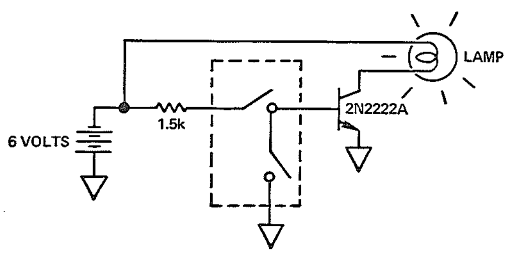
Thermoswitches and Thermocouples

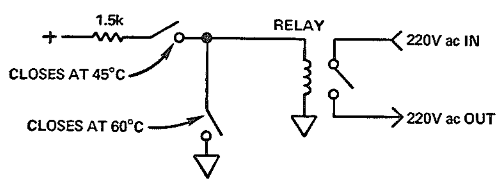
Chapter 7

THERMOSWITCHES

Thermally sensitive switches are easily interfaced in a variety of applications calling for simple and reliable circuitry. Figure 7-1 shows two interface circuits involving thermal switches. In (a), a dual-contact mercury thermoswitch is used on an assembly line as an inexpensive check of temperature in a small component oven. The thermometer bulb is inserted into the oven. If the temperature is within the desired limits, the lamp is lit.



a. Display application



b. Control

Figure 7-1. Thermoswitch applications (see also Figure 1-3)

In (b), two thermoswitches monitor the wall temperature of a chemical vat, which must remain between 45° and 60°C, while it is being filled. If the temperature is between those limits, the relay is energized, permitting the vat to be filled; temperatures outside the limits de-energize the relay, stopping the filling process. The 1.5kΩ resistors protect the relay contacts from passing excessive current (*snap-disc* relays have specifications on minimum (dry-circuit) current, as well as maximum contact current).

AMBIENT-REFERENCED THERMOCOUPLES

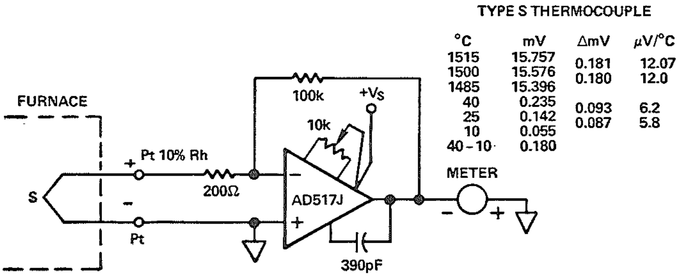
As we have noted in Chapter 1, thermocouples require cold-junction compensation if they must resolve temperature changes with precision better than the ambient temperature range at the cold junction. However, for high-temperature measurements to within a few percent, the cold junction may often be profitably left at room ambient.

Suppose, for example, that a Type S thermocouple* is used to measure temperatures of the order of 1500°C within a furnace, and the ambient temperature of the cold junction is 25°C ±15°C. Since the sensitivity of the thermocouple is 12μV/°C at 1500°C, and a change from 10° to 40°C at the cold junction produces a change of 180μV in the net output voltage, the equivalent ΔT at the active junction is 15°C for a full-scale change at the cold junction, or 1% of 1500°C.

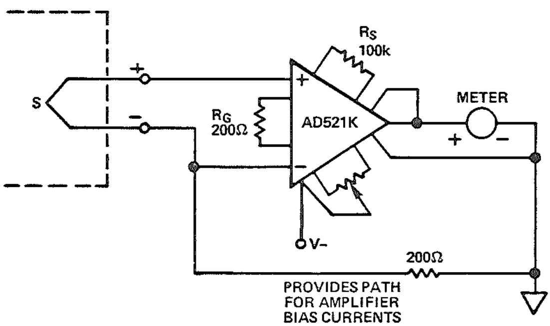
Figure 7-2 shows two ways of implementing this application. In (a), where the environment is not noisy and leads are short (or battery power can be used), an op amp provides the amplification. The indicated gain of 500 results in a full-scale output between 7.5V and 8.0V at 1500°C, with the amplifier zeroed. The amplifier's 3μV/°C max drift is somewhat less than that of the cold junction, so the overall precision can be expected to be to within about 2% at 1500°C. If calibration is desired, the amplifier's zero can be adjusted to take the cold-junction voltage into account, with an insignificant increase in drift (an offset of 142μV causes a change in drift rate of about 0.5μV/°C).

In (b), an instrumentation amplifier is used to reject common-mode noise. If there is no conductive return path from the thermocouple, resistance may be used (as shown) to provide a path for the amplifier's bias currents. The gain is determined by the ratio of the *gain* and *scale* resistors. The maximum offset drift spec of

*Abbreviated tables of thermocouple voltage and sensitivity for all popular types will be found at the end of this chapter.



a. Operational amplifier



b. Instrumentation amplifier

Figure 7-2. Ambient-referenced thermocouple applications

the AD521K at high gains is comparable to that of the cold junction.

COLD-JUNCTION COMPENSATION

If ambient temperature variation of the cold junction can cause significant error in the output of a thermocouple pair, there are two alternatives: maintain the cold junction at constant temperature, by some such technique as an ice bath or a thermostatically controlled oven, or subtract a voltage that is equal to the voltage developed across the cold junction at any temperature in the expected ambient range.

The latter option is usually the easier to implement. Figure 7-3, which is similar to Figure 5-3, shows a simple application, in which the variation of the cold-junction voltage of a Type J thermocouple–iron(+)–constantan–is compensated for by a voltage developed in series by the temperature-sensitive output current of an AD590 semiconductor temperature sensor.

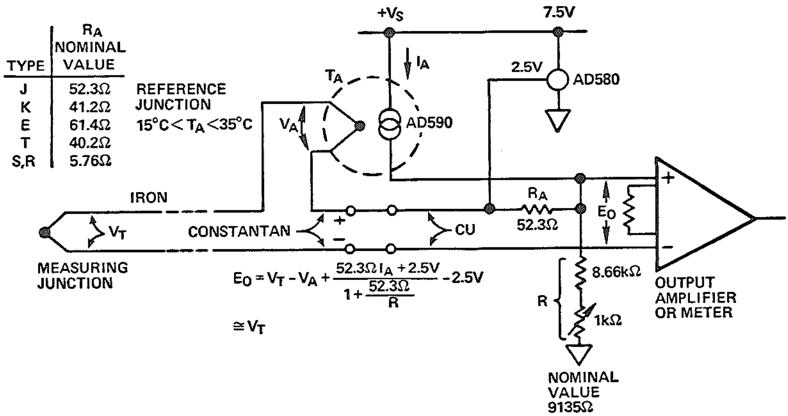


Figure 7-3. Cold-junction compensation circuit for type J thermocouple, employing AD590 to sense cold-junction ambient temperature and provide compensation over the ambient range 15°C to 35°C. Voltage across R_A compensates for V_A, and the 2.5V reference provides a 273μA current via R to offset the AD590's output current at 0°C.

The circuit is calibrated by adjusting R_T for proper output voltage with the measuring junction at a known reference temperature and the circuit near 25°C. If resistors with low tempcos are used, compensation accuracy will be to within ±0.5°C, for temperatures between +15°C and +35°C. Other thermocouple types may be accommodated with the standard resistance values shown in the table. For other ranges of ambient temperature, the equation in Figure 7-3 may be solved for the optimum values of R_T and R_A. If an instrumentation amplifier is used, gain and offset specifications should be appropriate for the temperatures being measured, the required precision, and the sensitivity of the thermocouples employed.

THERMOCOUPLE-BASED TEMPERATURE CONTROL

In the circuit of Figure 7-4, a thermocouple measures an object's temperature in an oven. The measured value is compared with a setpoint, and a heater is operated when the temperature drops below the set value, for temperatures to beyond 300°C.

The thermocouple is Type T—copper(+)–Constantan; the temperature-sensitive current of an AD590, flowing through the 40.2Ω resistance, provides a 40μV/°C cold-junction-compensation voltage. The AD590 is kept in intimate thermal contact with the cold

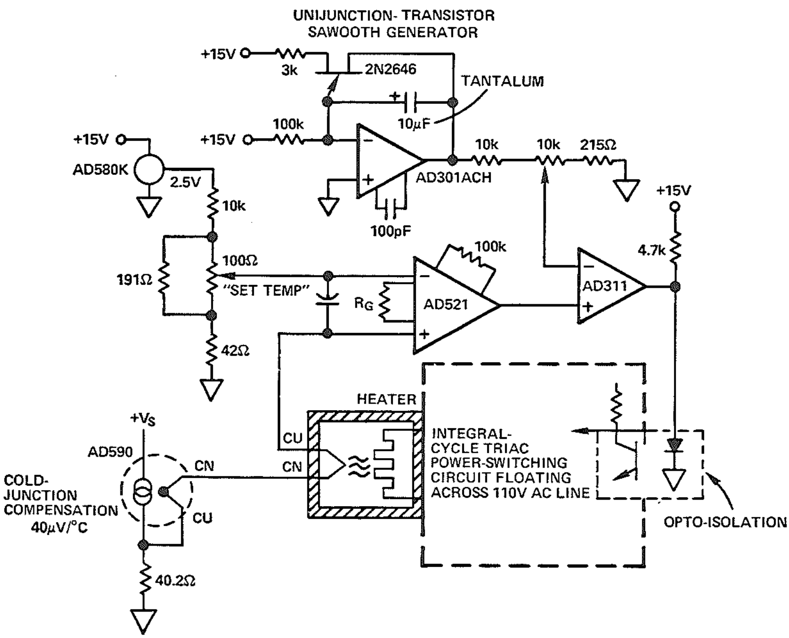


Figure 7-4. Temperature control circuit

junction. The difference between the set-point voltage and the compensated thermocouple output (minus about 11mV due to the AD590's 273.2μA output at 0°C) is amplified by the AD521, which is set for a gain of about 100.

The heater is ac-operated via a Triac, which provides current in increments of whole cycles of line frequency. The number of cycles is determined by comparing the output of the AD521 and a 1Hz negative-going sawtooth in the AD311 comparator. The larger the error (setpoint minus measured temperature), the greater the number of cycles of power to the heater per second. The sawtooth is generated by an integrator that is periodically reset by a unijunction transistor.

This scheme provides sensitive, fast-responding, and essentially smooth control of temperature at the measuring themocouple.

ISOLATED THERMOCOUPLE MEASUREMENT

In Figure 7-5, the small size of a surgically implanted thermocouple and the safety provided by an isolation amplifier combine to provide safe and accurate monitoring of the temperature in a labora-

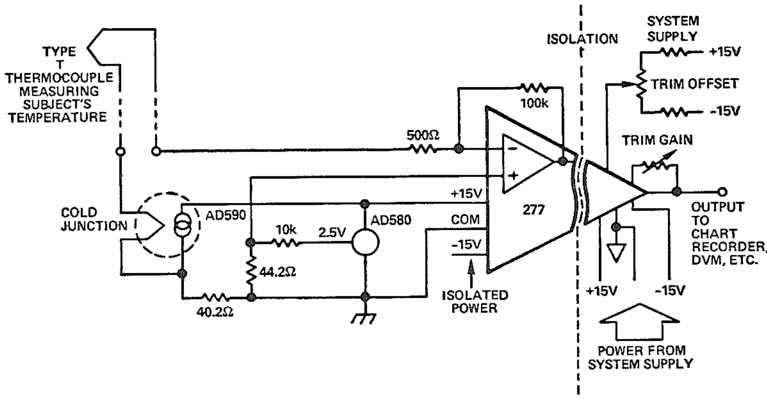


Figure 7-5. Isolated thermocouple measurement

tory animal's cerebral cortex. This circuit was used to study body-temperature regulation in sleeping monkeys.

Isolation is provided by the low-drift Model 277, which has an uncommitted operational amplifier for a front end and a low-impedance operational-amplifier output. It also provides auxiliary isolated front-end power, which is useful for driving the cold-junction compensation circuitry.

The Type T thermocouple is compensated by a cold-junction circuit similar to that of Figure 7-4, using an AD590's output current to develop a series voltage drop that matches the cold junction's -40μV/°C tempco. An AD580 and a voltage divider provide the 11mV of fixed offset required to null out the net output of the AD590 at 0°C. (In the previous application, this function was served by the set-point adjustment.)

The net thermocouple output is amplified (X200), transmitted across the amplifier's isolation barrier, and amplified further in the output amplifier. Any necessary calibration or offset adjustments are employed in conjunction with the output stage.

The animal is fully protected from shock hazard due to grounding problems because there is no galvanic (and little capacitive) path from its body to ground.

At the time this circuit was designed, the 2B50 isolated thermocouple amplifier was not available. If it were, the design problem would have been further simplified, since much of the external circuitry provided by the user would not be required.

THERMOCOUPLE-TO-FREQUENCY CONVERSION

If an analog quantity is converted to frequency, it can easily be isolated by optical techniques; and it can be converted to digital by counting over a predetermined interval. The AD537 V/f converter is a useful tool for performing such conversions, because it is easy to apply, requires little power, and is low in cost.

As Figure 7-6 shows, the heart of the AD537 is a current-to-frequency converter; frequency is determined by an externally connected capacitance. The current that establishes the frequency is buffered by a differential input stage that works in much the same way as an op amp. Thus, if a positive voltage, V_{IN}, is applied at the + input, and a resistance, R, is connected between the negative input and ground, the current that flows in the buffer output is V_{IN}/R. If a resistance, R_L, is connected between a voltage source, V_R, and the negative input terminal, it will add an offset current, $-V_R/R_L$, when V_{IN} is zero. (The effective resistance, that determines the sensitivity to V_{IN}, will then depend on the parallel combination of R and R_L). The frequency output is provided via an open-collector output stage, which can be referenced to an arbitrary voltage level. Frequency is nominally given by

$$f = 0.1 \frac{I}{C} \text{ hertz} \tag{7.1}$$

where I is in amperes, C is in farads, and 0.1 has the required dimensions, of HzF/A; for example, if C = 0.001μF and I_{max} = 1mA, then f_{max} = 100kHz.

The AD537 also has a reference output that is nominally equal to 1V, and a temperature-sensitive output of 1mV/K. The use of the reference output is demonstrated in this application; the use of the temperature-sensitive voltage in direct temperature-to-frequency conversion is discussed in Chapter 10.

In the application considered here, a Type E thermocouple–nickel–10% chromium(+)–Constantan–is used to measure temperatures in the range 700°C to 400°C. In this range, the thermocouple is quite linear, with an average sensitivity of 80.6μV/°C, and a full-scale output of 53.11mV at 700°C. We wish to have a frequency output of 10kHz/°C (7kHz full-scale). If precise operation at temperatures down to 0°C is imperative, some sort of linearizing would be necessary (see the Analog Devices *Nonlinear Circuits Handbook*, pages 92–97), but in many cases, such as the one treated here, operation is needed over only part of the range.

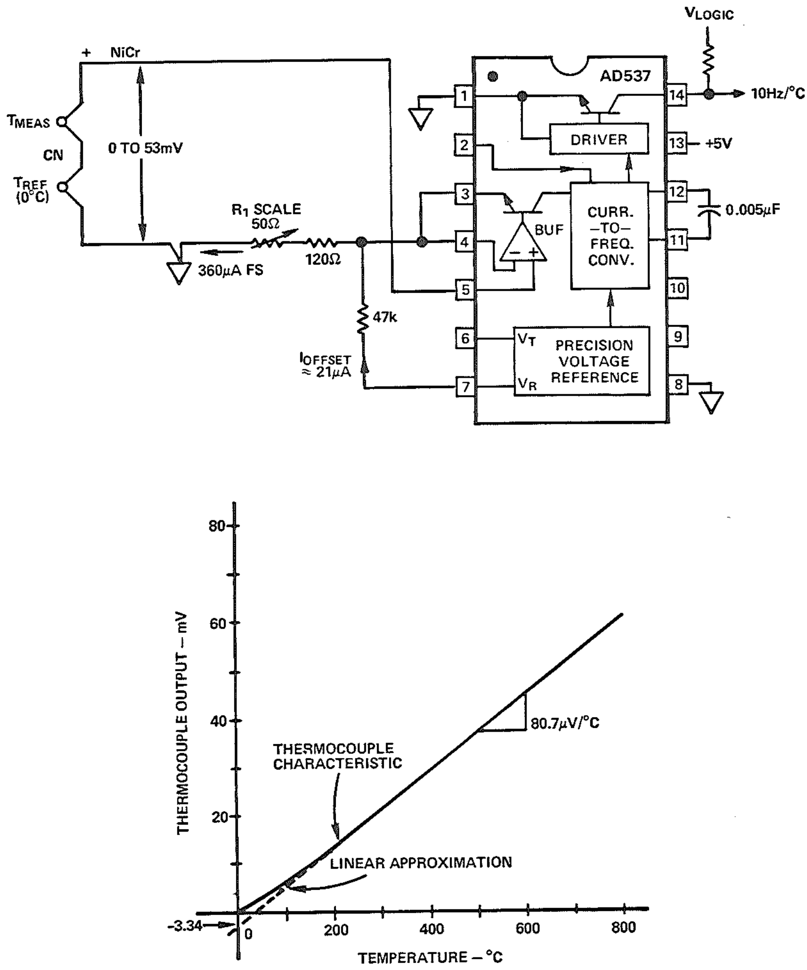


Figure 7-6. Type E thermocouple interface with the AD537 VFC (DIP package).

The circuit shown in Figure 7-6 provides good accuracy from +300°C to +700°C. If the temperature-voltage curve is extrapolated to 0°C, an offset of –3.34mV is seen to be required for the best fit. The small amount of current corresponding to this voltage is introduced without an additional calibration step by using the +1.00V output of the AD537. To adjust the scale, the thermocouple should be exposed to a known reference temperature near the upper end of the scale, and the frequency should be adjusted to the corresponding value with R1. The error should be below 1° over the range 400°C to 700°C.

THERMOCOUPLE-to-4-20mA TEMPERATURE TRANSMITTERS

The 2B52 and 2B53 families of signal-conditiong modules provide cold-junction compensation and amplification for all the popular thermocouple types. The output is in the form of current; a 4-to-20mA range corresponds to the total temperature span of interest. These devices are designed for two-wire operation; since they derive their power from the loop, both power and signals are transmitted over the same two wires. The 2B52 provides complete galvanic isolation between the thermocouple and the current loop; the 2B53, for less-demanding applications, has connections in common between input and output.

Figure 7-7 shows how a 2B52 is typically connected. Screw terminals are provided for connections to the external system, and the span and offset can be adjusted within the protective enclosure. The device provides a system solution to the problem of reliably measuring temperature and transmitting the information in a standard analog format, with a minimum of interface-design decisions.

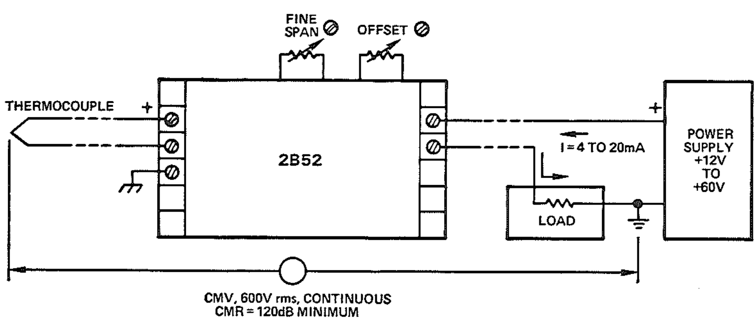


Figure 7-7 2B52 two-wire thermocouple signal transmitter. Gain and offset settings are determined by the temperature range. Open thermocouple is indicated by upscale saturation (downscale optional).

ISOLATED MULTIPLEXING OF THERMOCOUPLES

For applications where a number of thermocouples (similar or different) must be read out, a ready all-electronic system solution, competitive with flying-capacitor techniques, is available in the form of the 2B54 four-channel low-level isolator and the 2B56 cold-junction compensator (see also Figure 15-14).

The 2B54's four input channels are filtered and galvanically isolated from one another—and from the output—and protected for 750V rms common-mode or interchannel voltage, as well as 130V rms ac differential input voltage. Individually adjustable amplification (ranging from 25V/V to 1000V/V, for input spans of ±5mV to ±200mV and output span of ±5V) is provided for each channel, with low drift and noise. The 2B54 can detect open inputs, and the output is protected against continuous shorts to either supply or ground.*

If more than four channels are to be used, a number of 2B54's may be employed; a "three-state analog" output connection permits the outputs to be connected in common and enabled individually by a digital logic signal. Synchronized isolator drive circuitry eliminates beat-frequency errors.

Figure 7-8 shows an eight-channel temperature-measurement system employing eight thermocouples, two 2B54's and a 2B56 cold-junction compensator. The 2B56 is designed to operate with an external temperature-sensitive semiconductor element thermally integrated with the cold junction. The cold junction of each thermocouple will be compensated to 0°C to within ±0.8°C max over a range of ambient temperatures from +5°C to +45°C.

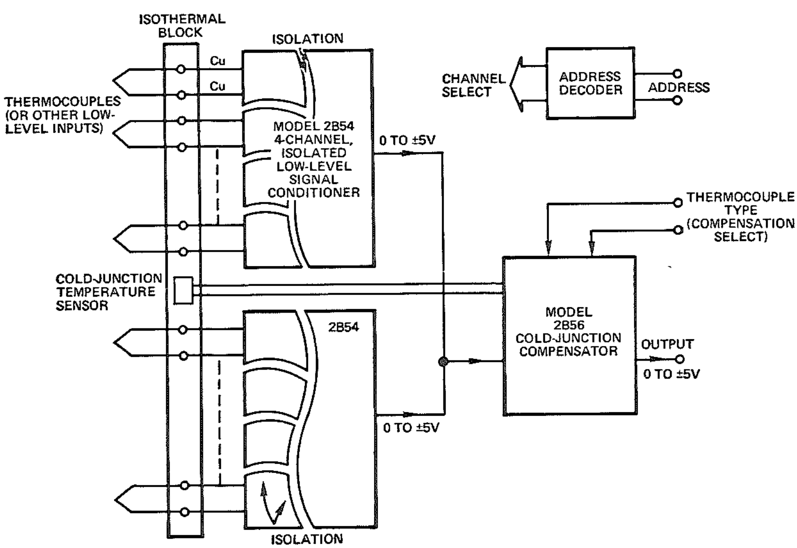


Figure 7-8. Temperature measurement system using isolated low-level multiplexer and cold-junction compensator

*The 2B54 can, of course, be used for isolating any combination of low-level sources (RTD's, strain gages, etc.); it is shown here with the thermocouples because of its affinity for the 2B56 cold-junction compensator.

As Figure 7-9 shows, the 2B56 has four digitally selectable compensation circuits, for J, K, T, and a user-determined type (or *none**). It is easy to see that a wide range of temperatures can be measured, using the optimum thermocouple for each range, and digital selection of compensation appropriate to the thermocouple type for each channel, as it is selected.

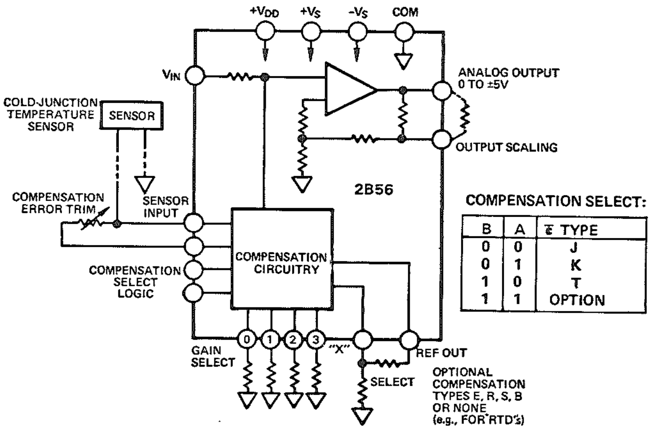


Figure 7-9. Functional Block Diagram of Cold-Junction Compensator

SCANNING DIGITAL READOUT AND PRINTING

The amplified thermocouple outputs from a single channel can, of course, be read out with a digital voltmeter.

With the AD2036 scanning thermocouple thermometer, 6 channels may be read out in °C or °F in a variety of ways (sequentially, single-channel continuously, or in a random sequence determined by BCD logic). The AD2036, operating with line voltage, provides isolation (for the six channels in common), cold-junction compensation, linearization, a/d conversion, and a variety of readout-control options. Three optional models will handle Types J, K, or T thermocouples, and nonisolated devices are available for operation with +5V or +12V power.

For a permanent record, without an expensive data logger, the AD2036 can be used with a number of available printers; for low-cost strip chart recording, an analog output is available. Figure 7-10 shows the details of an interface between the AD2036 and a Gulton ANP-9 thermal-head alphanumeric printer.

*e.g., if some of the multiplexed channels are RTD's or strain gages or thermocouples not requiring cold-junction compensation.

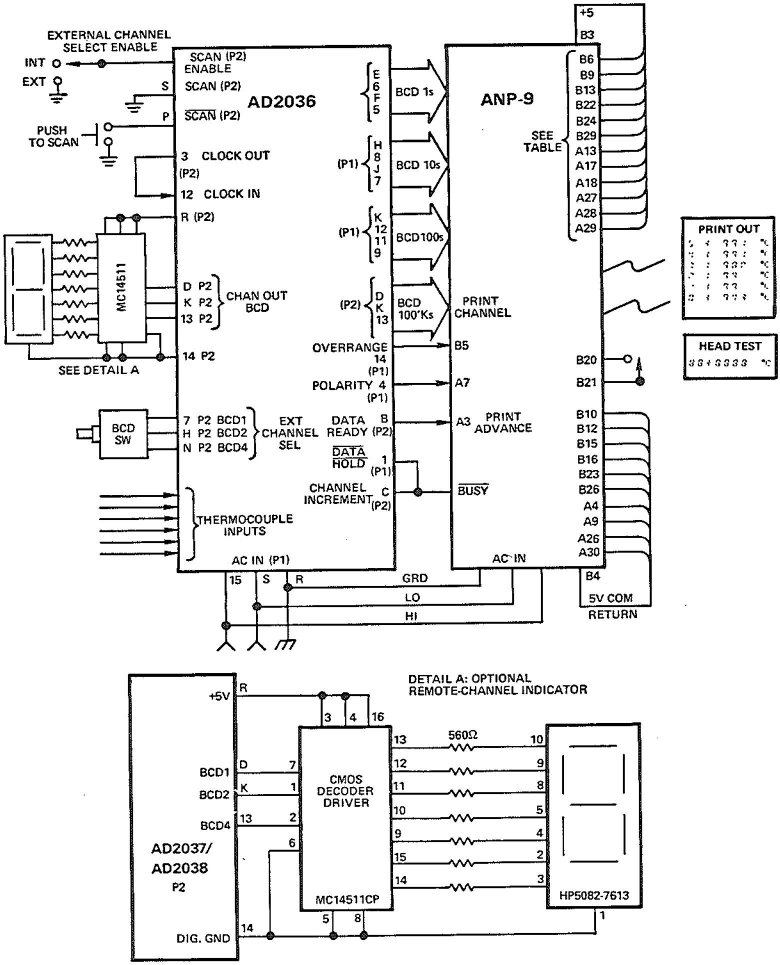


Figure 7-10. Interconnection of AD2036 and Gulton ANP-9 Printer

A scan of the channels is initiated via a pushbutton or other pulse source. When *data ready* goes high, $\overline{busy}$, from the printer, goes low. This *holds* the Data and Channel-Number outputs until the printer's $\overline{busy}$ goes high, releasing the *hold* and incrementing the channel counter. After 3.2s (in the standard unit), the *data ready* goes high and initiates a new cycle. After six cycles have been completed, the scan stops. Each time the scan is initiated, automatically or manually, the sequence will repeat.

For continuous scanning of all six channels, $\overline{scan}$ is held at logic zero. For continuous printing of a *single channel,* $\overline{scan}$ is held at logic zero, and the desired channel is selected, either by a manual switch setting (on the AD2036) or by external logic.

For external channel selection, the *scanner enable* line should be held low. Under external BCD control, the channel is immediately selected. If the $\overline{scan}$ line is pulsed low, the printer will print the selected channel's data six times and stop. If $\overline{scan}$ is held low, a continuous printout of the selected channel will result. Power (at +5V) is provided for external logic at the rear connector of the AD2036.

As the inset shows, the channel number (which is automatically printed as each channel's data is printed) may be *displayed* on a 0.3″ high-efficiency common-cathode H-P display. The channel BCD output operates a seven-segment decoder-driver, which, in turn, drives the LED. Power is furnished by the AD2036.

The detailed pin-to-pin connections between the AD2036 and the printer are listed in an application note available from Analog Devices.[1]

THERMOCOUPLE OUTPUT TABLES

Table 7-1 is an abbreviated listing of the most popular thermocouple pairs, condensed from data given in American National Standard C96.2-1973, published as ASTM document E 230-72. For the sake of compactness, thermocouple outputs, in millivolts, are given at each 100°C, along with the temperature coefficient at that temperature, in μV/°C. This form of presentation has the following virtues:

1. The basic data give a feeling for range and sensitivity of each thermocouple type. For example, one can quickly see that, although a Type E thermocouple is the most sensitive of all the types, it cannot be used for measurements at temperatures exceeding 1000°C.

2. In the absence of more-complete tables, it is easy to interpolate between the given values, to either a first order, using linear interpolation, or to better accuracy, using the variation of tempco between data points. For example, simple linear interpolation permits one to conclude that the output of a Type J thermocouple at 530°C is equal to 27.388 + 0.3(33.096 – 27.388) millivolts, or 29.100mV. The actual output, according to the above source, is 29.075mV.

(text continues on page 134)

[1] "Interfacing the AD2036 6-Channel Digital Scanning Thermometer with the ANP-9 Thermal Printer," by Steve Castelli

THERMOCOUPLE RESPONSES

TABLE 7-1. VOLTAGE AS A FUNCTION OF TEMPERATURE

Temperature	B		E		J		K
	Output	Tempco	Output	Tempco	Output	Tempco	Output
°C	mV	µV/°C	mV	µV/°C	mV	µV/°C	mV
− 200	—	—	− 8.824	25.1	− 7.890	21.8	− 5.891
− 100	—	—	− 5.237	45.1	− 4.632	41.1	− 3.553
0	+ 0.000	—	0.000	58.7	0.000	50.4	0.000
+ 100	+ 0.033	0.9	6.317	67.5	5.268	54.4	4.095
+ 200	+ 0.178	2.0	13.419	74.0	10.777	55.5	8.137
+ 300	0.431	3.05	21.033	77.9	16.325	55.4	12.207
+ 400	0.786	3.95	28.943	80.0	21.846	55.2	16.395
+ 500	1.241	5.0	36.999	80.8	27.388	55.9	20.640
+ 600	1.791	5.95	45.085	80.7	33.096	58.5	24.902
+ 700	2.430	6.8	53.110	79.8	39.130	62.3	29.128
+ 800	3.154	7.65	61.022	78.4	45.498	64.6	33.277
+ 900	3.957	8.4	68.783	76.7	51.875	62.4	37.325
+1000	4.833	9.1	76.358	75.0	57.942	59.2	41.269
+1100	5.777	9.75	—		63.777	57.8	45.108
+1200	6.783	10.35	—		69.536	57.2	48.828
+1300	7.845	10.9	—		—		52.398
+1400	8.952	11.2	—		—		—
+1500	10.094	11.6	—		—		—
+1600	11.257	11.7					
+1700	12.426	11.7					
+1800	13.585	11.5					

TABLE 7-2. TEMPERATURE AS A FUNCTION OF VOLTAGE READING

mV	B		E		J		K
	°C	°C/mV	°C	°C/mV	°C	°C/mV	°C
−10.000	—		—		—		—
− 5.000	—		− 94.4	21.70	− 109.1	25.10	− 153.7
− 2.000	—		− 35.3	18.40	− 40.8	21.10	− 53.1
− 1.000	—		− 17.3	17.60	− 20.1	20.40	− 25.9
0.000	+ 42.0	4°/µV	0.0	17.06	0.0	19.84	0.0
+ 1.000	449.6	220	16.8	16.64	19.6	19.25	+ 25.0
+ 2.000	634.2	160	33.2	16.21	38.9	19.08	+ 49.5
+ 5.000	1018.2	109	80.3	15.19	95.1	18.43	+ 122.0
+10.000	1491.8	87	153.0	14.02	186.0	18.03	246.3
+20.000	—		286.7	12.90	366.5	18.13	485.0
+30.000	—		413.2	12.47	546.3	17.57	720.8
+40.000	—		537.1	12.36	713.9	15.94	967.5
+50.000	—		661.1	12.47	870.2	15.79	1232.3
+60.000	—		787.0	12.71	1035.0	16.95	
+70.000	—		915.9	13.09	—		

	R		S		T		
Tempco µV/°C	Output mV	Tempco µV/°C	Output mV	Tempco µV/°C	Output mV	Tempco µV/°C	Temperature °C
15.2	–		–		- 5.603	15.8	- 200
30.5	–		–		- 3.378	28.4	- 100
39.5	0.000	5.25	0.000	5.4	0.000	38.8	0
41.4	0.647	7.5	0.645	7.3	4.277	46.8	+ 100
39.9	1.468	8.85	1.440	8.45	9.286	53.2	+ 200
41.5	2.400	9.75	2.323	9.1	14.860	58.1	+ 300
41.9	3.407	10.35	3.260	9.6	20.869	61.8	+ 400
42.6	4.471	10.9	4.234	9.9	–		+ 500
42.5	5.582	11.3	5.237	10.15	–		+ 600
41.9	6.741	11.8	6.274	10.55	–		+ 700
41.0	7.949	12.3	7.345	10.8	–		+ 800
39.9	9.203	12.7	8.448	11.2	–		+ 900
38.9	10.503	13.2	9.585	11.5	–		+1000
37.8	11.846	13.6	10.754	11.9			+1100
36.5	13.224	13.9	11.947	12.0			+1200
34.9	14.624	14.0	13.155	12.2			+1300
	16.035	14.1	14.368	12.2			+1400
	17.445	14.1	15.576	12.1			+1500
	18.842	13.9	16.771	11.8			+1600
	20.215	13.5	17.942	11.5			+1700
	–		–				+1800

	R		S		T		
°C/mV	°C	°C/mV	°C	°C/mV	°C	°C/mV	mV
	–		–		–		-10.000
43.48	–		–		-166.5	49.5	- 5.000
28.13	–		–		- 55.1	30.0	- 2.000
26.49	–		–		- 26.6	27.6	- 1.000
25.35	0.0	190.5	0.0	185.2	0.0	25.8	0.000
24.69	+ 145.0	122.7	+ 146.4	125.8	+ 25.2	24.6	+ 1.000
24.27	258.2	106.4	264.3	111.7	49.2	23.4	+ 2.000
24.42	548.2	90.1	576.6	99.0	115.3	20.9	+ 5.000
24.60	961.7	76.6	1035.8	86.2	213.3	18.6	+10.000
23.50	1684.1	73.5	–		385.9	16.3	+20.000
23.95	–		–		–		+30.000
25.48	–		–		–		+40.000
27.78	–		–		–		+50.000
							+60.000
							+70.000

3. The variation of tempcos from point to point provides a quick guide to linearity, both qualitative and quantitative. For example, the tempco of a Type J thermocouple changes by less than 0.7μV/°C over any part of the range from 200°C to 500°C.

4. The tempcos are important data for many applications in which the *variations* of temperature are important, rather than the absolute magnitude. In addition, they can be used to obtain a direct indication as to how good the performance of the associated interface circuitry must be.

Temperature in °C has been used exclusively in order to avoid any possibility of misinterpretation. In addition, °C conforms to SI standards for temperature units; the conversion to Fahrenheit, where required, is universally known and understood.

Table 7-2 is a convenient cross-reference to °C, from millivolts of thermocouple output. Since all measurements provide millivolts, rather than degrees, this table will be a useful means of translation. Both temperature and incremental sensitivity (in degrees Celsius per millivolt) are given, to make interpolation easier. If plotted, degrees vs. millivolts, it provides a graphic view of linearity, since the departure of values (measured on the vertical axis) from a straight line represent both the nonlinearity and the amount of correction required.