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Reference Circuits

*Circuits from the Lab™ reference circuits are engineered and tested for quick and easy system integration to help solve today's analog, mixed-signal, and RF design challenges. For more information and/or support, visit [www.analog.com/CN0271](http://www.analog.com/CN0271).*

Devices Connected/Referenced	
AD8495	Full K-Type Range 0°C to 50°C Thermocouple Amplifier with Cold Junction Compensation
AD8476	Low Power, Unity-Gain Fully Differential Amplifier and ADC Driver
AD7790	16-Bit, Single-Channel, Ultralow Power, Sigma-Delta ADC
ADR441	Ultralow Noise, 2.5 V, LDO, XFET Voltage Reference with Current Sink and Source

## K-Type Thermocouple Measurement System with Integrated Cold Junction Compensation

### EVALUATION AND DESIGN SUPPORT

#### Circuit Evaluation Boards

[CN-0271 Circuit Evaluation Board \(EVAL-CN0271-SDPZ\)](#)  
[System Demonstration Platform, SDP-B \(EVAL-SDP-CB1Z\)](#)

#### Design and Integration Files

[Schematics, Layout Files, Bill of Materials](#)

### CIRCUIT FUNCTION AND BENEFITS

The circuit shown in Figure 1 is a complete thermocouple signal conditioning circuit with cold junction compensation followed by a 16-bit sigma-delta ( $\Sigma$ - $\Delta$ ) analog-to-digital converter (ADC). The AD8495 thermocouple amplifier provides a simple, low cost solution for measuring K type thermocouple temperatures, including cold junction compensation.

A fixed gain instrumentation amplifier in the AD8495 amplifies the small thermocouple voltage to provide a 5 mV/°C output. The high common-mode rejection of the amplifier blocks common-mode noise that the long thermocouple leads can pick up. For additional protection, the high impedance inputs of the amplifier make it easy to add extra filtering.

The AD8476 differential amplifier provides the correct signal levels and common-mode voltage to drive the AD7790 16-bit,  $\Sigma$ - $\Delta$  ADC.

The circuit provides a compact low cost solution for thermocouple signal conditioning and high resolution analog-to-digital conversion.

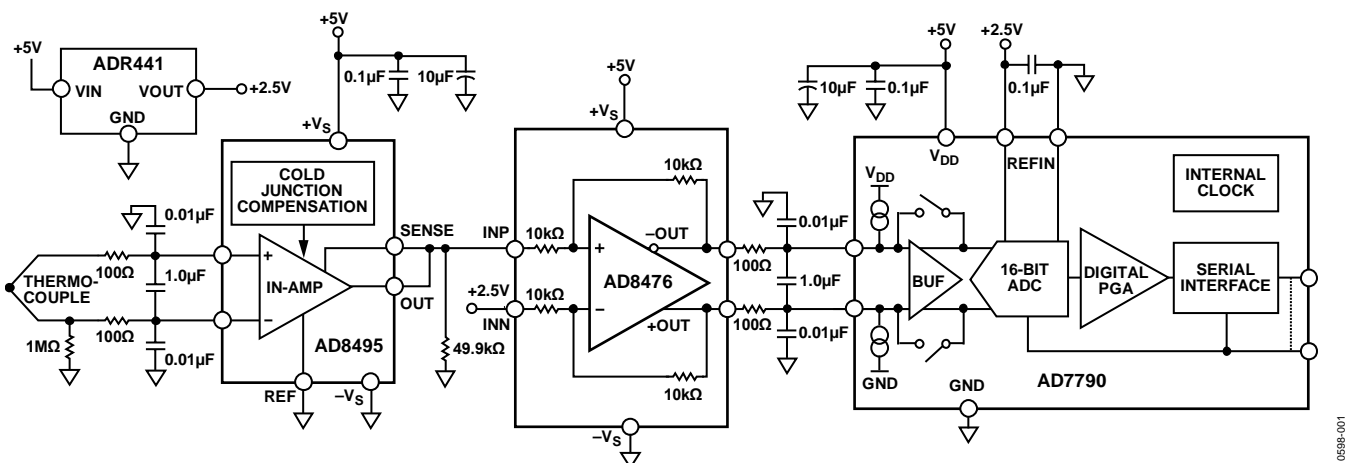


Figure 1. K-Type Thermocouple Measurement System with Integrated Cold Junction Compensation (Simplified Schematic: All Connections Not Shown)

#### Rev. A

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## CIRCUIT DESCRIPTION

The thermocouple is a simple, widely used component for measuring temperature. It consists of a junction of two dissimilar metals. These metals are connected at one end to form the measurement junction, also called the hot junction. The other end of the thermocouple is connected to the metal lines that lead to the measurement electronics. This connection forms a second junction: the reference junction, also called the cold junction. To derive the temperature at the measurement junction ( $T_M$ ), the user must know the differential voltage created by the thermocouple. The user must also know the error voltage generated by the temperature at the reference junction ( $T_R$ ). Compensating for the reference junction error voltage is called cold junction compensation. The electronics must compensate for any changes in temperature at the reference (cold) junction so that the output voltage is an accurate representation of the hot junction measurement.

The circuit uses the [AD8495](#) thermocouple amplifier on a single 5 V supply. The output voltage of the [AD8495](#) is calibrated for 5 mV/°C. On a single 5 V supply, the output is linear between approximately 75 mV and 4.75 V, corresponding to a temperature range of 15°C to 950°C. The output of the [AD8495](#) drives the noninverting input of the [AD8476](#) unity-gain differential amplifier, which converts the single-ended input to differential outputs for driving the [AD7790](#) 16-bit,  $\Sigma$ - $\Delta$  ADC.

A low-pass differential and common-mode filter before the input of the [AD8495](#) prevents RF signals, which, if allowed to reach the [AD8495](#), can be rectified and appear as temperature fluctuations. The two 100  $\Omega$  resistors and the 1  $\mu$ F capacitor form a differential filter with a cutoff frequency of 800 Hz. The two 0.01  $\mu$ F capacitors form common-mode filters with a cutoff frequency of 160 kHz. A similar filter is used at the output of the [AD8476](#) differential amplifier before the signal is applied to the [AD7790](#) ADC.

The [AD8495](#) inputs are protected from input voltage excursions up to 25 V from the opposite supply rail. For example, in this circuit, with a 5 V positive supply rail and the negative supply rail tied to GND, the part can safely withstand voltages at the inputs from -20 V to +25 V. Voltages at the reference and sense pins should not go beyond 0.3 V of the supply rails. This feature is of particular importance in applications with power supply sequencing issues that can cause the signal source to be active before the supplies to the amplifier are applied.

The theoretical resolution of the system can be calculated from the bandwidth, voltage noise density, and gain of the [AD8495](#). The peak-to-peak (noise free code) resolution in bits is

Noise Free Bits =

$$= \frac{\log \left[ \frac{V_{OUT\_MAX}}{6.6 \times \text{Voltage Noise Density} \times \text{Gain} \times \sqrt{1.57 \times \text{Bandwidth}}} \right]}{\log(2)}$$

$$= \frac{\log \left[ \frac{4.9 \text{ V}}{6.6 \times (32 \text{ nV}/\sqrt{\text{Hz}}) \times 122.4 \times \sqrt{1.57 \times 800 \text{ Hz}}} \right]}{\log(2)} = 12.4 \text{ bits}$$

The [AD8476](#) is a very low power, fully differential precision amplifier with integrated thin film, laser trimmed 10 k $\Omega$  gain resistors for unity gain. It is an ideal choice for this application because it presents a relatively high impedance load to the [AD8495](#).

The [AD7790](#) is a low power, complete analog front end for low frequency measurement applications. It contains a low noise, 16-bit,  $\Sigma$ - $\Delta$  ADC with one differential input that can be buffered or unbuffered.

## Test Results

An important measure of the performance of the circuit is the amount of linearity error. The [AD8495](#) output is accurate to within 2°C from -25°C to +400°C. To achieve even greater accuracy when operating at or outside of this range, a linearity correction algorithm must be implemented in software. The [CN-0271](#) evaluation software uses NIST thermoelectric voltage lookup tables to achieve an output error within 1°C from 15°C to 950°C.

Figure 2 compares the performance of the [AD8495](#) with the [CN-0271](#) system, and the result of applying the linearization correction to the ADC output. For details on how the algorithm was implemented in the software, see the [AN-1087 Application Note, Thermocouple Linearization When Using the AD8494/AD8495/AD8496/AD8497](#).

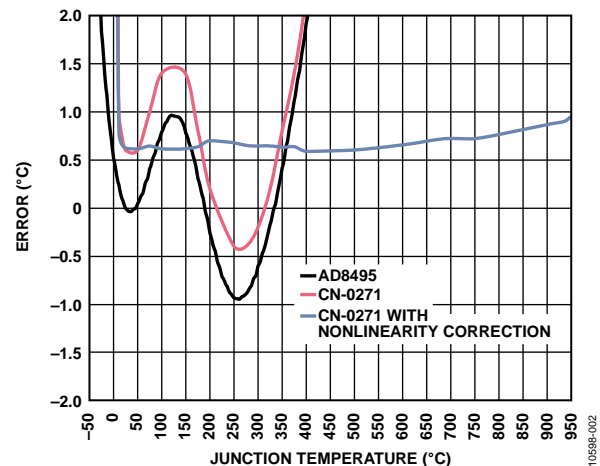


Figure 2. Output Error of [AD8495](#), Total [CN-0271](#) Circuit Error, and Total [CN-0271](#) Circuit Error with Thermocouple Nonlinearity Correction

The noise performance of the system is also important to the accuracy of the circuit. Figure 3 shows a histogram of 1,000 measurement samples. This data was taken with the [CN-0271](#) evaluation board connected to the [EVAL-SDP-CB1Z](#) System Demonstration Platform (SDP-B) evaluation board. Details of the setup are described in the Circuit Evaluation and Test section.

The measured peak-to-peak noise is approximately 6 LSBs (1 LSB =  $4.9 \text{ V} \div 65536 = 74.8 \mu\text{V}$ ), corresponding to 0.449 mV p-p and 13.4 bits of noise free resolution.

$$\text{Noise Free Bits} = \frac{\log\left(\frac{V_{IN\_MAX}}{\text{Noise}_{V_{p-p}}}\right)}{\log(2)} = \frac{\log\left(\frac{4.9 \text{ V}}{0.449 \times 10^{-3} \text{ V}_{p-p}}\right)}{\log(2)} = 13.4 \text{ bits}$$

This shows that the converter does not decrease the noise free resolution because the measured resolution of a fixed thermocouple input voltage results in approximately the same number of noise free bits as predicted by the theoretical output noise of the [AD8495](#).

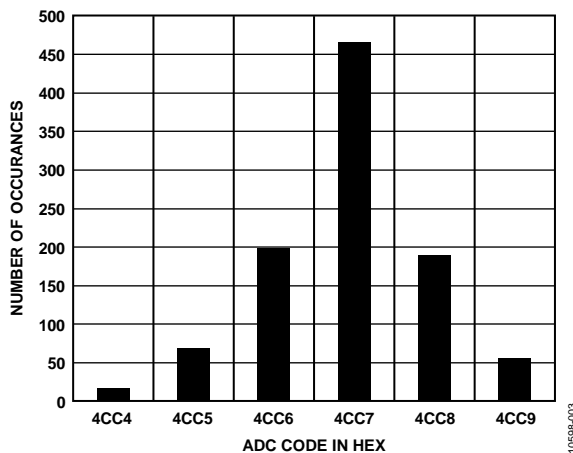


Figure 3. Histogram of Codes for 1,000 Samples at 120 Hz

A complete design support package for this circuit note can be found at [www.analog.com/CN0271-DesignSupport](http://www.analog.com/CN0271-DesignSupport).

## COMMON VARIATIONS

To measure negative temperatures, apply a voltage at the reference pin to offset the output voltage at 0°C. The output voltage of the [AD8495](#) is

$$V_{OUT} = (T_{MJ} \times 5 \text{ mV}/^\circ\text{C}) + V_{REF}$$

The complete K type thermocouple range of  $-200^\circ\text{C}$  to  $+1250^\circ\text{C}$  can be measured by modifying the circuit to run on dual supplies. When operating the [AD8495](#) on a single supply, measurement of temperatures less than ambient become nonlinear because the output starts to saturate close to the supply rail. To maintain accuracy at lower temperatures, use dual supplies or level-shift the output by applying the appropriate offset voltage to the reference pin.

The [AD8494](#) is calibrated for J type thermocouples. Both the [AD8494](#) and [AD8495](#) are optimized for reference junctions between  $0^\circ\text{C}$  and  $50^\circ\text{C}$ .

The [AD8496](#) (J type) and [AD8497](#) (K type) are optimized for reference junctions between  $25^\circ\text{C}$  and  $100^\circ\text{C}$ .

The circuit is proven to work with good stability and accuracy.

## CIRCUIT EVALUATION AND TEST

This circuit uses the [EVAL-CN0271-SDPZ](#) circuit board and the System Demonstration Platform (SDP-B) controller board ([EVAL-SDP-CB1Z](#)). The two boards have 120-pin mating connectors, allowing for the quick setup and evaluation of the performance of the circuit. The [EVAL-CN0271-SDPZ](#) contains the circuit to be evaluated, as described in this note, and the SDP-B controller board is used with the [CN-0271](#) evaluation software to capture the data from the [EVAL-CN0271-SDPZ](#) circuit board.

### Equipment Needed

The following equipment is needed:

- A PC with a USB port and Windows® XP or Windows Vista® (32-bit), or Windows® 7 (32-bit)
- The [EVAL-CN0271-SDPZ](#) circuit evaluation board
- The SDP-B controller board ([EVAL-SDP-CB1Z](#)) or the SDP-S controller board ([EVAL-SDP-CS1Z](#))
- The [CN-0271](#) SDP evaluation software
- The 6 V power supply ([EVAL-CFTL-6V-PWRZ](#)) or equivalent dc power supply

### Getting Started

Load the evaluation software by placing the [CN-0271](#) evaluation software CD in the CD drive of the PC. Using **My Computer**, locate the drive that contains the evaluation software.

### Functional Block Diagram

See Figure 1 of this circuit note for the circuit block diagram and the [EVAL-CN0271-SDPZ-SCH-RevA.pdf](#) file for the circuit schematics. This file is contained in the [CN-0271 Design Support Package](#).

**Setup**

Connect the 120-pin connector on the [EVAL-CN0271-SDPZ](#) circuit board to the **CON A** connector on the SDP-B controller board ([EVAL-SDP-CB1Z](#)). Use nylon hardware to firmly secure the two boards, using the holes provided at the ends of the 120-pin connectors.

With power to the supply off, connect the EVAL-CFTL-6V-PWRZ plug to the barrel connector designated by J5 on the board. If this is unavailable, connect the +6V and GND pins to the provided two pin screw of J4 on the board. Also, connect the USB cable supplied with the SDP-B board to the USB port on the PC.

Then, connect a K type thermocouple connector to J1 on the board and the other end to the test equipment.

**Test**

Launch the evaluation software and connect the USB cable from the PC to the mini-USB connector on the SDP-B board. Once USB communications are established, the SDP-B board can now be used to send, receive, and capture serial data from the [EVAL-CN0271-SDPZ](#) board.

Figure 4 shows a screenshot of the [CN-0271](#) SDP-B evaluation software interface, and Figure 5 shows a photo of the [EVAL-CN0271-SDPZ](#) evaluation board and the SDP-B board. Information regarding the SDP-B board can be found in the [UG-277](#) user guide.

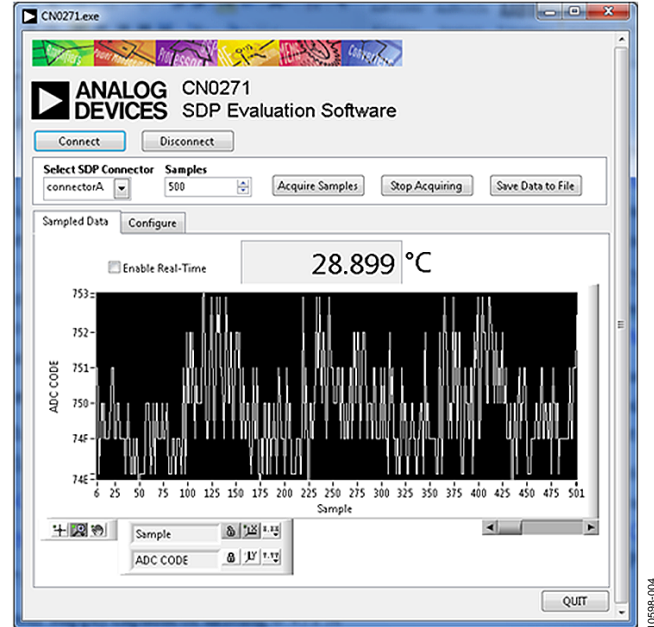


Figure 4. [CN-0271](#) SDP-B Evaluation Software Interface

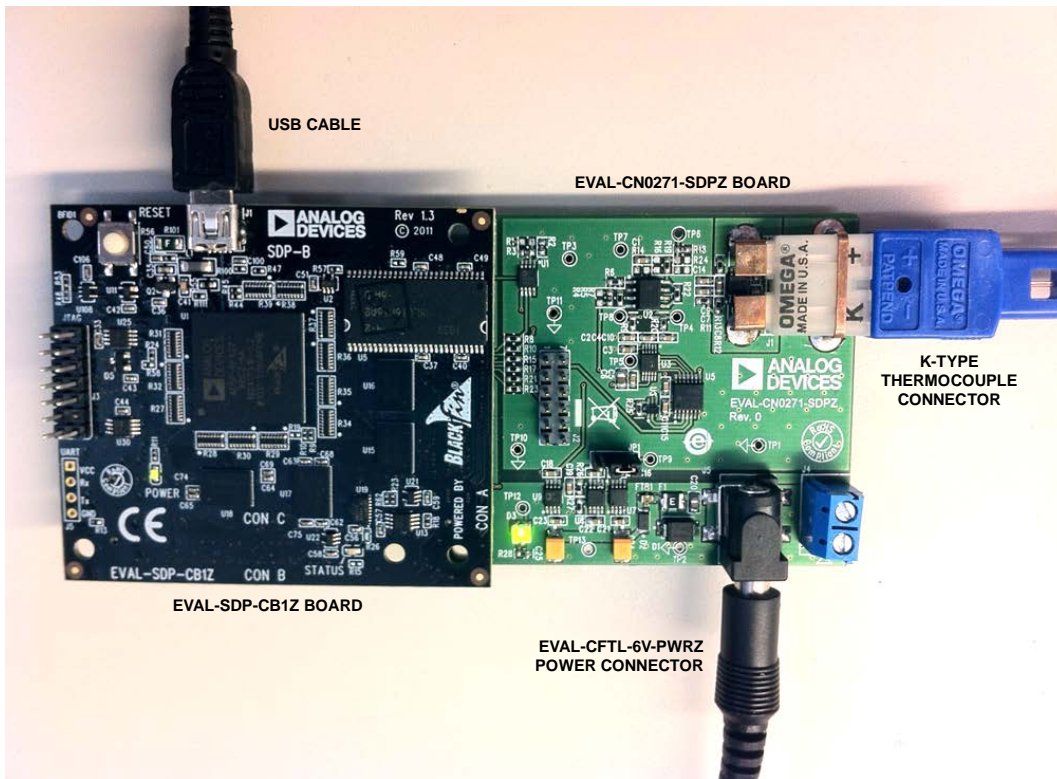


Figure 5. [EVAL-CN0271-SDPZ](#) Evaluation Board Connected to the SDP-B Board

**LEARN MORE**

CN0271 Design Support Package:

[www.analog.com/CN0271-DesignSupport](http://www.analog.com/CN0271-DesignSupport)

SDP-B User Guide

Ardizzoni, John. *A Practical Guide to High-Speed Printed-Circuit-Board Layout*, Analog Dialogue 39-09, September 2005.

Duff, Matthew and Towey, Joseph. *Two Ways to Measure Temperature Using Thermocouples Feature Simplicity, Accuracy, and Flexibility*. Analog Dialog 44-10, October 2010.

Malik, Reem. *Thermocouple Linearization When Using the AD8495/AD8496/AD8497*, Application Note AN-1087, Analog Devices.

MT-031 Tutorial, *Grounding Data Converters and Solving the Mystery of "AGND" and "DGND"*, Analog Devices.

MT-035, *Op Amp Inputs, Outputs, Single-Supply, and Rail-to-Rail Issues*, Analog Devices.

MT-036 Tutorial, *Op Amp Output Phase-Reversal and Input Over-Voltage Protection*, Analog Devices.

MT-068 Tutorial, *Difference and Current Sense Amplifiers*, Analog Devices.

MT-101 Tutorial, *Decoupling Techniques*, Analog Devices.

**Data Sheets and Evaluation Boards**

CN-0271 Circuit Evaluation Board (EVAL-CN0271-SDPZ)

System Demonstration Platform, SDP-B (EVAL-SDP-CB1Z)

AD8495 Data Sheet

AD8476 Data Sheet

AD7790 Data Sheet

ADR44x Data Sheet

ADP3336 Data Sheet

**REVISION HISTORY**

6/12—Rev. 0 to Rev. A

Changes to Figure 1 ..... 1

6/12—Revision 0: Initial Version

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