ANALOG DEVICES

AN-274
APPLICATION NOTE

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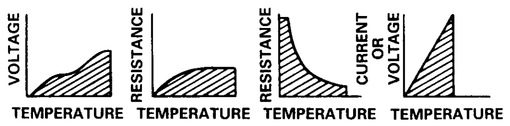
Taking the Uncertainty Out of Thermocouple Temperature Measurement (With the AD594/AD595)

by Bob LeFort and Bob Ries

Temperature is the most frequently measured physical parameter. However, the techniques of temperature measurement are grossly misunderstood, often resulting in serious inaccuracies or meaningless data. This application note is intended to clarify some of these common misunderstandings as well as present some interesting and useful circuit solutions.

TEMPERATURE TRANSDUCER TECHNOLOGIES

The most commonly-used electronic temperature measurement devices currently available include the thermocouple, the resistance temperature detector (RTD), the thermistor, and the integrated circuit temperature transducer. All have associated application benefits and limitations which are delineated in Table I.



	THERMOCOUPLE	RTD	THERMISTOR	IC SENSOR
LINEARITY		*		**
SENSITIVITY			*	**
RUGGEDNESS	*			
COST	**		*	*
STABILITY		*		
ACCURACY		**		*
RESPONSE TIME	*			
NOISE IMMUNITY				*
POWER DISP.	**			*
MAX TEMP RANGE[1] (°C)	−270 TO +2980	−180 TO +630	−80 TO +150	−55 TO +150

*GOOD
**EXCELLENT
[1] TEMPERATURE RANGE INDICATED IS NOT NECESSARILY FOR A SINGLE VERSION OF THE TRANSDUCER TYPE.

Table I. Sensor Comparison

THERMOCOUPLE CHARACTERISTICS

The thermocouple is the most widely used temperature sensor for instrumentation purposes. Because of this, the National Bureau of Standards (NBS) has extensively characterized various metal combinations, i.e., type J (Iron – Constantan), type K (Chromel – Alumel), type E (Chromel – Constantan), and type T (Copper – Constantan). Thermocouple qualities include inherent accuracy, wide temperature range, fast thermal response, ruggedness, low cost, repeatability, and versatility of application. In addition to being widely used, the thermocouple is also the most misunderstood temperature sensor. Terms such as cold junction compensation, Seebeck coefficient, and isothermal connections or blocks have caused confusion and anxiety for many users. This application note explains those terms and provides information that allows the reader to measure temperature accurately and easily.

THE THERMOCOUPLE LOOP

Two wires of dissimilar metal, when joined together at both ends, constitute the basic thermocouple loop (see Figure 1a). This loop generates a voltage proportional to the difference in temperature between the two junctions. Since the thermocouple is basically a differential temperature measuring device, measuring a single temperature requires that the temperature of one of the junctions (a reference junction) be known. Users of thermocouples have relied on a variety of techniques to determine and compensate for the reference or "cold" junction temperature.

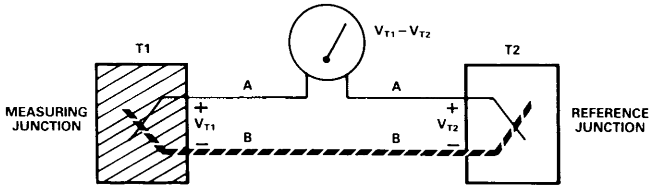


Figure 1a. Thermocouple Loop

ICE POINT REFERENCING

The voltage output of all thermocouples (as given in NBS tables) is referenced to 0°C. This means that the voltage across the thermocouple corresponds to the temperature of the measuring junction only if the reference junction is held at 0°C. This can be done with an ice point cell or an "ice bath" as shown in Figure 1b. Unfortunately these methods are awkward, expensive, and therefore only feasible in a laboratory setting. In a production environment it is impractical to maintain a reference junction at 0°C.

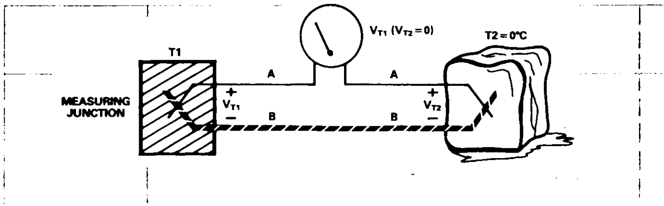


Figure 1b. Ice Point Reference

LAW OF INTERMEDIATE METALS

In practice, to eliminate the need for an explicit reference junction (as in Figure 1a) a direct connection equivalent to the basic thermocouple loop is made (see Figure 1c). The Law of Intermediate Metals states that a third metal (in most cases Copper) connected to the two dissimilar metals of a thermocouple will not have any effect on the output voltage, as long as the connections are at the same temperature.

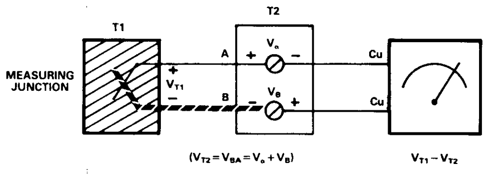


Figure 1c. "Indirect" Reference Junction

PRACTICAL THERMOCOUPLE MEASUREMENT

In a production environment an ice point reference can be eliminated by compensating for the voltage developed at the reference junction. This is done with a circuit which adds a voltage into the thermocouple loop, equal but opposite to that of the reference junction (see Figure 1d).

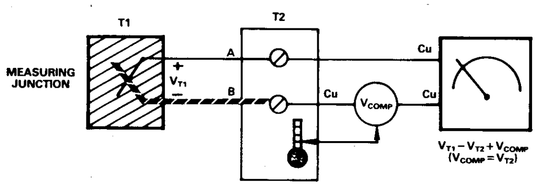


Figure 1d. Cold Junction Compensation

A device which accomplishes this and more is the AD594/AD595. The block diagram and basic connections are shown in Figure 2. The internal ice point compensation block monitors the reference junction temperature and adds the appropriate voltage into the thermocouple loop at the internal summing node. This net voltage is then amplified to a nominal output of 10mV/°C. The AD594 is factory calibrated for type J thermocouples, while the AD595 is set for type K.

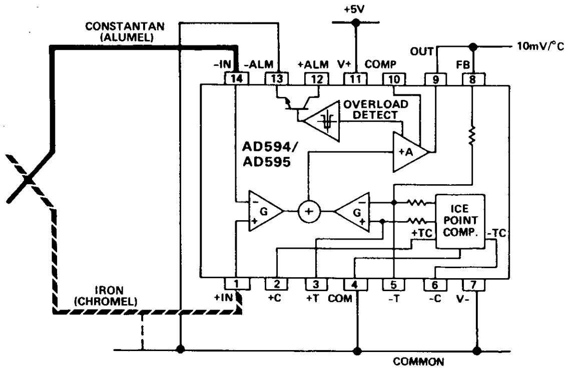


Figure 2. AD594/AD595 Block Diagram

SEEBECK COEFFICIENT

Seebeck coefficient of a thermocouple is defined as the rate of change of thermal voltage with respect to temperature at a given temperature and is usually expressed in µV/°C. Thermocouple nonlinearity is represented by the change in this coefficient over temperature. A graph of the Seebeck coefficient for various thermocouples is given in Figure 3.

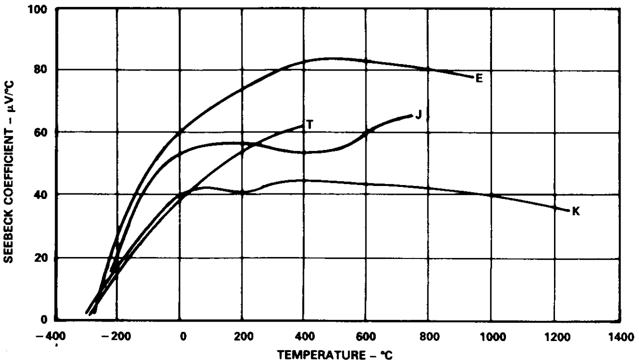


Figure 3. Seebeck Coefficient vs. Temperature

TYPES OF THERMOCOUPLES

The two characteristics generally used to differentiate thermocouple types are sensitivity and operating temperature range. The graph in Figure 4 portrays these characteristics for some popular combinations of metals.

While factory-calibrated to condition a J type thermocouple, the AD594 can condition an E type with just a simple external adjustment as shown in the AD594/AD595 data sheet. The AD595, calibrated for a K type thermocouple, may also be directly connected to a type T thermocouple with less than 0.2°C additional error.

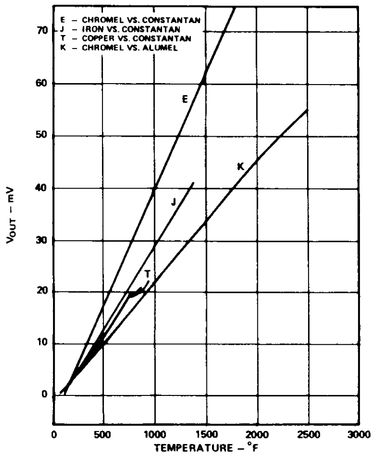


Figure 4. Thermocouple Output vs. Temperature

OPTIMIZING PERFORMANCE WITH THE AD594/AD595

Achieving the full rated accuracy from the AD594 or AD595 requires adherence to the following design guidelines:

1. **Cold Junction Errors**

   The AD594/AD595 has on-chip cold junction compensation. For this function to work correctly the device must be held at the same temperature as the thermocouple cold junction. Keep other components or heat sources from direct contact with the AD594/AD595 as their heat dissipation could cause cold junction compensation-related errors. (The AD594/AD595 draws only 160μA quiescent supply current; this minimizes self-heating related errors.)

2. **Circuit Board Layout**

   The printed circuit board connection layout (with the optional calibration resistors) illustrated in Figure 5 provides for thermal equilibrium between the cold junction and the AD594/AD595. Here the device and circuit board are thermally contacted in the copper printed circuit board tracks under pins 1 and 14. The reference junction is now composed of a copper-constantan (or copper-alumel) connection and copper-iron (or copper-chromel) connection, both of which are held at the same temperature as the AD594/AD595.

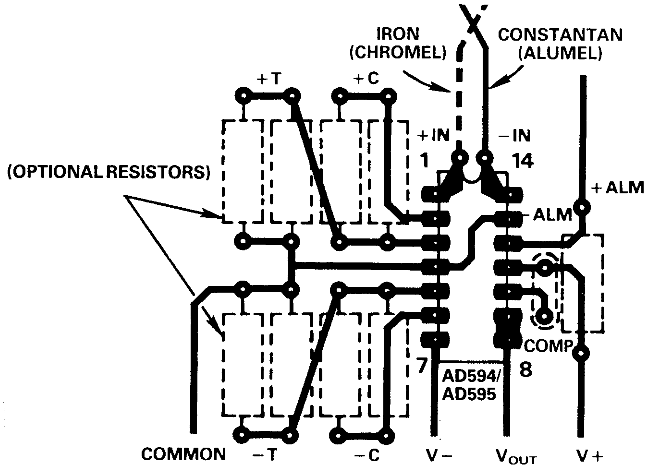


Figure 5. PCB Connections

3. **Soldering**

   To ensure secure bonding and to minimize I × R drops, clean the thermocouple wire to remove oxidation prior to soldering. Noncorrosive rosin flux is effective with iron, constantan, chromel, and alumel and the following solders: 95% tin – 5% antimony, 95% tin – 5% silver, or 90% tin – 10% lead.

4. **Grounding Considerations**

   The AD594/AD595 input stage has transistors which require bias currents to flow from the thermocouple inputs to ground. If this path is not provided these currents will drive the input stage into cutoff, causing the output to give a false reading. A direct connection to ground should be used to provide the return path.

5. **Minimizing Noise**

   Compensation capacitors between pins 9, 10 and 10, 11 will minimize the amplification of high frequency noise picked up by the thermocouple. The values shown in Figure 6 will provide a zero at 60Hz, but will increase the circuit's response time.

   To avoid I × R drops in the ground lines, all ground points should be directly connected to a central point. The 100Ω resistor combined with the 0.1μF capacitor will filter ripple and transient spikes on the supply lines.

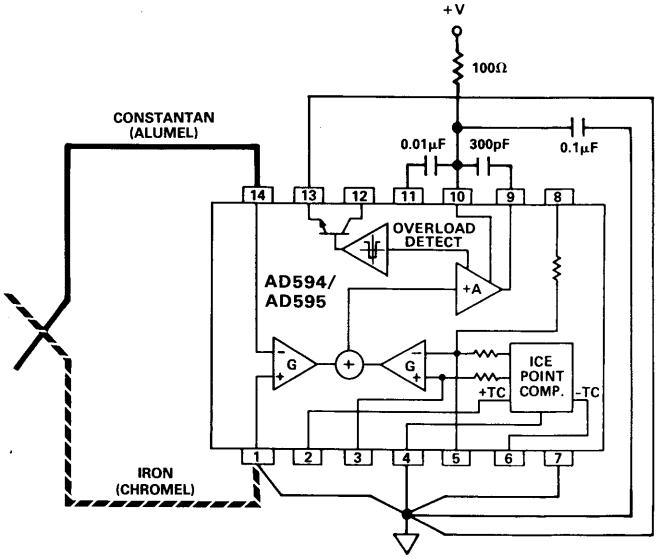


Figure 6. Reducing Errors through Filtering, Compensating and Grounding

EXTENDED AMBIENT TEMPERATURE ERROR CALCULATIONS

The ambient operating temperature range of the AD594/AD595 is specified from 0 to 50°C to minimize the errors associated with thermocouple nonlinearities (the varying Seebeck coefficient), and to optimize accuracy for a 25°C ambient. The AD594/AD595 ice point compensation voltage is linear and is matched to the best fit straight line of the thermocouple's output from 0 to 50°C. Outside of this range deviation between the thermocouple and the compensation voltage becomes more pronounced. This means that while the AD594/AD595 functions correctly outside of the rated temperature range, it may not remain within its specified temperature stability error limits. Table II provides a list of the calculated maximum errors associated with the commercial, industrial, and extended ambient operating temperature ranges. The ambient temperature refers to the device and reference junction. The measuring junction can be at any temperature within the thermocouple rated limits.

Ambient Temp. °C	AD594C Temp. Rej. Error °C	AD594C Total Error °C	AD594A Temp. Rej. Error °C	AD594A Total Error °C	AD595C Temp. Rej. Error °C	AD595C Total Error °C	AD595A Temp. Rej. Error °C	AD595A Total Error °C
−55	4.83	5.83	6.83	9.83	5.28	6.28	7.28	10.28
−25	1.98	2.98	3.23	6.23	2.04	3.04	3.29	6.29
0	0.62	1.62	1.25	4.25	0.62	1.62	1.25	4.25
+25	0.00	1.00	0.00	3.00	0.00	1.00	0.00	3.00
+50	0.62	1.62	1.25	4.25	0.62	1.62	1.25	4.25
+70	1.46	2.46	2.59	5.59	1.38	2.38	2.50	5.50
+85	2.25	3.25	3.75	6.75	1.99	2.99	3.49	6.49
+125	4.90	5.90	7.40	10.40	3.38	4.38	5.88	8.88

NOTE:
Temp. Rej. Error has two components. (a) Difference between actual reference junction and ice point compensation voltage times the gain (b) Offset and gain TCs extrapolated from 0 to 50°C limits. Total error is temp. rej. plus initial calibration error.

Table II. Maximum Calculated Errors at Various Ambient Temperatures

CIRCUIT IDEAS

OPTIONAL TRIMMING SCHEME

The circuit in Figure 7 nulls the residual calibration error of the AD594/AD595. The 15MΩ resistor insures that the offset is negative by injecting a current into −T (pin 5), corresponding to approximately a −3°C offset. The trimming potentiometer (R_{CAL}) allows the "forced" negative offset to be trimmed to zero by injecting a balancing current into +T (pin 3). This circuit makes it possible to null any calibration error with a single unidirectional trim.

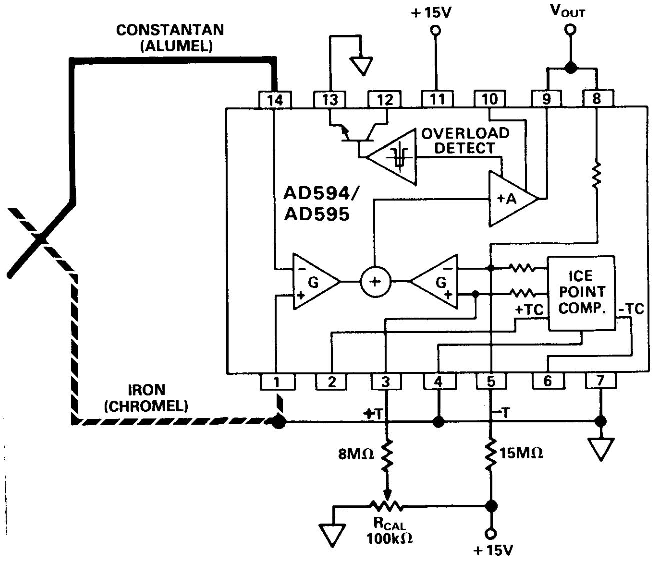


Figure 7. Calibration Error Adjustment

FAHRENHEIT OUTPUT

Figure 8 illustrates a circuit which allows the user to directly read a voltage output of 10mV/°F. The temperature scale conversion formula of;

Degrees Fahrenheit = (9/5) (Degrees Celsius) + 32

is entirely implemented in hardware. A current of 200nA/°C injected into pin 3 creates the 32°F offset while the resistor network on the output increases the gain by 9/5.

To calibrate the output:

1. Remove the thermocouple and input an ac signal to pins 1 and 14 of 10mV p-p, 100Hz. (By using an ac excitation the gain and offset adjustments are independent.)
2. Adjust R_{GAIN} for a p-p output of 3.481V (AD594) or 4.451V (AD595).
3. Reconnect a thermocouple which is in an ice bath or ice point cell at 0°C to pins 1 and 14.
4. Adjust R_{OFFSET} until the output reads 320mV.

The ideal transfer function for a Fahrenheit output AD594/AD595 when trimmed with thermocouple at 0°C is;

AD594 output = (Type J voltage + 919µV) × 348.12
AD595 output = (Type K voltage + 719µV) × 445.14.

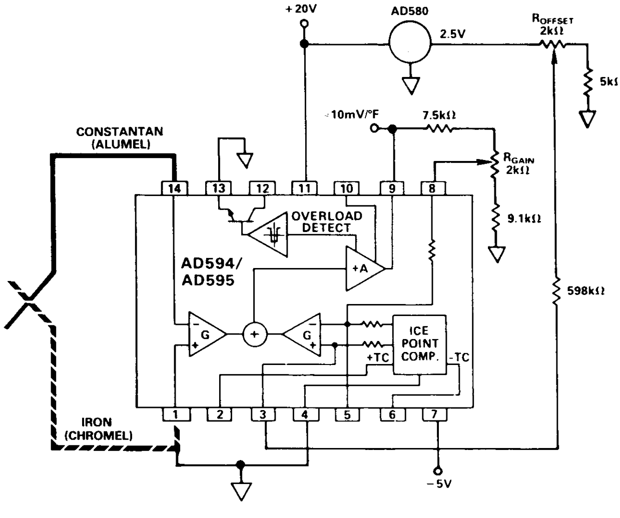


Figure 8. °C to °F Conversion

DIRECT MEAN TEMPERATURE

Average temperature can be measured directly with a single AD594/AD595 configured as shown in Figure 9. The output of this circuit equals $(T_1+T_2+T_3+\ldots T_N)/N$ (in °C) times a nominal 10mV/°C. With any number of thermocouple-resistor pairs in parallel the AD594/AD595 still provides for the correct cold junction compensation. The 300Ω series resistors minimize the currents circulating among the thermocouple branches. They will have positive/negative balancing voltage drops for thermocouples at temperatures lower/higher than the mean. This circuit also works well for generating a precise mean reading of an object which has significant thermal gradients.

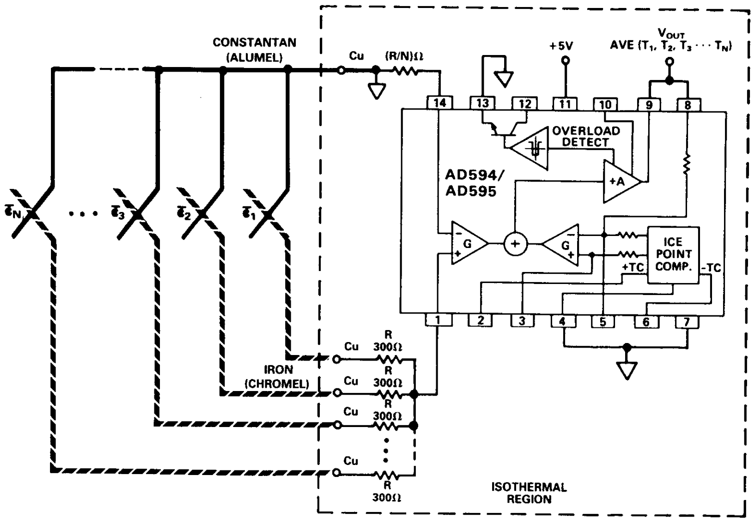


Figure 9. Measuring Average Temperature

TEMPERATURE MULTIPLEXING

Multiplexing thermocouple signals minimizes the number of AD594/AD595s required in a large temperature measuring data acquisition system (see Figure 10). This technique also serves another important function: it transforms the multiple reference junction connections from a terminal block assembly to a single junction at the AD594/AD595.

By placing a thermocouple beneath the AD594/AD595 (in thermal contact) and returning it to an isothermal connector, the reference junction voltages generated at the isothermal block are effectively cancelled. For a given multiplexer ON position, the Constantan (Alumel) – Copper junction in series with the Copper – Constantan (Alumel) junction contribute equal but opposite voltages. That is, since the block is isothermal, $V_1 = V_2$. Similar logic can be applied to the Iron (Chromel) – Copper junctions.

Because of these cancellations, the built-in cold junction compensator in the AD594/AD595 now compensates for the thermocouple directly underneath the IC. Thus, the terminal block can be at any remote location. The AD594/AD595 and the attached thermocouple, however, should remain in the 0 to 50°C range.

Using an AD7502, four temperatures can be monitored with a single AD594/AD595 (an AD7507 allows 8 temperatures). Approximately half of the thermocouple wire can be eliminated by using a single-ended multiplexer, however, the system will be more susceptible to common-mode noise pick-up.

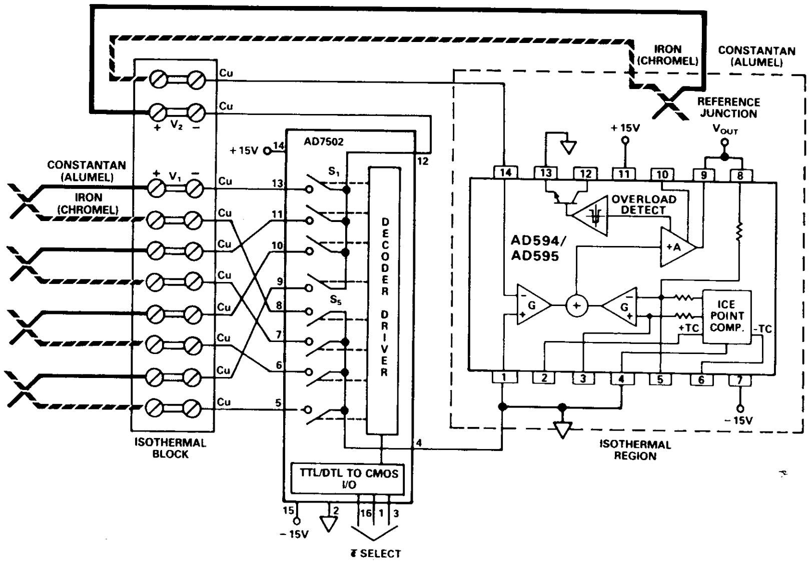


Figure 10. Multiplexing Thermocouples

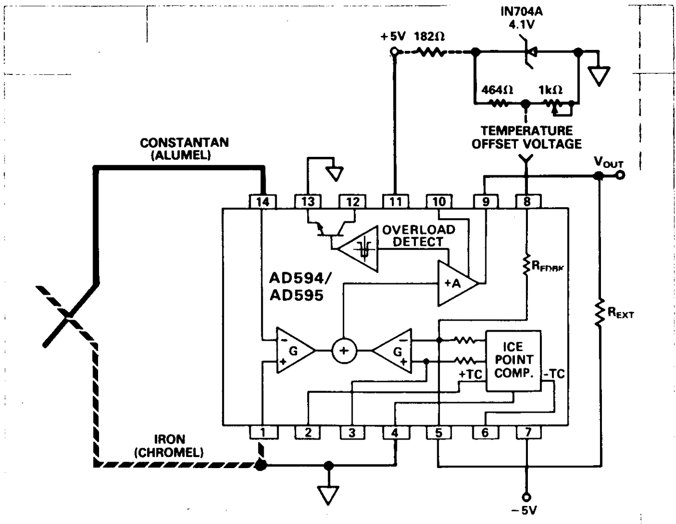


Figure 11. Zero Suppression and Sensitivity Change

OFFSETTING AND CHANGING THE GAIN

The circuit shown in Figure 11 serves two functions: 1) it allows the user to add an offset to the AD594/AD595 which shifts the output to read 0V at any temperature (i.e., suppress zero), and 2) it changes the gain of the AD594/AD595 enabling different output sensitivity (output voltage change per degree change of thermocouple).

Shifting the output to read 0V at a temperature other than 0°C is accomplished by applying an offset voltage to the feedback resistor (pin 8) and thus to the negative input of the right-hand amplifier connected to the summing node. The offset voltage (obtained from the output column of Table I in the AD594/AD595 data sheet) transposes the zero voltage output to the temperature equivalent of the applied voltage. The sensitivity can be increased/decreased by replacing the internal feedback resistors with a larger/smaller external resistance. One method to calculate the value of the new feedback resistance is:

1. Determine the desired output sensitivity (in mV/°C).
2. Decide on a temperature range T1 to T2.
3. Calculate the average thermocouple sensitivity over that temperature range; $(V_{T1} - V_{T2})/(T_1 - T_2)$.
4. Divide the desired sensitivity by the average thermocouple sensitivity: result of (1) ÷ calculated value in (3). This value is the new gain (G_{NEW}) of the AD594/AD595. If the calculations are done correctly this result will be dimensionless.
5. Measure the actual feedback resistance (pin 8 to pin 5), R_{FDBK}.
6. $R_{INTERNAL} = \dfrac{R_{FDBK}}{193.4-1} = \dfrac{\text{Result of (5)}}{193.4-1}$

   NOTE: Use 247.3 for an AD595 instead of 193.4.
7. The new feedback resistance, $R_{EXTERNAL} = (G_{NEW} - 1)(R_{INTERNAL})$ = (result from (4) − 1)(result from (6))

This technique makes it possible to measure a temperature range of 300 to 330°C with a 5V supply and an output of 100mV/°C starting with a 0V output at 300°C. A 4.1V zener diode and a resistor divider can be used to suppress zero.

CURRENT-MODE TRANSMISSION

When sending a signal through a noisy environment, it is preferred to transmit a current rather than a voltage. Figure 12 shows a method of transmitting the AD594/AD595 output signal as a current and then converting it back to a voltage at the control point.

In this circuit the feedback voltage at pin 9 forces the voltage across R_{SENSE} to equal the thermocouple voltage. Correctly choosing R_{SENSE}, (5.11Ω for AD594, 4.02Ω for AD595), generates a 10μA/°C current. Because the voltage across R_{SENSE} equals the thermocouple voltage, the reference junction voltage appears across the AD594/AD595 inputs. The amplifier +A drives the base of the 2N2222 transistor, converting the output voltage into a current.

Because the 160μA quiescent current flows through R_{SENSE}, it does not contribute any error. However, this means the minimum temperature that can be measured is 16°C. The accuracy of the circuit is determined by the initial AD594/AD595 calibration error and the match between R_{SENSE} and the 1kΩ current to voltage conversion resistor at the measurement point.

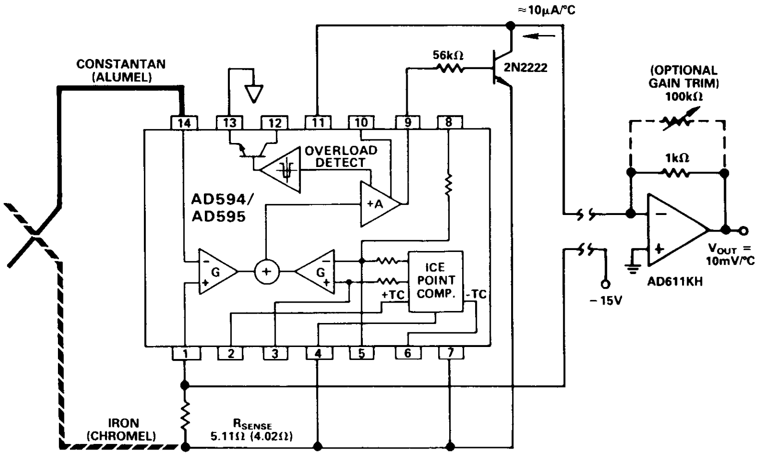


Figure 12. Remote Temperature Measurement