

# A Universal Ethernet Thermocouple Scanner

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## Abstract

The growing use of Ethernet interfaces in Aerospace and Industrial Process applications has created a need for an Intelligent Thermocouple Scanner to operate on an Ethernet network and complement Intelligent Pressure Scanners. The scanner must be able to accept several different thermocouple inputs, convert the signals to engineering units using NIST tables and output the data over a TCP/IP Ethernet link. The scanner must be able to withstand the harsh environments required for flight test, turbine tests, and other turbo machinery development testing. This paper describes the design process that resulted in an instrument that meets all of the environmental and operational characteristics for a laboratory, production facility, or development test cells.

## Introduction

Temperatures have historically been a difficult problem for instrument engineers. Thermocouples are normally sufficient for most measurements due to the availability of very accurate correction tables. However, the actual measurement has always had a relatively high degree of uncertainty. The most common problems are:

1. Thermocouples require a stable, known reference junction
2. Secondary junctions can cause significant errors

3. They are subject to noise problems

For high accuracy measurements, engineers have been forced to use RTD's. However, RTD's present a new set of problems to an engineer:

1. They require special signal conditioning.
2. Calibrations are difficult at best.
3. They are limited in temperature range
4. Size can be a problem
5. They are not vibration resistant

If the three most common problems inherent in thermocouples could be overcome, a thermocouple could give an engineer a very accurate measurement over a very wide range of temperatures. Two of the most common problems in thermocouple measurement could be eliminated if this measurement could be made and converted to engineering units in an instrument mounted close to the source, and send over a high speed digital connection to a host computer. If the instrument packaging and electronics could also provide the stable reference junction, then an engineer could use thermocouples for measurements that have historically been reserved for RTD's. Thus greatly simplifying an instrument engineers tasks.

### The Design Task

A team was assembled to design an intelligent thermocouple scanner. The team began the design process by interviewing potential customers, reviewing a market survey compiled with the help of sales representatives, and meeting with consultants. From these efforts, a design specification was completed. It called for a scanner consisting of a Universal Temperature Reference Junction(UTR), an interface board, a microprocessor board, and a power supply. The scanner would have to function in ambient temperatures from -30 °C to 50 °C and withstand vibration and shock levels consistent with flight test applications. The specification required that the scanner pass the CE requirements for both Light and Heavy Industrial environments. The initial design would accept up to 16 different shielded thermocouple inputs. The input configuration would be adaptable. Brass lugs would be available for users to connect thermocouple wires directly to the UTR. The UTR could also be adapted to accept various types of thermocouple connectors. The scanner communication would be Ethernet, TCP/IP. A secondary RS232 connection would be used for configuration only. The target accuracy of the instrument was  $\pm 0.5$  °C over the normal usable range of the input thermocouple.

### Universal Temperature Reference Junction

The two major sources of error in thermocouple measurements are secondary junctions and reference junction errors. Good instrumentation practices can eliminate the secondary junctions. Reference junction errors are more difficult to eliminate. An error in the measurement of the reference junction temperature will be a bias error that will directly affect the final calculated temperature. There are three accepted methods to correct for reference junction temperature:

1. Maintain the reference junction at a known fixed temperature.
2. Allow the reference junction temperature to vary and, either introduce a compensating emf into the circuit, or account for the temperature in software.
3. Allow the reference junction temperature to vary and adjust the readout instrument mechanically.

There are, of course, variations to each of these techniques, but effectively all of the variations are only performing one of the three methods listed. The errors introduced into the measurement vary with the method used.

1. A known fixed reference temperature may be generated by a Triple Point of Water Cell, an ice bath, or a constant temperature oven. Errors from the first two methods could be as small as  $\pm 0.0001$  °C. A constant temperature oven may induce errors of  $\pm 0.1$  °C. Although they offer excellent accuracy, the first two methods are not practical for a multichannel instrument. A constant temperature oven is a good alternative, but adds size, weight and cost.
2. Electrical compensation may be accomplished with hardware, software, or a combination of both. It may include the use of a zone box to keep all of the thermocouple junctions at a constant temperature. Errors from these methods will generally be  $\pm 0.1$  to  $\pm 0.3$  °C, depending on the method used to measure the reference junction temperature.
3. In this method, the readout device is mechanically connected to a mechanical temperature indicator in the instrument. Errors from this method could exceed  $\pm 0.3$  °C. It is the least practical of the three options.

The first decision by the design team was to use the electrical compensation method for the reference junction. An existing sixteen channel passive Universal Temperature Reference (UTR) was incorporated into the design. This product is an aluminum plate with three brass screw terminals (positive, negative and shield), for each of the sixteen inputs. The brass screw terminals are electrically isolated, yet thermally connected to the UTR plate. This UTR used a calibrated RTD to measure the temperature of the plate.

After the initial testing, it was determined that small temperature gradients could be measured across the UTR. The errors resulting from this were considered to be large enough to prevent the instrument from meeting the target accuracy.

The UTR plate was re-designed to include a second RTD to provide a more accurate measurement of the UTR temperature. A second set of tests showed that the UTR temperature error could be held to a maximum of  $\pm 0.05$  °C by averaging the two RTD's. Also, the addition of the second RTD allowed the addition of software tests for maximum gradient across the UTR and

RTD differences to further reduce the errors in the UTR temperature measurement.

## Package Considerations

As mentioned earlier in this paper, a major source of errors in thermocouple measurement is secondary junctions with temperature gradients at the junction points. This can be minimized by keeping all of the junction points at the same temperature. For this reason it was decided to house all of the critical components and connections to the signal board in a “zone box”. The zone box and internal mounting plates are fabricated from Aluminum to improve heat conduction and prevent hot spots from forming inside the module. The external components are fabricated from Stainless Steel to help isolate the module components from ambient temperature changes. Initially, the zone box was designed to be insulated to prevent temperature gradients, but tests showed that the accuracy of the reference junction temperature measurement could be improved by heating the zone box which in turn raised the temperature of the UTR above ambient temperature. When insulation was added to the instrument top cover, the UTR temperature remained several degrees above ambient temperature. This created an effect similar to the effect an internal oven might have had on the instrument without having to add the oven components and controls. By keeping the UTR temperature above the ambient temperature, small changes in ambient temperature have no effect on the UTR temperature. Tests showed that the response time of the UTR and zone box combination was about 4 hours. This very slow response prevented temperature gradients across the UTR, thus making the junction temperature insensitive to fast ambient temperature changes.

## Signal Board

This board proved to be the most difficult part of the project. The initial design was an analog input section consisting of sixteen isolation amplifiers, one for each thermocouple input, in order to achieve 1000 v DC isolation. The output of each input amplifier would be multiplexed to an programmable gain instrument amplifier. The signal from this amplifier was passed to a 16 bit A/D converter and finally passed to the microprocessor board. In theory, this appeared to be a good approach to prevent errors from grounded thermocouples and noise from DC voltage spikes. Although the board worked exactly as we had planned, it was a calibration nightmare. Calibrations required several hours as each input amplifier had several trim pots to adjust. Small temperature changes within the zone box caused large output errors. These errors could not be controlled, but only minimized by re-calibrating the unit whenever the UTR temperature had changed more than 0.5° C. This was not practical for a unit that might be installed in an outdoor test facility where temperature swings could exceed 40 degrees C during a test.

After some experimentation, the design team decided to try a different approach. The new design incorporated an 22 bit A/D converter for each thermocouple input. This solved several problems. First, the microvolt signals from the thermocouples would be converted to a digital signal almost immediately after leaving the reference junction which minimizes the effect of noise and circuit

drift. Second, the signal to noise ratio increased from 100 db to 160 db. And finally, any drift in the A/D converters could easily be corrected by permitting periodic zero and span correction of the A/D converters via a software command. When this command is executed, the A/D converters are switched off line, the spans are compared to a reference voltage and the inputs shorted to get an updated zero. The process can require up to several minutes depending on the setting of the average variable.

Once this new design was implemented, the project progressed smoothly to the prototype testing phase.

## Processor Board

The processor board selected was a proven design used in pressure scanning products. Minimal modifications were required to include this board in the thermocouple scanner. This board performed perfectly during all of the environmental tests.

## Software

The software, as it is with any product requiring software, was another difficult part of the project. The basic operating system was borrowed from an existing product. At first, it was assumed that the command and configuration variables would be identical, with only minor changes, to those used in current pressure scanning products. This proved to be an impractical idea as the thermocouple scanner presented new and different configuration and setup scenarios from those required for a pressure scanner. The basic commands remained the same, but configuration variables were different and several commands had to be added to the software.

The software was written to give a user a broad range of calibration options:

1. RTD Correction Coefficients for each RTD can be entered to correct for any errors in the RTDs. The correction curve may be a slope -intercept ( $y = mx + b$ ) or a second order polynomial ( $y = ax^2 + bx + c$ ). The number of setpoints to be used in each equation is selectable in software.
2. Channel Each channel may be calibrated by injecting a series of millivolt signals to each UTR channel and entering the information to the Digital Thermocouple Scanner. The software will build a correction table for each channel. Each channel correction table can have up to 7 points.
3. Extension Wire Each channel has an additional slope-intercept correction factor to help calibrate out the errors caused by extension wire.
4. A/D AutoCal The testing found that the most significant source of error in the short term was the zero drift of the A/D converters. A

software command was added that would switch the A/D converters off line to correct for zero and span drift. This function occurs automatically at power up and can be performed at intervals determined by the user.

Previous products had required a customer to purchase or write interface software to facilitate setup and data collection. For this product, the software was designed to offer a new approach to the interface problem. A small web server was obtained that could be embedded in the Digital Thermocouple Scanner software. An integral web page was written to complement this server. Thus a customer can interface to a Digital Thermocouple Scanner using any web browser that supports JAVA. A user can connect to the Digital Thermocouple Scanner(port 80) from a computer a LAN. Connections may be made from the internet. The Digital Thermocouple Scanner will respond just as any web site might respond. The web server will automatically connect to the TelNet port (port 23) so that commands can be sent to, and data collected from, the Digital Thermocouple Scanner. A customer connected to the Scanivalve Corp web site could have the web site interrogate the Digital Thermocouple Scanner and determine if the perating system was the current configuration. An updated operating system could be uploaded to the Digital Thermocouple Scanner. Troubleshooting and help files will also be available to a customer.

### Performance Testing

The performance of the unit was tested over the full range of ambient conditions using an oven, a Kaye Ice Point Reference, and a Beamex model TC305 Thermocouple Calibrator. The performance testing was broken down into three phases: breadboard, prototype and first article.

The first breadboard tests were conducted on the initial signal board design. The testing was limited to a two channel breadboard which proved the feasibility of that design and showed we could meet the target accuracy. Based on this testing, a sixteen channel signal board was built and tested. This phase of testing showed it would be almost impossible to maintain calibration accuracy for periods longer than a few days, unless the temperature of the device was held constant. Rather than install the entire instrument in an oven, the signal board was completely re-designed. Once the re-designed board was available, the breadboard tests were repeated. These tests showed that the new design was far superior to the initial design. The new design was almost insensitive to temperature changes, noise levels were considerably lower and calibration was easier. Thus improving the long term stability and accuracy.

Three modules were built for the prototype testing. One module was used for software development. The other two modules were used for temperature, accuracy, and environmental tests.

### Temperature Tests

The first temperature tests were to determine if the heating effect of the internal electronics had a deleterious effect on the UTR. Thermocouples were installed on all of the circuit boards in areas that might have, or cause, heating problems. Six thermocouples were installed on the UTR itself

to determine if temperature gradients existed. The unit was placed in an oven which was then cycled from room temperature to 50° C and then to room temperature. The unit was held at 50°C for four hours. This test showed that the UTR requires approximately 4 hours to reach equilibrium after a relatively fast increase in ambient temperature. A graph of this test is shown in figure 1.

The second series of tests were to determine the effect of a change in temperature on the UTR and electronics when the temperature is cycled to -30° C. The unit was placed in an oven which was then cycled from room temperature to -30 degrees C and then back to room temperature. The unit was held at -30°C for four hours. This test showed that the UTR requires approximately 4 hours to reach equilibrium after a relatively fast change in ambient temperature. A graph of this test is shown in figure 2.

During both of these tests the UTR temperature was monitored in two places. The graphs in figures 1 and 2 show no significant difference in temperature between the two points. During all of the tests, the temperature difference did not exceed 0.2° C. The maximum gradient was measured during the cold cycle testing at -30° C . A graph of the temperature difference during that test is shown in figure 3. Temperature gradients observed during the hot cycle testing were insignificant.

The data from these tests were used to determine if the placement of the RTD's actually provided a true indication of the temperature of the UTR. The data showed that the temperature across the UTR at any given temperature varied by less than .1°C. Since the outputs of the RTD's are averaged in software, the maximum expected reference junction error would be less than .05°C. This was determined to be acceptable. A graph of the RTD temperature readings is shown in figure 4.

During these tests, the temperature of the module varied from the ambient temperature by as much as 20° C. This could have had a long term detrimental effect on the electronics. To correct this, heat sinks were added to conduct the internal heat out of the package and the internal insulation was modified. This lowered the internal temperature rise to 8°C.

### Accuracy Tests

Accuracy tests were conducted on the second prototype module. The first test was to determine the accuracy of the RTD's. The RTD's used in the design were purchased with NIST certifications from the manufacturer. The RTD conditioning circuits were calibrated using voltage standards and standard resistors. The RTD's were then installed in a UTR instrumented with thermocouples. The fixture was placed in an oven which was cycled through several temperatures. The thermocouples were monitored with a calibrated thermocouple scanner manufactured by Hewlett Packard. The RTD's tracked the UTR temperature within acceptable limits of error. As a result of these tests, RTD calibration variables were added to the software. These variables permit a user to make fine adjustments to the RTD conversion to correct for any small errors in the RTD circuitry.

Thermocouple channel accuracy was verified using voltage tests. As a result of these tests,

calibration variables were added to the software which would permit a user to calibrate each input channel to correct for A/D and extension wire errors.

The final hardware tests performed were to verify that noise would not induce a significant error to the reading. Before these tests were performed, the design team first identified all of the possible thermocouple connections. Five possible input connections were identified:

1. Bonded, no shield
2. Unbonded, no shield
3. Shielded, shield connected at the Digital Thermocouple Scanner
4. Shielded, shield connected at the source
5. Unterminated probe

Because shielded thermocouples may be grounded at either the measurement point or at the measuring device, a software switch was added in order to give a user the opportunity to properly terminate a shielded thermocouple. The typical input circuits are shown in figures 5 through 9, respectively.

## Software

The software testing was divided into two parts. The first series of tests were to verify the conversion tables. The conversion tables, which conform to the International Temperature Scale of 1990(ITS90) , were derived from the NIST ITS-90 Thermocouple Database purchased from NIST. The conversion tables are built in 0.1° C increments for each thermocouple type that is enabled. The input voltage is converted to counts by the A/D converter. The counts are converted to an EMF in software and the EMF of the reference junction temperature is subtracted out before conversion to engineering units. Conversion to engineering units is by linear interpolation between points in the conversion tables. The accuracy of this software conversion was verified with a voltage standard using NIST thermocouple tables.

Once the conversion tables were verified, tests were run to verify the operation of the main body of the software. The Digital Thermocouple Scanner software had to perform the following tasks:

1. Set the Digital Thermocouple Scanner Physical Ethernet Address.
2. Read and filter the raw A/D counts that represent the temperature inputs.
3. Convert the A/D counts to the user chosen temperature units.
4. Receive and execute commands from the Ethernet link.
5. Output converted data, calibration data, setup parameters and status information over the Ethernet link.
6. Assist the user to troubleshoot module problems.
7. Support the web server.

The software tests were perhaps the most difficult part of the overall testing. Although it was relatively easy to verify the conversion tables, each command and configuration variable had to be tested in various module configurations. As this testing progressed, configuration variables and commands were added, to either enhance, or better define the module operation. Most of the

additions to the software improved the ability of a user to correct errors from A/D conversion, extension wire, and to troubleshoot module problems. The software will most likely continue to evolve as specific customer needs are identified. Each modification of the software will include a test of all functions and variables.

### Calibration

All calibration testing of the modules was performed using a Kaye Ice Point Reference and a Beamex Model TC305 Millivolt Standard and Thermocouple Simulator. All final calibrations of production units will be completed using these standards or equivalent.

### Environmental Testing

Environmental Testing included tests to certify compliance to EN55011 Class B and EN50082-2(1995). During this testing, several modifications were made to the hardware. This included added shielding and an improvement in the mechanical connection between assemblies. The result was an instrument that passed the CE requirements for Heavy and Light Industrial environments. Testing to MIL 810 for Shock and Vibration will be completed in 2001.

### Conclusion

This module has proved to be a reliable and accurate method to measure thermocouples. The high accuracy, high programmability and Ethernet interface gives a Test or Instrument Engineer a new and valuable tool for temperature data collection. Although the project missed the original completion date due to the redesign of the signal board, the decision to change from an analog to a digital design proved to be the key to the success of the project. All modules produced to date have performed well within the design specifications. All have maintained accuracy over time and environmental changes. The module has been proved to be a complement to existing pressure scanners.

### Acknowledgements

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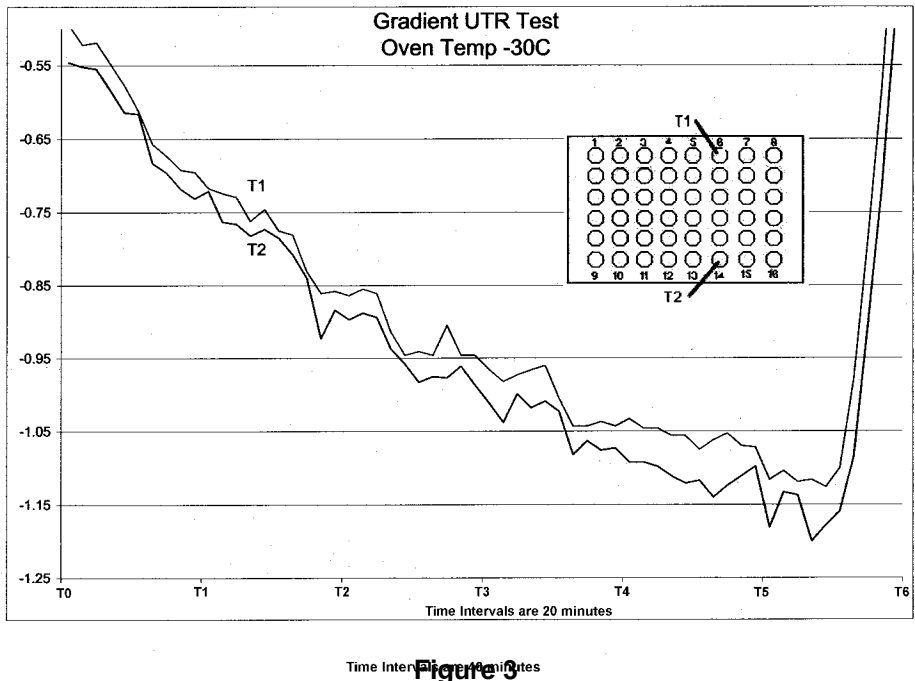


Figure 1

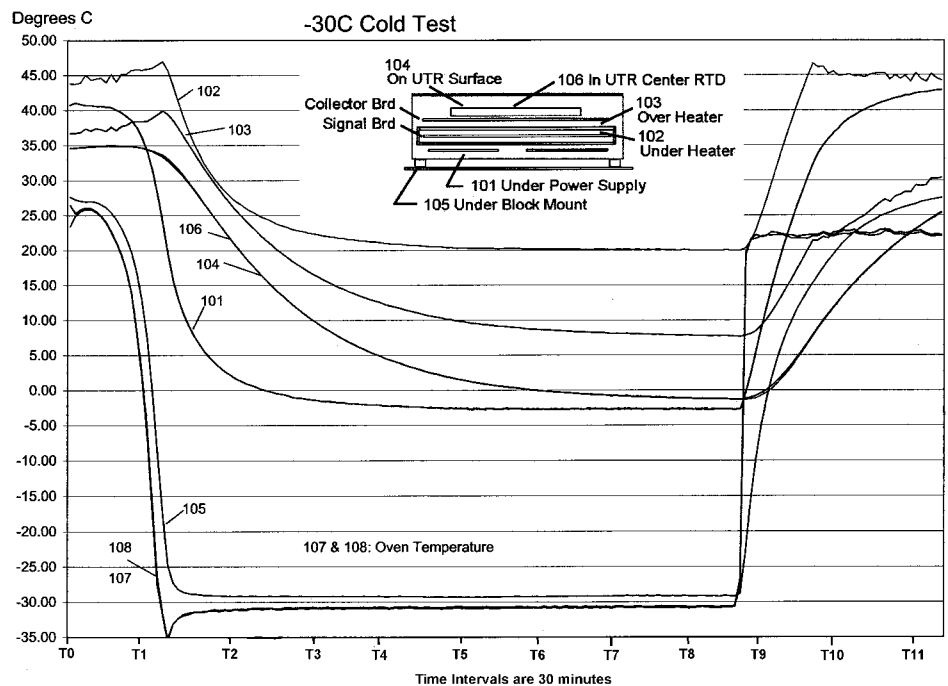


Figure 2

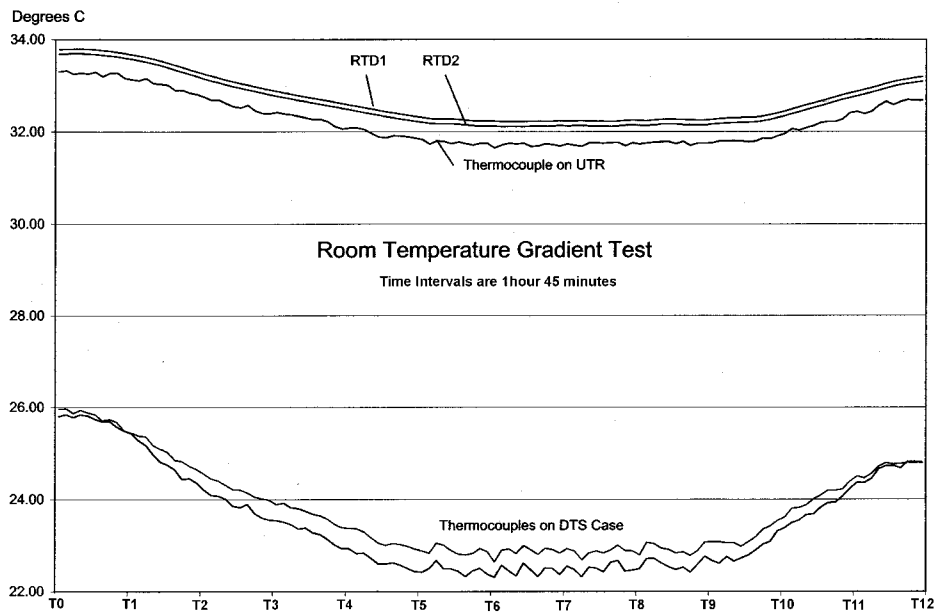


Figure 4

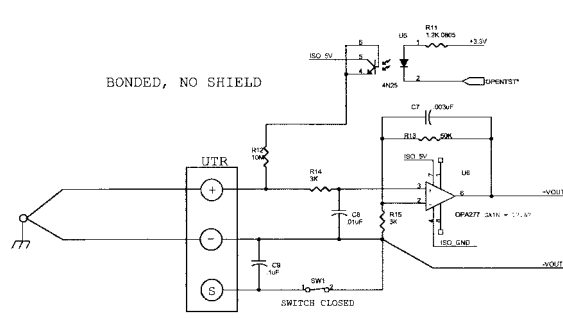


Figure 5

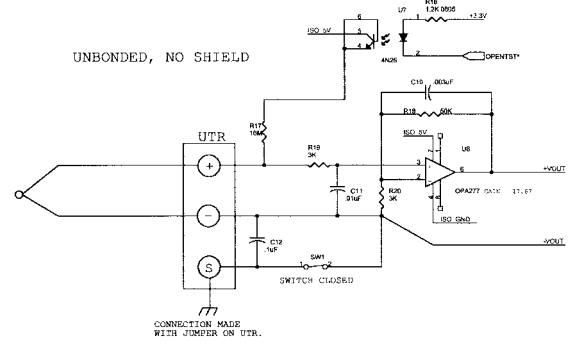


Figure 6

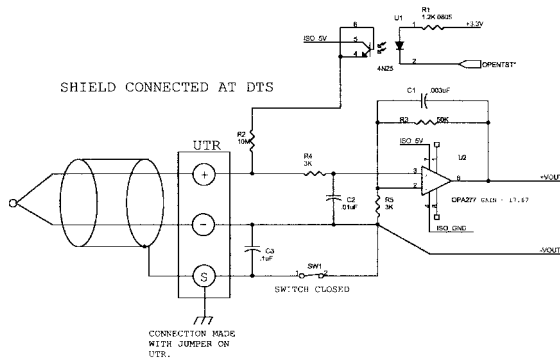


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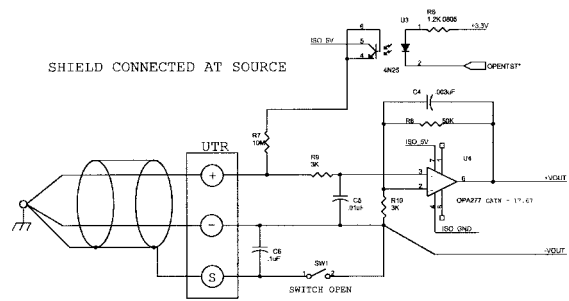


Figure 8

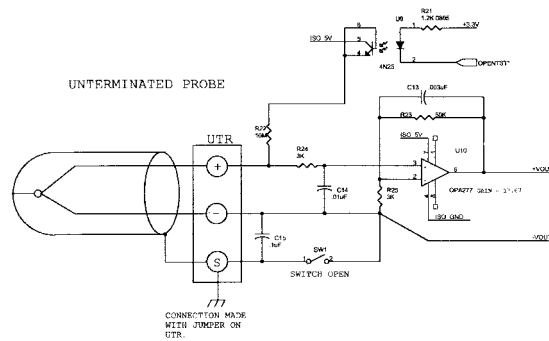


Figure 9