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1

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TITLE: ACQUISITION SYSTEMS FOR HEAT TRANSFER MEASUREMENT

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ACQUISITION SYSTEMS FOR HEAT TRANSFER MEASUREMENT

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ABSTRACT

Practical heat transfer data acquisition systems are normally characterized by the need for high-resolution, low-drift, low-speed recording devices. Analog devices such as strip chart or circular recorders and FM analog magnetic tape have excellent resolution and work well when data will be presented in temperature versus time format only and need not be processed further. Digital systems are more complex and require an understanding of the following components: digitizing devices, interface bus types, processor requirements, and software design.

This paper will discuss all the above components of analog and digital data acquisition, as they are used in current practice. Additional information on thermocouple system analysis will aid the user in developing accurate heat transfer measuring systems.

1. GENERAL

This paper will discuss present means of acquiring heat transfer data. Most of the information presented will apply to data acquisition systems in general, since new types of thermal measurement transducers are likely to appear and require a variety of processing techniques.

Because the most commonly used temperature transducer in practical application is the thermocouple junction, particular attention will be paid to data acquisition systems geared to thermocouple inputs. The only real difference between thermocouple acquisition systems and other types is in the signal level and speed requirements, which luckily are related inversely.

Thermocouple systems must be capable of resolving tenths of hundredths of a millivolt signals with virtually no voltage drift over time. Any connections in the thermocouple loop must be with known wire types and must be at a known temperature, to determine the total loop voltage. High-speed acquisition is usually not necessary, since thermal systems in power engineering exhibit changes on a time scale of minutes. This low-speed requirement allows the use of high-resolution acquisition systems that, if digital, are recording at rates less than 10 samples per second per channel.

2. ANALOG ACQUISITION SYSTEMS

For measurements that will not require further access to the data for accurate calculations, an analog acquisition system may be used. An analog system may best be defined as one that does not make use of discrete conversion steps, but reproduces the input signal as a voltage versus time trace on a recording medium. The recording medium is usually ink on paper for chart recorders, or magnetic tape for a multichannel analog recorder. Magnetic tape has the advantage of allowing repeated reproduction of the recorded signal, including replay at different speeds and output voltage levels.

Analog systems have the advantage of infinite resolution but are limited in accuracy and range. The recorded signal is usually available for viewing in real time (in user units if calibrated). The only total time limit is the size of the recording media avialable. One very practical advantage of most analog recording systems is that in the event of equipment failure during acquisition, the preceding data is still intact.

Some of the drawbacks of analog systems include slow response rates (<100 Hz for most systems); limitations on the number of channels of data input that may be easily recorded; the unavailability of data for further processing (except for magnetic tape); and finally, limitations produced by the physical resolution of the hardcopy device (pen size), even though resolution may be infinite in the electonics.

Analog magnetic tape makes a nice companion to a digital acquisition system, especially when signal levels or time resolution requirements are not known in advance. The data can be captured on FM tape and digitized by the data system at the same time, in parallel. If more time resolution is required, the tape may then be played back more slowly into the digital system. Of course, the same technique can be used with strip chart recorders or other analog systems if the original data were recorded on tape.

Since analog systems are usually smaller and less expensive than digital systems, they should be considered whenever one is planning a new test setup. These systems are particularly cost effective when the user is recording long-term data from an unattended site, when the data are to be used as a temperature history recording, or when the analog system is a backup for a more complicated digital configuration. The limitations of recording speed and number of input channels are not very important when one is dealing with heat transfer measurements.

3. DIGITAL ACQUISITION SYSTEMS

A digital data acquisition system has several advantages over an analog system. The first, and most obvious, advantage is the ability to store data for future retrieval and processing. This processing may be as simple as listing or plotting the data to a hardcopy device, or as complicated as performing a mathematical conversion. Other advantages include higher data acquisition rates and flexibility in setup Some disadvantages of a digital system are limited storage (most analog systems being limited only by the amount of recording tape or paper available), limited voltage resolution, and the possibility of loss of all data during the acquisition stage. An analog system, on the other hand, would still retain the data acquired before the condition causing failure.

The fundamental units of a digital acquisition system are the analog to digital converter (A/D) (or digital voltmeter), interface bus, processor and memory, storage media, and software. Each of these units will be examined in detail.

3.1 Digitizing Devices

A/Ds are devices that sample an input channel voltage at specified time intervals and convert the voltage into a binary number of steps or "counts." The resolution of the A/D is dependent on the number of steps of voltage division it has, each step being one binary value. A/Ds are available in a wide range of resolution and speed--the two being inversely related. Devices called transient digitizers are available at digitizing rates of up to 100 million samples per second (100 mHz), but their resolution is currently limited to 8 bits (+127, -128 units). More resolution is available at lower speeds, with the current upper limit of 16 bits (+32 767, -32 768). Negative values are usually sent in two's complement form, and the user must often perform sign bit extension to the computer's most significant bit. The data are often available for transfer in parallel (all bits at once) but some interfaces will require that the data be sent serially. Since the data as transferred are in counts, the conversion factor to user units is

$$V = C*C1 + C2. \qquad (1)$$

Equation (1) is a simple slope/offset correction where V is user units, C is the A/D count, C1 is a slope calibration factor (units/count), and C2 is the offset in user units. More detailed discussions of calibration are covered in Section 3.4, Software Designs. Most A/Ds have dc amplifiers built in, and adjustable voltage ranges are therefore common. Some digitizers (the transient digitizers) include a self-contained memory module to store the binary data at very fast speeds. The interface may then copy the data to computer memory or storage media at the interface transfer rate.

Digital voltmeters (DVMs) offer much more resolution than ordinary A/Ds. A resolution of 6-1/2 digits, not bits, over a variable range scale is not uncommon. This allows resolution of 0.000001 parts over the selected range. The 1/2 digit is actually the highest (most significant) decimal value and is allowed to be one (1) or zero (0) only. This means that a common set of range scales for a DVM might be plus and minus 0.10 V, 1.00 V, 10.00 V, 100.00 V, and 1000.00 V. This resolution costs speed, and most DVMs of this accuracy can only acquire a maximum of about 10 readings per second. Like most A/Ds, DVMs may be "short-cycled," or commanded to use a reduced resolution mode, which in turn increases their acquisition speed. Note, however, that transfer speed may increase as resolution decreases, since most DVMs send data in serial character strings and reduced resolution means fewer characters to send. Those that have a parallel or binary coded decimal (BCD) interface will have a faster transfer rate since all bits are sent at once over individual wires. Many DVMs also offer some form of internal data manipulation such as averaging (useful for removing ac line noise) or offset removal.

Because we are primarily concerned with heat transfer measurements, it is worth noting that high-speed digitizing devices are not necessary. Thermal transients, especially in power systems, usually occur over a time span of several minutes. We may therefore trade digitizing speed for the crucial resolution that is required for low-sensitivity transducers such as thermocouples and eddy current devices. High-resolution makes the multipurpose scanning DVM, with a variety of plug-in modules, a very cost-effective and versatile piece of equipment for heat transfer measurement.

3.2 Interface Bus Selection

Three interface busses, CAMAC, RS232C, and GPIB (IEEE-488), are common among present data acquisition systems. Note that no mention is made of direct processor digital I/O bus interfaces. Although the direct parallel interface is usually faster than the other three types mentioned, such an interface always requires custom installation and wiring--not to mention custom software. In addition, the direct I/O interface is usually more expensive than one of the standard ones and not nearly as versatile.

We might think of the parallel interface as a Ferrari automobile--wh· ' it works it's great. It is designed to do only one thing well, and that is go fast. But when it breaks, it's going to cost you a lot of time and money to get it fixed again. The three standard interfaces are more like Toyota, Ford and Lada: they are fairly plain, inexpensive, and versatile. However, we cannot get away from the parallel interface completely, since that is what eventually must connect the three standard interfaces to a mini- or large-computer I/O bus.

The CAMAC interface. The acronym is said to represent the words "Computer Automated Measurement And Control," and it is the one true international computer standard. The specifications originated in France and were meant to be used with high-speed nuclear physics counting and detection equipment. The standard itself is one of the best, most complete specifications ever written for electronic equipment. It covers not just the interfacing electronic protocol, but also the hardware-size and quality, extension capabilities, software-calling arguments, and general executable functions. CAMAC is the fastest of the three standard interfaces when it is used in the parallel transfer mode. There ar over 4000 different modules available from commercial vendors, most of them relating to pulse counting and detection, but also including thermocouple and A/D input devices. the transient digitizers mentioned in Section 3.1 are available only as CAMAC modules.

The CAMAC interface consists of a hardware rack with internal backplane wiring and power supplies (the "crate"), the individual electronic modules that plug into the crate, a special module called the "crate controller," and the computer interface that connects the crate controller to the host computer.

The crate provides power at $\pm$24 Vdc, $\pm$12 Vdc, and +6 Vdc to specified positions in the backplane connectors. Each crate has slots for 24 individual modules, but slot 24 is reserved for the crate controller module. The controller module has access to interrupt and command lines at each of the other slots and is the timing and protocol link between the host computer and each individual module. The data path in a CAMAC crate is 24 bits wide, but controllers are usually able to send and receive data of 24, 16, or 8 bits. There are several types of crate controller modules, a different type for each interface to which the crate may be connected. In addition, two ways to interconnect more that one crate on a "highway" system exist. One highway is for parallel data transfer; the other is for serial. There are special crate controllers for each of the crates on the highway, as for the master crate controller.

The CAMAC parallel or "branch" highway can support up to seven crates over total distances of up to 100 m (highway length is a function of wire size and shielding). The branch highway is a multiconductor cable terminated at one end and fed by the branch driver at the other. Maximum data transfer rates are up to 500 000 24-bit words per second (wps).

The serial highway can support up to 62 crates over a variety of transmission media with indeterminate total length. If wire cable is used, it consists of twisted, shielded pairs of conductors per bit and may be either bit serial (one pair of wires) or byte serial (eight pairs). A maximum transfer rate of 200 000 24-bit wps is possible in byte serial transfers, 20 000 wps in bit serial mode. The highway must form a circular or loop path, beginning and ending at the serial driver, which may reside in a crate on another highway.

One of the more recent advances in CAMAC technology is the use of single board computers as crate controller modules. This use makes the crate a stand-alone data acquisition and processing unit with internal memory and interfaces for storage media and graphics.

The individual modules in a crate may be more than one slot in width, and each must be addressed at a specific slot number. Therefore, provisions must be made in software for different crate configurations, or else the modules must be installed in the crate in an exactly specified order. The entire crate must be powered down to install or remove a module, and most external connections are made at the front panel of the module, which can result in a tangle of wiring.

The CAMAC standard supports 32 functions that fit into general groups of read, write, and command functions. The module manufacturer must specify the response of the individual modules to each function. Kits are available to allow the user to design and build his own CAMAC module to perform specific functions.

The GPIB interface. The General Purpose Interface Bus (IEEE standard 488) is the result of the demand for a serial interface of medium speed, with timing and protocol sufficient to assure data transfer over short-length lines. Total transmission path length may not exceed 20 m, and the maximum transfer speed is about one million 8-bit bytes per second, although handshake protocol assures that data are transfered at the rate of the slowest device participating. The maximum number of instruments on the interface at one time is 14, and the useful maximum data transfer rate for voltmeters is about 20 0000 8-bit bytes per second, not including digitizing time. The interface was first designed by the Hewlett-Packard Company to connect between their desktop calculators and I/O devices but has since become a widely used interface for data transfer in the United States.

The actual standard (IEEE-488) only deals with cabling, timing, and handshake protocol. Software is becoming standardized as it is supplied by the interface manufacturers.

The host computer must have an I/O bus to GPIB adapter to access the interface; then, from the user standpoint, the only commands that need to be sent often are read, write, clear, and local/remote switching. Data are sent serially as ASCII character bytes.

The GPIB interface cable is a parallel daisy-chain type of interconnect (all devices on the interface are in parallel), and the cable is easy to connect Devices on the cable may be connected or disconnected with the interface powered up.

Examples of the types of instuments that may be interfaced with the GPIB bus include scanning digital voltmeters, x-y plotters, different types of analyzers, relay or digital controllers, power supplies, and, of course, thermocouple reference junctions.

<u>The RS232C interface.</u> This interface is for low-speed, minimum protocol, ASCII character byte transfers. The full standard supports lines for transmitted data, received data, common return clear to send, ready to send, data terminal ready and a few other specialized hardware sensing lines. Data are sent as a series of ± 12 Vdc binary pulses, with a number of start and stop bits for timing. The total number of bits defining each character is not standard and depends on the hardware used at each end of the interface. By using no handshake protocol at all, the interface can make use of bidirectional MODEMS (MOdulatorDEModulator) to transfer data over long distances via telephone lines or dedicated cables.

This MODEM configuration uses only two wires to carry the data in a frequency-multiplexed manner. The MODEMS convert the RS232 ± 12 Vdc binary data levels into one of four audio frequency tones, two each for sender and receiver. Staight RS232 can be sent over a three-wire system using one line for transmitted data, one for receiver data, and a common return. It is easy to confuse which unit is the sender and which the receiver, so a switchable adapter is often necessary when using the RS232 interface. Data transmission speed of up to 9600 bits per second is possible over distances of several hundred meters using a three-wire system, and distance is unlimited using MODEMs at 1200 bits per second or less.

The MODEM frequencies are not an international standard, so things get even more confusing when one is using MODEM devices from different countries or even different manufacturers. A careful investigation of the operator's manual for all equipment to be used on the RS232 interface is necessary to determine how much of the standard is used and which lines must be hardwired high or low.

To decide which of these standard interfaces would best suit a certain installation, the user should consider transfer rate, transmission distance, number of devices to be accessed, and cost. Probably the two most important factors are what data throughput rate will be needed and whether the same system will be used for a variety of different test configurations. The CAMAC interface is the fastest and most versatile, but it is also expensive. The GPIB bus is a good general purpose interface, useful with a wide variety of devices over short distances. Finally, the RS232 interface is cheapest, but applications are limited by the lack of protocol. Although RS232 transmission speeds are low they are quite satisfactory for a small number of heat transfer data channels.

3.3 Processor Requirements

The current flood of small computers available for use with external digitizing devices may make it difficult to select a host device for a temperature acquisition system. The decision can be simplified by knowing just what is needed for the application.

The most important specification is that the unit support the standard interface selected for the area. If the manufacturer says "We don"t feel that that interface buys you anything," or "We can interface any instument in the world to our I/O bus," then the buyer should cross that model off the list. There are enough selections available that the buyer's specifications will be met by one or more of them.

The next most important specification is the ability of the processor to produce the type of output that the user desires. Most small computers will have some graphics capability, but hard copy output, including data listings, will require additional peripherals. The buyer must be sure these peripherals are available and supported with software and maintenance.

Storage media type and size needed are determined by the number of data the user needs to store and how often these data are to be accessed once they are written to storage. If few data are to be stored, and need to be accessed rarely, then a cassette audio tape storage system may be sufficient. In most cases though, the minimum storage available should be a floppy disk. If the data will be proccessed or plotted several times after acquisition, then a hard disk should be considered. These disks allow faster retrieval times.

The amount and type of data processing to be performed by the system should be considered when the buyer is examining the type of computer architecture. Since time-history data are usually processed from a data array, a built-in array processor capability can greatly speed repetitive operations. Likewise, a floating point processor will allow greater precision and speed when the user is dealing with operations involving fractional numbers.

One final consideration must be the language and operating system of the processor. BASIC is a slow-running language since it is interpreted into machine language a line at a time at run time but it is very flexible and extremely handy for setting up new devices on an interface. The oposite end of the language spectrum is machine language code, the direct numeric commands executed by the processor. This type of language is very fast, but also difficult to change or adapt. In addition, no floating point functions or statements exist other than as special subroutine calls. The worst drawback of machine language coding is the fact that it is not directly documented for human understanding as it is written. There must be a separate, written document explaining the code purpose and flow. Intermediate-level languages like FORTRAN and PASCAL are very powerful and fast. These "compiler" languages must be compiled into machine language by a separate program before the code can be executed. Because the code runs as machine language, it runs faster than BASIC; because the original source is in a user understandable language, it can be modified and debugged almost as easily as BASIC. There is a time delay between source correction and program execution while the code is recompiled, and the additional file requires more storage space.

Memory is usually an easily added expansion item (no one ever reduces their computer memory size), but a minimum size of 32k words (32768) will accommodate most acquisition system software.

3.4 Software Designs

Once digital data acquisition system components have been connected, the one factor that will determine how well the system is used is the quality of the software that the user interfaces with. The best hardware money can buy will be useless if the user finds the software is clumsy to use or must get special training. When writing software for data acquisiton systems, the designer must remember that the human operator may not be familiar with computer keyboard use and may resent being presented with a lot of decisions or independent actions.

The best type of software for these "hostile users" is usually a question and answer format that leads them through the setup and acquisition process. Default answers should be allowed wherever possible, and any new entry should then become the new default. The default values should be shown in a recognizable format at the end of every question. Figure 3.1 shows an example of this default-prompting question and answer format.

```
-Display section-
Overlay this plot on previous one [Y/N]:N
Plot over scan range [1,600]:1,300
X axis channels [12]:     (no change)
X axis scale (first,last,step) [0,500,100]:    (no change)
Y axis channels [1,3,5]:7,9,11
Y axis scale (first,last,step) [-100,100,20]:-200,100,25
```

Figure 3.1. Question and answer format example. User-entered responses are underlined. Default values are shown here as enclosed in brackets [].

- -- -- -- -- -

```
-Main Selection Menu-
1=Setup Parameters      2=Acquire Data        3=Display
4=Store to File         5=Recall from File    6=List
7=Plot                  8=Modify              9=Merge Files

Operation number?:
```

Figure 3.2. Menu format example.

When an independent decision point is reached, it is recommended that a menu-type format such as the one in Figure 3.2 be used. The different choices available to the operator should be displayed in a logical, easy to understand format, and a letter or number assigned to each of the choices. The operator enters the letter or number of the desired operation. and a new menu or question/answer section is displayed. There should always be a simple method of aborting any section and returning to the main menu.

Do not hesitate to display a lot of information when asking the operator for an input decision. Modern processors will have cathode ray tube displays, which operate at high data display rates. This high rate allows the program to display a detailed explanation of each step, even when the operator is experienced with the system and does not need the information.

Calibration is probably the most important and, naturally then, the most confusing part of any acquisition system setup. Every effort must be made to make the calibration section of the system software self-guiding and fail safe, while assuring that the operator provides the system with as accurate a voltage range for each transducer input as possible.

Mention must be made at this point of the importance of always storing the data points in the "raw" form as obtained directly from the digitizing device. This raw form may be either volts or A/D counts. Conversion from the raw form to engineering units form for display and listing is done according to Equation (1) using the slope and offset calibration factors obtained from the calibration routine. Data that have been converted to engineering units and then stored may later be found to be inaccurate because of a calibration error. It then becomes very difficult to correct all the data points, and inaccuracies may appear if correction factors are applied. These inaccuracies are due to round-off effects when data of a certain resolution have been multiplied by one factor and then divided by another.

The calibration procedure itself should consist of the application of high and low voltages to delimit a known engineering units span range. The voltage is read by the digitizing device, and the engineering units equivalent to that voltage span must be entered by the operator. A third voltage, referred to here as the "offset" voltage, allows the operator to assign an engineering units offset (usually zero) to a specific voltage value. The advantage of this offset voltage is that the calibration span voltage then does not need to be zero based but can be a negative through positive voltage span. This calibration will help to resolve polarity errors (which might be called digitizer hysteresis) that may be present in the digitizing device.

The resultant slope calibration factor for a linear transducer (volts for thermocouple calibrations) is determined by

$$C1 = (Espan)/(Vp - Vn), \qquad (2)$$

where Espan is the engineering units equivalent to the input voltage span determined by the positive calibration voltage Vp and the negative calibration voltage Vn. The offset calibration C2 is then determined by

$$C2 = Eo - C1*Vo, \qquad (3)$$

where Eo is the engineering units offset equivalent to the offset voltage Vo. Note that in Equations (2) and (3), the actual units for Vp, Vn, and Vo may not be volts, but rather the "counts" value from the digitizing device.

Figure 3.3 shows an example of a calibration sequence that is fairly easy for the operator to understand and interact with.

In the case of thermocouples or other non linear transducers, the data should still be calibrated and stored in linear terms--volts or counts. The correction from volts to linearized, referenced degrees should be done separately and may then be stored in another data channel in final units. This ensures that the original data still remain intact if a conversion error is later discovered.

```
Channel number to cal:7
Provide the positive going cal voltage to chan 7 input.
Ready to scan../        (any key input)
Ch 7 + cal= 5.237 v
Is that a good value [Y/N]:N
Ready to scan..
Ch 7 + cal= 5.005 v
Is that a good value [Y/N]:Y
Provide the negative (or zero) cal voltage to chan 7 input.
Ready to scan..]
Ch 7 - cal=-5.002 v
Is that a good value [Y/N]:Y
What was the engineering units value
of that 10.007 v cal span [ 25000.0]:500.0  (note default)
Provide the offset cal voltage to chan 7 input.
Ready to scan..
Ch 7 offset cal= 0.010 v
Is that a good value [Y/N]:Y
What is the units value of that offset [0.00]:  (no change)

Channel number to cal:   ('return' = done)
```

Figure 3.3. Calibration sequence example.

A good formula for converting raw thermocouple data to degrees is

$$D = a + bV + cV^2 + dV^3 + eV^4 \qquad (4)$$

D : resultant degrees

a,b,c,d,e : coefficients of the linearizing polynomial over a specific voltage/temperature range

V : referenced thermocouple voltage,

where V is obtained from

$$V = Vt + aTr^b \qquad (5)$$

Vt : thermocouple voltage

Tr : reference junction temperature

a,b : coefficients of the exponential function ax^b.

The exponential function aTr^b is used to convert reference junction temperature to equivalent thermocouple-type voltage. Both the polynomial and exponential functions operate best over a limited temperature range as determined by the thermocouple response curve. It may therefore be necessary to break the conversion process into several ranges of conversion and apply the different coefficients of the equations as a function of incoming thermocouple voltage.

Another form of linearizing correction that does not require a polynomial curve fit is the data replacement technique. The nonlinear curve of uncorrected versus corrected data is stored in a file as a series of point pairs (millivolts and degrees Celsius for example). The program compares uncorrected data from memory with the same units in the file (millivolts in our example). finds the match or interpolates between two adjacent points, and then replaces the data in memory with the appropriate data point from the other file channel. The calibration factors for the corrected units must also be replaced. Note that the term "replace" should actually refer to storing the new data values in another channel of memory to preserve the original data. This form of correction works best with a small number of data points, and the comparision channel of data in the file must be unidirectional, that is, always increasing or decreasing in value.

An item that deserves inclusion in this section is the belief by the author that a human observer needs only a specific number of data points on a plot or listing to define an event of interest. Furthermore, this specific number of points may be quantified and has in fact been determined by observation to be no greater than 4000 data points. This 4000-point number refers to the total number of data points of one single data channel that are necessary to define an event of interest. An event of interest is best described as the time frame containing data that are actually pertinent to an observation.

The actual importance of this "De Witt Criterion is that it helps the observer to determine the sample rate necessary to capture the event of interest, assuming that such an event time length can be predicted. The sample rate per channel is then determined by

$$Rs = 4000/Te \qquad (6)$$

Te : event time length in seconds

Rs : data sample rate per channel in samples/second.

Therefore, a test occurring over a long time period will result in a slower sample rate than one occurring quickly. Several examples of this effect are shown in Figures 3.4 through 3.6. Note that the number of points necessary to actually define the event is usually much lower than 4000. Of course in some rare cases the main event of interest may be of a long-term nature and may actually include several shorter events. Since memory and storage space are finite, the user must then settle for a compromise number of data po ts and sample rate. It will usually be found after the test tha the long-term event was actually the only event of interest, the resolution of the shorter events was just "nice to have."

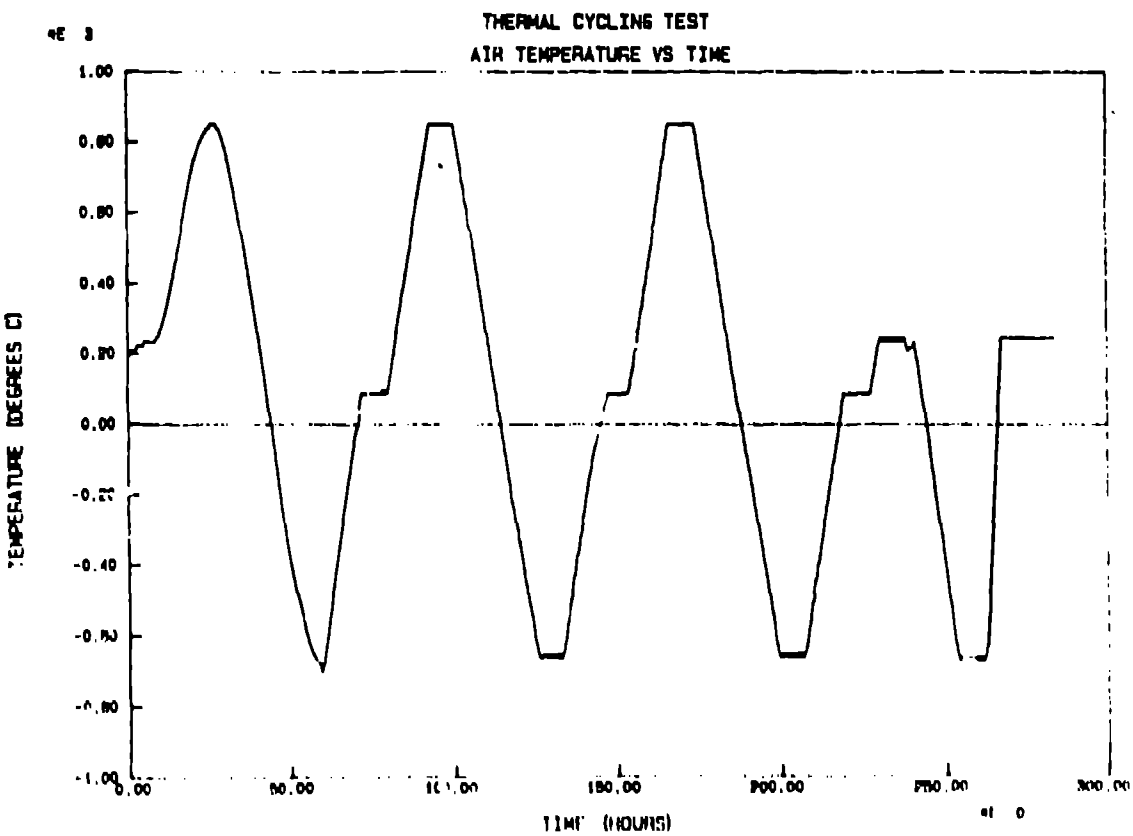

Figure 3.4. A long-term event of interest; 2200 data points per channel.

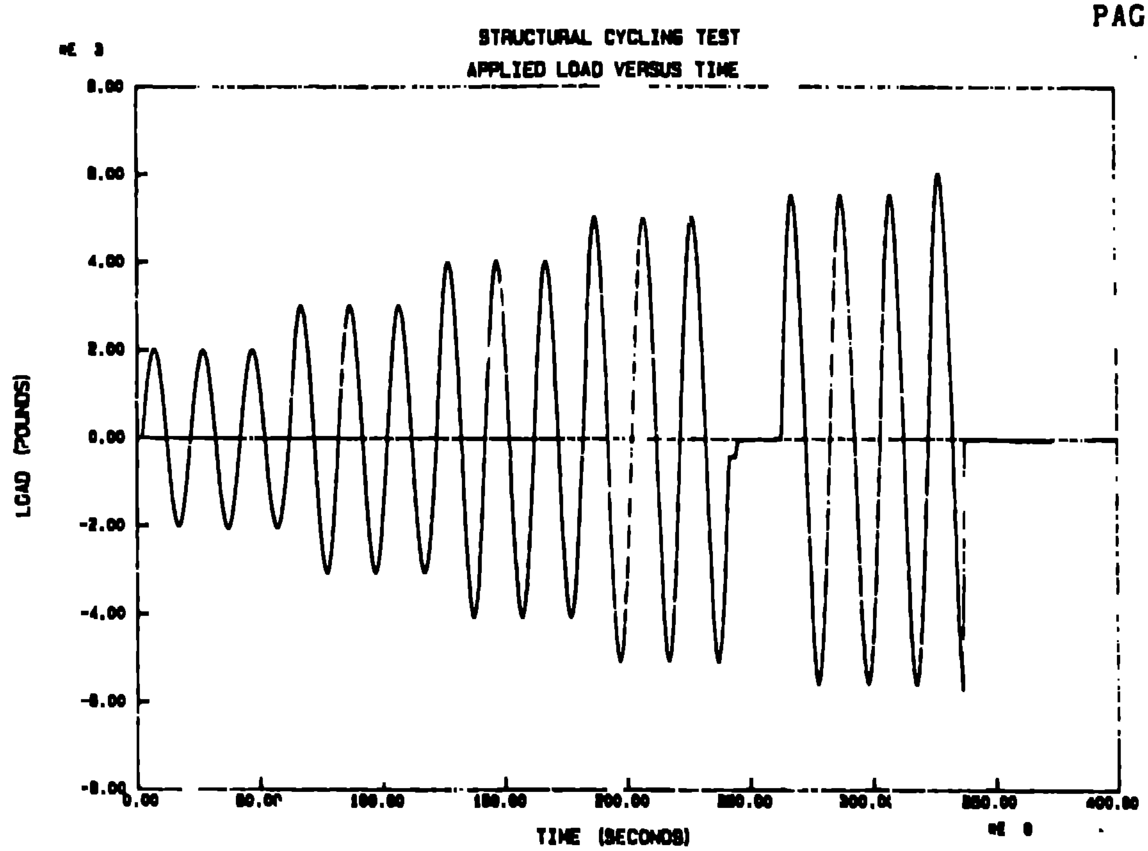

Figure 3.5. A fairly slow event of interest; 700 data points per channel.

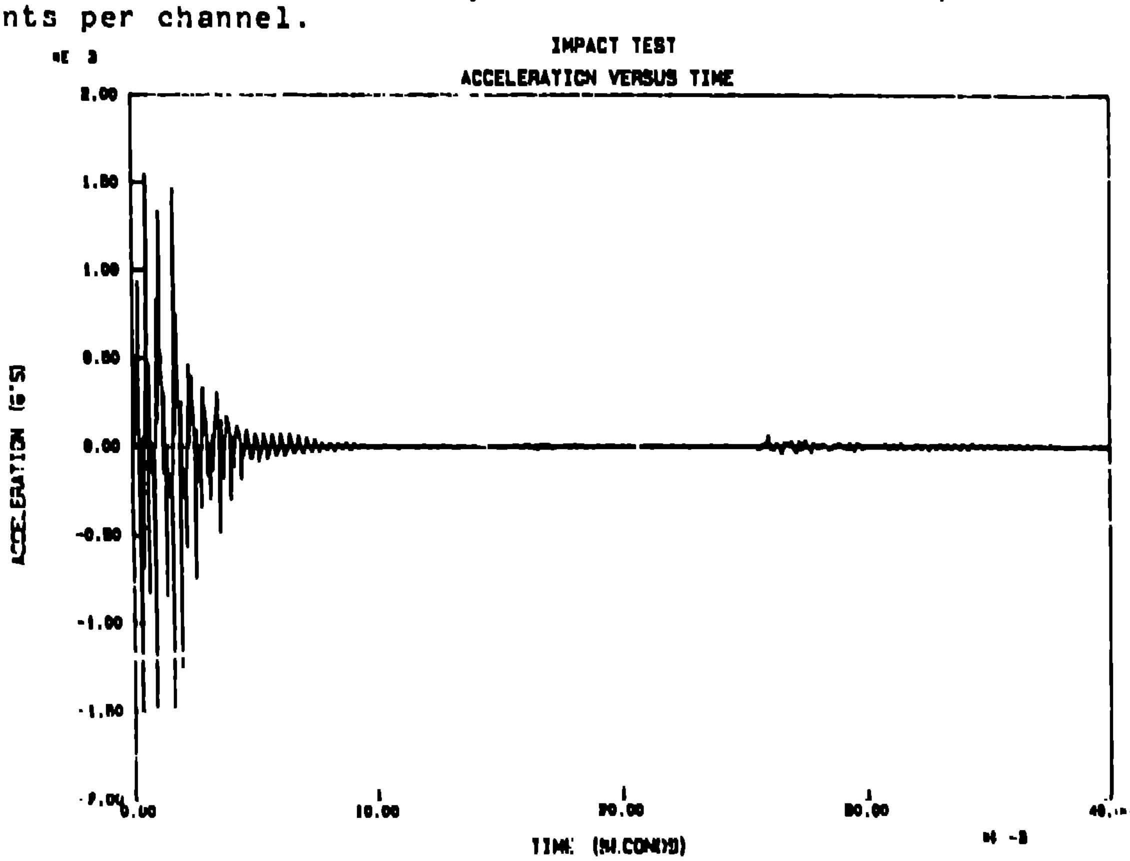

Figure 3.6. A quick event of interest; 4000 data points per channel.

One problem that has surfaced lately in the United States is the lack of a standard data transfer format for time-history data of the type acquired by the above-mentioned data acquisition systems. To make data transfer between such systems easier for all concerned, the Los Alamos National Laboratory has adopted a standard format. This Standard Data File Format is defined in Appendix A. The standard specifies text-character-based data strings to define the channel sequences, calibration factors, and data. The format is designed for easy data transmission over telephone line MODEMS.

4. STAND-ALONE DATALOGGERS

When a separate digital file of data is not needed for post processing, the user may elect to receive a simple data listing from a digital datalogger. This device is the simplest form of digital data acquisition and usually has no software requirements. Data may be presented in a listing format on paper and may be stored on a magnetic tape or disk. Most dataloggers also have a printing port for RS232C interface access.

Acquisition parameters are entered by front panel keypad in a structured question and answer response mode. These setup parameters are usually retained in memory when the device is powered down between tests. Some calculations may be performed on the incoming data, such as slope and offset conversion to engineering units, averaging, and limit detection.

Most dataloggers supporting thermocouples will use an isothermal connector block as the reference junction, with a resistive temperature device to read the connector temperature. This type of connector is described in more detail in Section 5. Internal conversion tables are then applied according to the thermocouple type to produce an output in degrees Celsius or Farenheit.

The datalogger-type device is a good alternative to both the analog and full digital data acquisition systems. The internal software cannot be modified, and data are usually not stored in digital format for future access, but digital accuracy and ease of interpretation are available for about the cost of a few strip chart recorders.

The typical datalogger will produce a printed listing similar to that of Figure 4.1, which shows temperatures, voltages, and times.

```
4          2.313MV
3          2.371MV
2          70.3*C
1          34.2*C
0          80.4*F
000:14:02:22
4          14.362MV
3          14.598MV
2          384.6*C
1          52.3*C
0          79.4*F
000:14:05:00
4          13.439MV
3          13.640MV
2          360.4*C
1          290.7*C
0          79.6*F
000:14:10:00
```

Figure 4.1. Typical datalogger printout.

5. THERMOCOUPLE APPLICATIONS

Thermocouples may be old-fashioned, non-linear, moderate resolution devices, but they are also very reliable and supply a self-generating output. For these and many other reasons thermocouples will continue to be used in thermal data acquisition systems for quite some time. Just because they have only two wires and no fancy signal conditioning requirements does not mean that thermocouple circuits can be taken lightly, as many an experimenter faced with "impossible" or even "questionable" temperature results can confirm.

In order to understand thermocouple circuits, a basic review of the "Laws" of these strange devices is in order. Then a more detailed approach to the solution of complex circuits can be attempted.

5.1 UNDERSTANDING THERMOCOUPLES

The most basic phenomenon involved in thermocouples is related to the fact that any electrical conductor, under open circuit conditions, will generate a voltage potential difference at the conductor ends when those ends are at different temperatures. This potential is probably due to charge distribution of free electrons as a result of the different temperatures.

In order to measure this voltage potential, the conductor must be placed in a circuit with a high impedence meter. If the same type of conductor is used in the meter circuit then there are no ends--the charges are free to redistribute. In order to monitor the generated voltage potential, the conductor must have the ends (which are still at different temperatures) connected to a dissimilar metal--one which has a different coefficient of thermal electromotive force. This "thermocouple junction" will generate a maximum output when the two conductors have an opposite polarity of thermal emf. Common thermocouple metal pairs such as platinum/iridium and Chromel (chromium-nickel) / Alumel (aluminum-nickel) are selected for maximum output and linearity over a specified temperature range.

Note that the voltage is generated due to the temperature difference between ends of each conductor type, not due to the presence of a heat source at the junction itself. The junction does not generate a voltage, it allows the voltage to be monitored. The junction is one pair of conductor ends, and a voltage is generated in each conductor when it's opposite ends are at different temperatures. This distinction is an important part of the circuit analysis method described in section 5.2.

Once the two conductor types are connected in a closed circuit, the generated voltage can be measured anywhere in the circuit with a high impedance meter (a low impedence device would allow the charges to redistribute faster than they were being generated--a short circuit). In order to simplify connections, most thermocouple circuits place the meter at one of the junctions. In order to understand that this connection may not effect the circuit output it is necessary to present several "Laws" of thermocouple circuits. Many such laws can be formulated, but all relate to the basic idea of an output being generated whenever opposite ends of a conductor are at different temperatures.

THE LAW OF INTERMEDIATE MATERIALS

"If metal C is inserted between metals A and B at one of the junctions, the temperature of C at any point away from the AC and BC junctions is immaterial. So long as the junctions AC and BC are both at the same temperature T1, the net emf is the same as if C were not there."

A meter circuit inserted at one of the thermocouple junctions acts as material C, with the AC and BC meter connections at the same temperature on the meter terminal strip. Both ends of C are at the same temperature, therefore no emf is generated to upset the circuit reading. Of course the temperature of the terminal strip must be known if the absolute temperature at the other ("hot") junction is to be calculated from the generated circuit voltage.

THE LAW OF INSERTED MATERIALS

"If a third homogeneous metal C is inserted into a thermocouple circuit with metals A and B, as long as the two new junctions are at the same temperature, the net emf of the circuit is unchanged, irrespective of the temperature of C away from the junctions."

This law applies to an inserted material, such as a meter, inserted at a point other than one of the junctions. Notice that the same conditions apply as in the first law--the ends of the new material must be at the same temperature--so no thermal emf is generated. Once again, the temperature of material C away from the ends (junctions) does not contribute an emf to the circuit. This fact is the basis of the remaining "law".

THE LAW OF INTERIOR TEMPERATURES

> "The thermal emf of a thermocouple with junctions at T-hot and T-ref is totally unaffected by temperature elsewhere in the circuit if the two metals used are each homogeneous"

This law refers not to a third material, but to localized temperature gradients (hot or cold) in the materials away from the junctions. If the circuit were to be broken at these gradients (a third material or meter circuit inserted) then an emf would be generated. Non-homogenous materials act as inserted materials since the thermal generating coefficient of the material changes, and if a thermal gradient exists between "ends" of these sections--a voltage is generated.

Since non-homogeneous materials act as inserted materials, it becomes very important to avoid introducing these anomolies into the thermocouple wire. Cold working due to bending and fatigue causes alloy changes, as does deformation (crimping) and welding. In the case of welding--most junctions are made this way, so the user must try to keep the heat affected area very small. This small heat-treated area may all be in the same temperature zone in the actual application, which helps to prevent erroneous signals.

One way to test for non-homogeneous material is to pass a heat gun or flame heat source along each leg of the thermocouple circuit while observing circuit output. The output will change only at those locations where changes in thermal generating coefficient occur (like junctions).

Intrinsic thermocouples. The Law of Intermediate Materials allows a third type of material to be inserted at a junction if the connections are at the same temperature. With this knowledge it is possible to use a third material, which is actually the material temperature to be measured, as a part of the thermocouple circuit. Standard practice is to spot weld the two thermocouple wires to the third material at the point of interest. The two wires do not have to touch each other--the third material is the intermediate conductor, assumed to be at uniform temperature. Even if the third material is not at uniform temperature, the result will be an average of the two junction temperatures.

Problems to be avoided with intrinsic thermocouples include system ground loops (current flowing in a thermocouple wire due to different ground potentials) and poor weld connections. The process of welding the wires onto the third material may actually introduce new alloys (non-homogenieties or junctions) in the thermocouple wire which can even change the thermocouple sensitivity, so the user must take care to use the lowest heat range necessary to bond the materials.

Zone boxes for connections. Since connectors and cable splices are non-homogeneous areas in a thermocouple circuit, extreme care must be taken to see that no temperature gradients exist across these areas. One good way to avoid these gradients is to place reference junctions and other connections in an insulated, uniform temperature box. The temperature of the box does not need to be known (unless there is a reference junction inside), it does not even have to be constant, but it must be uniform inside (no gradients). The idea is to prevent the ends of the inserted materials from being at different temperatures and generating voltages. A styrofoam picnic cooler works well as a zone box.

5.2 THERMOCOUPLE SYSTEM ANALYSIS

Because most practical measurements of temperature are taken with thermocouples, it makes sense to discuss a method of resolving circuit problems that may arise from complicated thermal gradients along the leads and at the reference junction. A method known as the "Gradient Approach," used by Dr. Robert Moffat [1] will be used to define these effects.

The net voltage of a thermocouple circuit can be described by the equation

$$Enet = \int_{T1}^{T2} e1 \, dt + \int_{T2}^{T1} e2 \, dt, \qquad (7)$$

where e1 and e2 are the absolute values of voltages from the two thermocouple metals 1 and 2.

$$e = dP/dT - u \qquad (8)$$

P : Peltier coefficient

u : Thompson coefficient

Equation (7) represents the theoretical possibility of determining net voltage by integrating the individual metal voltages caused by temperature along the wire. The e of each metal cannot be precisely calculated or measured, except as referenced to a common material, such as platinum. If voltages of all metals in the circuit are obtained as referenced to a common material, then the reference material effect will disappear. The values of voltage for materials referenced to platinum are available in the United States from the National Bureau of Standards monograph 125 [2].

The "Gradient Approach" relies on the fact that voltage is contributed only along those sections of the conductors where a temperature gradient dt is present (Section 5.1). If the two ends of one type of thermocouple wire are at different temperatures, then a voltage of known amount will be generated in the wire. If the two ends are at the same temperature, no voltage will be generated. Complicated thermocouple circuits (multiple-wire types) passing through several temperature gradients can be evaluated for net voltage contributions by considering only the temperatures of the ends of each conductor type.

Using tables that give the voltage output for different types of wire referenced to a common wire (platinum) enables the user to understand a complicated circuit like the one in Figure 5.1.

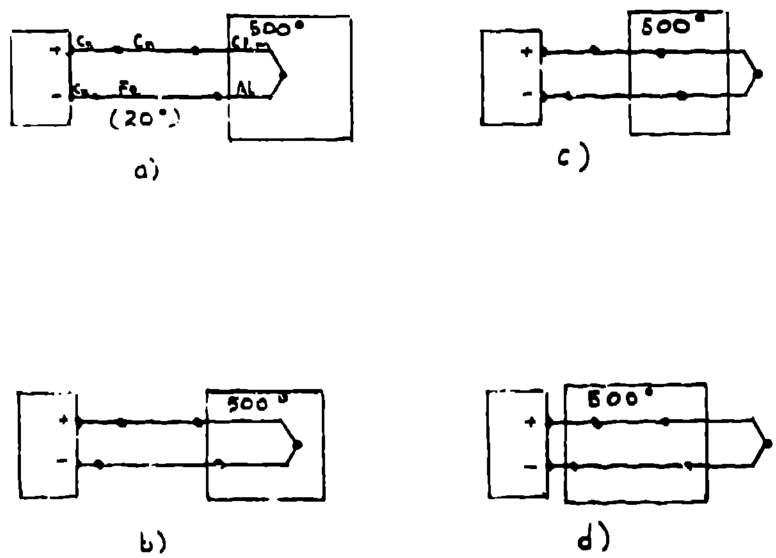

Figure 5.1. A complicated thermocouple circuit showing different parts of the circuit at different temperatures. The room temperature is 20 degrees C.

Figure 5.1 represents a circuit with copper wire connecting to Constantan, to Chromel, to the Chromel-Alumel thermocouple, Alumel to iron, and iron to copper. The readout device is a system with internal reference junction, so that a zero voltage input reads room temperature.

In Figure 5.1a, the Chromel-Alumel junction is at 500 degrees C, the rest of the circuit at a room temperature of 20 degrees C. Tracing the wires for temperature gradients, we find none along the copper from the positive terminal to the Constantan junction, and none along the Constantan wire. There is a +480 degrees C gradient (room temp to 500 degrees C) along the Chromel wire, which according to the U.S. National Bureau of Standards monograph 125 [2] results in a 15.523-millivolt signal referenced to platinum. The Alumel wire has a -480 degree gradient, resulting in a 4.265-mV voltage. The iron wire and the last copper wire to the negative terminal have no gradients. Summing the voltages encountered results in 15.523 + 4.265 = 19.788 mV. Since our readout device has been calibrated for K-type thermocouples, it reads this voltage as 480 degrees C + 20 degrees junction temp = 500 degrees C.

Figure 5.1b shows a circuit that results in an improper reading, because of the oven enclosing the Alumel-iron junction. A gradient of +480 degrees C exists along the Chromel wire (+15.523 mV), no gradient exists along the Alumel wire, but a -480 degree gradient does exist along the iron wire (-6.499 mV). The last coppper wire is gradient-free. The sum of the voltages is now 9.024 mV, which the readout device interprets as 22.5 + 20 = 42.5 degrees C.

Figure 5.1c shows gradients of +480 along the Constantan wire (-19.859 mV), -480 along the Chromel (-15.523 mV), +480 along the Alumel (-4.265 mV), and finally -480 along the iron (-6.499 mV) for a total voltage of -46.146 mV. The readout device faithfully interprets this value for a K-type thermocouple as -1127.5 + 20 = -1107.5 degrees C.

The final example, Figure 5.1d, shows gradients of +480 in copper (+5.92 mV), -480 in Chromel (-15.523 mV), +480 in Alumel (-4.265), and -480 in the last copper (-5.92 mV). The resultant -19.788 mV is read as -480 + 20 = -460 degrees C.

Further explanations of the use of the Gradient Approach to thermocouple systems may be found in Reference [1], including examples of graphical solutions to these problems.

Isothermal connectors for thermocouples. Using the "isothermal block" connector is one common method of connecting thermocouples into data acquisition and/or monitoring systems that helps to avoid reference junction problems. These connectors are usually a group of screw clamp terminals mounted close to each other on a printed circuit board. The board itself has a layer of solder like a grounding bus that spreads around all the terminal connectors. This solder layer acts as a thermal mass, keeping all the connector terminals at the same temperature on the board. A resistive temperature device (RTD), usually a platinum resistor in a constant current circuit, is also physically bonded to the solder layer at a central location (see Figure 5.2). The RTD is used to read the temperature of the solder layer and therefore the temperature of the connecting terminals. If the thermocouple wire leads are brought directly to this connector block, then the connector temperature is the reference junction of the thermocouple circuit. Since the RTD is reading the reference junction temperature, the acquiring device now has all the information necessary to convert the millivolt signals at the connector terminals into the true temperature at the thermocouple itself. Software to perform this conversion is discussed in Section 3.4.

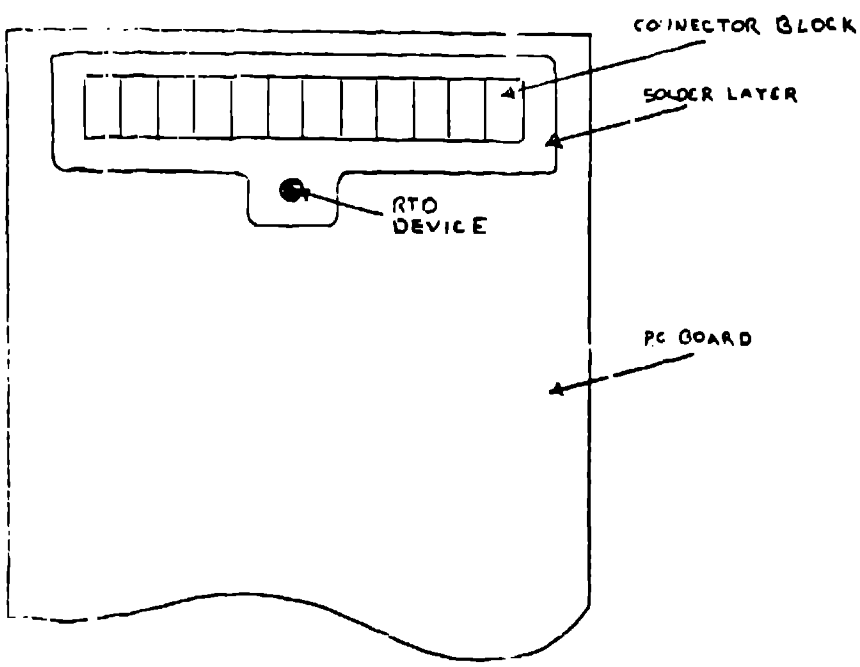

Figure 5.2. A resistive temperature device (RTD) isothermal block connector.

There is one other phenomenon regarding thermocouple circuits that is not always considered when one is making transient temperature measurements. Thermocouple wire will generate a significant transient voltage when subjected to dynamic strains. As a matter of fact, most electical wire will self-generate a voltage when the wire itself is dynamically strained, but thermocouple systems are most sensitive to this phenomenon because of the inherently low-level voltages generated by temperature.

The voltage generated is cyclic (Figure 5.3) and is apparently strain rate related. Voltage levels depend on the type of wire being used, but for a K-type (Chromel-Alumel) thermocouple, straining both leads, as would happen if someone were to trip on the wire, results in a 0.6 mv peak signal. That is equivalent to a 14 degrees C false temperature reading.

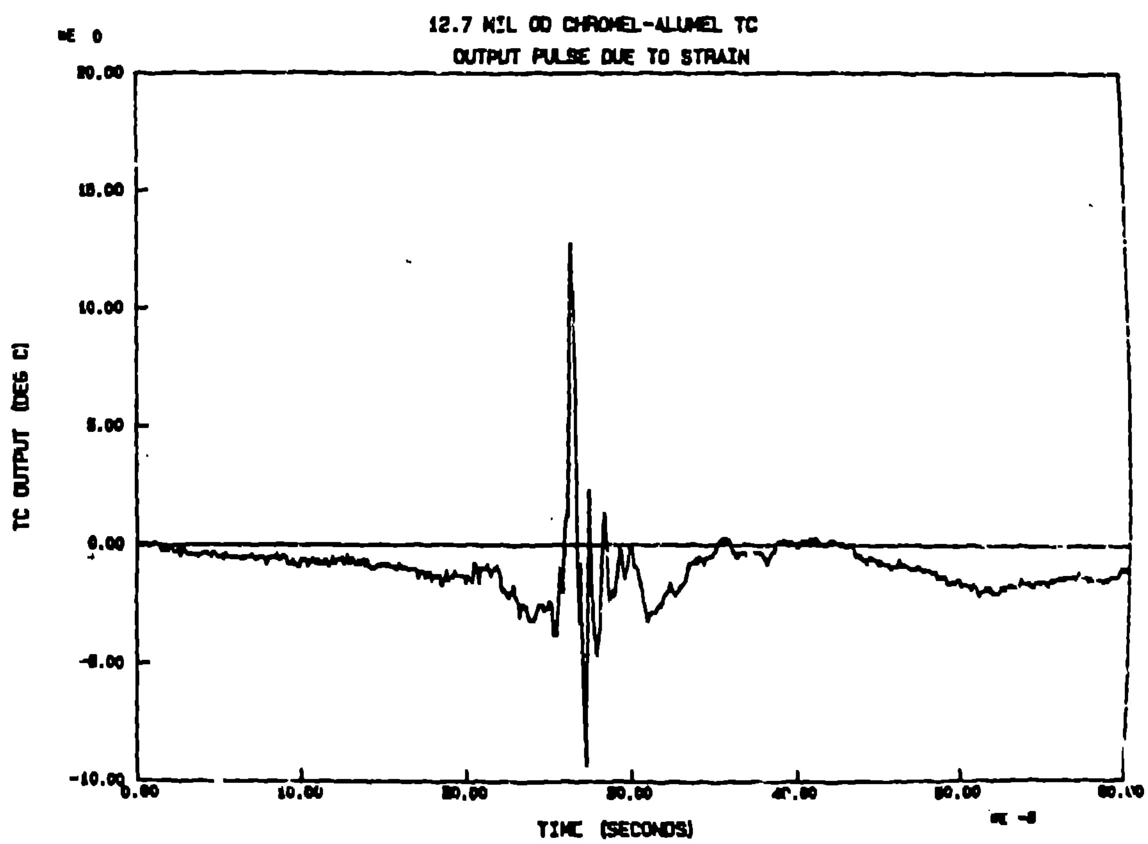

Figure 5.3. K-type thermocouple output pulse produced by strain.

This seemingly piezoelectric effect in what is generally regarded as a randomly oriented crystal structure has been mentioned before by Prof. P. K. Stein [3]. A modest experiment to attempt to evaluate the phenomenon was conducted by the author several years ago. A loop of wire was strung between two insulated poles about 15 cm apart. A pendulum was arranged so as to strike the wire at the center of its suspended portion. The impacting pendulum was also electrically insulated and could be positioned to strike the wire at adjustable angles. The two ends of The wire loop were fed to a high-impedance dc differential amplifier oscilloscope input. Every impact of the pendulum on the wire loop produced a voltage pulse output. Impact angles were varied, and a Faraday cage shield was used to try to eliminate any magnetic voltage effects. Even insulated single-strand copper "hook-up" wire exhibited a voltage output when impacted. For validation, the nylon insulation was stripped from a length of wire and the insulation was tested with no conductor present. The impact was more elastic, but the test setup registered no voltage.

An understanding of the cause of this self-generating noise phenomenon is not yet available, but research is being done. Users of thermocouples should be aware that false transient signals may appear as temperature readings when the thermocouples or their cables are exposed to dynamic strains. Note that this noise-generated pulse is approximately 15 degrees Celsius for this small strain (equivalent to someone jerking the wire). Most of the noise pulse occurred over a 10-ms time span. This time span may not be relevant to those users acquiring static, or slow rate of change, data, especially if they can allow a filter in the data path. The 15-degree temperature excursion may also be insignificant in measurements involving thousands of degrees. Note, however, that this phenomenon may help to explain some types of noise on occasions when the thermocouple leads are attached to a vibrating piece of equipment.

REFERENCES

1. Moffat, R.J. 1961. The Gradient Approach to Thermocouple Circuitry. Measurement Engineering Volume 1, pp. 646-656. Stein Engineering Services, Phoenix, Arizona.

2. Powell, R.L. et al. 1974. Thermocouple Reference Tables Based on IPTS-68. National Bureau of Standards Monograph 125, U.S. Department of Commerce.

3. Stein, P.K. 1981. Proceedings of the Western Regional Strain Gage Committee, Spring 1981 Meeting. Minutes of Delegate Workshop. Society for Experimental Stress Analysis.

APPENDIX A

STANDARD DATA FILE FORMAT FOR TIME-HISTORY TEST DATA

PURPOSE

The Standard Data File should be used for transfer of time-history data between digital data acquisition systems. The data may originate from mini-or microcomputers, desktop calculators or other sources. The originator of the data shall provide the data in the Standard File format, on floppy disk, hard disk, magnetic tape, or serially (phone lines).

GENERAL SPECIFICATIONS

The file shall be an ASCII text data file, written in character strings of 80 characters or fewer, each line terminated by a carriage return character. This file shall be compatible with a text editor and may be created or modified by such an editor.

Numeric values on a line are to be separated by commas and are to be right justified against the comma. Decimal points and E formats are allowed but not required. Leading spaces are allowed.

```
    EX: 17,3.467,-13.56,  52.789E-03,  5,16.01
```

A trailing comma is allowed at the end of a line of numeric data, but a leading comma will be treated as a zero entry.

```
   EX: 1,2,3,4.567,         is OK
       ,3,,6                reads as 0,3,0,6
```

Non numeric characters (anything other than 0123456789,.E+-) must not be included in a numeric string. Upper and lower case characters are allowed in non numeric strings; terminating periods (".") are not needed. Non-printing characters are not allowed in the file. Comment lines may be included anywhere in the file after the TITLE line, and must start with the exclamation character "!".

DATA FILE FORMAT

Blank lines (all spaces, or non printing characters) are ignored and may occur anywhere in the file. The first non blank line will be the TITLE line, a character string of 80 characters or fewer, describing the test in general terms.

The remainder of the file shall consist of Information Blocks (IBs) of specific data format. These IBs may be in any order in a file but must be in a specific order when sent serially over an RS232C line. These IBs are denoted by standard IB header lines of the format:

```
#NNNNNNNNN
```

Where NNNNNNNNN is a string of UPPER CASE characters, the first four (4) of which are unique among the IBs. Six (6) types of IB are specified here. The user may create and use others as long as the first four characters after the asterisk are unique. Obviously no line in the standard data file may begin with * except information block headers (beware of FORTRAN format overflow).

An IB is terminated by the header of the next IB, or by the end of file. Once again, the IBs may be in any order in a file, the reader need only input those that apply.

NOTE: If the data are to be transmitted over phone lines or will be accessed in a non recursive manner, it is required that the *CONFIGURATION IB be sent before the *CHANNELS IB and that the *SCANDATA IB be sent last. The last character sent may be a ctrl Z (EOF).

Following is a description of the six (6) specified IBs:

*DESCRIPTION (no format)

As many lines as desired of character or numeric strings may be present.

*CONFIGURATION (2 lines)

1: Number of channels (NC), number of scans (NS), clock channel, time at first scan, time per channel, time per scan

2: Time units character string

The first line will contain the number of data channels, the number of scans (1 scan = 1 look at all channels), and clock channel number (or 0 if using sequentially clocked multiplexing). If clock chan = 0, then the last three entries describe the time at the first scan, the time step between points (multiplexer clock rate) and time between scans. If a separate clock channel is used, these last three values could be zero. If a constant rate multiplexed scanner is used, then the time between scans will be equal to the number of scans times the time step between points.

The second line is a character string of time units: SECONDS, MINUTES, HOURS, etc.

NOTE: Although IBs may be present in any order in a file, it is expected that CONFIGURATION will precede CHANNELS or SCANDATA since NC and NS are needed then. It is the reader's responsibility to accept files that are not in this sequence (EX: REWIND and reread the file).

*DATE (1 line)

1: The test date and time in the format: DD-MMM-YYYY,HH:MMM:SS

*CHANNELS (3 lines per channel, NC*3 lines total)

1: Chan : Channel identification string

2: Channel Type string, Units string

3: Channel cal values for slope, offset, thermocouple reference

The channel identification string is 80 characters or fewer, preceded by the channel number and a colon.

The Type string is exactly ten (10) characters long (including trailing blanks) and describes the type of data calibration to use for the channel. The currently defined types are

LINEAR :apply the slope and offset calibrations to obtain working units.

NONLINEAR :undefined. The user must include an IB such as *CURVFIT to include curve-fitting coefficients.

K-OC :K-type thermocouple data (linear calibration factors of slope and offset still apply to get volts), voltage values are referenced to zero degrees Celsius.

K-REF :K-type thermocouple data referenced to another data channel, the reference channel is included in the third data line.

n-OC :same as K-OC for "n" type thermocouple.

The third line contains the numeric values for the channel slope and offset (true data = raw data* slope + offset), plus the reference channel for floating thermocouples. This last value must be zero if Type is other than n-REF.

```
*SCANDATA   (many lines)
  1:  1,ch 1 data,ch 2 data,ch 3 data,ch 4 data,ch 5 data
  2:  ch 6 data,ch 7 data, ....  (5 data points/line)
  n:  2,ch 1 data,ch 2 data,ch 3 data,,,, (each new scan begins
with scan number)
```

The data are now listed, five (5) channels per line, for each scan. The first entry of each scan group shall be scan number, written as an integer for ease of detection. Remember the 80 character line length limitation. The recommended format for each data point is 12 characters (G12.5 is nice).

If there are fewer than five (5) values on a line, only the values through NC need be valid. The line may be filled (padded) to five entries with garbage data.

```
*CHDATA   (many lines)
  1:  1,scan 1,scan 2,scan 3,scan 4,scan 5,
  2:  scan 6,scan 7,scan 8.....
```

This data format (optional) lists the data by channel in groups of 5 scan points. The first number in each channel group is the integer channel number.

As with *SCANDATA, if there are fewer than five values on a line, only the values through NS need be valid.

SAMPLE DATA FILE

```
Q13BOX9: SPECIMEN   3D-9, TRANSVERSE STATIC LOAD, 283 LB DEAD WT
*DESCRIPTION
Q-13 SCALE MODEL BUILDING, STATIC LOAD CYCLES APPLIED
LOAD IS +- 3 CYCLES OF 3000 LB INCREMENTS TO FAILURE
*CONFIGURATION
 15,    336, 15, 0.00000     , 01000E-04    ,  0.500
! 15 channels, 336 scans,, real time clock on channel 15
! time @ scan 1=0.0, 100kHz mux rate, 0.5 sec/scan
SECONDS
*DATE
04-JAN-83,14:07:52
*CHANNELS
1: RAM END LOWER LVDT  1
LINEAR    MILS
-0.16997     , -7.4788     ,   0
2:RAM END CENTER LVDT  2
LINEAR    MILS
-0.16807     , -19.496     ,   0
3:RAM END UPPER LVDT  3
LINEAR    MILS
-0.15957     ,  2.0745     ,   0
4:RAM END LOWER LVDT   4
LINEAR    MILS
-0.82988E-01, -75.270      ,   0
5:RAM END LOWER LDVT  5
LINEAR    MILS
-0.64171E-01, -21.433      ,   0
6:FAR END UPPER LVDT  6
LINEAR    MILS
-0.13072     , -2.8758     ,   0
7:FAR END UPPER LVDT  7
LINEAR    MILS
-0.13158     , -2.3684     ,   0
8:FAR END UPPER LVDT  8
LINEAR    MILS
-0.12793     , -1.2793     ,   0
9:FAR END LOWER LVDT  9
LINEAR    MILS
-0.87591E-01, -4.2044      ,   0
10:FAR END LWR LVDT  10
LINEAR    MILS
-0.73529E-01,  3.5294      ,   0
11:INSIDE ROOF LVDT  1
LINEAR    MILS
-0.43738E-01,  32.891      ,   0
12:INSIDE ROOF LVDT  5
LINEAR    MILS
-0.44990E-01,  17.456      ,   0
13:LOAD, FROM MTS
LINEAR    POUNDS
  9.7703     , 0.00000     ,   0
14:RAM STROKE, MTS
LINEAR    MILS
```

```
  1.2213    , -1509.5    ,  0
15:CLOCK, REAL TIME TYPE
LINEAR    SECONDS
 0.25000    , 0.00000    ,  0
*SCANDATA
     1,    -43,  -116,    13,  -907,  -334,
   -22,    -16,   -10,   -48,    49,
   752,    388,     0,  1236,     0,
     2,    -43,  -115,    13,  -907,  -334,
   -22,    -18,   -10,   -48,    49,
   752,    388,     0,  1236,     2,
     3,    -43,  -116,    13,  -907,  -334,
   -22,    -18,   -10,   -48,    48,
   752,    388,     0,  1236,     4,
     4,    -43,  -116,    13,  -907,  -334,
   -22,    -18,   -10,   -48,    48,
   752,    387,     0,  1236,     6,
     5,    -43,  -116,    13,  -907,  -334,
   -22,    -17,   -10,   -48,    48,
   752,    388,     0,  1236,     8,
     6,    -43,  -116,    12,  -907,  -334,
   -22,    -16,   -10,   -48,    48,
   752,    388,    14,  1240,    10,
     7,    -44,  -118,    12,  -907,  -334,
   -20,    -15,    -7,   -48,    49,
   752,    387,    65,  1250,    12,
```

etc...