	-0.53			
	1176	0.40			1.00						-0.36			-0.58						-0.13					
	1992	0.41	0.77	0.87	1.01	2.21	2.71				-0.37	-0.90	-1.13	-0.60	-1.32	-1.72				-0.15	-0.47	-0.58			
2	0	0.25	0.15	0.03	0.43	0.77	0.76	-0.42	-1.41	-1.94	0.13	-0.22	-0.39	-0.07	-0.75	-1.02	0.32	0.64	0.72	0.30	0.31	0.21	0.89	2.47	3.19
	24	0.57			0.61			0.47			0.15			0.37			0.56			-0.14			0.70		
	48	0.68			0.71			0.66			0.18			0.53			0.62			-0.21			0.73		
	72	0.66			0.73			0.60			0.15			0.48			0.56			-0.25			0.72		
	168	0.69	1.25	1.38	0.74	1.61	1.60	1.13	0.96	0.59	0.13	0.00	-0.08	0.47	0.60	0.70	0.13	1.09	1.60	-0.23	-0.71	-0.90	0.62	2.10	2.84
	432	0.31			1.03			0.85			-0.42			-0.82			0.06			-0.10			1.08		
	672	0.35	0.11	0.67	0.95	1.57	2.52	0.79	0.44	1.04	-0.40	-1.42	-1.22	-0.64	-2.00	-1.96	0.18	-0.06	0.47	-0.14	-0.66	-0.48	1.03	2.38	3.85
	1176	0.38			1.01			0.78			-0.37			-0.64			0.20			-0.12			1.05		
	1992	0.33	0.58	0.65	0.93	2.00	2.40	0.69	0.97	0.79	-0.42	-0.99	-1.19	-0.70	-1.49	-1.82	0.12	0.35	0.48	-0.14	-0.49	-0.56	0.92	2.66	3.66
3	0	0.26	0.10	0.11	0.45	0.95	1.12	-1.56	-2.09	-1.88	0.37	0.23	0.22	-0.09	-1.10	-1.30	0.59	0.81	0.82	0.79	1.50	1.65	1.48	3.30	3.81
	48	0.63			0.63			-0.37			0.32			0.54			0.82			0.04			1.09		
	72	0.63			0.66			-0.33			0.28			0.50			0.74			0.00			1.07		
	168	0.67	1.17	1.30	0.74	1.67	1.94	0.09	0.74	0.98	0.28	0.31	0.33	0.41	0.34	0.34	0.55	1.04	1.36	0.05	0.14	0.23	1.02	2.35	2.75
	432	0.29			1.05			-0.10			-0.17			-0.90			0.27			0.47			1.58		
	672	0.35	0.56	0.63	1.01	2.41	3.02	-0.04	0.91	1.68	-0.17	-0.55	-0.71	-0.73	-2.11	-2.72	0.38	0.38	0.18	0.40	0.92	1.23	1.52	3.51	4.23
	1176	0.36			1.02			-0.13			-0.13			-0.70			0.39			0.40			1.51		
	1992	0.36	0.61	0.69	0.99	2.29	2.90	-0.26	0.81	1.31	-0.13	-0.47	-0.58	-0.70	-1.83	-2.41	0.39	0.45	0.34	0.40	0.87	1.14	1.47	3.32	4.13

Table 6.7 (Continued)

Sensor ID	Time Hours	Ch 1			Ch 2			Ch 3			Ch 4			Ch 5			Ch 6			Ch 7			Ch 8		
		100	200	250	100	200	250	100	200	250	100	200	250	100	200	250	100	200	250	100	200	250	100	200	250
4	0	0.24	0.15	0.06	0.45	0.82	0.81	-0.45	-1.43	-1.86	0.11	-0.21	-0.38	-0.10	-0.79	-1.03	0.36	0.64	0.74	0.31	0.37	0.23	0.90	2.50	3.21
	672	0.33	0.57	0.62	0.98	2.21	2.69	0.94	1.32	1.45	-0.47	-1.12	-1.41	-0.74	-1.81	-2.30	0.12	0.25	0.24	-0.17	-0.45	-0.53	1.01	2.85	3.80
	1176	0.31			0.94			0.73			-0.40			-0.70			0.14			-0.11			0.99		
	1992	0.35	0.61	0.70	1.00	2.12	2.61	0.80	1.30	1.22	-0.44	-1.05	-1.27	-0.73	-1.59	-1.98	0.12	0.30	0.39	-0.17	-0.49	-0.60	0.95	2.68	3.66
5	0	0.25	0.16	0.10	0.46	0.82	0.88	-0.41	-1.30	-1.61	0.12	-0.23	-0.34	-0.09	-0.79	-1.01	0.37	0.63	0.70	0.35	0.31	0.29	0.90	2.48	3.12
	1992	0.32	0.57	0.65	0.90	2.01	2.43	0.58	0.80	0.76	-0.39	-0.98	-1.17	-0.69	-1.55	-1.86	0.14	0.38	0.50	-0.10	-0.43	-0.51	0.95	2.79	3.77
6	0	0.26	0.11	0.04	0.45	0.73	0.78	-0.40	-1.45	-1.86	0.13	-0.23	-0.37	-0.08	-0.79	-1.01	0.37	0.60	0.71	0.32	0.29	0.24	0.88	2.42	3.14
	6	0.43			0.51			-0.04			0.14			0.16			0.46			0.03			0.73		
	24	0.48			0.56			0.21			0.15			0.25			0.52			-0.01			0.74		
	48	0.57			0.62			0.42			0.13			0.40			0.55			-0.19			0.72		
	72	0.57			0.65			0.40			0.11			0.37			0.49			-0.22			0.70		
	168	0.61	1.06	1.21	0.71	1.48	1.69	0.74	0.56	0.31	0.11	-0.06	-0.15	0.31	0.40	0.45	0.37	1.01	1.47	-0.19	-0.63	-0.81	0.68	2.11	2.85
	432	0.67			0.77			0.76			0.11			+0.44			0.53			-0.23			0.75		
	672	0.69	1.21	1.26	0.77	1.55	1.65	0.84	0.69	0.26	0.05	-0.08	-0.17	0.45	0.61	0.60	0.59	1.31	1.56	-0.27	-0.73	-0.86	0.73	2.19	2.88
	1176	0.70			0.83			0.89			0.07			0.40			0.58			-0.22			0.76		
	1992	0.75	1.49	1.74	0.98	2.16	2.55	1.40	2.02	1.99	-0.05	-0.24	-0.29	0.25	0.43	0.54	0.48	1.20	1.54	-0.31	-0.86	-1.06	0.68	2.14	2.90
7	0	0.27	0.18	0.08	0.46	1.00	1.07	-1.60	-2.15	-1.94	0.37	0.28	0.20	-0.05	-1.00	-1.32	0.67	0.94	0.78	0.77	1.50	1.64	1.47	3.43	3.74
	24	0.47			0.50			-0.72			0.29			0.30			0.72			0.20			1.11		
	48	0.54			0.54			-0.74			0.31			0.44			0.78			0.13			1.16		
	72	0.54			0.57			-0.75			0.29			0.42			0.72			0.09			1.13		
	168	0.55	0.94	0.99	0.61	1.36	1.54	-0.47	-0.19	-0.03	0.29	0.32	0.31	0.32	0.25	0.15	0.60	1.13	1.30	0.15	0.27	0.39	1.09	2.48	2.86
	432	0.59			0.60			-0.59			0.29			0.47			0.74			0.08			1.15		
	672	0.68	1.20	1.30	0.73	1.63	1.86	-0.02	0.55	0.82	0.19	0.26	0.29	0.47	0.46	0.41	0.78	1.34	1.42	-0.01	0.09	0.21	1.10	2.46	2.83
	1176	0.61			0.68			-0.38			0.24			0.40			0.76			0.11			1.13		
	1992	0.67	1.23	1.30	0.75	1.64	1.78	-0.23	0.54	0.56	0.22	0.29	0.34	0.41	0.54	0.57	0.76	1.35	1.48	0.06	0.07	0.14	1.08	2.34	2.73

Table 6.7 (Continued)

Sensor ID	Time Hours	Ch 1			Ch 2			Ch 3			Ch 4			Ch 5			Ch 6			Ch 7			Ch 8		
		100	200	250	100	200	250	100	200	250	100	200	250	100	200	250	100	200	250	100	200	250	100	200	250
8	0	0.24	0.14	0.03	0.43	0.94	1.03	-1.82	-2.38	-2.32	0.35	0.27	0.20	-0.09	-1.01	-1.38	0.67	0.94	0.86	0.77	1.50	1.68	1.52	3.46	4.01
	48	0.48			0.49			-1.10			0.35			0.38			0.79			0.26			1.25		
	72	0.55			0.55			-0.90			0.32			0.44			0.76			0.11			1.18		
	168	0.58	0.94	0.96	0.61	1.31	1.49	-0.50	-0.33	-0.16	0.33	0.34	0.33	0.38	0.27	0.19	0.63	1.13	1.34	0.16	0.24	0.36	1.12	2.52	2.91
	432	0.62			0.63			-0.52			0.30			0.50			0.76			0.07			1.16		
	672	0.61	1.02	1.04	0.61	1.36	1.46	-0.40	-0.13	0.03	0.20	0.26	0.24	0.47	0.44	0.33	0.78	1.33	1.35	0.02	0.12	0.23	1.12	2.45	2.77
	1176	0.60			0.63			-0.53			0.25			0.41			0.79			0.11			1.15		
	1992	0.68	1.18	1.26	0.79	1.64	1.83	-0.14	0.46	0.53	0.21	0.25	0.26	0.38	0.41	0.39	0.75	1.31	1.42	0.06	0.12	0.19	1.10	2.41	2.81
9	0	0.23	0.05	0.00	0.41	0.70	0.81	-0.36	-1.50	-1.81	0.10	-0.29	-0.43	-0.12	-0.94	-1.15	0.32	0.36	0.64	0.29	0.29	0.24	0.82	2.39	3.17
	672	0.56	0.92	0.90	0.63	1.25	1.27	0.40	-0.05	-0.57	0.04	-0.09	-0.21	0.34	0.35	0.26	0.55	1.16	1.37	-0.15	-0.50	-0.62	0.77	2.16	2.90
	1176	0.62			0.70			0.47			0.11			0.38			0.57			-0.14			0.76		
	1992	0.69	1.20	1.30	0.80	1.55	1.71	0.70	0.75	0.35	0.06	-0.06	-0.14	0.37	0.56	0.62	0.56	1.25	1.54	-0.16	-0.66	-0.86	0.73	2.06	2.78
10	0	0.26	0.11	0.05	0.44	0.69	0.77	-0.32	-1.66	-1.96	0.15	-0.21	-0.36	-0.01	-0.79	-1.00	0.39	0.49	0.75	0.29	0.29	0.23	0.85	2.40	3.19
	1992	0.61	1.05	1.14	0.70	1.35	1.45	0.39	0.16	-0.26	0.06	-0.06	-0.12	0.32	0.51	0.60	0.54	1.23	1.55	-0.16	-0.62	-0.81	0.73	2.13	2.85

calibration temperature of 100 °C of all the channels of the most frequently tested sensors (i.e. sensors 1, 2, 3, 6, 7, and 8) are shown in Figure 6.17.

Each individual channel was investigated separately. The phenomena of interest were effects of calibration temperature, effects of environment (i.e., cycling temperature oven versus isothermal oven), effects of annealing (as created by the accident), and effects of frequency of testing on the channel performance.

From Table 6.7 and Figure 6.17, the following patterns were observed.

A. All channels of all the sensors showed most of the changes in their drift within the first 200 hours of exposure. Then, the drift was constant. This may be attributed to atomic re-ordering in the constituent material immediately after exposure when the metals release internal stresses caused by cold work. Once this phase was completed, the sensors showed an almost constant drift.

B. Other processes, such as annealing, would affect the drift rate of sensors. Unplanned annealing occurred after 264 hours of exposure. The sensors were exposed to a temperature of 580 °C that is higher than the calibration and usual environment temperatures. Overall, the annealing affected favorably - reducing the drift with various degrees of success (see channels 1,

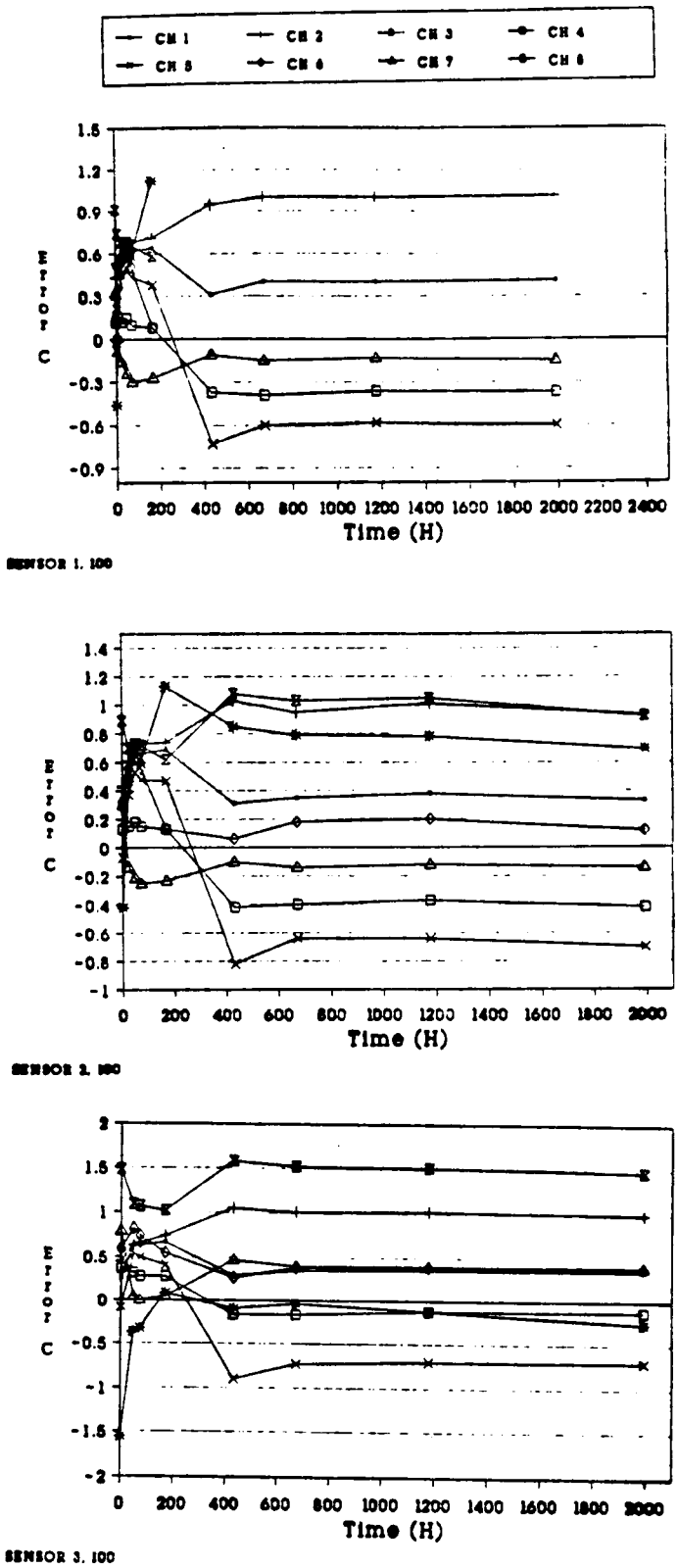
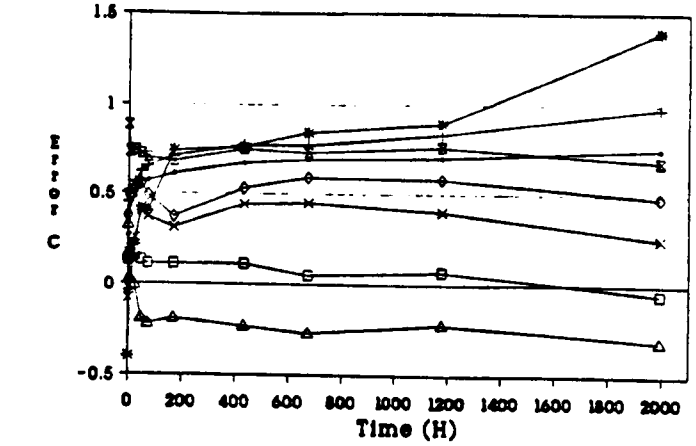
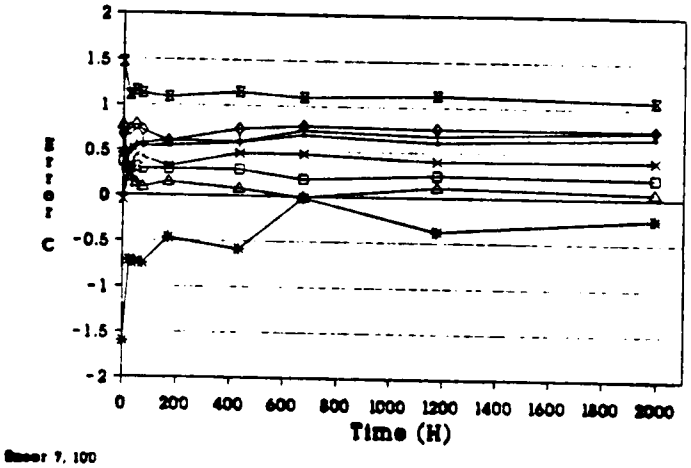


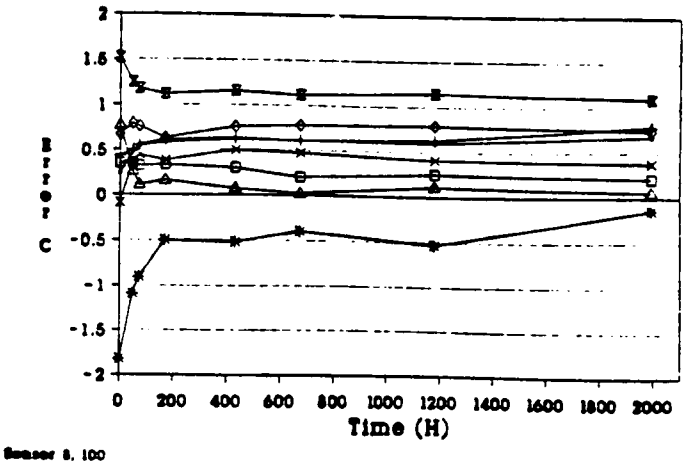
Figure 6.17 Drift Versus Time of the Most Frequently Tested Sensors of Group 1 Calibrated at 100 ^{0}C.



SENSOR 6, 100



Sensor 7, 100



Sensor 8, 100

Figure 6.17 (Continued).

2, 3, 5, and 7.) Annealing strongly influenced channels 4 and 5 resulting in a total shift in drift from positive to negative. Channel 8 was adversely affected by the annealing process. It showed an increase in drift. It must be noted that these conclusions were drawn by comparing the sensors that were annealed (in the isothermal oven) with the remaining sensors. Since each set was exposed to a different environment, a comparison was made of each channel's performance before annealing. Before annealing, both sets of sensors showed similar drift rates, which led to the conclusion that the abrupt and major change in drift after the accident can be attributed to annealing and not the difference in environment. In fact, the opposite conclusion was reached when the environmental effects were studied as described next.

C. The effect of environment, cycling versus isothermal, seemed to have a slight impact on the drift of various channels of this group. A comparison between the various channels for the first 168 hours (before the annealing) and no meaningful conclusion could be reached. For most of the channels, there was a slight increase in drift among the sensors placed in the isothermal oven over those in the thermal cycling oven. Only channel 8 showed a decrease in error among sensors 1 - 5 over sensors 6 - 10.

D. Calibrating the sensors at three different temperatures 100, 200 and 250 °C confirmed the short term tests finding that an increase in drift was observed by increasing the calibration temperature. Plots of error versus time for channel 2 of sensor 1 (selected at random) at 100, 200, and 250 °C are shown in Figure 6.18. Some channels showed a reverse effect at specific times instance (See Table 6.7).

E. The testing frequency analysis consisted of comparing sensor 1 (or 2 if necessary) with sensor 5 in the isothermal category, and comparing sensor 6 with sensor 10 in the thermal cycling category. Notice that sensors 1, 2, and 6 are the most frequently calibrated sensors while sensors 5 and 10 were removed from the environment and tested only once. Since the various sensors had different initial drift rates, pre-analysis calculations were needed to isolate the effects of testing frequency from other effects. The differences between the drift after 1992 hours of sensor x ($D_x(1992)$) and the initial drift ($D_x(0)$) for each channel (i.e. $D_x(1992)-D_x(0)$) were determined. These differences were calculated at 100, 200, and 250 °C for all eight channels of sensors 1 (or 2), 5, 6, and 10. The effect was then deduced by subtracting the calculated differences of sensor 5 or 10 from the differences calculated for sensors 1 or 6 respectively:

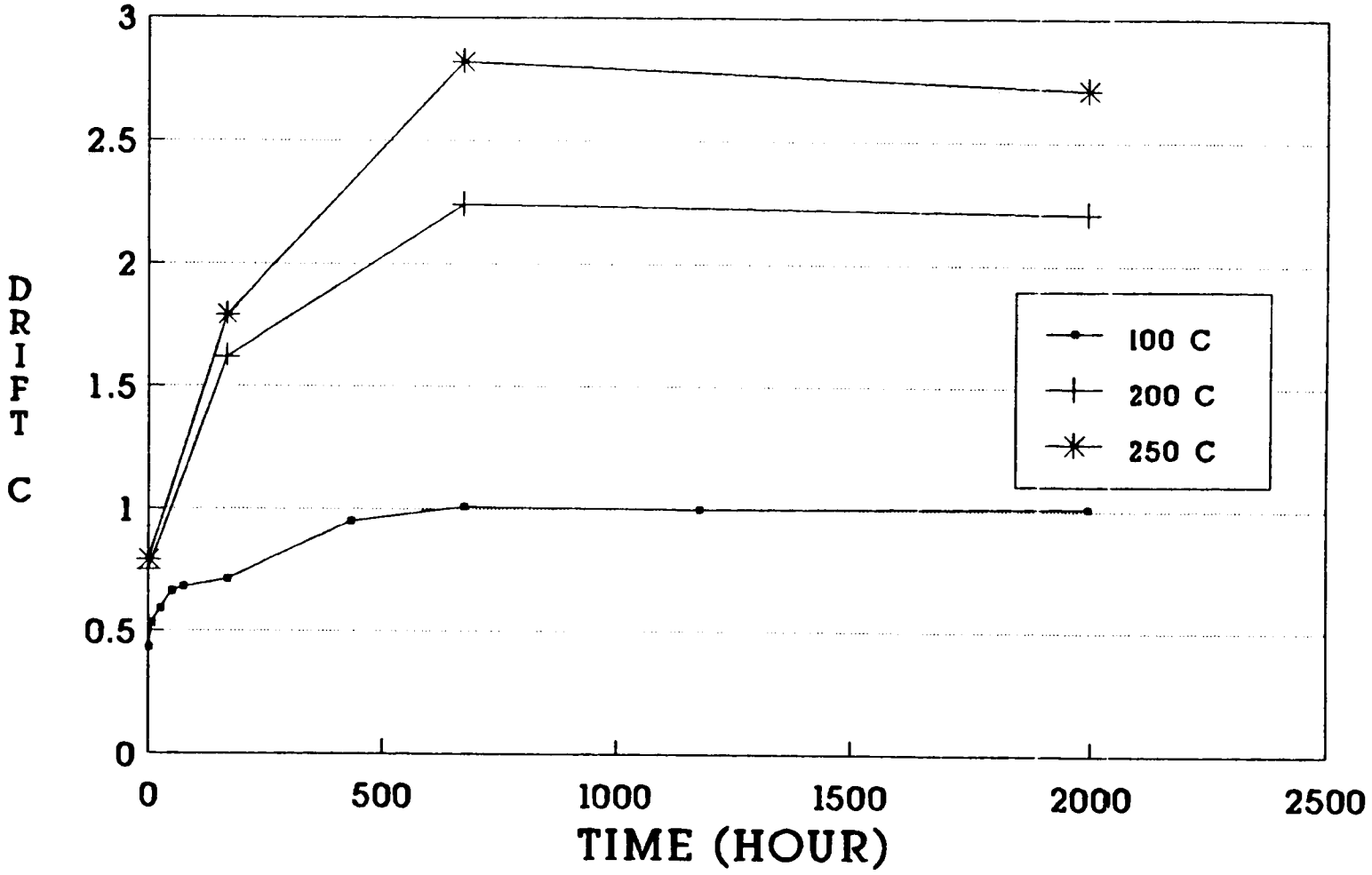


Figure 6.18 Effects of the Calibration Temperature on the Drift Rate of Channel 2 of Sensor 1.

$$\text{Effect of frequency} = [D_5(1992) - D_5(0)] - [D_1(1992) - D_1(0)].$$

The results of these calculations are presented in Table 6.8. The following observations were made: for channels 1, 2, 3, 4, and 7, the cycling environment produced larger overall effects due to frequent removal and testing of sensors than the isothermal environment. This may be due to the annealing effect, since annealing brought the initial and final drifts closer; which also decreased the differences between sensor 1 and 5. On the other hand, sensor 10 exhibited less change between its initial and final stage than sensor 6. Hence, the difference between those sensors was large. Channels 6 and 7 showed little or no effect. Channel 5 showed a small but opposite influence by the frequency of testing.

6.4.4 Weight Factors

The weight factors needed for the STMS were based on the performance of all the sensors regardless of the exposure environment since there is no a priori knowledge about the environment. It was necessary to determine the weight factors by considering the performance of all channels of all sensors. The method consisted of plotting the drift of each channel of each sensor in the group after 1992 hours of exposure as shown in Figure 6.19. The sensor number is

Table 6.8 Effects of the Frequency of Testing on the Drift Rates of Group 1

Channel Number	Difference Between Sensors 1 - 5			Difference Between Sensors 6 - 10		
	100 °C	200 °C	250 °C	100 °C	200 °C	250 °C
1	0.04	0.20	0.20	0.16	0.44	0.61
2	0.14	0.27	0.37	0.27	0.77	1.09
3	0.12	0.28	0.36	1.09	1.75	2.17
4	0.02	0.10	0.09	-0.11	-0.14	-0.16
5	0.08	0.25	0.17	0.00	-0.08	-0.05
6	0.03	-0.04	-0.04	-0.04	-0.14	-0.03
7	-0.01	-0.01	0.00	-0.18	-0.18	-0.28
8	-0.02	-0.12	-0.18	0.08	-0.01	0.10

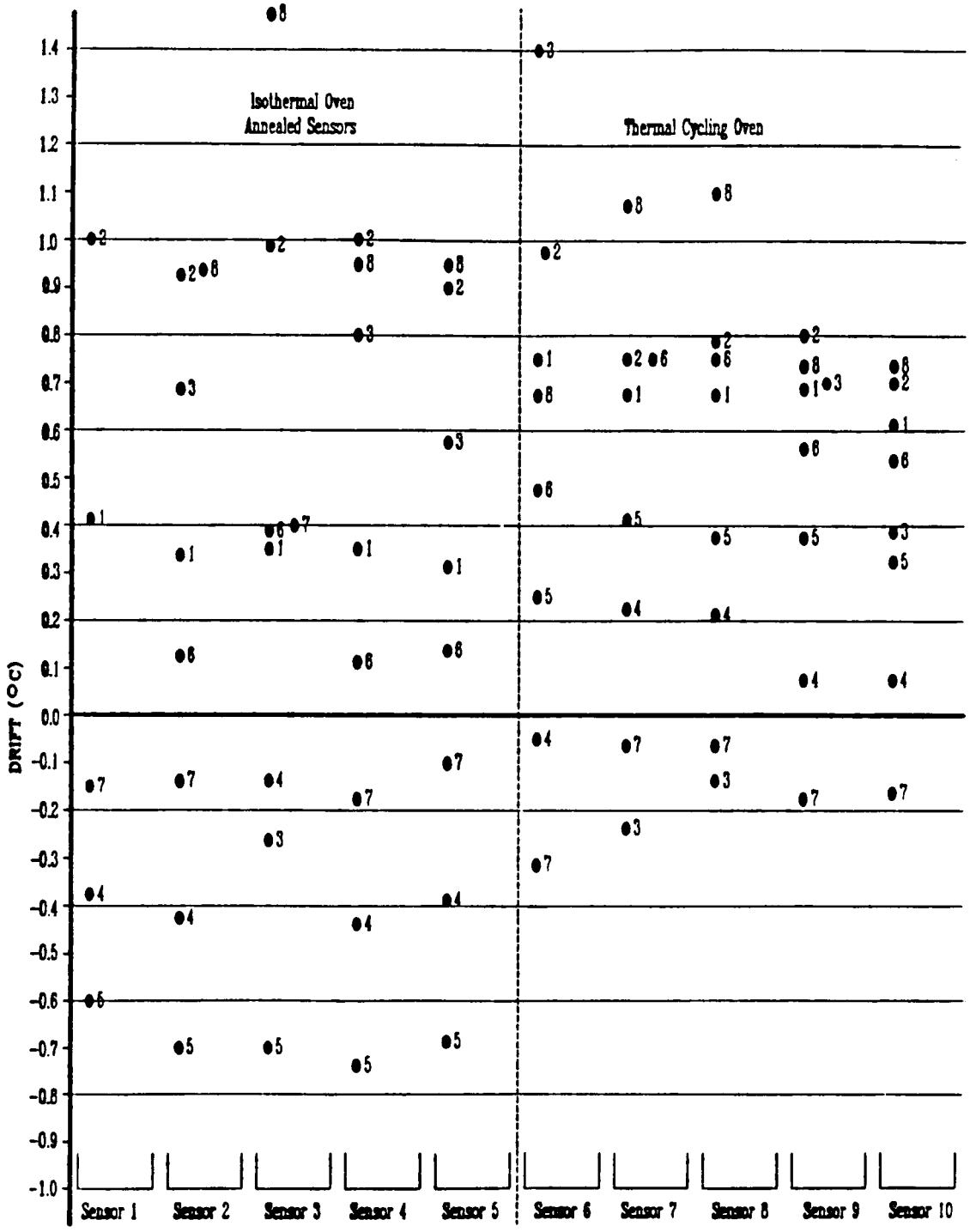


Figure 6.19 Inaccuracies of all the Sensors of Group 1 after 1992 Hours in the Ovens, and Calibrated at 100 ^{0}C.

plotted on the X-axis. The indexes 1 through 8 parallel to the Y-axis represent the channel numbers associated with the drift. The decision to use the drift values after 1992 hours for this analysis was made because they may be considered representative of the steady state drift of those sensors. Figure 6.19 provides an excellent method for comparing the performance of the various channels of the various sensors. To facilitate the weight assignments, lines parallel to the X-axis were drawn at 0.2 °C increments to divide the Figure into regions of various "importance." Eight regions were identified in the positive error side, and each of those regions was assigned a number between 1 and 8. The farther the region from the X-axis, the smaller the number. Next, channels in each region were counted. The weight factors were then calculated as

$$W(i) = \sum_{j=1}^{8} n_{ij} * j \qquad (6.10)$$

Where

W(i) = weight factor of channel i

n_{ij} = number of counts of channel i in region j in the positive or negative sides of the X-axis.

Finally, the weight factors were normalized and a percent value was determined for each channel. The results of these calculations are presented in Table 6.9 in the column titled Method 1.

Table 6.9 Weight Factors for Group 1.

Channel Number	%Weight Factors		Comments
	Method 1	Method 2	
1	13.23	12.23	
2	9.87	4.35	
3	11.66	7.55	
4	16.14	20.94	Negative Drift
5	13.45	12.78	
6	13.23	15.09	
7	17.49	25.56	Negative Drift
8	4.93	1.50	Worst performance

It is noticed that channels 7 and 4 produced negative drifts, while most of the remaining channels produced positive drifts. For the STMS to produce good accuracy channels 7 and 4 must have high weights in order to cancel the effects of the positive-drift channels. The weight assignment according to Equation (6.10), did not provide a good distinction between channels 7 and 4 and the remaining channels. Therefore, it was decided to add even more weight to all the negative and positive channels lying in the regions 5, 6, 7, and 8 by assigning them the multiplication factors of 2, 3, 4, and 5 respectively. The weight factors were then determined as follows:

$$W(i) = \sum_{j=1}^{8} n_{ij} * j * f \qquad (6.11)$$

Where

$$f = \begin{cases} 1 \text{ if } j = 1, 2, 3, 4 \\ 2 \text{ if } j = 5 \\ 3 \text{ if } j = 6 \\ 4 \text{ if } j = 7 \\ 5 \text{ if } j = 8 \end{cases}$$

The weights according to the new formula were determined and normalized. A percent weight was then determined as presented in Table 6.9 under "Method 2" heading.

To test these weight factors, the mean, the weighted average according to method 1, and the weighted average according to method 2 of the drift errors of each sensor of the group at selected exposure times and calibration temperature (selected at random) were calculated. The results of the calculations are shown in Table 6.10. It is

Table 6.10 Effect of Using Weight Factors on Reducing the Average Error.

Sensor ID	Temp. (°C)	Time (H)	Straight Average Error	Weighted Average Error	
				Method 1	Method 2
1	100	168	0.415	0.043	0.026
2	200	672	0.020	-0.040	-0.079
3	200	672	0.745	0.054	0.025
4	100	1992	0.235	0.013	-0.006
5	250	1992	0.571	0.017	0.030
6	100	672	0.481	0.050	0.035
7	200	672	0.816	0.090	0.074
8	100	1176	0.426	0.044	0.041
9	250	672	0.663	0.049	0.054
10	200	1992	0.716	0.063	0.038

clear that using the weight factors drastically reduced the average error. The weights derived according to the second method seemed to better reduce the average error than the first method. Hence, the weight factors used in the STMS will be those listed under method 2 in Table 6.9.

Performance of Group 2

The only thermoelements of group 2 are Ep and En and Nn. The first four channels were made entirely of type E TCs. Channels 5 and 6 consisted of Ep-Nn wire pairs, while channels 7 and 8 consisted of Nn-En pairs. Hence, it is expected to see three clusters of drifts; each cluster represents channels comprised of similar thermoelements. The calculated drifts can be found in Table 6.11. Plots of the drifts of sensors 11, 12, and 14 at 100 °C are shown in Figure 6.20. To facilitate comparison between all the sensors of this group, the drift rates of each channel after 2016 hours of exposure are plotted as shown in Figure 6.21. The reader is reminded that sensors 11, 12, and 13 were placed in the isothermal oven, while sensor 14 and 15 were placed in the thermal cycling oven.

By consulting Table 6.11 and Figure 6.20 and 6.21, the following observations are made:

A. The sensors exposed to the isothermal environment showed three different clusters of drifts. The first cluster consisted of channels 1, 2, 3, and 4 (Ep-En) that showed

Table 6.11 Drift Results of Group 2.

Sensor ID	Time Hours	Ch 1			Ch 2			Ch 3			Ch 4			Ch 5			Ch 6			Ch 7			Ch 8		
		100	200	250	100	200	250	100	200	250	100	200	250	100	200	250	100	200	250	100	200	250	100	200	250
11	0	0.19	0.19	0.16	0.19	0.18	0.15	0.18	0.18	0.15	0.22	+0.19	+0.16	+0.41	+0.87	+0.92	0.46	0.86	0.90	-0.27	-0.82	-0.95	-0.27	-0.80	-0.91
	6	0.52			0.49			0.50			0.51			0.59			0.59			0.31			0.27		
	24	0.57			0.54			0.54			0.56			0.64			0.66			+0.38			0.39		
	48	0.73			0.70			0.69			0.71			1.04			1.07			+0.13			0.07		
	72	0.26			0.25			0.26			0.26			0.87			0.89			-0.70			-0.71		
	264	0.35	0.54	0.59	0.31	0.52	0.57	0.30	0.53	0.59	0.33	+0.56	+0.60	0.91	2.03	2.48	0.96	2.08	2.53	-0.66	-1.64	-2.08	-0.62	-1.58	-2.06
	336	0.40			0.36			0.38			+0.40			+0.93			1.00			-0.55			-0.52		
	672	0.44	0.75	0.81	0.38	0.67	0.71	0.29	0.68	0.68	+0.39	+0.73	+0.80	+0.82	+1.86	+2.19	0.92	1.94	2.33	-0.36	-0.99	-1.29	-0.53	-1.07	-1.43
	1176	0.35			0.20			0.25			+0.30			+0.84			0.88			-0.51			-0.55		
	2016	0.44	0.71	0.87	0.28	0.69	0.81	0.39	0.70	0.86	+0.39	+0.73	+0.86	+0.92	+1.92	+2.42	0.91	2.02	2.49	-0.46	-1.08	-1.36	-0.51	-1.10	-1.39
12	0	0.19	0.19	0.16	0.16	0.17	0.15	+0.18	+0.19	+0.16	0.20	+0.16	+0.16	+0.43	+0.85	+0.90	0.44	0.84	0.90	-0.27	-0.79	-0.92	-0.24	-0.82	-0.89
	672	0.45	0.76	0.81	0.40	0.68	0.72	0.28	0.68	0.67	0.40	0.74	+0.80	0.86	2.01	2.37	0.96	2.07	2.49	-0.39	-1.11	-1.52	-0.56	-1.20	-1.66
	1176	0.39			0.19			0.24			+0.31			+0.85			0.88			-0.47			-0.50		
	2016	0.34	0.61	0.79	0.18	0.59	0.74	0.29	0.58	0.76	+0.30	+0.60	0.77	+0.79	+1.69	+2.17	0.78	+1.79	2.20	-0.52	-1.03	-1.20	-0.55	-1.08	-1.21
13	0	0.19	0.16	0.13	0.19	0.17	0.15	0.19	0.17	0.15	0.22	0.20	0.18	0.42	0.83	0.90	0.46	0.86	0.92	-0.26	-0.82	-0.97	-0.21	-0.77	-0.86
	2016	0.42	0.74	0.89	0.25	0.71	0.84	0.36	0.70	0.83	0.36	0.72	0.83	0.88	1.94	2.38	0.85	1.99	2.41	-0.48	-1.04	-1.29	-0.51	-1.08	-1.36
14	0	0.20	0.16	0.12	0.20	0.17	0.13	+0.20	+0.16	+0.12	0.23	0.18	0.14	+0.44	+0.84	+0.90	0.46	0.84	0.89	-0.26	-0.83	-1.01	-0.22	-0.81	-0.93
	6	0.44			0.42			+0.43			0.44			0.55			0.56			0.19			0.17		
	24	0.45			0.44			0.44			0.45			0.57			0.61			0.19			0.24		
	48	0.49			0.47			0.46			0.48			0.56			0.60			0.25			0.22		
	72	0.51			0.50			0.50			0.51			0.61			0.61			0.30			0.32		
	264	0.51	0.75	0.76	0.49	0.75	0.76	0.47	0.73	0.74	0.50	0.78	0.79	0.56	1.09	1.18	0.59	1.12	1.21	0.26	0.15	0.03	0.30	0.25	0.15
	336	0.56			0.54			+0.53			+0.55			+0.58			0.64			0.34			0.38		
	672	0.65	1.01	1.02	0.60	0.95	0.95	+0.45	0.90	0.86	+0.60	+1.00	+1.03	+0.57	+1.21	+1.24	0.66	1.24	1.35	0.50	0.54	0.51	0.35	0.53	0.42
	1176	0.57			0.33			+0.37			+0.49			+0.62			0.64			0.30			0.29		
	2016	0.65	1.09	1.18	0.47	1.06	1.17	+0.60	1.05	1.12	+0.61	+1.09	+1.18	+0.67	+1.32	+1.44	0.64	1.36	1.49	0.38	0.63	0.64	0.38	0.63	0.69
15	0	0.22	0.22	0.18	0.21	0.21	0.16	0.21	0.22	0.16	0.23	0.22	0.16	0.44	0.89	0.93	0.47	0.89	0.89	-0.23	-0.77	-0.90	-0.22	-0.76	-0.90
	2016	0.63	0.96	1.01	0.49	0.95	0.96	0.56	0.96	0.96	0.59	0.97	1.00	0.63	1.21	1.26	0.64	1.29	1.34	+0.41	+0.53	+0.51	+0.38	+0.49	+0.47

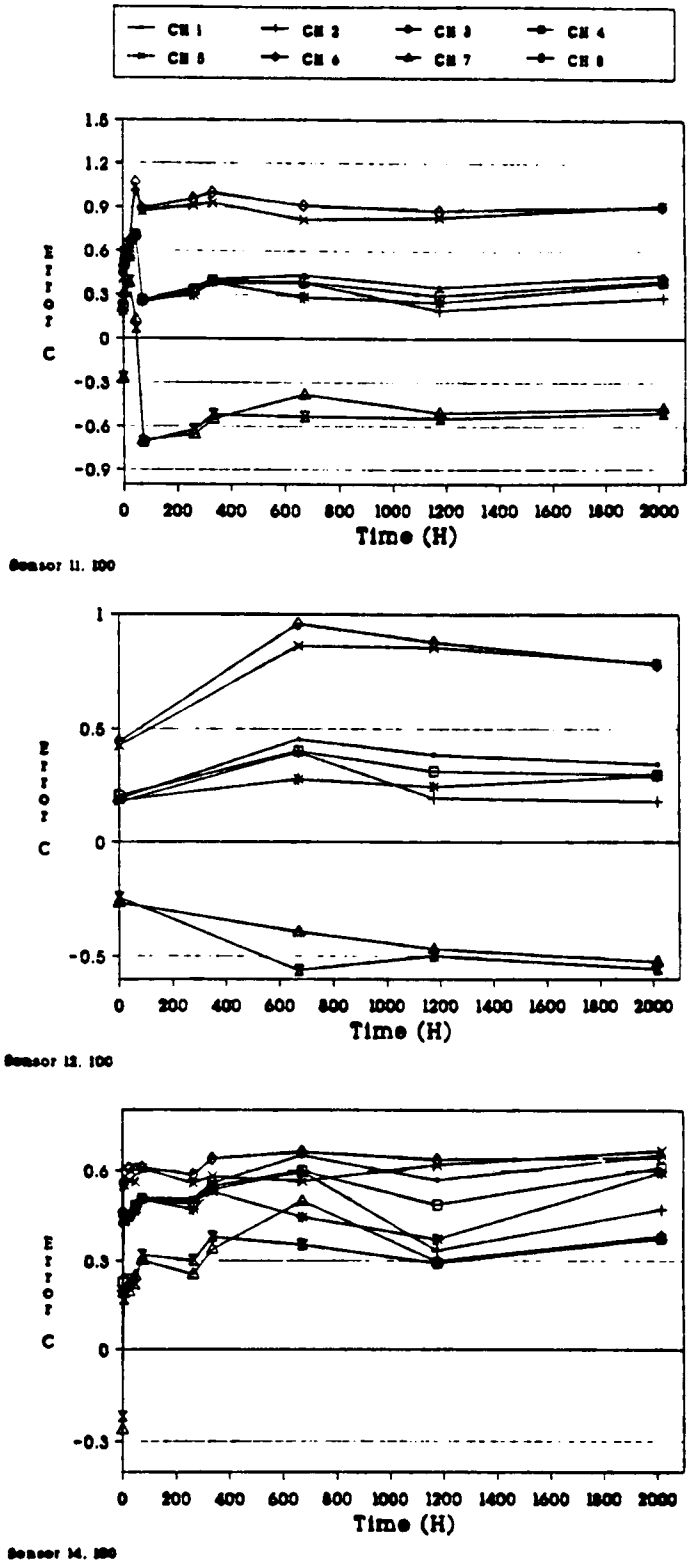


Figure 6.20 Drift Versus Time of the Most Frequently Tested Sensors of Group 2 Calibrated at 100 ^{0}C.

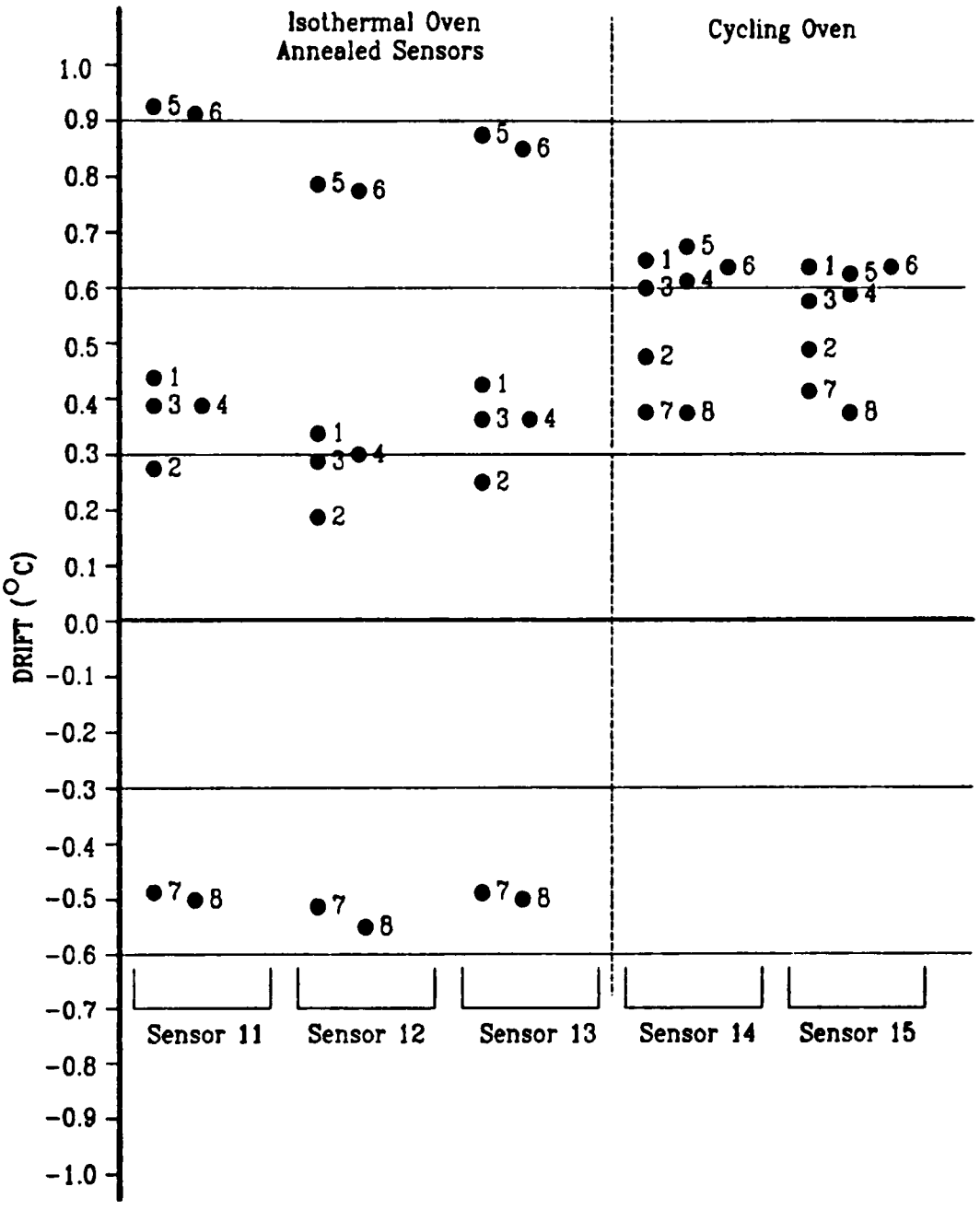


Figure 6.21 Inaccuracies of all the Sensors of Group 2 after 2016 Hours in the Ovens, and Calibrated at 100 ^{0}C.

errors between 0.18 to 0.43 °C. The second cluster consisted of channels 5 and 6 (Ep-Nn) with errors between 0.79 and 0.92 °C. The third cluster consisted of channels 7 and 8 (Nn-En) with errors between - 0.48 and - 0.55 °C. Such behavior can best be utilized in an STMS that assigns highest weights to channels 7 and 8 to offset the positive drifts of the remaining channels; high weights to channels 1, 2, 3, and 4; and low weights to channels 5 and 6. Such weighting system should lead to virtually zero tolerance on the measurements.

B. In the cycling region, however, the drift of all channels formed a single cluster between 0.38 and 0.67 °C. No negative drifts were noticed. It is believed that the main reason for distinction between the isothermal and cycling oven sensors can be attributed to the accidental annealing of the isothermal oven sensors. By comparing the performance of sensors 11 and 14 during the period prior to annealing (i.e., up to 48 hours), one finds that channels 1 through 6 of sensor 11 (exposed to isothermal environment) showed higher overall drift than sensor 14. Hence, if annealing did not occur, it could be concluded that sensor 11, 12, and 13 would behave like sensor 14 and 15. Channels 7 and 8 however, showed a decreased, but still positive, drift while the same channels of sensor 11 showed a high negative drift after 48 hours. This phenomenon may be

explained as follows: whatever mechanism causing the large drift in channels 1 - 6 (consisting mainly of Ep) of sensors 11, 12, 13 is also responsible for increasing the negative drift. For example, oxidation of chromium and its removal from Ep causing positive drift results in an increase of chromium in element Nn leading to a large negative drift. The mechanism may explain the large negative drift of channels 8 and 7 (Nn-En) and large positive drift of channels 5 and 6 (Ep-Nn) after the annealing of sensors 11, 12, and 13.

C. As the calibration temperature increased, so did the drift in both the positive and the negative directions.

D. Direct comparison between sensor 11, that was tested frequently, and sensor 13, that was tested once, after 2016 hours showed the following results: At 100 °C, sensor 12 indicated less than 0.06 °C decrease in Drift over sensor 11. At 200 °C, the difference in drift ranged between -0.04 to 0.04 °C. Most of the differences were less than 0.02 °C suggesting no dependance on testing frequency within statistical fluctuation. Similarly, comparisons at 250 °C indicated slightly larger differences in the positive and negative directions leading to the conclusion that there is no apparent dependance on testing frequency. Comparisons between sensor 14 which was frequently tested and sensor 15 tested only once, showed slightly different behavior.

At 100 °C, the differences were within -0.03 and +0.04 °C. Most of the differences were 0.02 °C or less. Hence, there is no apparent dependence on the testing frequency. At 200 and 250 °C, however, the difference fell within the ranges 0.07 - 0.14 °C and 0.13 to 0.22 °C respectively. Most of the differences were above 0.01 °C. Hence, there is a dependance on frequency of testing whereby sensors that were frequently tested showed slightly higher drift rates over those that were not so frequently removed from the environment, eventually cooled, then calibrated in the laboratory. One possible explanation of the behavior may be attributed to the nature of the thermal cycling environment which closely resembles the cooling and heating of the sensors by removal for testing purposes. That is, although sensor 14 was removed (hence, cooled then eventually re-heated) only nine times from the process, both sensor 15 and it were in essence cooled and heated every 6 hours for 2016 hours while they were in the oven. Therefore, the true effect of frequency of testing was more enhanced and apparent.

6.4.6 Performance of Group 3

This group consisted of the same wire combination as group 2 except for replacing Nn with Kn. Therefore, group 3 is expected to behave similarly to group 2. The drift

calculations are presented in Table 6.12. Plots of drifts at 100 °C of sensors 16, 17, and 19 are shown in Figure 6.22. One should notice that each sensor consists of 4 type E TCs (Ep-En), 2 type K TCs (Ep-Kn) and 2 non-standard TCs (Kn-En). To facilitate comparison between the various channels of all the sensors, drifts at 100 °C and after 2016 hours of exposure (as a representative of the steady error state) are shown in Figure 6.23. The following observations are made:

A. By comparing Figure 6.23 with 6.21, one can find the similarities and differences between both groups. Sensors 16, 17, and 18 showed the same behavior as sensors 11, 12, and 13; except the error magnitude of channels 7, 8, 5, and 6 are smaller. This resulted in only two apparent clusters or drifts, since channels 1 through 6 can be lumped into a single positive drift cluster. Overall, the drift rates of these sensors were smaller than those of group 2. Since sensors 11, 12, 13, 16, 17, and 18 were exposed to exactly the same environment and calibrated at the same temperature and time periods, the difference in behavior may then be attributed solely to replacing Nn with Kn. Kn is known for its oxidation resistance capability.

   Sensors 19 and 20 (cycling, not annealed) showed an overall larger spread of drift data than the equivalent sensors 14 and 15 of group 3. Three clusters

Table 6.12 Drift Results of Group 3.

Sensor ID	Time Hours	Ch 1			Ch 2			Ch 3			Ch 4			Ch 5			Ch 6			Ch 7			Ch 8		
		100	200	250	100	200	250	100	200	250	100	200	250	100	200	250	100	200	250	100	200	250	100	200	250
16	0	0.22	0.20	0.01	0.22	0.21	0.04	0.21	0.21	-0.05	0.24	+0.24	+0.07	+0.19	-0.36	-0.73	0.19	-0.32	-0.63	+0.29	+0.83	+0.74	+0.23	+0.83	+0.75
	6	0.47			0.46			0.46			0.47			0.30			0.26			0.61			0.62		
	24	0.56			0.53			0.53			0.54			0.37			0.33			+0.73			0.65		
	48	0.67			0.64			0.65			0.67			0.66			0.70			+0.57			0.47		
	72	0.30			0.26			0.30			0.30			0.58			0.62			-0.26			-0.24		
	264	0.35	0.55	0.57	0.33	0.53	0.54	0.33	0.53	0.54	0.35	+0.55	+0.57	0.62	0.98	1.26	0.66	1.02	1.30	-0.24	-0.06	-0.36	-0.20	-0.03	-0.32
	336	0.42			0.39			0.39			+0.39			+0.61			0.64			-0.06			-0.13		
	672	0.45	0.73	0.74	0.40	0.63	0.66	0.32	0.61	0.63	+0.39	+0.68	+0.71	+0.54	+0.88	+1.16	0.63	0.91	1.21	+0.01	+0.36	+0.09	-0.19	+0.26	-0.03
	1176	0.39			0.17			0.20			+0.31			+0.49			0.49			-0.03			-0.08		
	2016	0.37	0.74	0.92	0.27	0.71	0.85	0.32	0.70	0.87	+0.35	+0.72	+0.88	+0.50	+0.89	+1.32	0.46	0.94	1.33	-0.07	+0.43	+0.32	-0.13	+0.40	+0.29
17	0	0.21	0.15	0.04	0.19	0.15	0.02	+0.19	+0.16	-0.03	0.22	+0.18	+0.05	+0.11	-0.45	-0.77	0.16	-0.41	-0.67	0.30	+0.85	+0.85	+0.21	+0.80	0.72
	672	0.38	0.60	0.63	0.33	0.51	0.57	0.24	0.48	0.52	0.33	0.57	+0.62	0.43	0.63	0.90	0.51	0.67	0.95	+0.02	+0.39	+0.15	-0.13	+0.29	+0.07
	1176	0.33			0.06			0.11			+0.24			+0.39			0.37			-0.01			-0.06		
	2016	0.28	0.53	0.63	0.19	0.50	0.58	0.23	0.49	0.58	+0.26	+0.52	+0.59	+0.38	+0.47	+0.76	0.32	+0.55	0.75	-0.06	+0.45	+0.36	-0.14	0.44	+0.33
18	0	0.21	0.21	0.05	0.19	0.19	0.01	0.20	0.21	-0.03	0.23	0.22	0.07	0.11	-0.38	-0.75	0.17	-0.33	-0.62	+0.31	+0.68	+0.63	+0.19	+0.81	+0.65
	2016	0.35	0.67	0.75	0.25	0.63	0.70	0.32	0.67	0.77	0.34	0.68	0.78	0.45	0.67	0.91	0.43	0.80	1.05	-0.02	+0.50	+0.44	-0.09	+0.49	+0.42
19	0	0.20	0.18	0.06	0.20	0.19	-0.00	+0.19	+0.19	-0.04	0.23	0.22	0.05	+0.11	-0.40	-0.74	0.19	-0.34	-0.64	+0.29	+0.84	+0.84	+0.16	+0.82	+0.59
	6	0.42			0.41			+0.41			0.42			0.26			0.21			0.55			0.56		
	24	0.46			0.44			0.43			0.45			0.28			0.23			0.64			0.54		
	48	0.50			0.48			0.46			0.49			0.30			0.34			0.68			0.62		
	72	0.55			0.54			0.54			0.54			0.35			0.37			0.75			0.77		
	264	0.53	0.79	0.78	0.51	0.79	0.77	0.50	0.76	0.77	0.53	0.82	0.81	0.31	-0.10	-0.28	0.35	-0.05	-0.22	0.72	1.72	1.86	0.78	1.79	1.95
	336	0.56			0.55			+0.54			0.56			+0.33			0.37			0.78			0.78		
	672	0.70	1.15	1.30	0.65	1.07	1.24	+0.55	1.06	1.17	0.66	+1.14	+1.29	+0.36	+0.23	+0.17	0.45	0.29	0.22	0.95	2.04	2.41	0.79	1.98	2.33
	1176	0.57			0.23			+0.30			0.48			+0.29			0.27			0.75			0.71		
	2016	0.66	1.08	1.14	0.56	1.05	1.09	+0.61	1.06	1.13	0.64	+1.08	+1.15	+0.40	+0.16	-0.00	0.34	0.25	0.10	0.86	1.99	2.32	0.81	2.00	2.31
20	0	0.23	0.21	0.04	0.21	0.19	-0.01	0.21	0.23	-0.05	0.23	0.22	0.07	0.11	-0.38	-0.79	0.19	-0.33	-0.62	+0.36	+0.89	+0.85	+0.16	+0.80	+0.61
	2016	0.62	1.07	1.11	0.50	1.02	1.07	0.59	1.05	1.10	0.60	1.05	1.13	0.33	0.09	-0.06	0.28	0.18	0.02	+0.67	+2.06	+2.33	+0.79	+2.01	+2.35

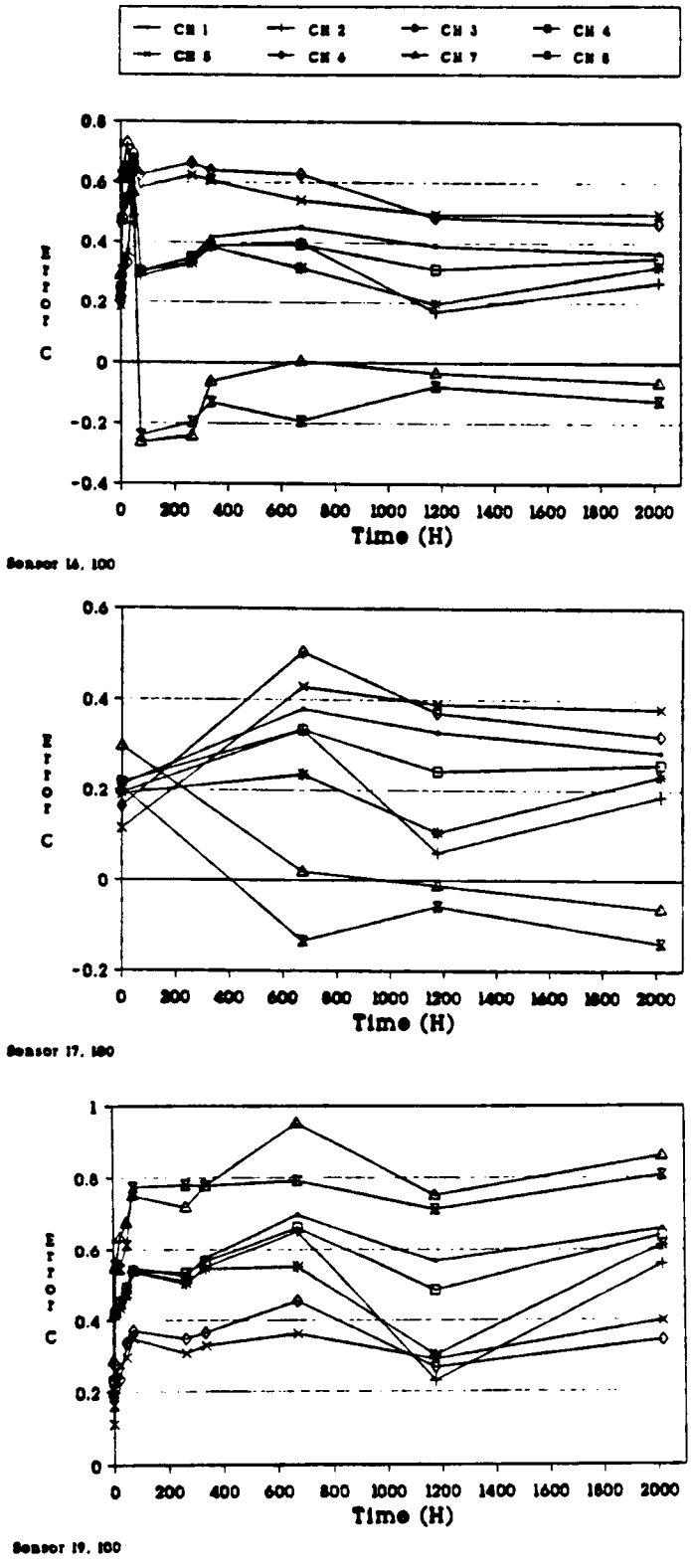


Figure 6.22 Drift Versus Time of the Most Frequently Tested Sensors of Group 3 Calibrated at 100 ^{0}C.

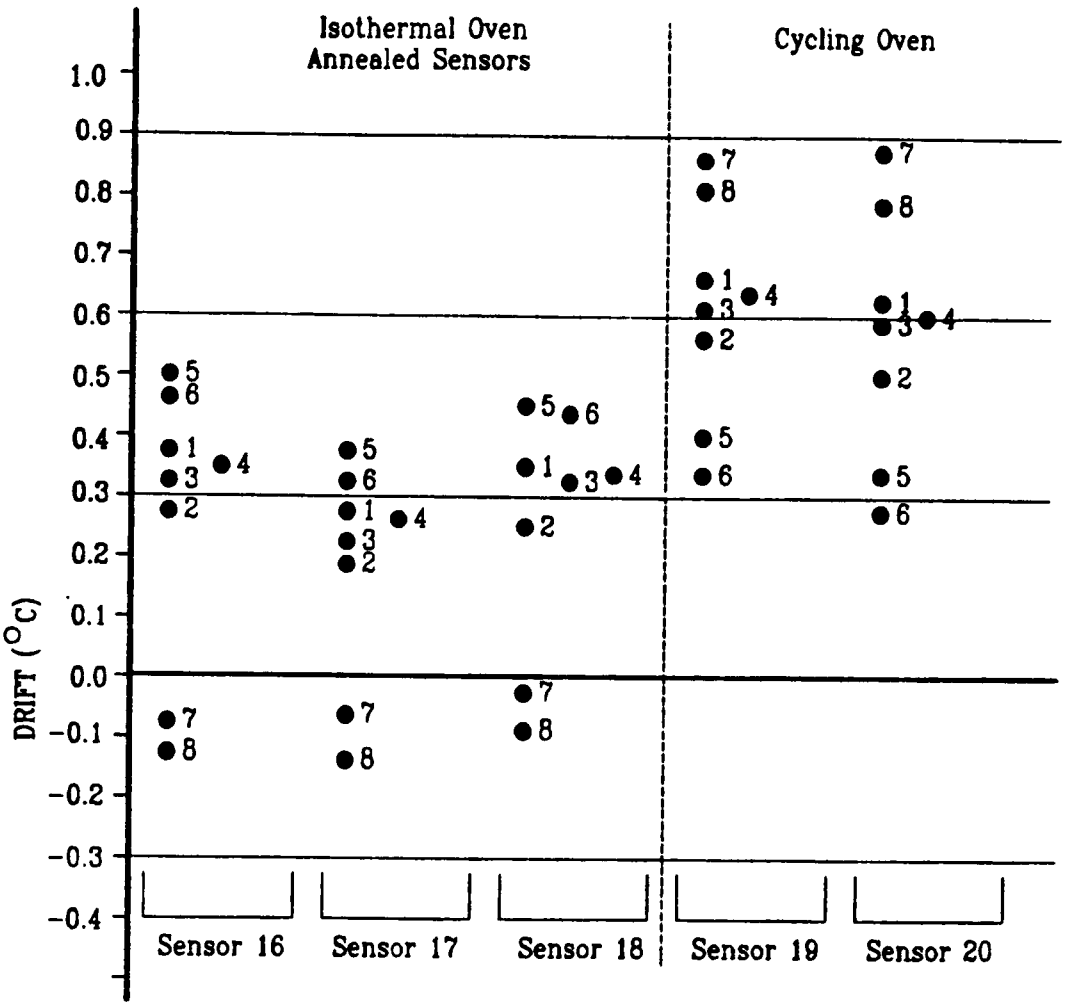


Figure 6.23 Inaccuracies of all the Sensors of Group 3 after 2016 Hours in the Ovens, and Calibrated at 100 °C.

may be identified even though they are close to each other. Cluster 1 consists of channels 5 and 6 (Type K TC) with positive drift between 0.28 and 0.4 °C. The second cluster consists of channels 1, 2, 3, and 4 (Type E TCs) with positive drift between 0.49 and 0.65 C. The third cluster consists of channels 7 and 8 (non-standard TCs, Kn-En) with drift range of 0.78 to 0.88 °C. The discrepancy between the behavior of both groups may be attributed to replacing Nn with Kn. The discrepancies between sensors 16, 17, 18 and sensor 19 and 20 are attributed to the environment (isothermal versus thermal cycling) and annealing of sensors 16, 17 and 18.

B. All the channels of the sensors placed in the isothermal oven showed an overall increase in drift as the calibration temperature increased. On the other hand, channels 5 and 6 (Type K TC) of sensors 19 and 20 showed a decrease in drift as the calibration temperature increased, while the rest of the channels showed an increase.

C. All channels of sensors 16 and 18 were compared after 2016 hours exposure to investigate the effect of frequency of testing on drift rates. Channels 1 through 6 showed an increase in drift as the frequency of testing increased. The increase in drift was more pronounced at 250 °C calibration point than at 100 °C. Channels 7 and 8, however, showed an opposite effect

whereby the drift decreased with frequency of testing.

All channels of sensors 19 and 20 were also compared after 2016 hours in the cycling oven. Channels 1, 2, 3, 4, 7 and 8 showed no (less than 0.02 °C) effect due to test frequency in either direction. Channels 5 and 6 showed up to 8/100th °C increase in drift as the frequency increases.

6.4.7 Performance of Group 4

This group utilizes the same thermoelements as group 1 with the exception of replacing Jp with Kn. All three sensors (i.e., 21, 22, and 23) of this group were inserted in the cycling oven. The drift calculations are presented in Table 6.13. Plots of the drifts of sensors 21 and 22 at 100 C are shown in Figure 6.24. The drifts of sensors 21, 22 and 23 at 100 °C after 2016 hours of exposure are shown in Figure 6.25. The following observations are made:

A. The drift of all sensors after 2016 hours and 100 °C calibration point was within the interval -0.55 and 0.80 °C. Channels 5 and 6 showed a negative drift, and the rest were positive. Therefore, the conditions were favorable to use weight factors to reduce the overall error drastically.

B. By consulting Table 6.13, it is clear that as the calibration temperature increased, the drift rate increased in the positive direction for channels 1, 2, 7

Table 6.13 Drift Results of Group 4.

Sensor ID	Time Hours	Ch 1			Ch 2			Ch 3			Ch 4			Ch 5			Ch 6			Ch 7			Ch 8		
		100	200	250	100	200	250	100	200	250	100	200	250	100	200	250	100	200	250	100	200	250	100	200	250
21	0	0.29	0.29	0.04	0.45	0.69	0.81	0.11	-0.43	-0.66	0.11	-0.19	-0.42	0.20	+0.15	+0.20	-0.38	-1.63	-1.77	+0.37	+1.02	0.73	-0.03	-0.68	-1.06
	6	0.43			0.57			0.24			0.02			0.31			-0.44			0.64			0.10		
	24	0.46			0.57			0.25			0.11			0.01			-0.36			+0.67			0.15		
	48	0.52			0.58			0.28			0.09			-0.13			-0.42			0.74			0.27		
	72	0.52			0.58			0.32			0.11			-0.04			-0.40			0.74			+0.25		
	168	0.54	0.84	0.78	0.62	1.15	1.19	0.33	-0.09	-0.30	0.12	-0.06	-0.18	-0.09	-0.43	-0.50	-0.42	-2.20	-2.60	+0.75	+1.79	+1.94	+0.29	-2.94	+0.12
	336	0.56			0.61			0.32			+0.11			-0.18			-0.52			+0.68			+0.34		
	672	0.60	0.96	0.97	0.66	1.25	1.29	0.36	0.02	-0.20	+0.12	-0.04	-0.15	-0.14	-0.54	-0.68	-0.48	-2.29	-2.60	+0.79	+1.95	+2.17	+0.36	+0.48	+0.36
	1176	0.63			0.70			0.38			+0.10			-0.18			-0.58			0.78			+0.39		
	2016	0.69	1.13	1.23	0.80	1.45	1.58	0.49	0.23	0.12	+0.09	-0.07	-0.14	-0.23	-0.69	-0.91	-0.56	-2.42	-2.99	+0.74	+1.94	+2.33	+0.39	+0.56	+0.66
22	0	0.25	0.30	0.03	0.41	0.69	0.78	+0.07	-0.41	-0.67	0.08	-0.16	-0.39	+0.17	+0.18	+0.21	-0.42	-1.56	-1.73	0.33	+1.04	+0.74	-0.06	-0.64	-1.04
	168	0.53	0.82	0.77	0.59	1.10	1.15	0.30	-0.15	-0.33	0.15	-0.05	-0.14	-0.05	-0.40	-0.45	-0.39	-2.15	-2.51	+0.77	+1.79	+1.94	+0.31	+0.29	+0.14
	336	0.57			0.61			0.31			+0.14			-0.16			-0.51			+0.71			+0.37		
	672	0.58	0.94	0.94	0.62	1.18	1.22	0.32	-0.05	-0.27	+0.14	-0.01	-0.10	-0.09	-0.50	-0.61	-0.45	-2.23	-2.71	0.81	+1.95	+2.17	0.37	0.48	+0.41
	1176	0.63			0.68			0.36			0.14			-0.16			-0.56			0.84			0.44		
	2016	0.69	1.14	1.22	0.76	1.42	1.51	0.44	0.20	0.05	0.12	-0.00	-0.07	-0.19	-0.64	-0.83	-0.53	-2.37	-2.91	0.79	2.02	2.38	0.43	0.65	0.72
23	0	0.29	0.25	0.04	0.47	0.86	0.81	0.13	-0.44	-0.69	0.12	-0.19	-0.40	0.24	+0.21	+0.21	-0.35	-1.58	-1.77	+0.35	+0.98	+0.76	-0.04	-0.74	-1.07
	2016	0.69	1.10	1.21	0.77	1.41	1.53	0.47	0.21	0.05	0.10	-0.05	-0.11	-0.21	-0.67	-0.87	-0.53	-2.38	-2.95	+0.75	+1.96	+2.35	+0.42	+0.59	+0.68

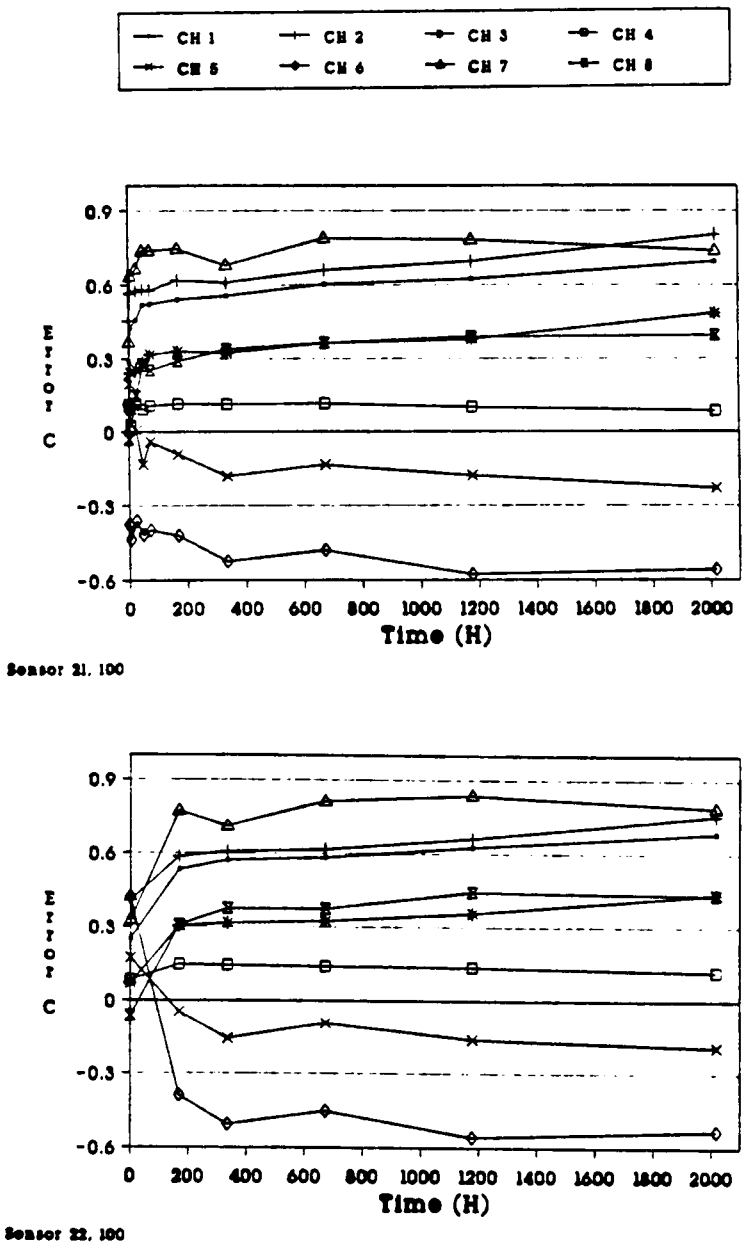


Figure 6.24 Drift Versus Time of the Most Frequently Tested Sensors of Group 4 Calibrated at 100 ^{0}C.

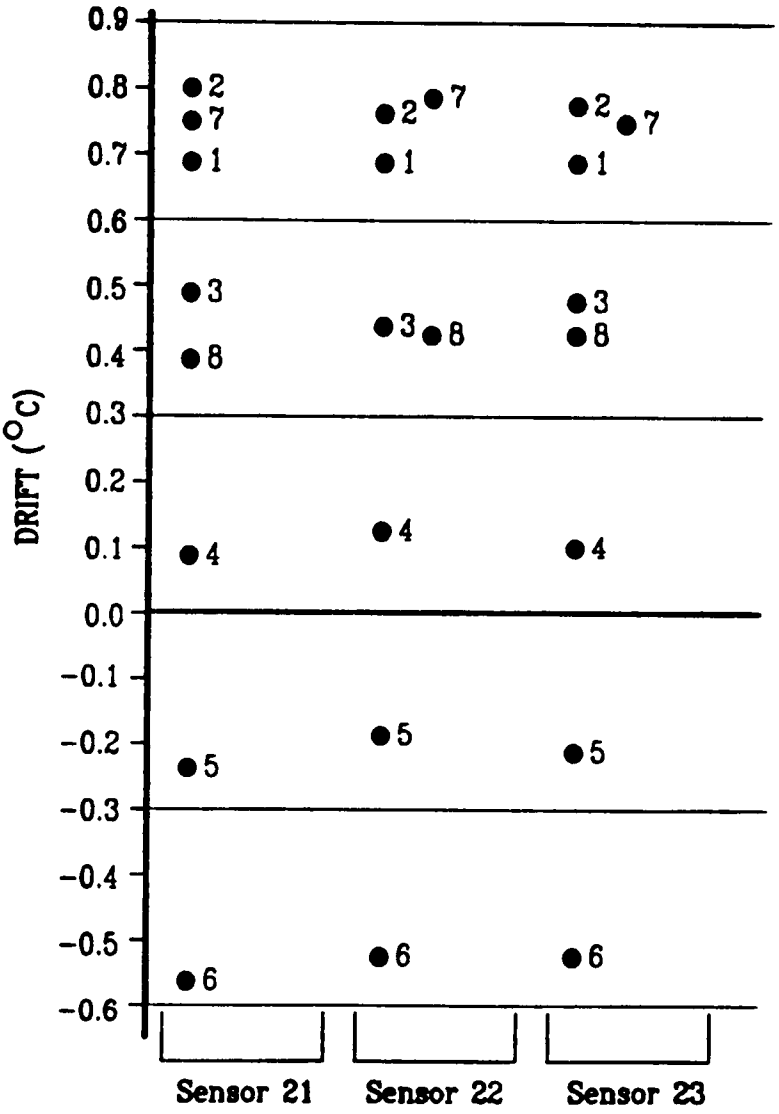


Figure 6.25 Inaccuracies of all the Sensors of Group 4 after 2016 Hours in the Ovens, and Calibrated at 100 ^{0}C.

and 8. Channels 3, 4, 5 and 6, however, showed an increase in drift in the negative direction.

C. Sensors 21 and 23 were compared to determine if the frequency of removal from the high temperature environment would have any effect on the sensors' drift. Initial calculations were made in order to remove the effect of the initial drift of the sensor from the test frequency analysis. This was accomplished by subtracting drifts of all the channels at all the temperatures at time 0 of sensor 23 from those of sensor 21. The resulting numbers represent the difference in the initial state of the sensors. Next, the same subtraction process was made at 2016 hour points. The resulting numbers represented the differences in the final state of those sensors. Finally, the initial state differences were subtracted from the final state differences resulting in the true effects of the test frequency. The final differences were within -0.06 °C and 0.05 °C. The majority of the values were evenly distributed around 0 °C. Hence, it can safely be concluded that the effect of sensor removal from the process for testing purposes was negligible for this group.

6.4.8 Performance of Group 5

Thermoelements similar to those used in Group 1 are used in this group with the exception of replacing Jp with another En thermoelement. This group, consisting of sensors 24, 25 and 26, was placed entirely in the cycling oven, and was not exposed to high temperature annealing. The resulting drifts are presented in Table 6.14. Plots of the drifts at 100 °C calibration point are shown in Figure 6.26. The drifts of all channels of all sensors at 2016 are plotted as shown in Figure 6.27. The following observations and analyses are made.

A. Channels 2, 5, 7 and 8 of sensor 26 showed huge errors. The common element between those channels is Nn. Therefore two possibilities were investigated.

   1. That Nn wire was detached at the measuring junction.
   2. That a wire other than Nn was accidentally used in fabricating the sensor.

   The first possibility was ruled out since resistance measurements between the various wire pairs of those channels was low (less than 2 Ohms) indicating no junction detachment. Furthermore, there was consistent and measurable, though erroneous, emfs generated at those channels. This also led to the belief that the second hypothesis was correct. This, unfortunately, limits the frequency of testing investigation to only the remaining four channels.

Table 6.14 Drift Results of Group 5.

Sensor ID	Time Hours	Ch 1			Ch 2			Ch 3			Ch 4			Ch 5			Ch 6			Ch 7			Ch 8		
		100	200	250	100	200	250	100	200	250	100	200	250	100	200	250	100	200	250	100	200	250	100	200	250
24	0	0.25	0.26	0.07	0.44	0.89	0.87	0.06	-0.18	-0.51	0.11	-0.19	-0.39	+0.28	+0.19	+0.21	-0.13	-0.86	-1.33	-0.57	-1.63	-2.37	-0.09	-0.75	-1.24
	6	0.45			0.59			0.22			0.09			0.07			-0.11			-0.31			0.11		
	24	0.50			0.60			0.27			0.12			-0.05			-0.11			-0.23			0.21		
	48	0.56			0.62			0.29			0.11			-0.15			-0.09			-0.14			0.32		
	72	0.56			0.58			0.33			0.10			-0.13			-0.11			-0.11			+0.34		
	168	0.56	0.86	0.92	0.63	1.19	1.33	0.33	+0.35	+0.25	0.13	-0.04	-0.12	-0.08	-0.40	-0.52	-0.09	-0.59	-0.86	-0.14	-0.71	-1.14	+0.33	+0.31	+0.24
	336	0.58			0.64			0.33			+0.12			-0.22			-0.16			-0.07			+0.38		
	672	0.60	1.00	1.04	0.66	1.29	1.36	0.35	0.52	+0.38	+0.12	-0.04	-0.12	-0.11	-0.54	-0.68	-0.07	-0.55	-0.82	-0.05	-0.57	-1.00	+0.36	+0.47	+0.46
	1176	0.67			0.73			0.43			+0.11			-0.20			-0.11			0.02			+0.44		
	2016	0.72	1.22	1.35	0.80	1.58	1.76	0.51	0.78	0.78	+0.09	-0.07	-0.14	-0.24	-0.73	-0.93	-0.08	-0.51	-0.74	+0.05	-0.29	-0.56	+0.40	+0.59	+0.66
25	0	0.13	-0.20	-0.43	0.47	0.82	0.88	0.12	-0.22	-0.44	-0.09	-0.69	-1.00	+0.19	+0.20	+0.17	-0.13	-0.86	-1.29	-0.48	-1.63	-2.24	-0.42	-1.81	-2.39
	168	0.39	0.41	0.25	0.62	1.15	1.23	0.34	+0.36	+0.19	-0.08	-0.56	-0.84	-0.10	-0.45	-0.55	-0.08	-0.59	-0.89	-0.08	-0.66	-1.15	-0.07	-0.71	-1.20
	336	0.38			0.60			0.30			-0.09			-0.20			-0.15			-0.07			-0.08		
	672	0.46	0.59	0.47	0.68	1.26	1.34	0.39	+0.55	+0.43	-0.07	-0.52	-0.79	-0.14	-0.58	-0.76	-0.06	-0.51	-0.78	0.04	-0.45	-0.82	0.00	-0.46	-0.65
	1176	0.49			0.71			0.42			-0.06			-0.18			-0.09			0.03			0.05		
	2016	0.54	0.75	0.68	0.73	1.46	1.58	0.48	0.67	0.62	-0.07	-0.49	-0.75	-0.24	-0.65	-0.83	-0.07	-0.50	-0.74	0.06	-0.36	-0.65	0.06	-0.35	-0.66
26	0	0.27	0.12	-0.10				0.24	0.07	+0.15	-0.09	-0.67	-0.99				-0.13	-0.89	-1.27						
	2016	0.72	1.12	1.20				0.64	1.05	1.13	-0.07	-0.46	-0.69				-0.07	-0.47	-0.70						

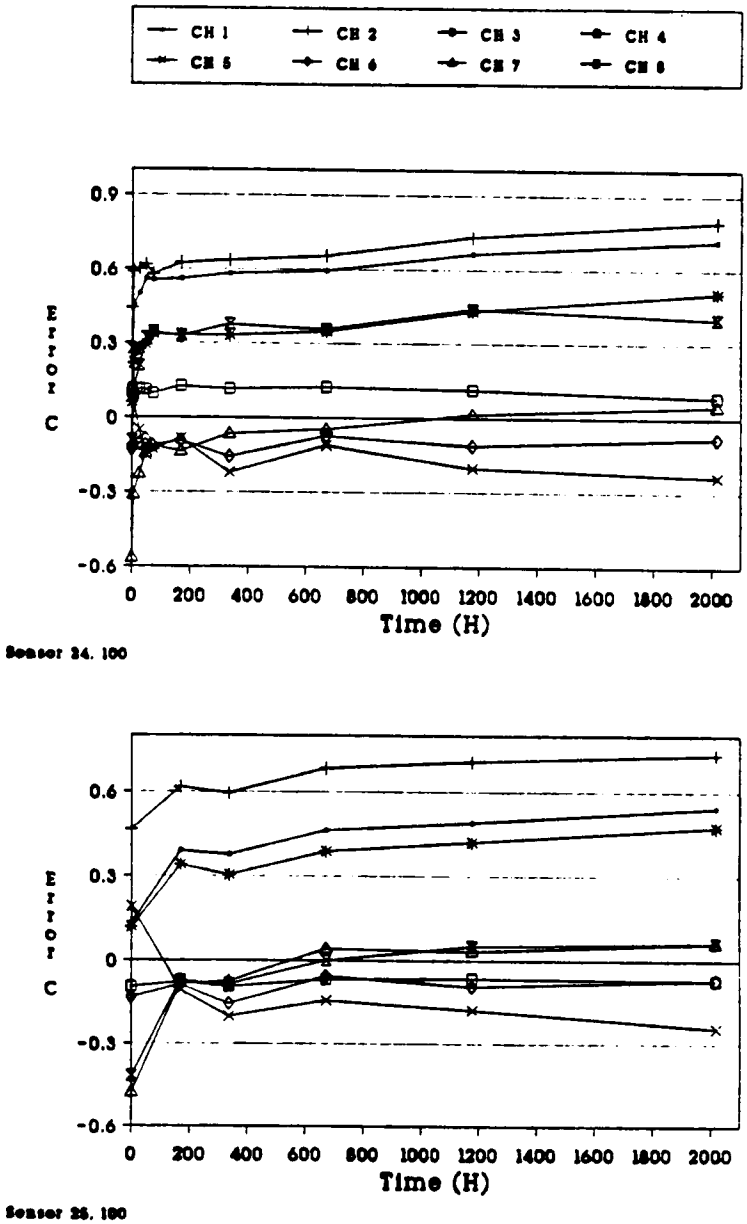


Figure 6.26 Drift Versus Time of the Most Frequently Tested Sensors of Group 5 Calibrated at 100 ^{0}C.

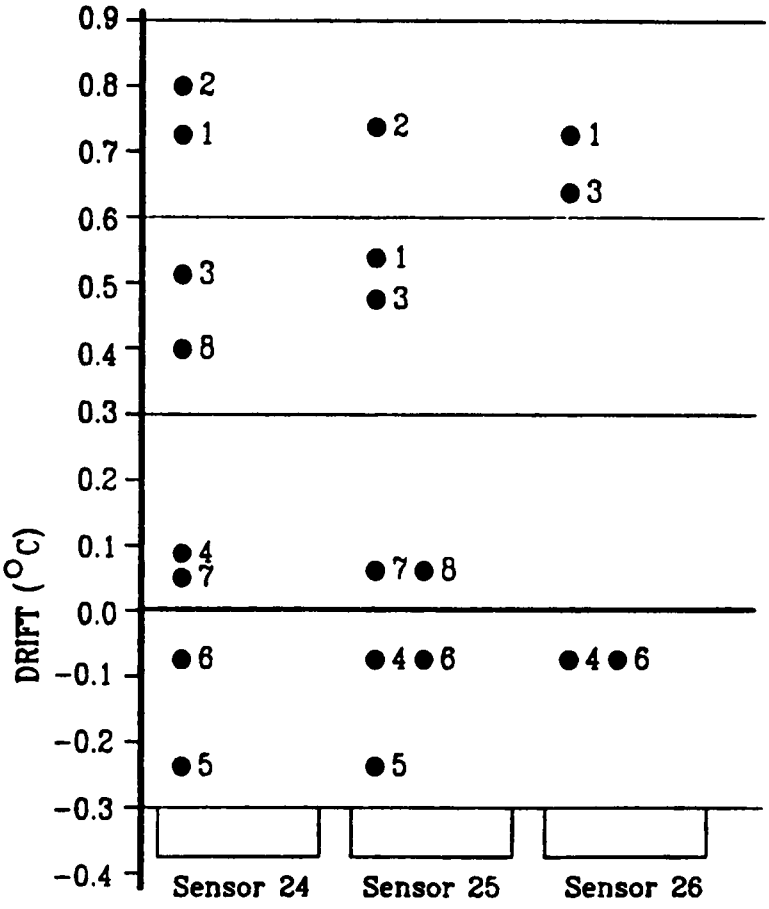


Figure 6.27 Inaccuracies of all the Sensors of Group 5 after 2016 Hours in the Ovens, and Calibrated at 100 °C.

In general, this group showed relatively small errors as can be seen in Figures 6.26 and 6.27 and Table 6.14. Channels 4, 5, 6, and 7 produced errors with the range of 0.09 to -0.25 °C at 100 °C calibration.

B. Channels 1, 2, and 8 showed a positive increase in drift as the calibration temperature increased. The remaining channels showed an increase in the negative direction as the calibration temperature decreased.

C. Sensor 24 and 26 were analyzed to investigate the effects of test frequency. Calculations similar to the ones used in Section 6.4.7 were carried out on channels 1, 3, 4, and 6 (since the remaining channels of sensor 26 are not usable). Although the differences in the initial states (at 0 hour) between sensors 24 and 26, and the differences in the final state (at 2016 hours) of both sensors are, in some cases, large (-0.66 or 0.55 °C), the differences between the initial and final states were mostly minimal (less than 0.1 °C) and distributed about 0 °C. Hence, it can be assumed that there are no appreciable effects due to sensor removal from the process for calibration.

6.4.9 Intra-Groups Comparison and Summary of Results

In the previous sections, the performance of each of the five MTC groups were analyzed. To complete the analysis, the performance of each group with respect to the

other groups must be carried out. The comparison is complicated since each group showed a range of maximum and negligible drifts depending on the wire combinations. Therefore analyzing the performance of each wire pair that is used in more than one group may provide insights and explanations to these extremes of behavior.

There are seven different thermoelement pairs that were used in more than one group. Those are: Ep-En, Ep-Nn, Np-En, Nn-En, Np-Nn, Ep-Kn, and Kn-En. An attempt is made to study the performance of those TCs in each group. To facilitate the study, the average of the final drifts of all the channels utilizing Ep-En of all the sensors of group 1 that were placed in the isothermal oven is calculated. Similar number was found for the sensors that were placed in the cycling oven. The same procedure is used for each group that utilize Ep-En. The entire procedure is repeated for each of the remaining wire pairs. The results of these calculations are presented in Table 6.15. The channels that were not used in more than one group were also added to this Table to complete the analysis.

The Ep-En combination (i.e., Type E TCs), showed consistent behavior in all of the groups. Annealing the TCs resulted in reducing the drift by about 50%.

The Ep-Nn combination produced slightly larger drift in all the groups that Ep-En. The largest drift is in group 1. This may be attributed to using Jp in this group while it

Table 6.15 Average Errors at 100 °C after 2016 Hours of Exposure as Indicated by the Various TC Pairs in all the Sensors of Each MTC Group.

Thermoelement and Status A=Annealed N=Not Annealed		Average Error (°C)				
		Group 1	Group 2	Group 3	Group 4	Group 5
Ep-En	A	0.354	0.333	0.294	-	-
	N	0.68	0.578	0.598	0.69	0.602
Ep-Nn	A	0.966	0.855	-	-	-
	N	0.804	0.645	-	0.777	0.765
Np-En	A	-0.35	-	-	-	-
	N	0.108	-	-	0.103	-0.045
Nn-En	A	-0.684	-0.508	-	-	-
	N	0.346	0.388	-	0.43	0.143
Np-Nn	A	-0.032	-	-	-	-
	N	-0.106	-	-	-0.21	-0.24
Ep-Kn	A	-	-	0.423	-	-
	N	-	-	0.338	0.467	-
Kn-En	A	-	-	-0.085	-	-
	N	-	-	0.833	0.760	-
Ep-Jp	A	0.453	-	-	-	-
	N	0.424	-	-	-	-
Jp-En	A	0.193	-	-	-	-
	N	0.618	-	-	-	-
Jp-Nn	A	1.073	-	-	-	-
	N	0.864	-	-	-	-
Np-Kn	A	-	-	0.433	-	-
	N	-	-	0.31	-	-

was removed from group 2. Np was also not used in group 2. However, Np was utilized in group 5, which closely resembles group 1 without Jp, which also produced lower drifts.

Annealing resulted in a slight increase in drift. Group 2 showed the biggest change due to annealing since the unannealed sensors showed the lowest drift rates.

The Np-En TCs showed the lowest overall drift rates. Annealing of these TCs in group 1 caused them to have a larger negative drift.

Nn-En, in the annealed state, showed large negative drifts. In the unannealed state, the drift was positive, with group 5 showing the least drift.

Np-En (i.e., Type N TC) showed low negative drift in both the annealed and unannealed states.

Ep-Kn showed moderate drift in both annealed and unannealed state. Its drifts are approximately half of that of Ep-Nn. Hence, one may jump to the conclusion that replacing Nn with Kn would result in reducing the drift rates. However, if Kn-En performance is considered, one will see that in the unannealed state Kn-En TCs resulted in twice the drift that is experienced by Nn-En. Hence, replacing Nn with Kn in the absence of Jp may not reduce the drift rate if the MTCs are not annealed. In the annealed state, however, group 3 (where Kn replaced Nn) did show a reduction in the drift rates.

The accidental annealing of some of the sensors of groups 1, 2, and 3 had different effects on those sensors. Although it led to reducing the drift of channel 6 of group 1, it caused an overall increase in drift of the remaining channels. An advantage to this increase in drift is that channels 5 and 4 showed an increase in drift in the negative direction. Such process could result in a higher accuracy of measurements by the STMS where the negative errors would cancel out the positive errors. This effect can be enhanced with the use of weight factors.

Similar behavior has occurred in group 2 which consists of only three different types of wire combinations. Those are Ep-En, Ep-Nn, and Nn-En. The annealed sensors showed an increase in drift (some in the negative directions). However, the drifts of this set of sensors was less than the comparable ones of group 1. The annealed sensors of group 3 showed, overall, the lowest drift rates. The only difference between group 3 and 2 is that Kn replaced Nn of group 2. The reader is reminded that this group consists of 4 Type E TCs (Ep-En), 2 Type K TCs (Ep-Kn) and 2 non-standard TCs (Kn-En) that utilize parts of Type E and Type K thermoelements.

When the unannealed sensors including sensors of groups 4 and 5 were also compared, group 2 showed the least overall drift.

All the groups showed an increase in drift both in the positive or negative direction, as the calibration temperature increased.

The effect of frequency of testing varied from group to group. Sensors of group 1 placed in the cycling oven showed an increase in drift as a result of frequent removal from the environment and testing in the laboratory. The sensors placed in the isothermal oven also showed an increase, though smaller, in drift due to increased testing frequency. The amount of increase varied from channel to channel. Sensors of group 2 that were placed in the cycling oven showed negligible increase in drift at 100 °C, and a noticeable increase in drift at 250 °C; while sensors placed in the isothermal oven and were accidentally annealed, showed a negligible change in drift. Sensors of group 3 that were placed in the cycling oven showed an increase in drift at 250 °C for some of the channels. The remaining sensors showed an increase in drift in channels 1 through 6, and a decrease in drift in channels 7 and 8. Groups 4 and 5 were negligibly affected by the frequency of testing.

In conclusion, group 5 showed the lowest drift rates among the five groups in the unannealed state. The difference between group 1 and 5 lies in replacing Jp (i.e., the contamination effect of pure iron was eliminated) with another En wire. hence, the overall sensitivity to temperature of group 5 is higher than that of group 1. In

the annealed state, group 3 showed the lowest drift rates. In this case, wires Jp, Np, and Nn of group 1 were replaced with Kn, and an extra En and Ep wires. Hence, the overall contamination effect of pure iron was eliminated; while the sensitivity to temperature was increased dramatically. Furthermore, six wire pairs of this group showed large decrease in drift due to annealing while the remaining channels showed only a slight increase in drift.

CHAPTER 7

OPERATIONAL EXPERIENCE WITH THE STMS

The STMS has been subjected to extensive debugging and testing processes to ensure its reliability and credibility. The "user friendly" software is fully operational. It performs the desired functions as planned. Typical screen displays are presented in the next section.

The testing apparatus consisted of a small heater that heats water, and the STMS. The water temperature was determined by a mercury thermometer. When the MTC is inserted in the hot water, the STMS tracks the water temperature with very good agreement. No detectable difference is noticed between the STMS's displayed temperature and the mercury thermometer readings except during fast transients. Since, the MTC is insulated, it typically lags slightly behind the actual process temperature. The time response of the MTC may be the subject of future work.

On a few occasions, the interface seems to be susceptible to spurious noise. This noise triggers the counter and causes an unplanned closing of the next relay. This leads to erroneous temperature measurement because of the mismatch between the relay that the microprocessor assumes is on and the actual relay that is on. The problem

is easily solved by cutting off the power supply to the interface, and re-executing the STMS.BAS code. This process turns on relay 1, which provides a reference starting point to the code. Although, the occurrences of this problem is small, provisions to protect against it must be incorporated in the design of future commercial STMSs.

7.1 Displays

When the power to the amplifiers, interface, and pc is turned on the following sequence of events occur.

1. Upon the DOS prompt, the user must enter the command

```
c:\>PCLLDR STMS
```

to load and run the STMS code.

2. The system requests information regarding the type of monitor and graphics card used. The present PC is a Zenith XT with color monitor. Therefore, the user must input "C" or "c" indicating a color monitor. Next the title screen appears.

3. Upon pressing any key, the system displays the main menu, shown in Figure 7.1. If the user selects options 3, 4, or 5, then the corresponding sub-menus appear as shown in Figures 7.2, 7.3, and 7.4.

4. If the user selects option 3 of the main menu, and option 1 of the corresponding sub-menu, a graph indicating the maximum (Cyan) and minimum (Red) temperatures that were recorded in every hour of the past month. A simulated

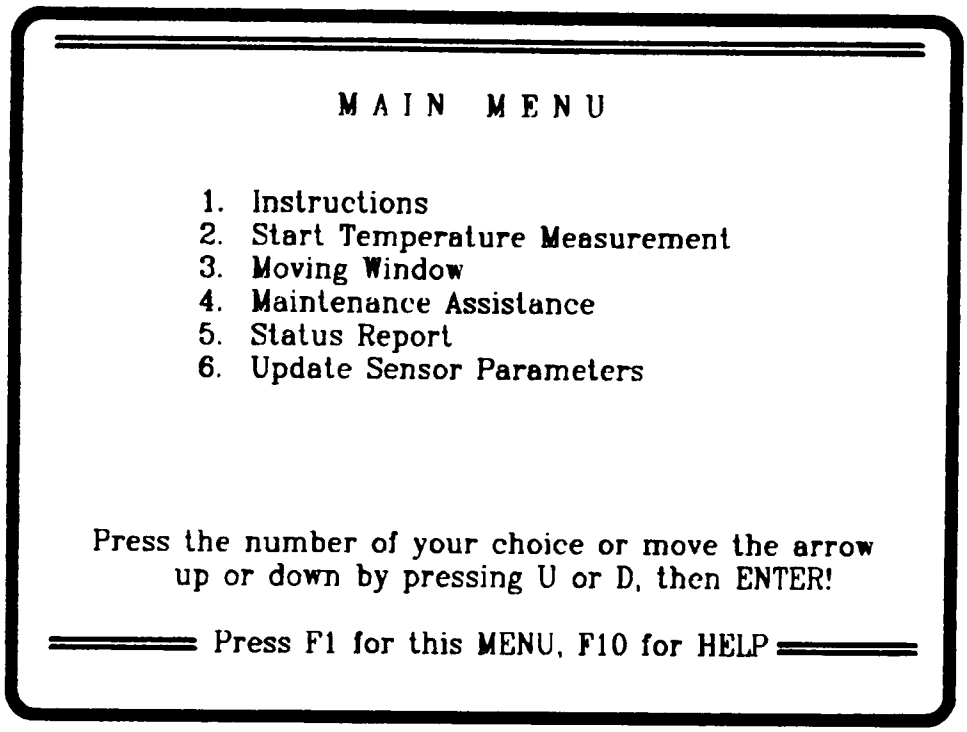


Figure 7.1 The Main Menu Screen.

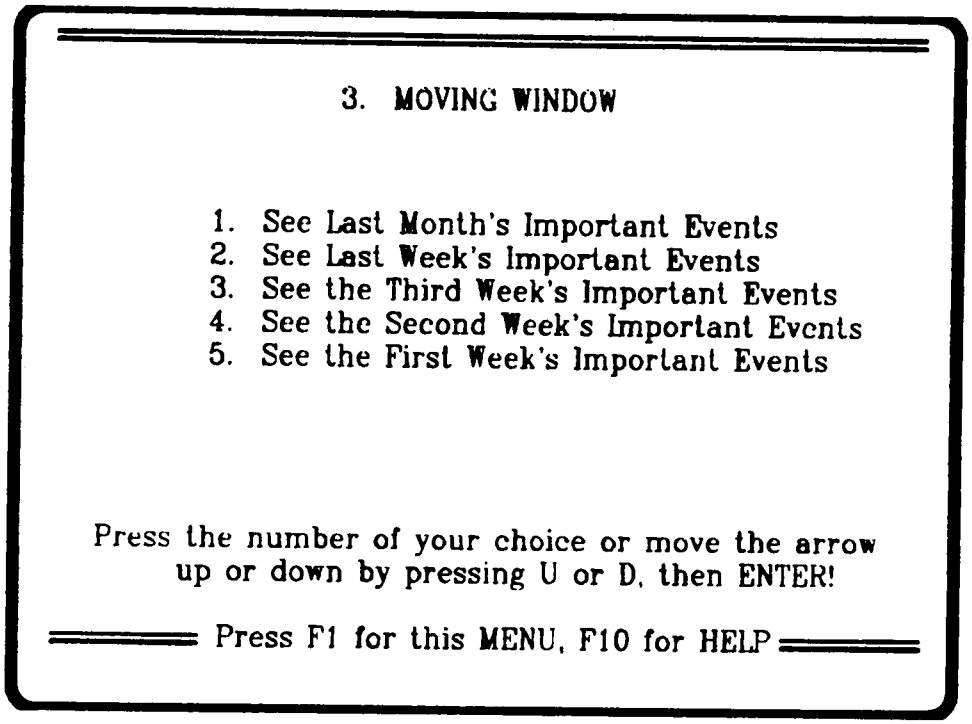


Figure 7.2 The Moving Window Sub-Menu Screen.

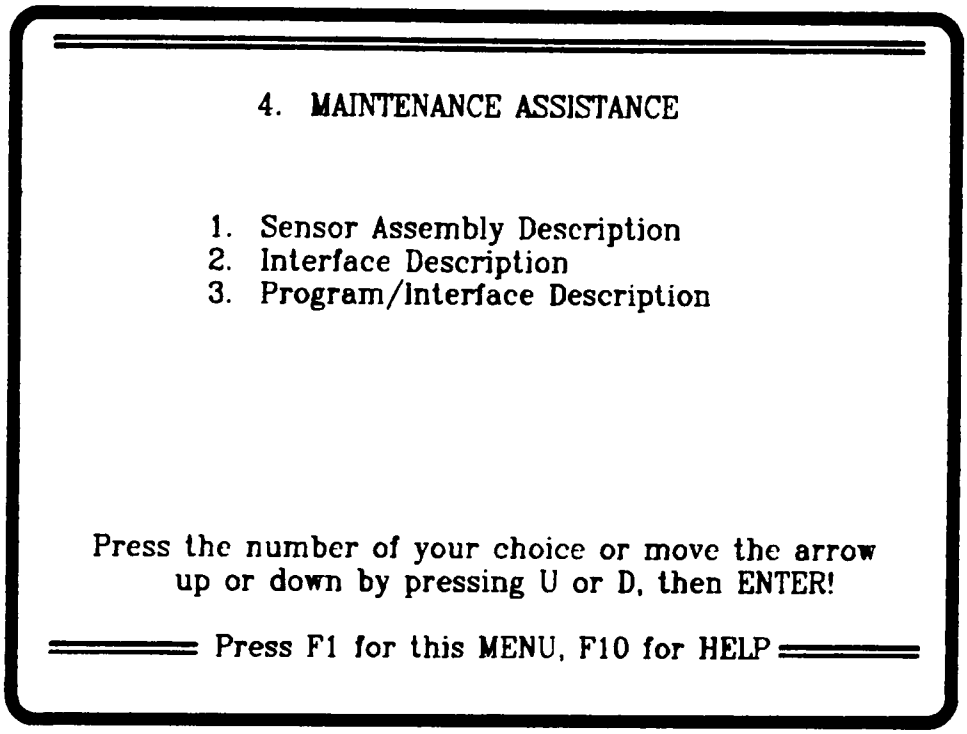


Figure 7.3 The Maintenance Assistance Sub-Menu Screen.

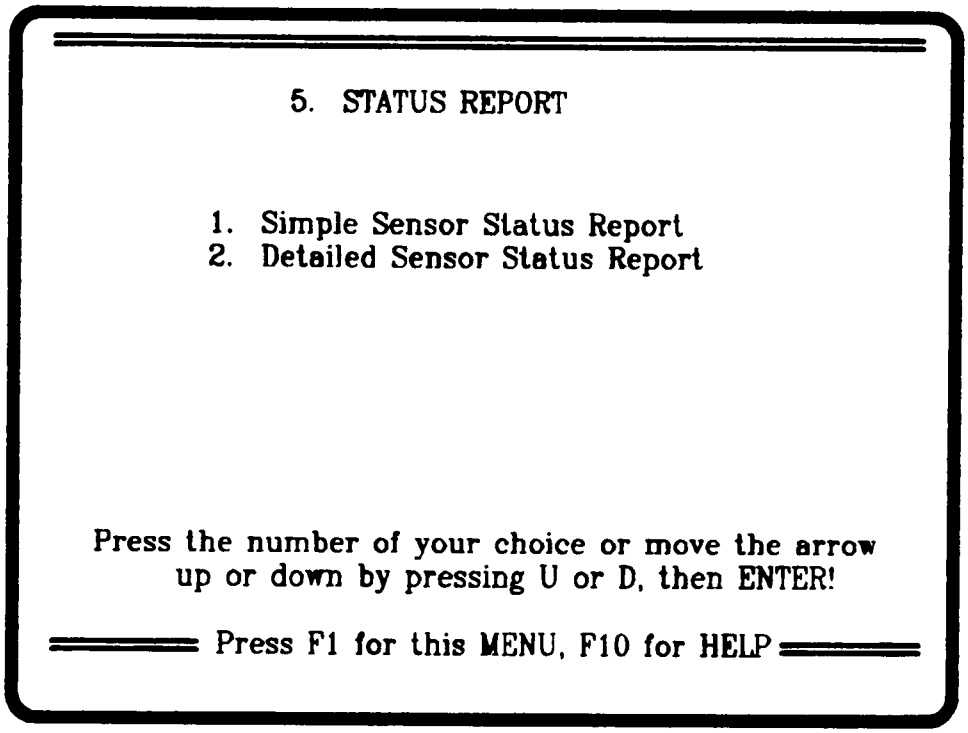


Figure 7.4 The Status Report Sub-Menu Screen.

display is shown in Figure 7.5.

5. If the sensor parameters are to be modified, the sixth option of the main menu is selected. For example, in order to replace the old weight factors with the weight factors that were developed based on the actual experimental performance of group one (as described in Chapter 6, Section 6.4.4), then

a. Select option 6 in the main menu

b. Answer with "N" (or "n") to all the questions (indicating no parameter modification desired) until the system displays a question about the weight factors.

c. Answer with "Y" (or "y") to the question

Do you wish to update the constant weight factors (Y/N)?

d. Answer with "Y" (or "y") when the system displays the messages

The current weight factor used in conjunction with channel (1) is:

x

Does this value need to be changed? (Y/N)

(where x represents the last weight factor available in the system's memory)

e. On the same screen, the system requests the new weight factor by displaying the message

Input the new weight factor?,

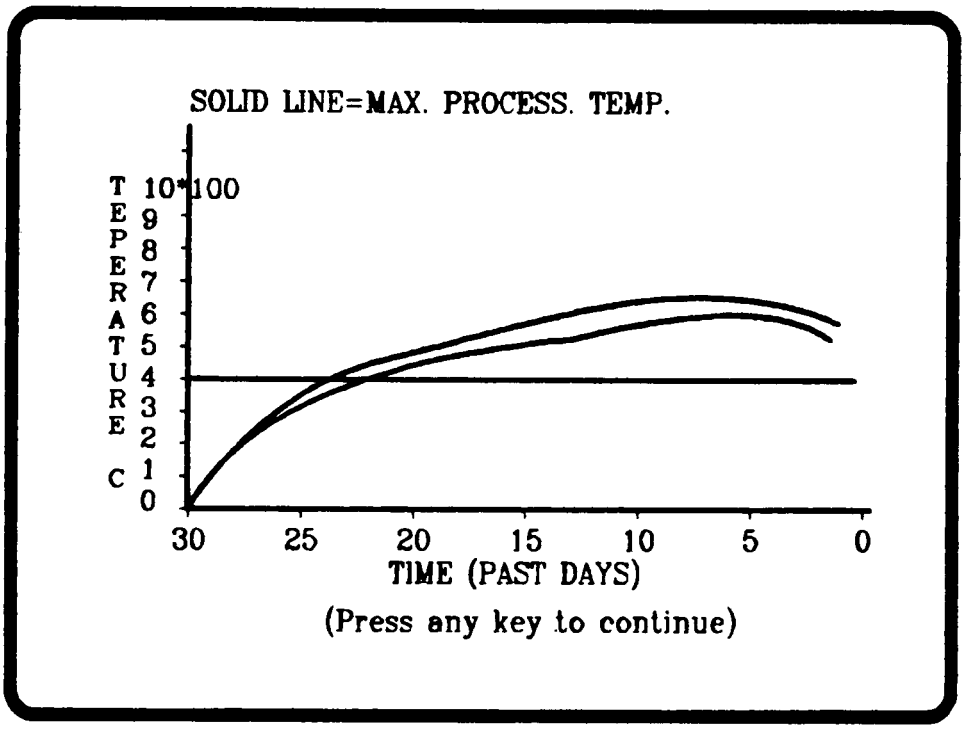


Figure 7.5 A Typical Screen of Simulated One Month History of Hourly Maximum and Minimum Temperatures.

and waiting for the user's input. The user enters the proper value which can be found in Table 6.9.

f. The system clears the screen, and repeats steps 5.d and 5.e for each of the remaining channels.

g. The user can answer with "N" for the last question regarding the last date of maintenance.

h. Finally, the systems displays the message

Updating the PARM.DAT file ....

Then, the Main Menu screen appears again.

6. When the second option is selected to start the temperature measurement process, the initial questions must be answered (as discussed in Chapter 5, Section 5.4.2). Then, depending on the user's choice of Mode of Operation, the system displays the Normal Mode screen, shown in Figure 7.6, or the Fast Mode screen, shown in Figure 7.7.

7.2 System Speed

The system is slowest when the normal mode option is selected because the signal validation process is performed after every eight samples (one from each channel) are collected. When a PC-XT is used, this operation lasts for an average of 5 seconds. If an AT microprocessor is used, then this time is reduced.

In the commercial STMS, it is expected that the dedicated microprocessor will be much faster than the PC-XT microprocessor since the entire software will be "hardwared"

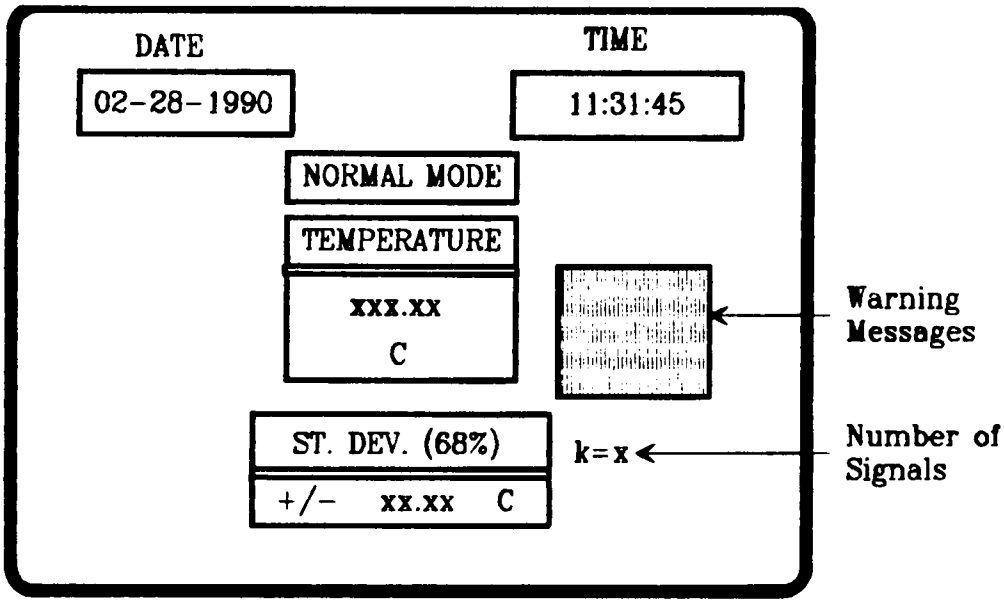


Figure 7.6 The Normal Mode Screen.

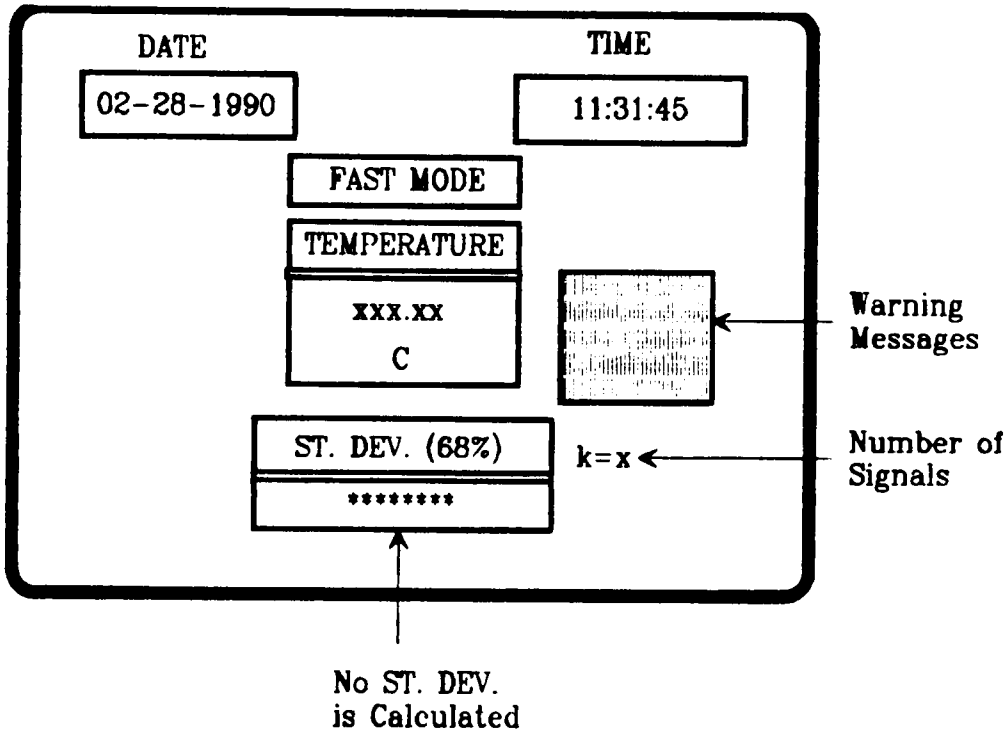


Figure 7.7 The Fast Mode Screen.

into the microprocessor. Furthermore, the size of the software may be reduced by eliminating some of the main menu options and the associated files.

CHAPTER 8

SUMMARY AND CONCLUSIONS

7.1 Summary and Conclusions

The first of a new line of microprocessor-based smart temperature measurement systems (STMS) has been developed and tested at the Nuclear Engineering Department of the University of Tennessee at Knoxville. The system depends on the availability of eight redundant signals, provided through a specially designed multi-lead thermocouple (MTC) and consequently utilizing on line signal validation methods, for self checking. Other intelligent duties such as communication, computation, maintenance assistance, and status reporting are also performed by the STMS.

The STMS consists of a sensor and a transmitter. The sensor consists of a five lead MTC made from the thermo-elements chromel (Ep), constantan (En), nicrosil (Np), nisil (Nn), and iron (Jp). Although ten redundant temperature measurements are possible using a 5 lead MTC, only eight signals were useful using these thermo-elements. Low sensitivity to variation in the process temperature resulted in eliminating the two remaining signals (Ep-Np, and Jp-Np).

Interpolation polynomials describing the relationship between the emf and temperature for the standard and non-standard wire pairs were obtained experimentally in the temperature range of 100 °C to 300 °C, and verified

theoretically. There was good agreement between the theoretical and experimental polynomials. The theoretical polynomials were then used in the software to convert the raw analog signals to meaningful temperature measurements.

The transmitter of the STMS currently consists of a unique microprocessor controlled interface that provides a mechanism for switching between the various thermo-element pairs and a data acquisition board with 12 bit A/D and D/A convertors housed inside a personal computer. Other parts of the transmitter include two linear amplifiers, a power supply, and a screw terminal panel. The entire operation of the system is controlled by a computer code.

In a commercial STMS the entire hardware of the present transmitter will be replaced with a single miniature device housing a dedicated microprocessor, signal conditioning devices, and an interface.

Welding the five different alloys (one for each thermoelement) in a single junction, and encasing them in a 1/4 inch stainless steel sheath then exposing such sensors to elevated process temperature for a long period of time led to obvious concerns about the long term drift of those sensors. Hence, a great deal of effort was diverted toward qualifying the MTCs for long term use in industrial processes. This was accomplished by inserting five different MTC groups (including the original design group) into two ovens for a period of three months. The first oven

was cycling between 200 and 300 °C every six hours, while the other was maintained at 300 °C. Sensors of each group were removed and calibrated at various time intervals during the three month period. Several factors, such as the effect of the calibration temperature, type of environment, annealing, frequency of testing, and type of elements used in the MTC, on the drift rate of the sensors were investigated. It can be concluded that the drift of MTCs in the simulated environment is comparable to drifts experienced by standard two lead TCs. Furthermore, when weight factors were used to find the average absolute error of the eight measurements indicated by each sensor of group 1 (the original design), a drastic reduction in errors were observed.

7.2 Future Work

This research represents a pilot study in the field of smart sensors at the University of Tennessee at Knoxville (UTK). The STMS is the first smart system fully developed at UTK that is aimed at improving temperature measurement at nuclear power plants and other industries. There are several aspects of this research that may be subject for further investigations before the STMS is ready to be commercialized. A list of those areas follows.

A. Expand our knowledge of MTCs behavior under simulated industrial environments by:

1. Fabricating and testing more MTCs of the same Types discussed in this Dissertation to improve the statistical quality of the present work.

2. Fabricating new Types of MTCs. Some of the new MTCs may incorporate Pt-67 as one of the thermo-elements which may simplify converting the emf to temperatures by simply using published interpolation polynomials.

3. Studying the MTCs behavior at elevated temperatures (500 to 1000 °C) since gross drifts and sensor failures typically occur at high temperature.

B. Modify the STMS to accommodate different Types of MTCs.

C. Test the STMS in a live process.

D. Develop the commercial type STMS as discussed in Section 5.6.

E. Develop a network of STMSs capable of communicating among themselves.

F. Introduce the element of diversity to the STMS by modifying it to accommodate other smart sensor designs, such as the dual/diverse sensors (sensors containing an RTD and a TC or more) and the melt/freeze sensors (sensors containing an encapsulated pure metal that typically melts below the normal process temperature and, hence, provides a calibration point) in a single super sensor setting.

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APPENDIX:

LISTING OF THE APPLICATION AND AUXILIARY PROGRAMS

LISTING OF THE STMS.BAS CODE

```
00001 GOTO 89
00010 0!      C
00030 .97      C
00089 KEY OFF
00091 CLS:PRINT:PRINT
00092 PRINT "                                        HI":PRINT:PRINT
00093 PRINT"         BEFORE WE BEGIN...."
00094 PRINT"             PLEASE PRESS THE LETTER THAT
      CORRESPONDS TO       THE TYPE OF MONITOR"
00095 PRINT"            AND CARD THAT YOU HAVE ON YOUR
      COMPUTER"
00096 PRINT:PRINT:PRINT"                    C =====> COLOR
      MONITOR AND COLOR CARD"
00097 PRINT"                 M =====> MONO MONITOR AND MONO
      CARD"
00098 PRINT"                CM =====> COLOR MONITOR AND MONO
      CARD"
00100 PRINT:PRINT:PRINT:PRINT"     ....CONSULT YOUR COMPUTER
      MANUAL IF YOU ARE NOT SURE...."
00110 PRINT:PRINT:LOCATE 20,35 :INPUT Q$:IF Q$="c" THEN
      Q$="C"
00115 P=1
00120 IF Q$="C" OR Q$="c" THEN Q$="C"
00125 IF Q$="C" THEN 130 ELSE GOTO 500
00127 '=================================================
00130 SCREEN 1:COLOR 1,2:CLS:FOR J=1 TO 9:COLOR J,1:NEXT
00150 COLOR 1,4,1:LOCATE 2,5:COLOR ,3:PRINT"SMART
      TEMPERATURE"
00155 LOCATE 4,5:COLOR ,3:PRINT"MEASUREMENT SYSTEM"
00160 LOCATE 9,5:PRINT"Developed by:":LOCATE 11,5:
      PRINT"Majed N. Natour"
00165 LOCATE 12,25:PRINT"MARCH 15,1989"
00170 LOCATE 23,8:PRINT"Hit any key"
00175 LINE (319,2)-(0,199),2:LINE (319,1)-(0,199),2:LINE
      (316,0)-(0,199),3
00180 LINE (317,0)-(0,199),3:LINE (318,0)-(0,199),2:LINE
      (319,0)-(0,199),2
00185 LINE (319,3)-(163,99),3
00190 LINE -(150+RND*143,100+RND*93),RND*5+1,BF:A9$=INKEY$:
      IF A9$="" THEN 190
00194 GOTO 20000
00195 ' ================================================
00200 ' PCLAB BASIC definition file (long names)
00202 ' This file may be MERGEd with a user program
00204 ' to define routine offsets and establish the PCLAB
00206 ' segment.
00208 ADC.VALUE=3 : ADC.ON.TRIGGER=6 : SETUP.ADC=9 :
```

```
        ADC.SERIES=12
00210 BEGIN.ADC.DMA=15 : TEST.ADC.DMA=18 : WAIT.ADC.DMA=21
00212 DAC.VALUE=24 : DAC.ON.TRIGGER=27 : SETUP.DAC=30 :
        DAC.SERIES=33
00214 BEGIN.DAC.DMA=36 : TEST.DAC.DMA=39 : WAIT.DAC.DMA=42
00216 SET.CLOCK.DIVIDER=45 : SET.SLOW.CLOCK=48 :
        SET.CLOCK.FREQUENCY=51
00218 SET.CLOCK.PERIOD=54 : ENABLE.FOR.INPUT=57 :
        ENABLE.FOR.OUTPUT=60
00220 INPUT.DIGITAL.VALUE=63 : OUTPUT.DIGITAL.VALUE=66
00222 INPUT.DIGITAL.ON.TRIGGER=69 :
        OUTPUT.DIGITAL.ON.TRIGGER=72
00224 SET.ERROR.CONTROL.WORD=75 : GET.ERROR.CODE=78 :
        SELECT.BOARD=81
00226 SET.BASE.ADDRESS=84 : SET.DMA.CHANNEL=87 :
        SET.ADC.RANGE=90
00228 SET.ADC.CHANNELS=93 : SET.DAC.RANGE=96 :
        SET.LINE.FREQUENCY=99
00230 SET.TOP.GAIN=102 : SET.TIMEOUT=105 : GET.DT.ERROR=108
        : RESET.DT=111
00232 GET.DT.STATUS=114 : CALL.WFC=117 : CALL.WFO=120 :
        CALL.WFI=123
00234 STOP.ADC.DMA=126 : STOP.DAC.DMA=129
00236 CONTINUOUS.ADC.DMA=132 : CONTINUOUS.DAC.DMA=135
00238 DELAY=138 : STROBE=141 : WAIT.ON.DELAY=144 :
        GENERATE.CLOCK=147
00240 COUNT.EVENTS=150 : READ.EVENTS=153 : GET.FREQUENCY=156
        : STOP.CLOCK=159
00242 INITIALIZE=162 : TERMINATE=165 : ISBX.READ=168 :
        ISBX.WRITE=171
00243 FIND.DMA.LENGTH=174 : ENABLE.SYSTEM.CLOCK=177 :
        DISABLE.SYSTEM.CLOCK=180
00244 DEF SEG=&H0  ' get the PCLAB segment
00246 PCLSEG = PEEK ( &H4FE ) + 256*PEEK ( &H4FF )
00248 DEF SEG=PCLSEG ' REM address the PCLAB segment
00250 GOTO 870
00260 '================================================
00270 DIM WTX(720),WTN(720)
00500 CLS:REM **********************THE MONO TITLE
        SCREEN*******************
00505 SCREEN 0,0,0
00510 CLOSE
00512 WIDTH 80
00514 CST=0
00516 DEF SEG=0
00518 POKE(&H180),CST
00520 CLEAR
00522 CST=PEEK(&H180):Q$="M"
00524  COLOR 7,0,0
00526 CLS:KEY OFF
00528 FOR I=2 TO 79:LOCATE 1,I:PRINT CHR$(205);:LOCATE
        25,I:PRINT CHR$(205);:NEXT
```

```
00530 LOCATE 25,25:PRINT"Please wait for few seconds";
00532 LOCATE 4,22:PRINT"S M A R T    T E M P E R A T U R E "
00534 LOCATE 6,22:PRINT"M E A S U R E M E N T    S Y S T E
      M"
00540 LOCATE 12,26:PRINT"DEVELOPED BY:  MAJED NATOUR"
00546 LOCATE 20,27:PRINT"     MARCH 15, 1989"
00600 GOSUB 7790      ' to wait 5 seconds
00850 REM ================================================
00860 REM  Define the polynomial coefficients of all the MTC
      pairs
00870 DEFDBL Y,B,Z,W,Q,F,T,X
00872 Y(1)=-5.172285158550949D-03:B(1)=+17.06493667399991#
00874 Z(1)=-.234631802416061#:W9(1)=+6.918500330641564D-03
00876 Q(1)=-1.181054119490099D-04:F(1)=+8.76157058474214D-07
00877 REM ..................................................
00878 Y(2)=-.0273294306552998#:B(2)=+27.60827767558658#
00880 Z(2)=-.3862178819254041#:W9(2)=+1.042302478685997D-02
00882 Q(2)=3.945916986936027D-06:F(2)=-3.648670092726292D-06
00883 REM ..................................................
00884 Y(3)=+1.553016505591586#:B(3)=+114.1889828162748#
00886 Z(3)=-22.09275594451901#:W9(3)=+3.699050096081919#
00888 Q(3)=-.3232329297995875#:F(3)=+1.122770519955196D-02
00889 REM ..................................................
00890 Y(4)=+4.337818470776256D-02:B(4)=+20.66649943155062#
00892 Z(4)=-.4033156315140332#:W9(4)=+1.453676531156134D-02
00894 Q(4)=-3.066151109081261D-04:F(4)=2.728883574276697D-06
00895 REM ..................................................
00896 Y(5)= .1437387905589276#:B(5)= 44.27579467661417#
00898 Z(5)=-2.238432529582496#:W9(5)= .1968485762349701#
00900 Q(5)=-9.770471180672757D-03:F(5)=1.998689799167508D-04
00901 REM ..................................................
00902 Y(6)=-1.766695429250831D-02:B(6)= 19.75671839805#
00904 Z(6)=-.2028284495409025#:W9(6)= 9.728538676881726D-03
00906 Q(6)=-1.827932131774901D-04:F(6)= 8.06177043843892D-07
00907 REM ..................................................
00908 Y(7)=-3.014612255356042D-02:B(7)= 38.6920016722579#
00910 Z(7)=-1.106879476217728#:W9(7)= 5.605095979854013D-02
00912 Q(7)=-1.529365552215722D-03:F(7)=1.449802895026053D-05
00914 REM ..................................................
00916 Y(8)= .1035948769531387#:B(8)= 34.71882401542098#
00918 Z(8)= .6684963632505969#:W9(8)=-.1098967950729275#
00920 Q(8)=1.906409339392212D-02:F(8)=-8.498296876631173D-04
00925 '================================================
00927 ' The coefficients of V(T)
00930 OPEN "Coeff.dat" FOR INPUT AS #1
00940 FOR I=1 TO 8
00942 INPUT #1,BB(I)
00944 INPUT #1,ZZ(I)
00946 INPUT #1,W8(I)
00947 INPUT #1,QQ(I)
00948 INPUT #1,FF(I)
00950 NEXT:CLOSE
```

```
01000 REM ================================================
01010 REM  data acquisition and checking part
01020 IF Q$="C" THEN SCREEN 0,1,0 ELSE SCREEN 0,0,0
01030 IF Q$="C" THEN COLOR 15,1,1 ELSE COLOR 7,0,0
01035 WIDTH 80:CLS
01040 LOCATE 3,15:PRINT "Do you wish to obtain a hard copy
        of the data? (Y/N)"
01045 LOCATE 5,37:INPUT PT$
01047 IF PT$="y" OR PT$="Y" THEN PT$="Y":GOTO 1050
01048 IF PT$="n" OR PT$="N" THEN PT$="N":GOTO 1050
01049 GOTO 1040
01050 LOCATE 7,15:PRINT"How many samples per CYCLE do you
        wish to have?"
01055 LOCATE 9,37:INPUT CL
01060 LOCATE 11,15:PRINT "What mode do you wish the system
        to operate in"
01070 LOCATE 13,25:PRINT"  Fast   mode -----> Type  F":PRINT
01080 LOCATE 15,25:PRINT"  Normal mode -----> Type  N":PRINT
01090 LOCATE 20,37:INPUT MD$
01097 IF MD$="f" OR MD$="F" THEN MD$="F":GOTO 1100
01098 IF MD$="n" OR MD$="N" THEN MD$="N":GOTO 1100
01099 GOTO 1090
01100 CLS:LOCATE 7,15
01101 PRINT"Do you want the system to use variable or
        constant weights? (V/C)"
01102 LOCATE 9,37:INPUT WT$
01104 IF WT$="c" OR WT$="C" THEN WT$="C": GOTO 1110
01106 IF WT$="v" OR WT$="V" THEN WT$="V": GOTO 1110
01108 GOTO 1102
01109 '================================================
01110 REM   SETUP THE DATA ACQUISITION BOARD
01115 REM FOR INPUT SIGNALS
01120 ANALOG.VALUE%=0
01140 HIGH.V!=+10!:LOW.V!=-10!:RANGE!=HIGH.V!-LOW.V!:
        NOC!=4096!:LSB!=RANGE!/NOC!
01150 GAIN%=1:SCALED.LSB!=LSB!/GAIN%:
    SCALED.LOW!=LOW.V!/GAIN%
01160 REM FOR OUTPUT SIGNALS
01170 PORT.SELECT%=1
01180 CALL ENABLE.FOR.OUTPUT (PORT.SELECT%)
01190 DIGITAL.LINE%=0:D.MASK%=2^DIGITAL.LINE%
01300 '================================================
01305 ' OBTAIN DATA NECESSARY FOR THE GCC FROM
        GCCPARM.DAT
01310 OPEN "GCCPARM.DAT" FOR INPUT AS #1
01330 FOR I=1 TO 8
01340 INPUT #1,ERB(I)
01350 NEXT:CLOSE
01351 IF WT$="C" THEN 1352 ELSE 1355
01352 OPEN "weight.DAT" FOR INPUT AS #1
01354 FOR I=1 TO 8:INPUT #1,W(I):NEXT:CLOSE:GOTO 1370
01355 OPEN "weight.var" FOR INPUT AS #1
```

```
01356 FOR I=1 TO 8:INPUT #1,W(I):NEXT:CLOSE
01360 ' OBTAIN SENSOR DATA FROM PARM.DAT FILE
01370 OPEN "PARM.DAT" FOR INPUT AS #1
01375 INPUT #1,ID$
01380 INPUT #1,VLOC$
01385 INPUT #1,MOT,SL,GS,GT,DT$:CLOSE
01387 SV=1        'in normal mode signal validation is done
          at each sample
01390 IF PT$="Y" THEN LPRINT DATE$
01395 CHOUR=1     'initial hour count ohour=>used for
          updating moving window file
01396 OHOUR=VAL(LEFT$(TIME$,2))*3600+VAL(MID$(TIME$,4,2))*60
          +VAL(RIGHT$(TIME$,2))
01398 IF MD$="N" THEN 3000
01400 '=================================================
01410 REM FAST MODE
01420 IF Q$="C" THEN SCREEN 0,1,0 ELSE SCREEN 0,0,0
01430 IF Q$="C" THEN COLOR 15,1,1 ELSE COLOR 7,0,0
01445 WIDTH 80:CLS
01450 LOCATE 5,20:PRINT"In the fast mode, the system will
          focus on a user"
01460 LOCATE 7,20:PRINT"specified channel and monitor it
          until otherwise"
01470 LOCATE 9,20:PRINT"instructed or when the cycle is
          over.  At the end of"
01472 LOCATE 11,20:PRINT"the cycle, the system defaults to
          the NORMAL mode. "
01473 LOCATE 13,20:PRINT"The system will also perform signal
          validation"
01475 LOCATE 15,20:PRINT"at a user specified time intervals"
01476 GOSUB 9000
01480 LOCATE 5,20:PRINT"Which channel do you wish to
          monitor? (1 - 8)"
01490 LOCATE 7,20:PRINT"The system recommends channels 1, 7,
          or 6"
01500 LOCATE 10,37:INPUT CH
01505 IF CH<1 OR CH>8 THEN 1480
01510 LOCATE 12,20:PRINT"After how many samples do you wish
          the system to "
01520 LOCATE 14,20:PRINT"perform the signal validation
          checks"
01530 LOCATE 17,20:PRINT"Perform validation after every"
01540 LOCATE 17,60:PRINT"samples":LOCATE 17,52:INPUT SV
01542 IF SV>CL THEN 1543 ELSE GOTO 1560
01543 LOCATE 19,20:PRINT"CHOOSE A LOWER VALUE!":GOTO 1510
01545 ' =================================================
01550 REM SUBROUTINE TO PULSE THE COUNTER TO THE CORRECT
          RELAY
01560 SCREEN 1:IF P=CH THEN GOTO 1607
01570 IF P<CH THEN CK=CH-P
01575 IF P>CH THEN CK=8-P+CH
01580 FOR I=1 TO CK:D.STATE$="L":D.VALUE%=&H0:IF P=8 THEN P=0
```

```
01585 CALL OUTPUT.DIGITAL.VALUE (PORT.SELECT%, D.MASK%,
        D.VALUE%)
01590 FOR J=1 TO 50:J=J+1:NEXT     'waiting
01595 D.STATE$="H":D.VALUE%=&HFFFF
01600 CALL OUTPUT.DIGITAL.VALUE (PORT.SELECT%, D.MASK%,
        D.VALUE%)
01605 P=P+1:FOR J=1 TO 50:J=J+1:NEXT:NEXT
01607 '' TITLE SCREEN
01608 IF Q$="C" THEN SCREEN 0,1,0 ELSE SCREEN 0,0,0
01609 IF Q$="C" THEN COLOR 15,1,1 ELSE COLOR 7,0,0
01610 WIDTH 80:CLS
01615 CLS:SCREEN 1:COLOR 1,3:LOCATE 1,2:PRINT"    DATE
        TIME"
01620 VIEW:KEY OFF
01630 VIEW (10,10)-(100,25),,1
01640 VIEW (220,10)-(290,25),,1
01650 VIEW (110,45)-(210,75),,1
01670 VIEW (110,75)-(210,120),,1
01680 VIEW (110,30)-(210,40),,2
01690 VIEW (100,130)-(220,145),,1
01700 VIEW (100,145)-(220,175),,1
01705 LOCATE 5,15:COLOR 4,1,1:PRINT "FAST MODE"
01720 LOCATE 8,16:PRINT "TEMPERATURE":LOCATE 15,20:PRINT"C"
01730 LOCATE 18,14:PRINT "ST. DEV. (68%)"
01750 LOCATE 21,14:PRINT "+/-":LOCATE 21,26:PRINT"C"
01790 ''--------------------------
01800 OLDT=VAL(LEFT$(TIME$,2))*3600+VAL(MID$(TIME$,4,2))*60
        +VAL(RIGHT$(TIME$,2))
01810 REM START COLLECTING DATA FROM THE SINGLE CHANNEL
01811 ' Initialize the high and low value counters
01812 FOR I=1 TO 8:CHIGH(I)=0:CLOW(I)=0:NEXT
01815 KF=0       'SAMPLE COUNTER INCREMENTED BY 1 AFTER EACH
        CHECK UP
01820 KF=KF+1:FOR LL=1 TO SV 'SV==># OF SAMPLES TAKEN BEFORE
        DOING CROSS CHECK
01825 CHANNEL%=0          'FOR MTC SIGNAL COLLECTION
01830 CALL ADC.VALUE (CHANNEL%, GAIN%, ANALOG.VALUE%)
01870 VOLTAGE!=(ANALOG.VALUE%*SCALED.LSB!)+SCALED.LOW!
01875 X1=VOLTAGE!*1000/GS
        +F(P)*X^5!
01880 CHANNEL%=1          'FOR ON-BOARD TEMP. MEASUREMENT
01890 CALL ADC.VALUE (CHANNEL%, GAIN%, ANALOG.VALUE%)
01900 VOLTAGE!=(ANALOG.VALUE%*SCALED.LSB!)+SCALED.LOW!
01905 BT=(VOLTAGE!*1000/GT)-273.16
01907 V(p)=BB(P)*BT+ZZ(P)*BT^2!+W8(P)*BT^3!
        +QQ(P)*BT^4!+FF(P)*BT^5!
01908 X=V(P)+X1
01909 T(P)=Y(P)+B(P)*X+Z(P)*X^2!+W9(P)*X^3!+Q(P)*X^4!
01910 LOCATE 13,18:PRINT USING "###.##";T(P)
01912 LOCATE 13,1:PRINT"BOARD TEMP":LOCATE 15,1:PRINT
        USING"###.#";BT
01913 LOCATE 20,1:PRINT"RELAY #":LOCATE 21,1:PRINT P
```

```
01915 LOCATE 21,14:PRINT"......."
01920 KF=KF+1:NEXT
02005 ''---------------------------
02007 '  TO CHECK THE SENSOR IN THE FAST MODE
02170 REM The following performs statistics
02180 REM and signal validation for the new sensor
02220 IF PT$="N" THEN 2290
02250 LPRINT"I     TIME      TEMPERATURE    STANDARD
        DEVIATION"
2260 LPRINT"I -----------  --------------
        ------------------"
02290 LOCATE 3,3:PRINT DATE$:LOCATE 3,29:PRINT TIME$
02293 ' ....................................
02294 ' Start pulsing the counter and collecting data from
        the eight channels
02296 CHANNEL%=0:FOR I=1 TO 8:IF P=8 THEN P=0
02298 D.STATE$="L":D.VALUE%=&H0
02300 CALL OUTPUT.DIGITAL.VALUE
        (PORT.SELECT%,D.MASK%,D.VALUE%)
02302 D.STATE$="H":D.VALUE%=&HFFFF
02304 CALL OUTPUT.DIGITAL.VALUE (PORT.SELECT%,
        D.MASK%,D.VALUE%)
02305 P=P+1:LOCATE 20,1:PRINT"RELAY #":LOCATE 21,1:PRINT P
02307 CALL ADC.VALUE (CHANNEL%, GAIN%, ANALOG.VALUE%)
02309 VOLTAGE!=((ANALOG.VALUE%*SCALED.LSB!)+SCALED.LOW!)
        *1000/GS
02310 X1(I)=VOLTAGE!:
02312 NEXT:CHANNEL%=1          'FOR ON-BOARD TEMP.
        MEASUREMENT
02314 CALL ADC.VALUE (CHANNEL%, GAIN%, ANALOG.VALUE%)
02316 VOLTAGE!=(ANALOG.VALUE%*SCALED.LSB!)+SCALED.LOW!
02317 BT=(VOLTAGE!*1000/GT)-273.16
02318 FOR I=1 TO 8: V(I)=BB(I)*BT+ZZ(I)*BT^2!
        +W8(I)*BT^3!+QQ(I)*BT^4!+FF(I)*BT^5!
02320 X(I)=X1(I)+V(I)
02330 T(I)=Y(I)+B(I)*X(I)+Z(I)*X(I)^2!+W9(I)*X(I)^3!
        +Q(I)*X(I)^4!+F(I)*X(I)^5!
02350 NEXT
02360 GOSUB 5000         'GCC
02580 LOCATE 13,18:PRINT USING "###.##";AVE
02590 LOCATE 21,14:PRINT USING "###.##";SD
02600 GOSUB 6500          'TO CHECK THE SIGNALS AGAINST THE
        SYSTEM LIMITS
02610 IF PT$="Y" THEN 2612 ELSE 2622
02612 M$="           ####.##   ####.# "
02615 LPRINT TIME$;
02620 LPRINT USING M$;AVE;SD
02622 IF ABS(AVE-T(P))>ERB(P) THEN 2635
02630 IF KF>CL THEN 3000 ELSE 1820
02635 CLS:SCREEN 0,0,0:COLOR 1,3:LOCATE 7,5:PRINT"W A R N I
        N G   W A R N I N G"
02636 LOCATE 9,5:PRINT"THIS CHANNEL HAS EXCEEDED ITS
```

```
        TOLERANCE"
02638 LOCATE 13,5:PRINT"............................."
02639 LOCATE 15,5:PRINT"I AM SWITCHING TO THE NORMAL"
02640 LOCATE 17,5:PRINT"OPERATING MODE.............":
        GOSUB 7790:SCREEN 0,0,0
03000 '================================================
03002 '
03004 ' NORMAL OPERATING MODE
03005 ''---------------------------
03010 CLS:SCREEN 2:SCREEN 1:COLOR 1,3:LOCATE 1,2:PRINT"
        DATE                          TIME"
03020 VIEW:KEY OFF
03030 VIEW (10,10)-(100,25),,1
03040 VIEW (220,10)-(290,25),,1
03050 VIEW (110,45)-(210,75),,1
03060 VIEW (110,75)-(210,120),,1
03080 VIEW (110,30)-(210,40),,1
03085 VIEW (100,130)-(220,145),,1
03090 VIEW (100,145)-(220,175),,1
03105 LOCATE 5,15:PRINT "NORMAL MODE"
03120 LOCATE 8,16:PRINT "TEMPERATURE":LOCATE 15,20:PRINT"C"
03130 LOCATE 18,14:PRINT "ST. DEV. (68%)"
03150 LOCATE 21,14:PRINT "+/-":LOCATE 21,26:PRINT"C"
03200 SV=1:FOR I=1 TO 8:CHIGH(I)=0:CLOW(I)=0:NEXT
        'Initialize counters
03220 IF PT$="N" THEN 3265
03250 LPRINT"I     TIME      TEMPERATURE    STANDARD
        DEVIATION"
03260 LPRINT"I -----------  --------------
        ------------------"
3265 OLDT=VAL(LEFT$(TIME$,2))*3600+VAL(MID$(TIME$,4,2))*60
        +VAL(RIGHT$(TIME$,2))
03270 KF=0:FOR II=1 TO CL
03280 KF=KF+1
03290 LOCATE 3,3:PRINT DATE$:LOCATE 3,29:PRINT TIME$
03293 ' ....................................
03294 ' Start pulsing the counter and collecting data from
        the eight channels
03296 GOSUB 4000:FOR I=1 TO 8:
03300 V(I)=BB(I)*BT+ZZ(I)*BT^2!+W8(I)*BT^3!
        +QQ(I)*BT^4!+FF(I)*BT^5!
03310 X=V1(I)+V(I)
03311 T(I)=Y(I)+B(I)*X+Z(I)*X^2!+W9(I)*X^3!+Q(I)*X^4!
        +F(I)*X^5!
03312 NEXT
03350 GOSUB 5000
03580 LOCATE 13,18:PRINT USING "###.##";AVE
03590 LOCATE 21,14:PRINT USING "###.##";SD
03600 GOSUB 6500
03610 IF PT$="Y" THEN 3612 ELSE 3630
03612 M$="           ####.##   ####.# "
03615 LPRINT TIME$;
```

```
03620 LPRINT USING M$;AVE;SD
03630 NEXT:GOTO 3270
03790 REM ================================================
04000 'subroutine to collect data
04010 REM input signals
04020 CHANNEL%=0:FOR I=1 TO 8
04080 CALL ADC.VALUE (CHANNEL%, GAIN%, ANALOG.VALUE%)
04140 VOLTAGE!=((ANALOG.VALUE%*SCALED.LSB!)+SCALED.LOW!)
          *1000/GS
04170 V1(P)=VOLTAGE!
04180 '================================================
04190 REM output signals
04210 CALL ENABLE.FOR.OUTPUT (PORT.SELECT%)
04230 D.STATE$="L":D.VALUE% = &H0:IF P=8 THEN P=0:FOR J=1 TO
          5000!:NEXT
04240 CALL OUTPUT.DIGITAL.VALUE (PORT.SELECT%, D.MASK%,
          D.VALUE%)
04260 D.STATE$="H":D.VALUE% = &HFFFF
04265 FOR J=1 TO 5000!:NEXT
04270 CALL OUTPUT.DIGITAL.VALUE (PORT.SELECT%, D.MASK%,
          D.VALUE%)
04275 P=P+1:LOCATE 20,1:PRINT "RELAY #":LOCATE 21,1:PRINT P
04280 NEXT
04300 '================================================
04310 REM get board' temperature
04350 CHANNEL%=1:FOR I=1 TO 2:FOR J=1 TO 500: J=1+J:NEXT
04380 CALL ADC.VALUE (CHANNEL%, GAIN%, ANALOG.VALUE%):NEXT
04430 VOLTAGE! = (ANALOG.VALUE% * SCALED.LSB!) + SCALED.LOW!
04450 BT=(VOLTAGE!*1000/GT)-273.16  't=board's temperature
          in deg. C
04455 IF BT<0 THEN 4550
04460 LOCATE 12,1:PRINT "B.T.":LOCATE 13,2:PRINT USING
          "###.#";BT
04550 CHANNEL%=0 'this is needed to avoid added voltage due
          to initial contact
04580 CALL ADC.VALUE (CHANNEL%, GAIN%, ANALOG.VALUE%)
04670 RETURN
04680 ' ================================================
05000 ' gcc test
05020 'initial setting
05080 'subroutine to determine the inconsistency indexes and
          estimate the temp.
05090 L=8:K=8:NMAX=0:PC=0 'SAMPLE, AND total # of meas
05110 FOR I=1 TO 8:NT(I)=T(I):NEXT
05120 S=0:FOR I=1 TO 8:S=S+T(I):NEXT
05150 K=K-NMAX
05160 FOR I=1 TO 8:PINC(I)=PINC(I)-NMAX:NEXT
05170 FOR I=1 TO 8:PINC(I)=0:NEXT  'INITIALIZE THE PR.INC. +
          WT. COUNTER
05175 FOR I=1 TO 7:IF F(I)=-1 THEN 5280 'DO NOT COMPARE A
          FAILED ELEMENT
05180 IF T(I)=0 THEN 5280
```

```
05190 FOR J=I+1 TO 8:IF F(J)=-1 THEN 5270 'DO NOT COMPARE
      WITH A FAILED ELEMENT
05200 IF T(J)=0 THEN 5270
05210 IF ABS(T(I)-T(J))>=(ERB(I)+ERB(J)) THEN 5220 ELSE 5250
05220 IF PC=0 THEN 5225 ELSE 5230   'update the CINC(i) only
      in the first sweep
05225 CINC(I)=CINC(I)+1:CINC(J)=CINC(J)+1 'INCREASE
      CUMULATIVE INCONS. COUNTER
05230 PINC(I)=PINC(I)+1:PINC(J)=PINC(J)+1 'INCREASE PRESENT
      INCONS. COUNTER
05240 GOTO 5270
05250 IF PC=0 THEN 5255 ELSE 5270   'update the CINC(i) only
      in the first sweep
05255 CINC(I)=CINC(I)-1:CINC(J)=CINC(J)-1  'DECREASE CUM.
      NCONS. COUNTER BY
05260                               '1 FOR GOOD BEHAVIOR
05270 NEXT
05280 NEXT:PC=1     'to avoid updating cinc(i) again
05300 FOR I=1 TO 8:IF T(I)=0 THEN 5320
05310 IF PINC(I)>0 THEN 5360 'THERE EXIST INCONS. PAIRS
05320 NEXT
05350 GOTO 5600     'ESTIMATE WITH W(I)=1
05360 ' FIND THE MIN, MAX INCONSISTENCIES
05370 MININC=8:MAXINC=0:FOR I=1 TO 8:IF T(I)=0 THEN 5400
05380 IF MININC>PINC(I) THEN MININC=PINC(I)
05390 IF MAXINC<PINC(I) THEN MAXINC=PINC(I)
05400 NEXT
05410 ' FIND THE NUMBER OF MEAS. WITH INC. INDEX=MAX. INDEX
05420 NMAX=0:FOR I=1 TO 8:IF T(I)=0 THEN 5450
05430 IF PINC(I)<>MAXINC THEN 5450
05440 NMAX=NMAX+1:IF MININC<=0 THEN 5570 ELSE T(I)=0
05450 NEXT
05460 IF MAXINC=0 THEN 5600
05470 IF MININC<=0 THEN 5560
05480 IF MAXINC=K-1 THEN 5650
05490 IF NMAX=1 THEN 5150
05500 IF NMAX=K THEN 5505 ELSE GOTO 5510
05505 LOCATE 23,15:PRINT"No Estimate":LOCATE
      13,18:PRINT"------"
05507 LOCATE 21,14:PRINT"------":LOCATE 23,15:
      PRINT"**********":GOTO 5740
05510 IF NMAX=K-1 THEN 5520 ELSE 5150
05520 FOR I=1 TO 8:IF F(I)<0 THEN 5550
05530 IF T(I)=0 THEN 5550
05540 AVE=T(I)
05550 NEXT:GOTO 5720
05570 SP1=0:FOR I=1 TO 8:SP1=SP1+PINC(I):NEXT
05580 LPRINT"K= "K
05600 AVE=0:FOR I=1 TO 8:IF T(I)=0 THEN 5630
05610 SSS=W(I)*(K-1-PINC(I))
05620 AVE=AVE+(SSS*T(I)/SSS)
05630 NEXT:AVE=AVE/K
```

```
05632 S2=0:FOR I=1 TO 8:IF F(I)<0 OR T(I)=0 THEN 5636
05634 S2=S2+((AVE-T(I))^2)
05636 NEXT:SD=SQR(S2/(K-1))
05640 GOTO 5720
05650 IF K=NMAX THEN 5700 ELSE K=K-NMAX
05660 FOR I=1 TO 8:PINC(I)=PINC(I)-NMAX:NEXT
05690 GOTO 5170
05700 IF K=L THEN 5710 ELSE GOTO 5500
05710 LOCATE 23,15:PRINT"No Estimate":LOCATE 13,18:
        PRINT"------"
05715 LOCATE 21,14:PRINT"------":LOCATE 23,15:
        PRINT"**********"
05718 '=================================================
05720 'Find the deviation of the individual signals from the
        true mean
05740 FOR I=1 TO 8
05750 IF F(I)<0 THEN 5770
05760 IF T(I)>0 THEN 5770
05766 IF NT(I)>AVE THEN CHIGH(I)=CHIGH(I)+1 ELSE
        CLOW(I)=CLOW(I)+1
05770 NEXT
05999 '=================================================
06000 'CHECK END OF CYCLE STATUS
06010 IF KF>CL THEN 6020 ELSE 6490
06020 IF PT$="Y" THEN LPRINT"End of this cycle........."
06030 NC=0:FOR I=1 TO 8:IF F(I)<0 THEN 6035 ELSE NC=NC+1
06035 NEXT
06200 'UPDATE STATUS FILE
06210 OPEN "stat.cur" FOR OUTPUT AS #1
06220 FOR I=1 TO 8
06230 PERINC(I)=SV*CINC(I)*100/(NC*CL)
06240 PERH(I)=SV*CHIGH(I)*100/CL
06250 PERL(I)=SV*CLOW(I)*100/CL
06260 PEROK(I)=100-(PERH(I)+PERL(I))
06270 PRINT #1,I,ERB(I),W(I),PERINC(I),PERH(I),PERL(I),
        PEROK(I)
06280 NEXT:CLOSE
06340 FOR I=1 TO 8
06350 IF CINC(I)>.95*NC*CL/SV THEN 6370
06360 IF CINC(I)>.5*NC*CL/SV THEN 6390 ELSE GOTO 6400
06370 F(I)=-1:W(I)=0:OPEN "fail.ch" FOR APPEND AS 3
06375 PRINT #3,"channel ";I;"has failed at ";TIME$;"on
        ";DATE$:CLOSE:GOTO 6400
06390 W(I)=(1-(CINC(I)/(NC*CL/SV)))
06400 NEXT
06405 OPEN "weight.var" FOR OUTPUT AS #1
06410 FOR I=1 TO 8:PRINT #1,W(I):NEXT:CLOSE
06490 RETURN
06500 'END OF SINGLE SAMPLE SET CHECKS
06510 IF MOT<=AVE THEN 6520 ELSE 6530
06520 LOCATE 10,29:PRINT"Max. Op. T.":LOCATE 11,29:PRINT"has
        been  "
```

```
06525 LOCATE 12,29:PRINT"exceeded   ":GOTO 6560
06530 IF AVE>=(MOT-15) THEN 6540 ELSE 6550
06540 LOCATE 10,29:PRINT"Current T.  ":LOCATE 11,29:PRINT"is
      within   "
06545 LOCATE 12,29:PRINT"15 C from   ":LOCATE 13,29:
      PRINT"Max. Op. T. ":GOTO 6560
06550 LOCATE 10,29:PRINT".....":LOCATE
      11,29:PRINT"....."
06555 LOCATE 12,29:PRINT".....":LOCATE
      13,29:PRINT"....."
06560 IF SL<=AVE THEN 6570 ELSE 6580     'sensor limit check
06570 LOCATE 14,29:PRINT"Sensor limit":LOCATE 15,29:
      PRINT"has been  "
06575 LOCATE 16,29:PRINT"exceeded   ":GOTO 6610
06580 IF AVE>=(SL-50) THEN 6590 ELSE 6600
06590 LOCATE 14,29:PRINT"Current T.  ":LOCATE 15,29:PRINT"is
      within   "
06595 LOCATE 16,29:PRINT"50 C from   ":LOCATE
      17,29:PRINT"sensor limit":GOTO 6610
06600 LOCATE 14,29:PRINT".....":LOCATE
      15,29:PRINT"....."
06605 LOCATE 16,29:PRINT".....":LOCATE
      17,29:PRINT"....."
06610 LOCATE 20,29:PRINT"k=";K:IF K<=4 THEN COLOR 12,,7 ELSE
      6612
06611 GOTO 6620
06612 IF K<=6 THEN COLOR 14,7 ELSE 6615
06613 GOTO 6620
06615 COLOR 1,3
06620 IF AVE>MAXT THEN MAXT=AVE
06625 IF AVE<MINT THEN MINT=AVE
06630 NEWT=VAL(LEFT$(TIME$,2))*3600+VAL(MID$(TIME$,4,2))*60
      +VAL(RIGHT$(TIME$,2))
06640 IF (NEWT-OHOUR)>3600 THEN 6660 ELSE 6999
06650 'update wind.dat file
06660 OPEN "wind.dat" FOR INPUT AS #1
06665 OHOUR=VAL(LEFT$(TIME$,2))*3600+VAL(MID$(TIME$,4,2))*60
      +VAL(RIGHT$(TIME$,2))
06670 FOR I=1 TO 719
06680 INPUT #1,WTX(I),WTN(I)
06690 NEXT:CLOSE:FOR I=1 TO 718:
      WTX(I)=WTX(I+1):WTN(I)=WTN(I+1):NEXT
06700 WTX(719)=MAXT:WTN(719)=MINT:OPEN "wind.dat" FOR OUTPUT
      AS #1
06710 FOR I=1 TO 719:PRINT #1,WTX(I);",";WTN(I):NEXT:MAXT=0:
      MINT=10000:CLOSE
06999 RETURN
07790 REM 5 SECONDS WAITING
07800 V1=VAL(LEFT$(TIME$,2))*3600+VAL(MID$(TIME$,4,2))*60
      +VAL(RIGHT$(TIME$,2))
07810 V2=VAL(LEFT$(TIME$,2))*3600+VAL(MID$(TIME$,4,2))*60
      +VAL(RIGHT$(TIME$,2))
```

```
07820 IF V2<V1 THEN GOTO 7800 ELSE IF (V2-V1)>5 THEN RETURN
      ELSE GOTO 7810
07830 ' ================================================
07840 REM 2 SECONDS WAITING
07850 V1=VAL(LEFT$(TIME$,2))*3600+VAL(MID$(TIME$,4,2))*60
      +VAL(RIGHT$(TIME$,2))
07860 V2=VAL(LEFT$(TIME$,2))*3600+VAL(MID$(TIME$,4,2))*60
      +VAL(RIGHT$(TIME$,2))
07870 IF V2<V1 THEN GOTO 7800 ELSE IF (V2-V1)>2 THEN RETURN
      ELSE GOTO 7860
07880 ' ================================================
09000 PRINT:PRINT:LOCATE ,20:PRINT"(Press any key to
      continue)"
09010 DD$=INKEY$:IF DD$="" THEN GOTO 9010 ELSE CLS:RETURN
10000 ' ================================================
10005 '          INSTRUCTIONS
10007 ' ================================================
10010 CLS: IF Q$<>"C" THEN 10020
10015 SCREEN 2:SCREEN 0:COLOR 0,11:CLS
10020 CLS:OPEN "instruct.txt" FOR INPUT AS #1
10030 PRINT:PRINT:PRINT:IF EOF(1) THEN 20000
10040 LINE INPUT #1,LIN$
10050 IF LIN$="B" THEN LINE INPUT #1,LIN$
10060 IF LIN$="E" THEN GOTO 10080
10070 PRINT LIN$:GOTO 10040
10080 GOSUB 9000:GOTO 10030
10090 ' ================================================
12000 '================================================
12001 IF Q$="C" THEN SCREEN 0,1,0 ELSE SCREEN 0,0,0
12002 WIDTH 80
12010 IF Q$="C" THEN COLOR 15,1,1 ELSE COLOR 7,0,0
12011 CLS:KEY OFF
12030 FOR I=2 TO 79:LOCATE 1,I:PRINT CHR$(205);:LOCATE
      25,I:PRINT CHR$(205);:NEXT
12050 LOCATE 25,22:PRINT"Press F1 for MAIN MENU, F10 for
      HELP";
12060 IF Q$="C" THEN COLOR 10
12065 LOCATE 3,25:PRINT"5.  STATUS REPORTS"
12070 IF Q$="C" THEN COLOR 14
12080 LOCATE 7,20:PRINT"1. Simple Sensor Status Report"
12090 LOCATE 9,20:PRINT"2. Detailed Sensor Status Report"
12099 IF Q$="C" THEN COLOR 10
12100 LOCATE 21,16:PRINT"Press the number of your choice or
      move the arrow"
12102 LOCATE 22,16:PRINT"    up or down by pressing U or D,
      then ENTER!"
12110 SZI=1:ORI=1
12120 IF Q$="C" THEN COLOR 15 ELSE COLOR 7
12122 ON SZI GOSUB 12210,12220
12130 A$=INKEY$:IF A$="" GOTO 12130
12132 IF A$="1" GOTO 13000
12134 IF A$="2" GOTO 14000
```

```
12144 IF A$="D" OR A$="d" GOTO 12160
12146 IF A$="U" OR A$="u" GOTO 12180
12150 Z=ASC(A$):IF Z=13 GOTO 12190 ELSE GOTO 12130
12160 SZI=SZI+1:IF SZI=3 THEN SZI=1
12161 IF Q$="C" THEN COLOR 1 ELSE COLOR 0
12162 ON ORI GOSUB 12210,12220
12164 IF Q$="C" THEN COLOR 15 ELSE COLOR 7
12166 ON SZI GOSUB 12210,12220
12168 ORI=SZI :GOTO 12130
12180 SZI=SZI-1:IF SZI=0 THEN SZI=2
12181 IF Q$="C" THEN COLOR 1 ELSE COLOR 0
12182 ON ORI GOSUB 12210,12220
12184 IF Q$="C" THEN COLOR 15 ELSE COLOR 7
12186 ON SZI GOSUB 12210,12220
12188 ORI=SZI :GOTO 12130
12190 ON SZI GOTO 13000,14000
12210 LOCATE 7,18:PRINT CHR$(26)
12212 RETURN
12220 LOCATE 9,18:PRINT CHR$(26)
12222 RETURN
12300 '=================================================
13000 'Simple Sensor Status Report
13020 SCREEN 0,1,0
13030 COLOR 15,1,1
13035 WIDTH 80:CLS
13040 LOCATE 3,15:PRINT "Do you wish to obtain a hard copy
      of the data? (Y/N)"
13045 LOCATE 5,37:INPUT PT$
13047 IF PT$="y" OR PT$="Y" THEN PT$="Y":GOTO 13050
13048 IF PT$="n" OR PT$="N" THEN PT$="N":GOTO 13050
13049 GOTO 13045
13050 CLS
13060 LOCATE 2,10:PRINT "Simple Sensor Status Report"
13070 LOCATE 4,10:PRINT"Date: ";DATE$:LOCATE 4,40:
      PRINT"TIME: ";TIME$
13090 LOCATE 6,1:PRINT"------------------------------
      ------------------------------------------"
13100 PRINT"Channel   Error Bound  Weight   %Inconsistency
      %High    %Low    %OK"
13102 PRINT"   #            (C)     Factor"
13105 LOCATE 9,1:PRINT"==================================
      ======================================"
13107 OPEN "stat.cur" FOR INPUT AS #1
13110 FOR MM=1 TO 8:INPUT #1,I,ERB(I),W(I),PERINC(I),
      PERH(I),PERL(I),PEROK(I)
13120 LOCATE 9+MM,4:PRINT I:LOCATE 9+MM,11:PRINT ERB(I)
13122 LOCATE 9+MM,23:PRINT W(I):LOCATE 9+MM,38:PRINT
      PERINC(I)
13124 LOCATE 9+MM,50:PRINT PERH(I):LOCATE 9+MM,59:PRINT
      PERL(I)
13126 LOCATE 9+MM,69:PRINT PEROK(I)
13130 NEXT:CLOSE
```

```
13200 LOCATE 19,10:PRINT"The following channels have
      failed: "
13210 CCC=0:FOR I=1 TO 8:IF W(I)>0 THEN 13230
13220 LOCATE 20,10*CCC+10:PRINT"Ch(";I;")";:CCC=CCC+1
13230 NEXT
13240 IF CCC=0 THEN 13250 ELSE 13260
13250 LOCATE 20,20:PRINT "NONE"
13260 GOSUB 9000
13490 IF PT$="N" THEN 13999
13495 LPRINT"================================
      ========================="
13500 LPRINT:LPRINT "Simple Sensor Status Reprot"
13510 LPRINT:LPRINT"Date: ";DATE$;"          ";"TIME: ";TIME$
13520 LPRINT"----------------------------------------
      ------------------------------"
13530 LPRINT"Channel   Error Bound  Weight   %Inconsistency
       %High    %Low    %OK"
13540 LPRINT"   #           (C)     Factor"
13550 LPRINT"================================
      ======================================="
13560 CC=0:FOR I=1 TO 8
13570 LPRINT
I;TAB(14);ERB(I);TAB(25);W(I);TAB(38);PERINC(I);
      TAB(52);PERH(I);
13580 LPRINT ;TAB(60);PERL(I);TAB(68);PEROK(I)
13610 NEXT:LPRINT
13620 LPRINT"The following channels have failed: "
13630 FOR I=1 TO 8:IF W(I)>0 THEN 13650
13640 LPRINT"Ch(";I;")";:CC=1
13650 NEXT:IF CC=0 THEN LPRINT"NONE"
13999 GOTO 20000
14000 'Detailed Sensor Status Report
14020 SCREEN 0,1,0
14030 COLOR 15,1,1
14035 WIDTH 80:CLS
14040 LOCATE 3,15:PRINT "Do you wish to obtain a hard copy
      of the data? (Y/N)"
14045 LOCATE 5,37:INPUT PT$
14047 IF PT$="y" OR PT$="Y" THEN PT$="Y":GOTO 14050
14048 IF PT$="n" OR PT$="N" THEN PT$="N":GOTO 14050
14049 GOTO 14045
14050 CLS
14060 LOCATE 2,10:PRINT "Detailed Sensor Status Report"
14070 LOCATE 4,10:PRINT"Date: ";DATE$:LOCATE 4,40:
      PRINT"TIME:";TIME$
14072 OPEN "parm.dat" FOR INPUT AS #1
14074 INPUT #1,ID$:INPUT #1,VLOC$:INPUT #1,MOT,SL,GS,GT,DT$
      :CLOSE:CLS
14076 LOCATE 4,10:PRINT"Sensor Identification Number
      ..... ";ID$
14078 LOCATE 6,10:PRINT"Sensor location
      ..... ";VLOC$
```

```
14080 LOCATE 8,10:PRINT"Sensor maximum operating temperature
      ......";SL;"C"
14082 LOCATE 10,10:PRINT"Amplifier's gain setting for the
      sensor ....";GS
14084 LOCATE 12,10:PRINT"Amplifier's gain setting for board
      T. ......";GT:GOSUB 9000:CLS
14090 LOCATE 6,1:PRINT"------------------------------
      ----------------------------------------"
14100 PRINT"Channel   Error Bound  Weight   %Inconsistency
      %High    %Low    %OK"
14102 PRINT"   #           (C)     Factor"
14105 LOCATE 9,1:PRINT"==============================
      ========================================"
14107 OPEN "stat.cur" FOR INPUT AS #1
14110 FOR MM=1 TO 8:INPUT #1,I,ERB(I),W(I),PERINC(I),
      PERH(I),PERL(I),PEROK(I)
14120 LOCATE 9+MM,4:PRINT I:LOCATE 9+MM,11:PRINT ERB(I)
14122 LOCATE 9+MM,23:PRINT W(I):LOCATE 9+MM,38:PRINT
      PERINC(I)
14124 LOCATE 9+MM,50:PRINT PERH(I):LOCATE 9+MM,59:PRINT
      PERL(I)
14126 LOCATE 9+MM,69:PRINT PEROK(I)
14130 NEXT:CLOSE
14200 LOCATE 19,10:PRINT"The following channels have failed:
      "
14210 CCC=0:FOR I=1 TO 8:IF W(I)>0 THEN 14230
14220 LOCATE 20,10*CCC+10:PRINT"Ch(";I;")";:CCC=CCC+1
14230 NEXT
14240 IF CCC=0 THEN 14250 ELSE 14260
14250 LOCATE 20,20:PRINT "NONE"
14260 GOSUB 9000
14490 IF PT$="N" THEN 14999
14495 LPRINT"================================
      ======================="
14500 LPRINT:LPRINT "Detailed Sensor Status Report"
14510 LPRINT:LPRINT"Date: ";DATE$;"         ";"TIME:
      ";TIME$:LPRINT
14512 LPRINT"Sensor Identification Number ............
      ";ID$:LPRINT
14513 LPRINT"Sensor location ........................
      ";VLOC$:LPRINT
14514 LPRINT"Sensor maximum operating temperature
      ......";SL;"C":LPRINT
14515 LPRINT"Amplifier's gain setting for the sensor
      ....";GS:LPRINT
14517 LPRINT"Amplifier's gain setting for board T.
      ......";GT:LPRINT
14520 LPRINT"------------------------------
      ----------------------------------------"
14530 LPRINT"Channel   Error Bound  Weight   %Inconsistency
       %High    %Low    %OK"
14540 LPRINT"   #           (C)     Factor"
```

```
14550 LPRINT"================================
      ========================================="
14560 FOR I=1 TO 8
14570 LPRINT I;TAB(14);ERB(I);TAB(25);W(I);TAB(38);
      PERINC(I);TAB(52);PERH(I);
14580 LPRINT ;TAB(60);PERL(I);TAB(68);PEROK(I)
14610 NEXT:LPRINT
14620 LPRINT"The following channels have failed: "
14630 CC=0:FOR I=1 TO 8:IF W(I)>0 THEN 14650
14640 LPRINT"Ch(";I;")";:CC=1
14650 NEXT:IF CC=0 THEN LPRINT"NONE"
14999 GOTO 20000
15000 '================================================
15005 CLS
15010 REM  PARAMETER UPDATE SUBROUTINE.....
15020 '
15030 OPEN "PARM.DAT" FOR INPUT AS #1
15040 INPUT #1,ID$
15042 INPUT #1,VLOC$
15044 INPUT #1,MOT,SL,GS,GT,DT$:CLOSE
15050 LOCATE  3,10:PRINT"THE CURRENT SENSOR IDENTIFICATION
      NUMBER IS "ID$
15060 LOCATE  5,10:PRINT"HAS THAT IDENTIFICATION NUMBER BEEN
      CHANGED? (Y/N)"
15070 LOCATE 7,39:INPUT Q1$
15080 IF Q1$="N" OR Q1$="n" THEN 15150
15090 LOCATE 9,10:PRINT"INPUT THE NEW SENSOR IDENTIFICATION
      NUMBER!"
15095 LOCATE 11,25:INPUT ID$
15150 CLS:LOCATE  3,10:PRINT"THE CURRENT SENSOR LOCATION IS
      "VLOC$
15160 LOCATE  5,10:PRINT"HAS THE SENSOR LOCATION BEEN
      CHANGED? (Y/N)"
15170 LOCATE 7,39:INPUT Q1$
15180 IF Q1$="N" OR Q1$="n" THEN 15250
15190 LOCATE 9,10:PRINT"INPUT THE NEW SENSOR LOCATION!"
15195 LOCATE 11,25:INPUT VLOC$
15250 CLS:LOCATE  3,10
15255 PRINT"THE MAXIMUM PROCESS OPERATING TEMPERATURE (C) IS
      "MOT
15260 LOCATE  5,10:PRINT"HAS THAT TEMPERATURE BEEN CHANGED?
      (Y/N)"
15270 LOCATE 7,39:INPUT Q1$
15280 IF Q1$="N" OR Q1$="n" THEN 15300
15290 LOCATE 9,10:PRINT"INPUT THE NEW MAXIMUM PROCESS
      TEMPERATURE (C)!"
15295 LOCATE 11,25:INPUT MOT
15300 CLS:LOCATE  3,10
15305 PRINT"THE MAXIMUM SENSOR OPERATING TEMPERATURE (C) IS
      "SL
15310 LOCATE  5,10:PRINT"HAS THAT TEMPERATURE BEEN CHANGED?
      (Y/N)"
```

```
15315 LOCATE 7,39:INPUT Q1$
15320 IF Q1$="N" OR Q1$="n" THEN 15350
15325 LOCATE 9,10:PRINT"INPUT THE NEW MAXIMUM PROCESS
      TEMPERATURE (C)!"
15330 LOCATE 11,25:INPUT SL
15350 CLS:LOCATE  3,10:PRINT"THE CURRENT MTC SIGNAL
      AMPLIFICATION FACTOR IS "GS
15360 LOCATE  5,10:PRINT"HAS THE AMPLIFIER GAIN BEEN
      CHANGED? (Y/N)"
15370 LOCATE 7,39:INPUT Q1$
15380 IF Q1$="N" OR Q1$="n" THEN 15450
15390 LOCATE 9,10:PRINT"INPUT THE NEW AMPLIFICATION
      CONSTANT!"
15395 LOCATE 11,25:INPUT GS
15450 CLS:LOCATE  3,10
15455 PRINT"THE CURRENT INTERFACE TEMPERATURE SIGNAL
      AMPLIFICATION FACTOR IS "GT
15460 LOCATE  5,10:PRINT"HAS THAT FACTOR BEEN CHANGED?
      (Y/N)"
15470 LOCATE 7,39:INPUT Q1$
15480 IF Q1$="N" OR Q1$="n" THEN 15500
15490 LOCATE 9,10:PRINT"INPUT THE NEW AMPLIFICATION
      CONSTANT!"
15495 LOCATE 11,25:INPUT GT:CLS
15500 CLS:LOCATE 3,10
15502 INPUT"Do you wish to update the GCC parameters?
      (Y/N)";Q1$
15504 IF Q1$="N" OR Q1$="n" THEN 15600
15506 OPEN "gccparm.dat" FOR INPUT AS #2
15508 FOR I=1 TO 8:INPUT #2,ERB(I)
15512 NEXT:CLOSE
15515 FOR I=1 TO 8:CLS:LOCATE 3,10
15517 PRINT"The values for the GCC parameters for
      channel ("I") are:"
15520 LOCATE 5,10:PRINT"                                  Error
      bound = ";ERB(I)
15528 LOCATE 13,10:PRINT"Does this value need to be
      changed? (Y/N)"
15529 LOCATE 14,39:INPUT Q1$
15530 IF Q1$="N" OR Q1$="n" THEN 15550
15535 LOCATE 16,10:INPUT"                        Input the
      error bound = ";ERB(I)
15550 NEXT
15558 OPEN "gccparm.dat" FOR OUTPUT AS #2
15562 FOR I=1 TO 8:PRINT #2,ERB(I)
15565 NEXT:CLOSE:GOTO 15600
15600 CLS:LOCATE 3,10
15602 INPUT"Do you wish to update the constant weight
      factors (Y/N)";Q1$
15604 IF Q1$="N" OR Q1$="n" THEN 15700
15606 OPEN "weight.dat" FOR INPUT AS #2
15608 FOR I=1 TO 8:INPUT #2,W(I)
```

```
15612 NEXT:CLOSE
15615 FOR I=1 TO 8:CLS:LOCATE 3,10
15617 PRINT"The current weight used in conjunction with
      channel ("I") is:"
15620 LOCATE 5,39:PRINT W(I)
15628 LOCATE 7,10:PRINT"Does this value need to be changed?
      (Y/N)"
15629 LOCATE 9,39:INPUT Q1$
15630 IF Q1$="N" OR Q1$="n" THEN 15650
15635 LOCATE 11,10:INPUT"Input the new weight ";W(I)
15650 NEXT
15658 OPEN "weight.dat" FOR OUTPUT AS #2
15662 FOR I=1 TO 8:PRINT #2,W(I);",";
15665 NEXT:CLOSE
15700 CLS:LOCATE  3,10:PRINT"THE SENSOR WAS MAINTAINED ON
      "DT$
15710 LOCATE  5,10:PRINT"HAS THE SENSOR BEEN UPDATED SINCE?
      (Y/N)"
15720 LOCATE 7,39:INPUT Q1$
15730 IF Q1$="N" OR Q1$="n" THEN 15890
15740 LOCATE 9,10:PRINT"INPUT THE NEW MAINTENANCE DATE!"
15750 LOCATE 11,25:INPUT DT$:CLS
15890 LOCATE 10,10:PRINT"I AM UPDATING THE PARAMETER FILE
      ........":GOSUB 7850
15900 OPEN "PARM.DAT" FOR OUTPUT AS #1
15910 PRINT #1,ID$;",";VLOC$;",";MOT;",";
      SL;",";GS;",";GT;",";DT$
15920 CLOSE
15930 GOTO 20000                    'TO MENU
19990 REM ******************* M E N U
      ************************************
19995 REM
20000 CLOS E:IF Q$="C" THEN SCREEN 0,1,0 ELSE SCREEN 0,0,0
20001 CLOSE:OPEN "p.dat" FOR OUTPUT AS #1:PRINT #1,P,MAXT,
      MINT: CLOSE
20002 WIDTH 80
20004 IF Q$="C" THEN CST=1 ELSE CST=0
20005 DEF SEG=0
20006 POKE(&H180),CST
20007 CLEAR:OPEN "p.dat" FOR INPUT AS #1:INPUT #1,P,MAXT,
      MINT:CLOSE
20008 CST=PEEK(&H180):IF CST=1 THEN Q$="C" ELSE Q$="M"
20009 GOTO 30000
20010 IF Q$="C" THEN COLOR 15,1,1 ELSE COLOR 7,0,0
20011 CLS:KEY OFF
20030 FOR I=2 TO 79:LOCATE 1,I:PRINT CHR$(205);:LOCATE 25,I:
      PRINT CHR$(205);:NEXT
20050 LOCATE 25,22:PRINT"Press F1 for this MENU, F10 for
    HELP";
20060 IF Q$="C" THEN COLOR 12
20065 LOCATE 3,31:PRINT"M A I N    M E N U"
20070 IF Q$="C" THEN COLOR 11
```

```
20080 LOCATE 7,23:PRINT"1. Instructions"
20090 LOCATE 9,23:PRINT"2. Start Temperature Measurement"
20092 LOCATE 11,23:PRINT"3. Moving Window"
20094 LOCATE 13,23:PRINT"4. Maintenance Assistance"
20096 LOCATE 15,23:PRINT"5. Status Report"
20098 LOCATE 17,23:PRINT"6. Update Sensor Parameters"
20099 IF Q$="C" THEN COLOR 12
20100 LOCATE 21,16:PRINT"Press the number of your choice or
        move the arrow"
20102 LOCATE 22,16:PRINT"    up or down by pressing U or D,
        then ENTER!"
20110 SZI=1:ORI=1
20120 IF Q$="C" THEN COLOR 15 ELSE COLOR 7
20122 ON SZI GOSUB 20210,20220,20230,20240,20250,20260
20130 A$=INKEY$:IF A$="" GOTO 20130
20132 IF A$="1" GOTO 10010
20134 IF A$="2" GOTO 200
20136 IF A$="3" GOTO 23000
20138 IF A$="4" GOTO 21000
20140 IF A$="5" GOTO 12000
20142 IF A$="6" GOTO 15000
20144 IF A$="D" OR A$="d" GOTO 20160
20146 IF A$="U" OR A$="u" GOTO 20180
20150 Z=ASC(A$):IF Z=13 GOTO 20190 ELSE GOTO 20130
20160 SZI=SZI+1:IF SZI=7 THEN SZI=1
20161 IF Q$="C" THEN COLOR 1 ELSE COLOR 0
20162 ON ORI GOSUB 20210,20220,20230,20240,20250,20260
20164 IF Q$="C" THEN COLOR 15 ELSE COLOR 7
20166 ON SZI GOSUB 20210,20220,20230,20240,20250,20260
20168 ORI=SZI :GOTO 20130
20180 SZI=SZI-1:IF SZI=0 THEN SZI=6
20181 IF Q$="C" THEN COLOR 1 ELSE COLOR 0
20182 ON ORI GOSUB 20210,20220,20230,20240,20250,20260
20184 IF Q$="C" THEN COLOR 15 ELSE COLOR 7
20186 ON SZI GOSUB 20210,20220,20230,20240,20250,20260
20188 ORI=SZI :GOTO 20130
20190 ON SZI GOTO 10010,200,23000,21000,12000,15000
20210 LOCATE 7,18:PRINT CHR$(26)
20212 RETURN
20220 LOCATE 9,18:PRINT CHR$(26)
20222 RETURN
20230 LOCATE 11,18:PRINT CHR$(26)
20232 RETURN
20240 LOCATE 13,18:PRINT CHR$(26)
20242 RETURN
20250 LOCATE 15,18:PRINT CHR$(26)
20252 RETURN
20260 LOCATE 17,18:PRINT CHR$(26)
20262 RETURN
20900 '================================================
21000 IF Q$="C" THEN SCREEN 0,1,0 ELSE SCREEN 0,0,0
21002 WIDTH 80
```

```
21010 IF Q$="C" THEN COLOR 15,1,1 ELSE COLOR 7,0,0
21011 CLS:KEY OFF
21030 FOR I=2 TO 79:LOCATE 1,I:PRINT CHR$(205);:LOCATE 25,I:
      PRINT CHR$(205);:NEXT
21050 LOCATE 25,22:PRINT"Press F1 for MAIN MENU, F10 for
      HELP";
21060 IF Q$="C" THEN COLOR 10
21065 LOCATE 3,25:PRINT"4.  MAINTENANCE ASSISTANCE"
21070 IF Q$="C" THEN COLOR 14
21080 LOCATE 7,20:PRINT"1. Sensor Assembly Description"
21090 LOCATE 9,20:PRINT"2. Interface Description"
21092 LOCATE 11,20:PRINT"3. Program/Interface Coordination"
21099 IF Q$="C" THEN COLOR 10
21100 LOCATE 21,16:PRINT"Press the number of your choice or
      move the arrow"
21102 LOCATE 22,16:PRINT"    up or down by pressing U or D,
      then ENTER!"
21110 SZI=1:ORI=1
21120 IF Q$="C" THEN COLOR 15 ELSE COLOR 7
21122 ON SZI GOSUB 21210,21220,21230
21130 A$=INKEY$:IF A$="" GOTO 21130
21132 IF A$="1" GOTO 35000
21134 IF A$="2" GOTO 36000
21136 IF A$="3" GOTO 37000
21144 IF A$="D" OR A$="d" GOTO 21160
21146 IF A$="U" OR A$="u" GOTO 21180
21150 Z=ASC(A$):IF Z=13 GOTO 21190 ELSE GOTO 21130
21160 SZI=SZI+1:IF SZI=4 THEN SZI=1
21161 IF Q$="C" THEN COLOR 1 ELSE COLOR 0
21162 ON ORI GOSUB 21210,21220,21230
21164 IF Q$="C" THEN COLOR 15 ELSE COLOR 7
21166 ON SZI GOSUB 21210,21220,21230
21168 ORI=SZI :GOTO 21130
21180 SZI=SZI-1:IF SZI=0 THEN SZI=3
21181 IF Q$="C" THEN COLOR 1 ELSE COLOR 0
21182 ON ORI GOSUB 21210,21220,21230
21184 IF Q$="C" THEN COLOR 15 ELSE COLOR 7
21186 ON SZI GOSUB 21210,21220,21230
21188 ORI=SZI :GOTO 21130
21190 ON SZI GOTO 35000,36000,37000
21200 '================================================
21210 LOCATE 7,18:PRINT CHR$(26)
21212 RETURN
21220 LOCATE 9,18:PRINT CHR$(26)
21222 RETURN
21230 '================================================
21232 RETURN
22900 ' The Moving Window Submenu:
22910 ' The Maintenance Assistance Submenu:
23000 IF Q$="C" THEN SCREEN 0,1,0 ELSE SCREEN 0,0,0
23002 WIDTH 80
23010 IF Q$="C" THEN COLOR 15,1,1 ELSE COLOR 7,0,0
```

```
23011 CLS:KEY OFF
23030 FOR I=2 TO 79:LOCATE 1,I:PRINT CHR$(205);:LOCATE 25,I:
      PRINT CHR$(205);:NEXT
23050 LOCATE 25,22:PRINT"Press F1 for MAIN MENU, F10 for
      HELP";
23060 IF Q$="C" THEN COLOR 10
23065 LOCATE 3,25:PRINT"3.  MOVING WINDOW"
23070 IF Q$="C" THEN COLOR 14
23080 LOCATE 7,20:PRINT"1. See Last Month's Important
      Events"
23090 LOCATE 9,20:PRINT"2. See last Week's Important Events"
23092 LOCATE 11,20:PRINT"3. See the Third Week's Important
      Events"
23094 LOCATE 13,20:PRINT"4. See the Second Week's Important
      Events"
23096 LOCATE 15,20:PRINT"5. See the First Week's Important
      Events"
23099 IF Q$="C" THEN COLOR 10
23100 LOCATE 21,16:PRINT"Press the number of your choice or
      move the arrow"
23102 LOCATE 22,16:PRINT"    up or down by pressing U or D,
      then ENTER!"
23110 SZI=1:ORI=1
23120 IF Q$="C" THEN COLOR 15 ELSE COLOR 7
23122 ON SZI GOSUB 23210,23220,23230,23240,23250
23130 A$=INKEY$:IF A$="" GOTO 23130
23132 IF A$="1" GOTO 24000
23134 IF A$="2" GOTO 25000
23136 IF A$="3" GOTO 26000
23138 IF A$="4" GOTO 27000
23139 IF A$="5" GOTO 28000
23144 IF A$="D" OR A$="d" GOTO 23160
23146 IF A$="U" OR A$="u" GOTO 23180
23150 Z=ASC(A$):IF Z=13 GOTO 23190 ELSE GOTO 23130
23160 SZI=SZI+1:IF SZI=6 THEN SZI=1
23161 IF Q$="C" THEN COLOR 1 ELSE COLOR 0
23162 ON ORI GOSUB 23210,23220,23230,23240,23250
23164 IF Q$="C" THEN COLOR 15 ELSE COLOR 7
23166 ON SZI GOSUB 23210,23220,23230,23240,23250
23168 ORI=SZI :GOTO 23130
23180 SZI=SZI-1:IF SZI=0 THEN SZI=5
23181 IF Q$="C" THEN COLOR 1 ELSE COLOR 0
23182 ON ORI GOSUB 23210,23220,23230,23240,23250
23184 IF Q$="C" THEN COLOR 15 ELSE COLOR 7
23186 ON SZI GOSUB 23210,23220,23230,23240,23250
23188 ORI=SZI :GOTO 23130
23190 ON SZI GOTO 24000,25000,26000,27000,28000
23210 LOCATE 7,18:PRINT CHR$(26)
23212 RETURN
23220 LOCATE 9,18:PRINT CHR$(26)
23222 RETURN
23230 LOCATE 11,18:PRINT CHR$(26)
```

```
23232 RETURN
23240 LOCATE 13,18:PRINT CHR$(26)
23242 RETURN
23250 LOCATE 15,18:PRINT CHR$(26)
23252 RETURN
24000 ' ================================================
24010 ' TO PLOT THE LAST MONTH'S IMPORTANT EVENTS
24020 '
24022 OPEN "PARM.DAT" FOR INPUT AS #1
24023 INPUT #1,ID$
24024 INPUT #1,VLOC$
24025 INPUT #1,MOT,GS,GT:CLOSE
24030 OPEN "WIND.DAT" FOR INPUT AS #1
24035 CLS:J=1:DIM WTX(722),WTN(722),T5N(170),T5X(170)
24037 PRINT MOT
24040 FOR I=1 TO 719:INPUT #1,WTX(I),WTN(I):NEXT:CLOSE
24050 FOR I=0 TO 143
24070 T5X(I)=WTX(J)        'T5X=MAX. TEMP. IN EVERY 5 HOURS
24080 T5N(I)=WTX(J)        'T5N=MIN. TEMP. IN EVERY 5 HOURS
24090 FOR J=I*5 TO I*5+4
24100 IF T5X(I)<WTX(J) THEN T5X(I)=WTX(J)
24110 IF T5N(I)>WTN(J) THEN T5N(I)=WTN(J)
24120 NEXT:NEXT
24130 '  DRAW THE AXIS
24140 SCREEN 1:LINE (30,5)-(30,155),1
24150 LINE (30,155)-(310,155),1
24155 S5=155-(MOT/6):LINE (30,S5)-(310,S5),2
24160 LOCATE 6,1:PRINT"T":LOCATE 7,1:PRINT"E":LOCATE 8,1:
      PRINT"M"
24170 LOCATE 9,1:PRINT"P":LOCATE 10,1:PRINT"E":LOCATE 11,1:
      PRINT"R"
24180 LOCATE 12,1:PRINT"A":LOCATE 13,1:PRINT"T":LOCATE 14,1:
      PRINT"U"
24190 LOCATE 15,1:PRINT"R":LOCATE 16,1:PRINT"E"
24195 LOCATE 18,1:PRINT"C":LOCATE 1,4:PRINT"*100"
24200 FOR I=0 TO 29:LINE (30+9.33*I,155)-(30+9.33*I,157),1:
      NEXT
24205 FOR I=0 TO 9:LINE (28,5+16.667*I)-(30,5+16.667*I),1:
      NEXT
24210 LOCATE 21,4:PRINT"30    25    20    15    10    5
            0"
24220 LOCATE 22,10:PRINT"TIME (PAST DAYS)"
24230 LOCATE 1,3:PRINT"9":LOCATE 3,3:PRINT"8":LOCATE 5,3:
      PRINT"7"
24240 LOCATE 7,3:PRINT"6":LOCATE 10,3:PRINT"5":LOCATE 12,3:
      PRINT"4"
24250 LOCATE 14,3:PRINT"3":LOCATE 16,3:PRINT"2":LOCATE 18,3:
      PRINT"1"
24260 LOCATE 20,3:PRINT"0"
24270 LOCATE 1,6:PRINT"   SOLID LINE=MAX. PROCESS. TEMP."
24800 FOR I=0 TO 143:S1=30+I*2:S2=155-(T5X(I)/6):PSET
      (S1,S2),1:NEXT
```

```
24840  FOR I=0 TO 143:S3=30+I*2:S4=155-(T5N(I)/6):PSET
       (S3,S4),2:NEXT
24850 LOCATE 23,5:PRINT"(Press any key to continue)"
24860 DD$=INKEY$:IF DD$="" THEN GOTO 25860:SCREEN 2:SCREEN 1
24870 GOTO 20000
25000 '=================================================
25010 ' TO PLOT THE LAST WEEK'S IMPORTANT EVENTS
25020 '
25022 OPEN "PARM.DAT" FOR INPUT AS #1
25023 INPUT #1,ID$
25024 INPUT #1,VLOC$
25025 INPUT #1,MOT,GS,GT:CLOSE
25030 OPEN "WIND.DAT" FOR INPUT AS #1
25035 CLS:DIM WTX(722),WTN(722)
25040 FOR I=1 TO 719:INPUT #1,WTX(I),WTN(I):NEXT:CLOSE
25130 '  DRAW THE AXIS
25140 SCREEN 1:LINE (30,5)-(30,155),1
25150 LINE (30,155)-(310,155),1
25155 S5=155-(MOT/6):LINE (30,S5)-(310,S5),2
25160 LOCATE 6,1:PRINT"T":LOCATE 7,1:PRINT"E":LOCATE 8,1:
       PRINT"M"
25170 LOCATE 9,1:PRINT"P":LOCATE 10,1:PRINT"E":LOCATE 11,1:
       PRINT"R"
25180 LOCATE 12,1:PRINT"A":LOCATE 13,1:PRINT"T":LOCATE 14,1:
       PRINT"U"
25190 LOCATE 15,1:PRINT"R":LOCATE 16,1:PRINT"E"
25195 LOCATE 18,1:PRINT"C":LOCATE 1,4:PRINT"*100"
25200 FOR I=0 TO 7:LINE (30+40*I,155)-(30+40*I,157),1:NEXT
25205 FOR I=0 TO 9:LINE (28,5+16.667*I)-(30,5+16.667*I),1:
       NEXT
25210 LOCATE 21,4:PRINT"7    6    5    4    3    2    1
            0"
25220 LOCATE 22,10:PRINT"TIME (PAST DAYS)"
25230 LOCATE 1,3:PRINT"9":LOCATE 3,3:PRINT"8":LOCATE 5,3:
       PRINT"7"
25240 LOCATE 7,3:PRINT"6":LOCATE 10,3:PRINT"5":LOCATE 12,3:
       PRINT"4"
25250 LOCATE 14,3:PRINT"3":LOCATE 16,3:PRINT"2":LOCATE 18,3:
       PRINT"1"
25260 LOCATE 20,3:PRINT"0"
25270 LOCATE 1,6:PRINT"   SOLID LINE=MAX. PROCESS. TEMP."
25800 FOR I=551 TO 719:V9=V9+1:S1=30+V9*1.667:
       S2=155-(WTX(I)/6):PSET (S1,S2),1
25805 NEXT
25840 V9=-1:FOR I=551 TO 719:V9=V9+1:S3=30+V9*1.667:
       S4=155-(WTN(I)/6):PSET (S3,S4),2
25850 NEXT:LOCATE 23,5:PRINT"(Press any key to continue)"
25860 DD$=INKEY$:IF DD$="" THEN GOTO 25860:SCREEN 2:SCREEN 1
25870 GOTO 20000
26000 ' ================================================
26010 ' TO PLOT THE THIRD WEEK'S IMPORTANT EVENTS
26020 '
```

```
26022 OPEN "PARM.DAT" FOR INPUT AS #1
26023 INPUT #1,ID$
26024 INPUT #1,VLOC$
26025 INPUT #1,MOT,GS,GT:CLOSE
26030 OPEN "WIND.DAT" FOR INPUT AS #1
26035 CLS:DIM WTX(722),WTN(722)
26040 FOR I=1 TO 719:INPUT #1,WTX(I),WTN(I):NEXT:CLOSE
26130 '  DRAW THE AXIS
26140 SCREEN 1:LINE (30,5)-(30,155),1
26150 LINE (30,155)-(310,155),1
26155 S5=155-(MOT/6):LINE (30,S5)-(310,S5),2
26160 LOCATE 6,1:PRINT"T":LOCATE 7,1:PRINT"E":LOCATE 8,1:
      PRINT"M"
26170 LOCATE 9,1:PRINT"P":LOCATE 10,1:PRINT"E":LOCATE 11,1:
      PRINT"R"
26180 LOCATE 12,1:PRINT"A":LOCATE 13,1:PRINT"T":LOCATE 14,1:
      PRINT"U"
26190 LOCATE 15,1:PRINT"R":LOCATE 16,1:PRINT"E"
26195 LOCATE 18,1:PRINT"C":LOCATE 1,4:PRINT"*100"
26200 FOR I=0 TO 7:LINE (30+40*I,155)-(30+40*I,157),1:NEXT
26205 FOR I=0 TO 9:LINE (28,5+16.667*I)-(30,5+16.667*I),1:
      NEXT
26210 LOCATE 21,4:PRINT"14   13   12   11   10   9    8
      7"
26220 LOCATE 22,10:PRINT"TIME (PAST DAYS)"
26230 LOCATE 1,3:PRINT"9":LOCATE 3,3:PRINT"8":LOCATE 5,3:
      PRINT"7"
26240 LOCATE 7,3:PRINT"6":LOCATE 10,3:PRINT"5":LOCATE 12,3:
      PRINT"4"
26250 LOCATE 14,3:PRINT"3":LOCATE 16,3:PRINT"2":LOCATE 18,3:
      PRINT"1"
26260 LOCATE 20,3:PRINT"0"
26270 LOCATE 1,6:PRINT"   SOLID LINE=MAX. PROCESS. TEMP."
26800 FOR I=383 TO 551:V9=V9+1:S1=30+V9*1.667:
      S2=155-(WTX(I)/6):PSET (S1,S2),1
26805 NEXT
26840 V9=-1:FOR I=383 TO 551:V9=V9+1:S3=30+V9*1.667:
      S4=155-(WTN(I)/6):PSET (S3,S4),2
26850 NEXT:LOCATE 23,5:PRINT"(Press any key to continue)"
26860 DD$=INKEY$:IF DD$="" THEN GOTO 26860:SCREEN 2:SCREEN 1
26870 GOTO 20000
27000 ' ================================================
27010 ' TO PLOT THE SECOND WEEK'S IMPORTANT EVENTS
27020 '
27022 OPEN "PARM.DAT" FOR INPUT AS #1
27023 INPUT #1,ID$
27024 INPUT #1,VLOC$
27025 INPUT #1,MOT,GS,GT:CLOSE
27030 OPEN "WIND.DAT" FOR INPUT AS #1
27035 CLS:DIM WTX(722),WTN(722)
27040 FOR I=1 TO 719:INPUT #1,WTX(I),WTN(I):NEXT:CLOSE
27130 '  DRAW THE AXIS
```

```
27140 SCREEN 1:LINE (30,5)-(30,155),1
27150 LINE (30,155)-(310,155),1
27155 S5=155-(MOT/6):LINE (30,S5)-(310,S5),2
27160 LOCATE 6,1:PRINT"T":LOCATE 7,1:PRINT"E":LOCATE 8,1:
      PRINT"M"
27170 LOCATE 9,1:PRINT"P":LOCATE 10,1:PRINT"E":LOCATE 11,1:
      PRINT"R"
27180 LOCATE 12,1:PRINT"A":LOCATE 13,1:PRINT"T":LOCATE 14,1:
      PRINT"U"
27190 LOCATE 15,1:PRINT"R":LOCATE 16,1:PRINT"E"
27195 LOCATE 18,1:PRINT"C":LOCATE 1,4:PRINT"*100"
27200 FOR I=0 TO 7:LINE (30+40*I,155)-(30+40*I,157),1:NEXT
27205 FOR I=0 TO 9:LINE (28,5+16.667*I)-(30,5+16.667*I),1:
      NEXT
27210 LOCATE 21,4:PRINT"21   20   19   18   17  16   15
      14"
27220 LOCATE 22,10:PRINT"TIME (PAST DAYS)"
27230 LOCATE 1,3:PRINT"9":LOCATE 3,3:PRINT"8":LOCATE 5,3:
      PRINT"7"
27240 LOCATE 7,3:PRINT"6":LOCATE 10,3:PRINT"5":LOCATE 12,3:
      PRINT"4"
27250 LOCATE 14,3:PRINT"3":LOCATE 16,3:PRINT"2":LOCATE 18,3:
      PRINT"1"
27260 LOCATE 20,3:PRINT"0"
27270 LOCATE 1,6:PRINT"   SOLID LINE=MAX. PROCESS. TEMP."
27800 FOR I=215 TO 383:V9=V9+1:S1=30+V9*1.667:
      S2=155-(WTX(I)/6):PSET (S1,S2),1
27805 NEXT
27840 V9=-1:FOR I=215 TO 383:V9=V9+1:S3=30+V9*1.667:
      S4=155-(WTN(I)/6):PSET (S3,S4),2
27850 NEXT:LOCATE 23,5:PRINT"(Press any key to continue)"
27860 DD$=INKEY$:IF DD$="" THEN GOTO 27860:SCREEN 2:SCREEN 1
27870 GOTO 20000
28000 ' ================================================
28010 ' TO PLOT THE FIRST WEEK'S IMPORTANT EVENTS
28020 '
28022 OPEN "PARM.DAT" FOR INPUT AS #1
28023 INPUT #1,ID$
28024 INPUT #1,VLOC$
28025 INPUT #1,MOT,GS,GT:CLOSE
28030 OPEN "WIND.DAT" FOR INPUT AS #1
28035 CLS:DIM WTX(722),WTN(722)
28040 FOR I=1 TO 719:INPUT #1,WTX(I),WTN(I):NEXT:CLOSE
28130 '  DRAW THE AXIS
28140 SCREEN 1:LINE (30,5)-(30,155),1
28150 LINE (30,155)-(310,155),1
28155 S5=155-(MOT/6):LINE (30,S5)-(310,S5),2
28160 LOCATE 6,1:PRINT"T":LOCATE 7,1:PRINT"E":LOCATE 8,1:
      PRINT"M"
28170 LOCATE 9,1:PRINT"P":LOCATE 10,1:PRINT"E":LOCATE 11,1:
      PRINT"R"
28180 LOCATE 12,1:PRINT"A":LOCATE 13,1:PRINT"T":LOCATE 14,1:
```

```
        PRINT"U"
28190 LOCATE 15,1:PRINT"R":LOCATE 16,1:PRINT"E"
28195 LOCATE 18,1:PRINT"C":LOCATE 1,4:PRINT"*100"
28200 FOR I=0 TO 7:LINE (30+40*I,155)-(30+40*I,157),1:NEXT
28205 FOR I=0 TO 9:LINE (28,5+16.667*I)-(30,5+16.667*I),1:
        NEXT
28210 LOCATE 21,4:PRINT"28   27   26   25   24  23   22
        21"
28220 LOCATE 22,10:PRINT"TIME (PAST DAYS)"
28230 LOCATE 1,3:PRINT"9":LOCATE 3,3:PRINT"8":LOCATE 5,3:
        PRINT"7"
28240 LOCATE 7,3:PRINT"6":LOCATE 10,3:PRINT"5":LOCATE 12,3:
        PRINT"4"
28250 LOCATE 14,3:PRINT"3":LOCATE 16,3:PRINT"2":LOCATE 18,3:
        PRINT"1"
28260 LOCATE 20,3:PRINT"0"
28270 LOCATE 1,6:PRINT"   SOLID LINE=MAX. PROCESS. TEMP."
28800 FOR I=47 TO 215:V9=V9+1:S1=30+V9*1.667:
        S2=155-(WTX(I)/6):PSET (S1,S2),1
28805 NEXT
28840 V9=-1:FOR I=47 TO 215:V9=V9+1:S3=30+V9*1.667:
        S4=155-(WTN(I)/6):PSET (S3,S4),2
28850 NEXT:LOCATE 23,5:PRINT"(Press any key to continue)"
28860 DD$=INKEY$:IF DD$="" THEN GOTO 28860:SCREEN 2:SCREEN 1
28870 GOTO 20000
29000 ' ================================================
30000 ON KEY(1) GOSUB 20000
30002 KEY(1) ON
30004 ON KEY(2) GOSUB 31000
30006 KEY(2) ON
30008 ON KEY(10) GOSUB 40000
30010 KEY(10) ON
30100 GOTO 20010
31000 IF Q$="C" THEN SCREEN 0,1,0 ELSE SCREEN 0,0,0
31002 WIDTH 80
31010 IF Q$="C" THEN COLOR 15,1,1 ELSE COLOR 7,0,0
31011 CLS:KEY OFF
31030 FOR I=2 TO 79:LOCATE 1,I:PRINT CHR$(205);:LOCATE 25,I
        :PRINT CHR$(205);:NEXT
31060 IF Q$="C" THEN COLOR 10
31080 LOCATE 7,25:PRINT"Do you want to go to DOS? (Y/N)"
31130 A$=INKEY$:IF A$="" GOTO 31130
31140 IF A$="Y"  OR A$="y" THEN SYSTEM
31150 GOTO 20000
35000 ' ================================================
35005 '          MAINTENANCE ASSISTANCE PART 1
35007 ' ================================================
35010 CLS: IF Q$<>"C" THEN 35020
35015 SCREEN 2:SCREEN 0:COLOR 0,11:CLS
35020 CLS:OPEN "MAINT1.TXT" FOR INPUT AS #1
35030 PRINT:PRINT:PRINT:IF EOF(1) THEN 20000
35040 LINE INPUT #1,LIN$
```

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35050 IF LIN$="B" THEN LINE INPUT #1,LIN$
35060 IF LIN$="E" THEN GOTO 35080
35070 PRINT LIN$:GOTO 35040
35080 GOSUB 9000:GOTO 35030
36000 ' ================================================
36005 '         MAINTENANCE ASSISTANCE PART 2
36007 ' ================================================
36010 CLS: IF Q$<>"C" THEN 36020
36015 SCREEN 2:SCREEN 0:COLOR 0,11:CLS
36020 CLS:OPEN "MAINT2.ASC" FOR INPUT AS #1
36030 PRINT:PRINT:PRINT:IF EOF(1) THEN 20000
36040 LINE INPUT #1,LIN$
36050 IF LIN$="B" THEN LINE INPUT #1,LIN$
36060 IF LIN$="E" THEN GOTO 36080
36070 PRINT LIN$:GOTO 36040
36080 GOSUB 9000:GOTO 36030
37000 ' ================================================
37005 '         MAINTENANCE ASSISTANCE PART 3
37007 ' ================================================
37010 CLS: IF Q$<>"C" THEN 37020
37015 SCREEN 2:SCREEN 0:COLOR 0,11:CLS
37020 CLS:OPEN "MAINT3.ASC" FOR INPUT AS #1
37030 PRINT:PRINT:PRINT:IF EOF(1) THEN 20000
37040 LINE INPUT #1,LIN$
37050 IF LIN$="B" THEN LINE INPUT #1,LIN$
37060 IF LIN$="E" THEN GOTO 37080
37070 PRINT LIN$:GOTO 37040
37080 GOSUB 9000:GOTO 37030
40000 IF Q$="C" THEN SCREEN 0,1,0 ELSE SCREEN 0,0,0
40002 WIDTH 80
40010 IF Q$="C" THEN COLOR 15,1,1 ELSE COLOR 7,0,0
40011 CLS:KEY OFF
40030 FOR I=2 TO 79:LOCATE 1,I:PRINT CHR$(205);:LOCATE 25,I:
      PRINT CHR$(205);:NEXT
40060 IF Q$="C" THEN COLOR 10
40065 LOCATE 3,31:PRINT"     H E L P      "
40070 IF Q$="C" THEN COLOR 11
40080 LOCATE 7,20:PRINT"F1 : Main MENU"
40090 LOCATE 9,20:PRINT"F2 : Quit to DOS"
40092 LOCATE 11,20:PRINT"F10 : This HELP screen"
40099 IF Q$="C" THEN COLOR 10
40100 LOCATE 21,16:PRINT"      Press any key to go to the
   MAIN MENU        "
40130 A$=INKEY$:IF A$="" GOTO 40130
40200 GOTO 20000
```

LISTING OF INSTRUCT.ASC FILE

B

INSTRUCTIONS:

This program was developed as a part of the Smart Temperature Measurement System developed by Majed N. Natour at the University of Tennessee, Knoxville. The main functions of the program are:

1. Collect the analog signals from the sensor
2. Convert those signals to temperature
3. Correct and analyze the values
4. Perform cold junction compensation
5. Display the temperature and the accuracy
6. Track the sensor performance
7. Provide status reports
8. Provide a moving graphical display of the important events
   over a one month period
9. Provide maintenance assistance.

E
B

The program is a user friendly and menu driven piece of software. The main selections on the menu are:

1. INSTRUCTIONS:

   Selecting this item introduces the user to the various aspects of this program.

2. SIGNAL ACQUISITION/PROCESSING:

   This is the core of the program where signals received from the interface are processed and validated. The various parameter and status files are updated periodically by this part. This part is also responsible for the controlling the interface logic to regulate the sequence in which the relays are activated.

E

B

3. MOVING WINDOW:

This part displays the sensor history of important events (i.e. the maximum and the minimum temperatures attained) over a one month period. The history file WIND.DAT is updated every hour. The user has the option to see graphical displays of the history for a whole month, or any particular week of the month. Since, the display represents the past history, ZERO day implies the current day

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4. MAINTENANCE ASSISTANCE:

This part contains a description of the various HARDWARE components of the smart system.

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5. STATUS REPORT:

This part is responsible for displaying the status of the system. items of interests are:

Which parts (wire pairs) are reliable?
Which parts of the sensor have failed?
and so on..

E
B

6. UPDATE SENSOR PARAMETERS:

This part has to be selected whenever external changes or replacements have been performed on the system.

E
B

The user may interrupt the execution of the program at any time by pressing the F1, F2, or F3 function buttons where:

F1 ==> Main Menu

F2 ==> "Exit to DOS" option

F3 ==> Help screen

E

B

SENSOR ASSEMBLY DESCRIPTION:

The sensor part of the smart temperature measurement system consists of a twelve inches long, quarter inch diameter, insulated multilead thermocouple (MTC). There are five, 24 Gage, leads in the MTC joined at a single junction called the Measuring Junction (MJ). The MJ was created by twisting the five wires around each other, then welding them.

E
B

Type of Wires:

The wires used in this system are:

1. Chromel (Ep, positive, Purple)
2. Constantan (En, negative, Red)
3. Nicrosil (Np, positive, Blue)
4. Nisil (Nn, negative, Black)
5. Iron (Jp, positive, White)

E
B

Connectors:

The connectors are a standard type miniature connectors where wires Ep and En are connected to the positive and negative legs of the Purple (type E) connector, wires Np and Nn, are connected to the positive and negative legs of the Orange connector (type N), and wire Jp is connected to the positive leg of the Black connector (type J).

E
B

Extension Wires:

The extension wires consist of standard type E, N, and the positive type J wires. They are connected to three jacks (i.e. E (Purple), N (Orange), and J (Black)) on one end. The extension wires have the standard color codes (i.e Ep is Purple, En is Red, Np is Orange, Nn is Red, and Jp is White). Notice that the type N colors for the sensor and the extension wires are different.

On the other end, the extension wires are inserted inside the interface as described in the next section.

E

B

Possible Sources of Error:

Grounded Junction:

This is easily detected by measuring the resistance between one of the wires and the sheath. If the resistance is HIGH (i.e. greater than a few Megaohms) then there is no grounding.

If the resistance is low (i.e. less than few ohms) then the MJ is grounded, and the sensor should be replaced.

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Loose or Disjoint Connector:

Measure the resistance across the connector leg and the wire that is connected to it. If the resistance is high then the wire is not connected properly. Open the connector and reconnect the wire.

Repeat the test for all the connectors.

E
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Disjoint MJ:

Measure the resistance across between a wire and each of the remaining wires. If the resistance is high, then measure the resistance between those wires and the remaining wires to determine which of the wire pair is disconnected.

E

B

INTERFACE DESCRIPTION:

The interface is designed to use two input channels and one output channel of the data acquisition board. The Data acquisition board (Model Number DT 2801-A) is a multi input/output, analog/digital channels with twelve bit resolution. It is developed by Data Translation. The main data acquisition software used to manipulate the board is Data Translation's PCLAB used in conjunction with BASICA.

A Data Translation screw terminal panel (Model Number DT-707) is used to connect the MTC's interface to the DT 2801-A board.

E
B

The interface consists of:

1. a set of eight relays
2. a relay control logic
3. an on-board temperature circuit
4. a counter reset circuit
5. a power supply
6. a case and insulation

The following is a detailed description of these parts.

E
B

1. Relays:

A set of eight relays (Model Number W171 DIP-21, developed by Magnecraft), driven by +5 volts power supply, are used in the interface to obtain measurements from all the different MTC wire pair combination. The relays are of the double pole - double throw type. Therefore, both the positive and the negative MTC wire pairs can be connected to each relay.

The positive output of all the relays share a single line while the negative output of all the relays share another single line -- since only one relay will be turned closed at any instance while the rest are left open. Both lines are connected to input Channel 0 of the DT 707.

Each relay has a diode (Model Number IN4001) connected to the coil pins (# 2, and 6) to provide protection for the circuit after a sudden power cut-off.

E
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2. Relay Control Logic:

To regulate the sequence in which each relay is turned on, a logic circuit consisting of

1. A counter 74193 driven by +5 volts supply.

2. A decoder (BCD-to-Decimal 7442 decoder driven by a +5v supply.
3. A set of eight PNP transistor-resistor circuits driven by a +5 volts power supply to supply enough current to drive the relays since the decoder signals are too weak to drive the relays. Each set consists of:

E
B

a. a 10k Ohms resistor between the +5v line and the corresponding pin on the output of the decoder (i.e. one of pins 0 through 7);
b. a 4.7k Ohms resistor between the decoder and the Base of the PNP transistor;
c. a PNP transistor (Model Number ECG 150 PNP-Si) with the Base connected to the 4.7k Ohms resistor, the Emitter connected to the +5v supply, and the Collector connected to the relay's pin # 2.

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3. The Board Temperature Circuit:

To determine the reference junction temperature at the place of initial contact between the MTC wires and measuring circuit, the following circuitry is used:

a. a solid state temperature device (Model Number AD590, developed by Omega Company);
b. a 100 Ohms variable resistor;
c. a 910 Ohms resister; and
d. a +5v power source.

The output of this circuit is fed to channel 1 of the input of the DT2801-A board after amplification.

E
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4. Counter Reset Circuit:

This circuit is designed to reset the counter to send 0000 output signal, which activates relay #1, by sending a HIGH (+5 volts) signal to the counter Pin #14. Hence, the software can determine the exact relay that is turned on at the beginning of the program execution. The resetting HIGH signal can be sent to the counter by one of two ways:

a. upon powering up the interface, or
b. the HIGH output of Pin #7 is diverted to Pin #14 (the reset Pin) by a special circuit since only the first eight output signals of the counter are needed to turn on the eight relays, while the counter is capable of producing sixteen output signals. Therefore, the ninth pulse is used to activate relay 1 instead of the imaginary relay 9.

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The circuit consists of:

a. a 4232 Positive OR Gate;
b. a +5v supply;
c. a 10 micro Farad Capacitor; and
d. a 1k Ohms resistor.

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5. Case and Insulation:

It is important to keep the relay set at a uniform and constant temperature (i.e., reference junction temperature). Therefore, the circuit board has been encased in a fiberglass insulation. The whole assembly is then encased in a 1/4 inch thick Aluminum casing.

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6. Power Supply

A single 5 volt power supply is used to provide the entire interface with 5 volts. The power supply is connected to the regular 110v AC line.

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Functional Description of the Interface:

Upon turning the power supply on, the resetting circuit provides a high pulse to pin #14 on the counter due to the capacitor effect. This pin resets the counter to send a LOW signal across pins 7, 6, 2, and 3. Hence, this configuration corresponds to a 0000 binary code which in turn results in activating (LOW) pin #1 on the decoder. Hence, relay #1 is turned on. At this point a measurement of the signal from that relay is made.

E
B

Next, the software is used to have the DT2801-A send a LOW (0 volts) then HIGH (+5 volts) signal to the counter's input. Hence, the output of the counter reads 0 0 0 1 which results in activating pin #2 of the decoder by making it indicate LOW while pin #1 is deactivated by turning it to HIGH. Hence, relay 2 is turned on. The process of pulsing the decoder, then measuring the voltage across the relays is repeated several times as the relationship between the counter output and the relays activated is shown in the following table:

E
B

COUNTER PIN				RELAY ACTIVATED
7	6	2	3	
0	0	0	0	1
0	0	0	1	2
0	0	1	0	3
0	0	1	1	4
0	1	0	0	5
0	1	0	1	6
0	1	1	0	7
0	1	1	1	8
1	0	0	0	RESETS COUNTER TO
0	0	0	0	1

E
B

The circuit has been designed to reset the counter upon finishing the ninth pulse by connecting pin #7 to the input pin #1 of the OR Gate. The OR Gate follows the truth table below :

PIN 1	PIN 2	PIN 3
0	0	0
1	0	1
0	1	1
1	1	1

Hence, when pin #7 of the counter reads HIGH on the ninth pulse, the output of the OR gate pin #3, which is connected to the counter's reset pin #14, reads HIGH. Hence, the counter is reset, and relay #1 is turned on again.

E
B

After the eighth measurement is taken, the computer switches to Channel 1, to collect the Temperature of the board signal. That signal is designed so that the output of the AD590 is 1k/mv absolute. Therefore, the board temperature (BT) is given as

$$BT = \frac{M*1000}{G} - 273.16$$

where

M ==> the measured value in volts;
G ==> the amplifiers gain factor.

E
B

The eight MTC signals are processed and compensated for the Reference Junction Temperature (RJT). The process temperature is then displayed on the PC screen. Next, the program repeats the process of sending pulses to the interface, then collecting the MTC signals for processing.

E

B

Possible Sources of Error:

- No power to the board.
- Wires are loose or disconnected, check the various wires to ensure conductivity of signals.
- loose resistors transistors.
- bad relays, counter, decoder, OR gate.

E

LISTING OF MAINT3.ASC FILE

B

PROGRAM/INTERFACE COORDINATION:

This program has been developed to be user friendly and flexible. The software keeps track of sensor performance by storing and retrieving information in auxiliary files. So, most of the information regarding sensor will not be lost in case of power failure. However, it is of utmost importance for the software to recognize the correct relay that is turned on.

E
B

The most important parameter to track is P with values from 1 to 8. The value of P is updated every time the counter is pulsed. Therefore, the value of P corresponds to the correct relay that is turned on. If the counter is triggered by accident (due to an electric spike, then erroneous measurements will be made since the measured Emfs will be used in the wrong interpolation polynomials.

E
B

If for any reason, the software seems to display a chaotic temperature, you may simply

a. turn off the power to the interface
b. discontinue the current program execution
c. reconnect the power supply to the interface, and
d. run the program by typing "start"

E
B

By cutting the power off the interface, the special resetting circuit on the interface will insure that relay 1 is on. Furthermore, the program is developed with a starting P value of 1. Hence, this process insures that the program and interface are coordinated.

E

LISTING OF P.DAT FILE

```
 1              0              0
```

LISTING OF COEFF.DAT FILE

```
 5.859969006059057D-02    ,    4.721421503976961D-05
,-8.708183574651815D-08   ,-9.379571329657253D-11
,-6.665399409392274D-14
 3.622102080218785D-02    ,    1.835331013972980D-05
,-1.728179231891608D-08   ,-2.213786283582319D-11
,-2.915307000475409D-14
 8.757412276882765D-03    ,    1.483806701333354D-05    ,
6.768127502467306D-09     ,    4.531809233051449D-11    ,
2.514349902602015D-14
 4.838748832680124D-02    ,    4.569243222426703D-05
,-7.308364296673614D-08   ,-9.120117090472120D-11
,-1.340967215905123D-13
 2.258570415966324D-02    ,    2.578961879907883D-05
,-4.355037317275275D-08   ,-6.689789889952643D-11
,-1.495887646732769D-13
 .050615693348076 5       ,    2.630174168598080D-05
,-1.003734370480343D-07   ,-6.966654791561612D-11    ,
1.070308806994663D-13
 2.584513482839525D-02    ,    1.910894685094369D-05
,-2.176131551413165D-08   ,-2.258759074915265D-11
,-3.245523174809987D-14
 2.880281888452882D-02    ,-1.597364813410791D-05    ,
1.689883362203533D-07     ,-6.122090147332881D-10    ,
2.865248873338532D-12
```

LISTING OF GCCPARM.DAT FILE

```
 2 , 2 , 2 , 2 , 2 , 2 , 2 , 2
```

LISTING OF PARM.DAT FILE

```
MTC1-1,cold leg, 200 , 200 , 222 , 30 ,8/9/89
```

LISTING OF SPRT.DAT FILE

```
 .3156119 , 0 , 12.96253 , 20.53014 , 14.01552 , 2.123245
,-2.677803 , 0 ,======
```

LISTING OF STAT.CUR FILE

```
1               2               1               21.875          0
        3.125           96.875
2               2               1               21.875          0
        0               100
3               2               1               21.875          0
        3.125           96.875
4               2               1               21.875          0
        3.125           96.875
5               2               1               21.875          0
        3.125           96.875
6               2               1               21.875          0
        3.125           96.875
7               2               1               21.875          0
        3.125           96.875
8               2               1               21.875          0
        0               100
```

LISTING OF WEIGHT.VAR FILE

```
1
1
1
1
1
1
1
1
```

LISTING OF WEIGHT.DAT FILE

```
12.23 , 4.35 , 7.55 , 20.94 , 12.78 , 15.09 , 25.56 , 1.5 ,
```

LISTING OF WIND.DAT FILE

```
2               1
4               2
6               3
8               4
10              5
12              6
14              7
16              8
18              9
20              10
.               .
.               .

190             95
192             96
194             97
196             98
198             99
200             100
100             80
101             81
102             82
103             83
104             84
.               .
.               .

715             695
716             696
717             697
718             698
719             699
720             700
```

VITA

Majed N. Natour was born December 17, 1958, in Amman, Jordan. He received his elementary, preparatory, and secondary education in the Jordanian Public School System.

In November, 1977, he came to the USA to pursue his higher education. He attended the English Language Institute at Belmont, NC, and obtained an English Diploma in December 1977. He attended Gaston College in the Spring quarter of 1978. He transferred to the University of Tennessee at Knoxville in June of 1978. He received a Bachelor of Science Degree (with honors) in Nuclear Engineering in June, 1982. He pursued his higher education at the same university where he received his Master of Science in Nuclear Engineering in March, 1986. He continued to pursue the Doctor of Philosophy Degree in Nuclear Engineering at the University of Tennessee, Knoxville. He received his Ph.D. in May, 1990. He was involved in artificial intelligence and advanced sensors research.

He is a member of the National Engineering Honor Society, the American Nuclear Society, the American Association for Artificial Intelligence, and the Instrument Society of America.