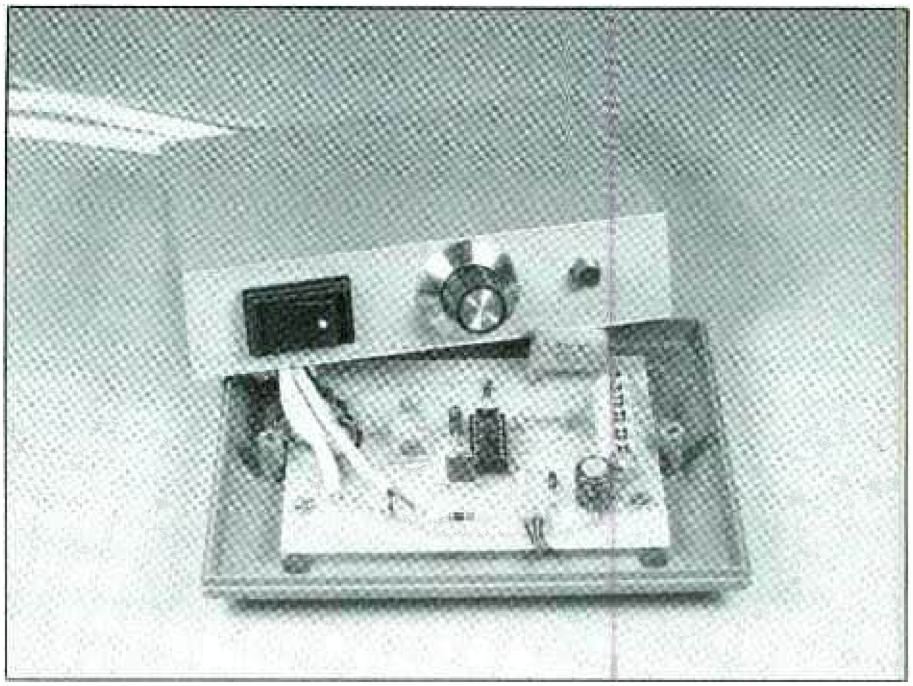
Proportional Temperature Controller

A circuit that provides precise control of temperatures for darkroom film processing and other applications

By Jan Axelson & Jim Hughes



Proportional control is a type of automatic control that is used in applications where precision is important, such as in developing color photographic film. For consistent results, film-developing chemicals must be maintained at a specific constant temperature during processing (for example, 100 degrees Fahrenheit ±0.5 degree for color slides).

A proportional controller can automatically maintain this or a lower or higher temperature used in other processing applications. The controller described here automatically maintains a constant preset temperature in three gallons of water that serves as a holding bath for containers of photographic chemicals. Our controller's design is made quite simple, and the project is low in cost to build, thanks to the Signetics TDA1023 integrated circuit time-proportional triac trigger device that controls current through a triac and an immersion heater.

Proportional Control Concept

Understanding how proportional control works requires a basic understanding of how controllers in general work. Figure 1 is a block diagram of a simple on/off temperature-control system you might find in an oven or household heating system. The system consists of a sensor, setpoint selector, error detector, controller and, finally, a heater.

Temperature changes caused by perhaps a change in resistance, voltage or volume causes the sensor to react. The setpoint adjustment (a temperature setting dial, for example) tells the system what temperature is desired. The error detector compares the sensed temperature with the desired temperature and signals the controller to take action to reduce

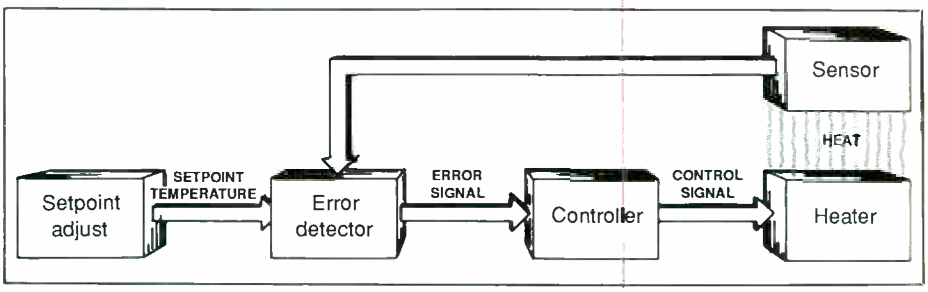


Fig. 1. A simple on/off temperature-control system for an oven.

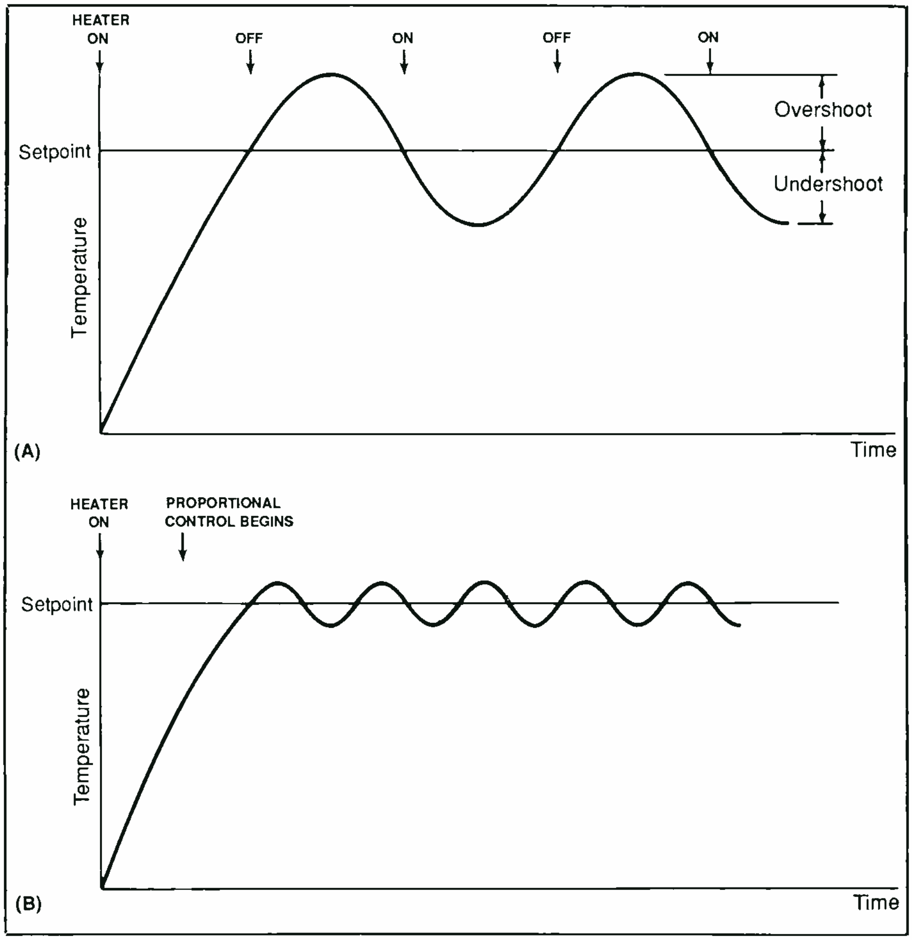


Fig. 2. Characteristic performance of on/off temperature-control system (A) and proportional control system (B).

the error if there is a difference between the two temperatures. The controller then turns the heater on or off as instructed.

Figure 2A shows the limitation of this kind of control. Because the heater does not turn off or on until the temperature has already reached the setpoint, the temperature overshoots and undershoots the desired level. In many situations, a few degrees fluctuation like this is not critical. However, for photography applications, where there is little room for error, a way of keeping the temperature precisely "on the mark" is needed.

Figure 2B shows the more precise control made possible by proportional control. Precision is achieved by anticipating the setpoint. As the temperature approaches the desired value, the controller gradually cuts back power to the heater. This fine tunes the system and prevents large deviations from the setpoint.

Signetics' TDA1023 is specifically meant for use in proportional controllers. As shown in Fig. 3, this IC contains buffers for setpoint and sensor inputs, a comparator, control gate, timing generator and even a small dc power supply. (Pinouts for the TDA1023 are shown in Fig. 4.)

Power from the 117-volt ac line is provided to the TDA1023 at RX. The on-chip supply provides an 8-volt reference for the sensing circuit at Vz, eliminating any need for a separate dc power supply.

A comparator compares the setpoint voltage at CI with the sensor voltage at UR and generates an error signal that is fed to a control gate. Notice that a timing generator also affects the comparator. Inputs PR and TB set the range and period of a control cycle, which typically lasts anywhere from a fraction of a second to a minute. This control cycle is the key to the proportional-control action of the circuit.

As the sensor voltage approaches the setpoint, the control gate is enabled for just part of each cycle, in proportion to the magnitude of the measured error. In turn, the control gate enables an output amplifier to provide gate-current pulses to a triac connected in series with a heater.

When the temperature is near the desired point, the heater is turned on just long enough to maintain the temperature without overshooting it. Figure 5 shows how the current through the heater varies as the temperature changes in relation to the setpoint.

Other features of the TDA1023 are a fail-safe circuit, an internal resistor for use with sensitive triacs, adjustable hysteresis in the comparator, and an optional translation circuit for finer setpoint control. To minimize radio-frequency interference (rfi), a zero-crossing detector synchronizes the gate pulses with the zero crossings of the ac line voltage.

About the Circuit

Shown in Fig. 6 is the complete schematic diagram of the heater control circuit. Power is applied to it via the RX input at pin 6 of *IC1* through the current-limiting network made up of *C3* and *R6*.

Temperature sensor *R2* is a negative-temperature-coefficient (ntc) thermistor. As the thermistor's temperature rises the resistance of *R2* drops. At room temperature, *R2*'s resistance is about 50,000 ohms. Raising the temperature to 100 degrees Fahrenheit causes *R2*'s temperature to drop to about 25,000 ohms.

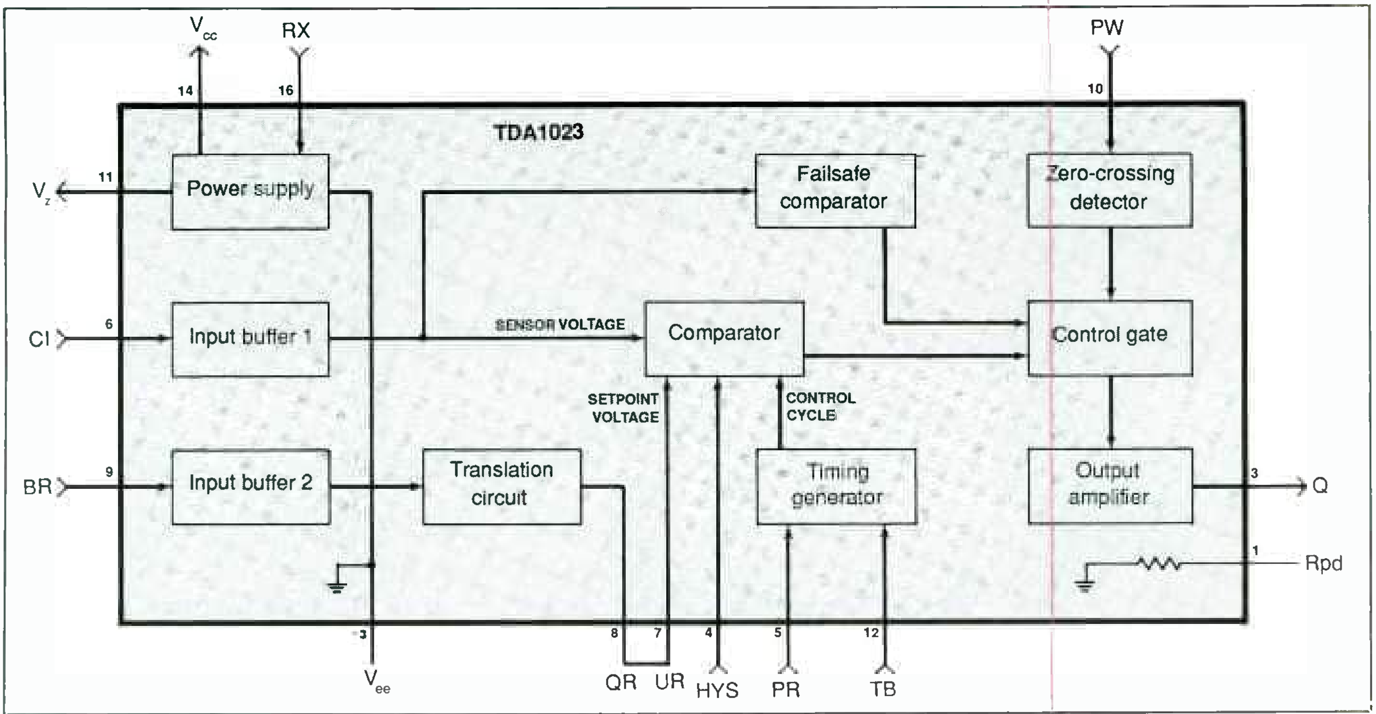
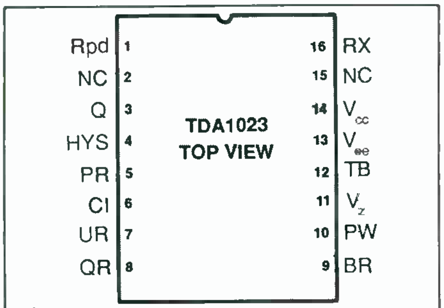


Fig. 3. Internal details of Signetics' TDA1023 time-proportional triac trigger integrated circuit.



Pin No.	Legend	Meaning
1	Rpd	Internal pull-down resistor
2	NC	Not connected
3	Q	Output
4	HYS	Hysteresis control input
5	PR	Proportional range control input
6	CI	control input
7	UR	Unbuffered reference input
8	QR	Reference buffer output
9	BR	Buffered reference input
10	PW	Pulse width control input
11	V_Z	Reference supply output
12	TB	Firing burst repetition control input
13	V_{ee}	Ground connection
14	V_{cc}	Positive supply connection
15	NC	Not connected
16	RX	External resistor connection

Fig. 4. Case configuration and pinouts for the Signetics TDA1023.

Resistor *R1* and thermistor *R2* make up a voltage divider between the 8-volt reference and ground, and the voltage at pin 6 of *IC1* is the sensor input to the internal comparator. Resistors *R3* and *R5* and potentiometer *R4* control the setpoint at pin 9 of the IC, which connects via the translation circuit at pin 7.

Capacitor *C4* sets a period of about 6 seconds for the control cycle. Pin 5 of *IC1* is left open (no connection) to select a proportional range of 80 millivolts. This means that the duty cycle (on time) of the gate pulses at pin 3 varies from 0 to 100 percent over an 80-millivolt change at pin 6. Grounding pin 5 would increase this range to 400 millivolts.

The open HYS input at pin 4 of *IC1* selects minimum hysteresis, or dead band, of 20 millivolts in the comparator.

This circuit is designed to control a 200-watt immersion heater that plugs into ac receptacle *SO1* and whose heating element is immersed in a 4-gallon plastic tub filled with water. Triac *Q1* controls power to the heater. When pin 3 of *IC1* outputs gate pulses, *Q1* turns on and current flows through the triac, heater and neon-lamp indicator *I1*. When the gate pulses cease, *Q1* turns off and cuts off power to the heater.

Resistor *R8* limits the current to *Q1*'s gate, and resistor *R7* sets the width of the triac's gate pulse. Smoothing is provided by *C1*.

Construction

Just about any traditional board-wiring method can be used to build this project. If you wish, you can fabricate your own printed-circuit board using the actual-size etching-and-drilling guide shown in Fig. 7. Alternatively, you can use unclad perforated board with holes on 0.1" centers and suitable Wire Wrap or soldering hardware. Whichever method you choose, it is a good idea to use a socket for *IC1*.

Though most component values and types are not critical, here are some things to keep in mind when selecting components: Resistor *R1* should be a 1-percent precision type because it is part of the temperature-sensing circuit (its exact value is not

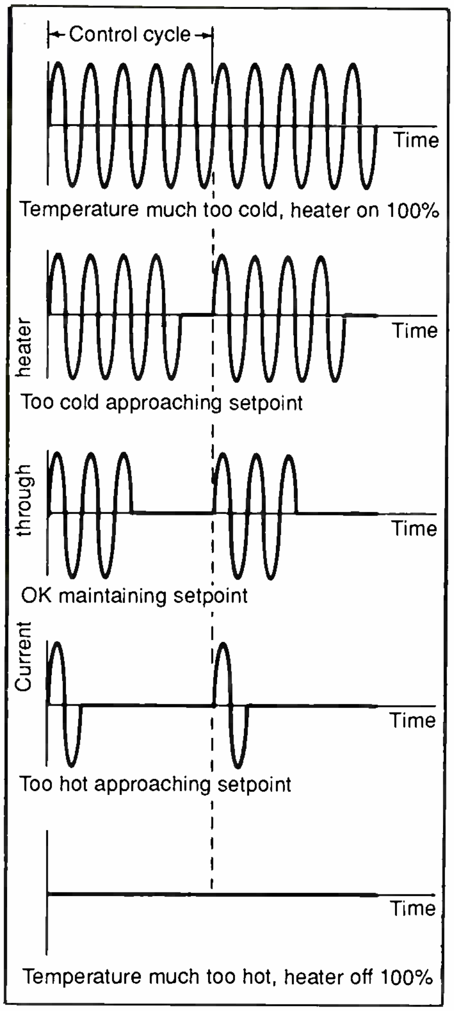


Fig. 5. Using proportional control current to power a heater varies according to how close the temperature is to the setpoint.

that important, but its resistance must be stable and not vary with temperature). Notice, too, that *R6* is a 1-watt power resistor and is used with *C3* to take care of the important function of limiting input current to *IC1*. If you must make a substitution in this network, it is safer to experiment with slightly smaller values for *C3* or larger values for *R6*. Finally, *C4* can be either a tantalum (preferable) or aluminum electrolytic capacitor. Though aluminum electrolytics are not recommended for use in timing circuits, due to their characteristically high leakage, you can use one here because the exact length of the timing cycle is not super-critical.

After installing the IC socket, wire the board exactly as shown in Fig. 8 (or use the layout in Fig. 8 as a rough guide to component arrangement on perforated board and refer back to Fig. 6 for wiring details). Be sure to orient *C1, C4* and *Q1* properly before soldering their leads into place. Also, to provide adequate heat dissipation, mount power resistor *R6* so that there is ⅛″ of air space between it and the top of the board.

Use pliers to bend the leads of the triac to conform to the hole arrangement on the board for its leads and mounting tab. Bend the leads at the appropriate points so that they form a right angle pointing toward the metal rear surface of the triac. Plug the leads into the holes in the board, solder them into place and trim away any excess lead length. Then place a small washer between the triac's mounting tab and board and use a 4-40 × ¼″ or ⅜″ machine screw and nut to secure it to the board.

To make the cables for the circuit, you need a standard ac extension cord or an ac line cord with plug and a chassis-mount ac receptacle, 48″ of two-conductor cable (zip cord will do fine) and some solid hookup wire. Cut the extension cord in half, separate the cut ends for a distance of about 2″ and strip about ¼″ of insulation from all four conductors. Tightly twist together the fine wires in each conductor and sparingly tin with solder.

Strip 2″ of insulation from both conductors at one end of the two-conductor cable. Remove ¼″ of insulation from both and slide a 1″ length of small-diameter heat-shrinkable tubing over each. Trim the leads of the thermistor to ¾″ long and form a small hook in each. Connect and solder the leads of the thermistor individually to each of the prepared conductors of the cable. Push the tubing up over the soldered connections and shrink into place.

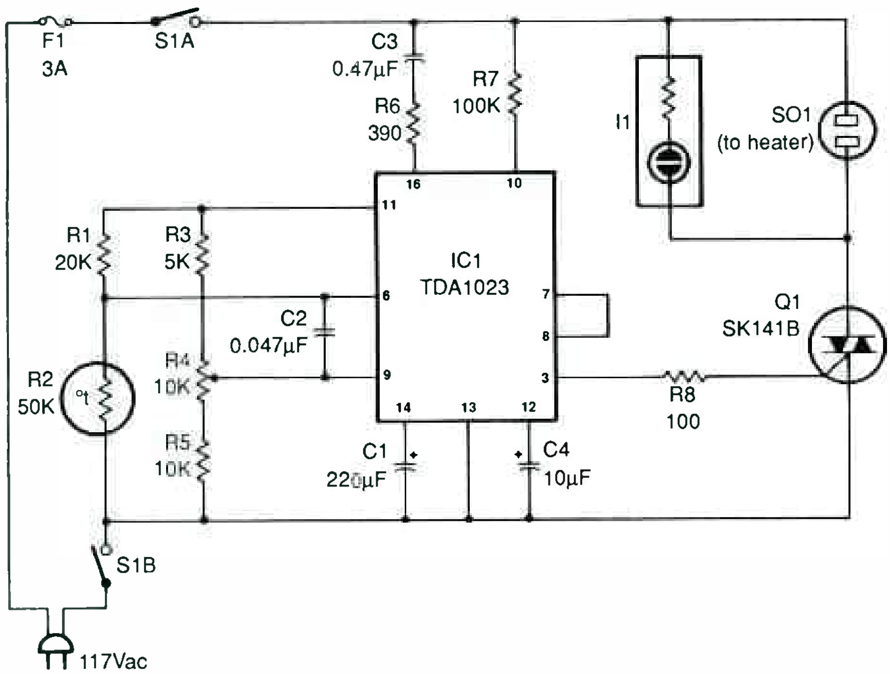
Slip a 2″ length of ¼″-diameter heat-shrinkable tubing over the thermistor end and shrink it into place so that only the thermistor is visible and that all connections and wires are sealed inside. Separate the conductors at the other end of the cable for a distance of about 1″ and trim ¼″ of insulation from each. Once again, tightly twist together the fine wires in each conductor and sparingly tin with solder.

Now strip ¼″ of insulation from both ends of eight 8″ lengths of hookup wire. Connect and solder one end of two of these wires to the the leads of the neon-lamp assembly, three more wires to the lugs of the potentiometer and the three remaining wires to the lugs of the switch. Slide a ½″ to ¾″ length of small diameter heat-shrinkable tubing over the lamp assembly wires and shrink it into place to cover the connections.

To prepare the enclosure, begin by machining the mounting holes for the lamp assembly, switch, potentiometer, fuse holder and circuit-board assembly and the entry holes for the thermistor cable and line cord. You have a choice of using either a chassis-mount ac receptacle or the receptacles at the end of a standard ac extension cord for *SO1*. If you use the former, you must cut a slot and two hardware mounting holes for it in the chassis; if the latter, simply drill a single hole for exit of the cord. Use of an ordinary ac extension cord, of course, is the easier way to go in terms of work involved

A chassis-mounted ac receptacle for *SO1* requires an extra 5″ or so length of two-conductor zip cord or separate 14-gauge stranded hookup wire to connect it to the circuit board assembly.

Mount the lamp, potentiometer and fuse holder in their respective holes. Then, referring to Figs. 6 and 8, plug the free ends of the wires on these components into the respective holes in the circuit board and solder them into place. The 4″ wires con-



PARTS LIST

Semiconductors
C1—TDA1023 time-proportional triac trigger (Signetics)
Q1—SK141B or similar 200-PIV triac
Capacitors
C1—220-μF, 200-volt electrolytic
C2—0.047-μF ceramic disc
C3—0.47-μF, 200-volt polyester film
C4—10-μF tantalum (or aluminum electrolytic; see text)
Resistors (¼-watt, 10% tolerance)
R1—20,000 ohms (1% tolerance; see text)
R2—Negative temperature coefficient thermistor; 50,000 ohms at 25 degrees Celsius
R3—5,000 ohms
R5—10,000 ohms
R6—390 ohms (1 watt)
R7—100,000 ohms
R8—100 ohms
R4—1,000-ohm, linear-taper, panel-mount potentiometer
Miscellaneous
F1—3-ampere fuse
I1—Panel-mount neon-lamp assembly
S1—Dpst 3-ampere switch
Printed-circuit board or perforated board and Wire Wrap or soldering hardware; 16-pin IC socket; suitable enclosure; standard ac extension cord or ac line cord with plug and chassis-mount ac receptacle (see text); fuse holder; pointer-type knob for R4; two-conductor cable; plastic tube for thermistor (see text) and silicone adhesive; heat-shrinkable tubing; cable ties; ½″ metal spacers; machine hardware; hookup wire; solder; etc.

Fig. 6. Complete schematic diagram of the proportional temperature controller.

nected to the switch and fuse holder will be connected later. Line the ac line cord hole, thermistor entry hole and extension-cord exit hole if you use the extension-cord arrangement for *SO1* with rubber grommets. Pass the free ends of the cords through their respective grommet-lined holes and tie a knot about 6″ from the prepared ends inside the enclosure to serve as strain reliefs.

Plug into the appropriate holes in the board and solder into place the *SO1* lines and the *R2* thermistor cable. Then mount the circuit-board assembly using ½″ spacers and 4-40 or 6-32 × ¾″ machine screws, lockwashers and nuts.

Locate the free end of the last wire coming from the switch and connect and solder it to one lug of the fuse holder. Then connect and solder one ac line cord conductor to the other lug of the fuse holder and the other to the remaining switch lug.

Plug the fuse into its holder and the IC into its socket. With regard to the latter, make sure that the IC is properly oriented (see Fig. 8) and that no pins overhang the socket or fold under between IC and socket as you seat the IC. Now gather up the loose wires into a neat bundle and use plastic cable ties or waxed lacing cord to hold them together. Slide the knob onto the shaft of the potentiometer control.

Checkout and Use

With no heater plugged into *SO1*, rotate the control to roughly mid-position and plug the controller's line cord into an ac outlet. Using a multimeter set to read dc volts, check at pin 14 of *IC1* for the presence of about 14 volts. This voltage is not smoothly regulated; hence, a variation of about ±0.3 volt or so is normal. Also check for the 8-volt dc reference potential at pin 11 of the IC. (*Caution:* When working inside the powered project, keep firmly in mind that several points of the circuit are at potentially hazardous 117-volt ac line potential, including *Q1*'s hold-down screw. So exercise caution when taking voltage readings in the circuit.) If the voltages check out okay, power down the project. If not, double check all wiring and soldering and all components for proper placement and orientation.

To fully check out and use the proportional temperature controller, you need a so-called "beverage heater" like the one shown in the lead photo. Immersible heaters that have a skirt around the heating element are best because the skirt holds the element away from the side of the holding tub with which it is used.

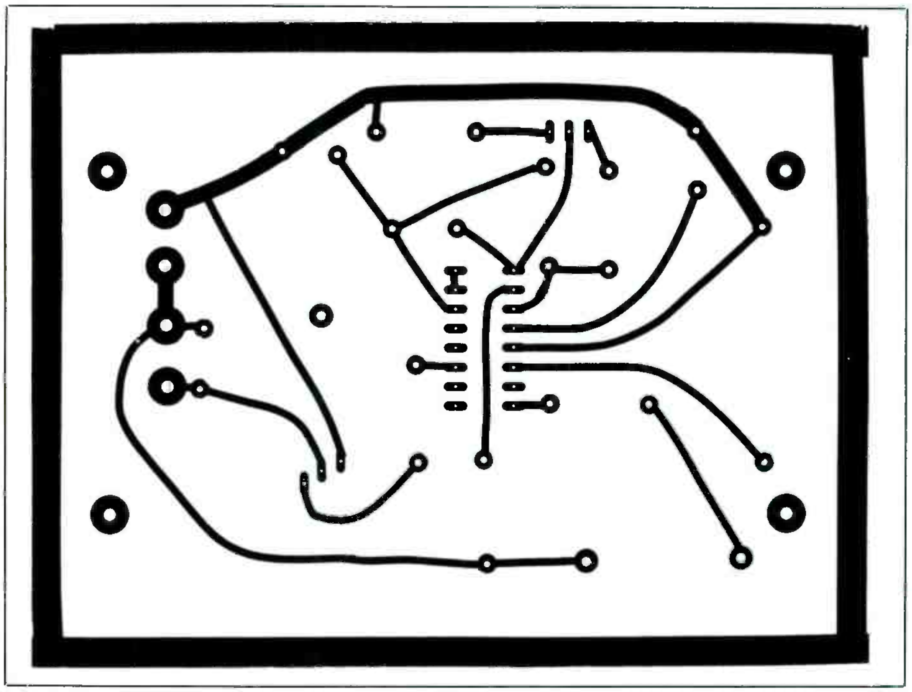


Fig. 7. Actual-size etching-and-drilling guide for printed-circuit board.

You also need a four-gallon plastic tub, a plastic or metal tube that is sealed at one end to hold the thermistor, and an accurate thermometer for monitoring and calibration.

Slide the thermistor into the tube and seal the open end with silicone adhesive or gasket seal. If you are unable to locate a tube with one sealed end, you can use one with both ends open simply by sealing both with silicone adhesive.

Securely fasten the thermistor assembly and immersible heater to the side of the plastic tub. One way to do this is to punch holes in the tub well above the water line and loop the ties through the holes and around the tube and the plug on the heater. Do not allow the heater's coil to rest against the side of the tub. Fasten the heater so that filling the tub with 2.5 gallons of water will immerse the heating coil but not the electric cord. Use the "maximum fill" line on the heater as a guide to maximum water level in the tub.

Never attempt to operate the immersion heater unless it is in water. Most heaters have a safety fuse that will permanently blow if you do this and the coil overheats.

Fill the tub to the proper level with cold water and place an accurate thermometer in the water. Plug the heater's power cord into *SO1* and turn on the project. The neon-lamp indicator should now light up, indicating that the project is delivering power to the heating element to heat the water.

As the water warms to the setpoint, you will see the proportional controller in action as the neon lamp turns off for a short portion of each cycle, indicating that the heater is being cycled off. At this point, the temperature should begin to stabilize, as indicated on the thermometer.

If the heater does not turn on at all, however, measure the voltages at the sensor and setpoint inputs at pins 6 and 7 of *IC1*. For the heater to come on, the voltage on pin 6 must be greater than that on pin 7.

By adjusting the setting of the potentiometer control on the project's front panel in increments and monitoring the temperature, you should be able to set the temperature of the water in the tub to any point in a range from about 80 to 105 degrees Fahrenheit. Of course, the exact range depends on the values of your

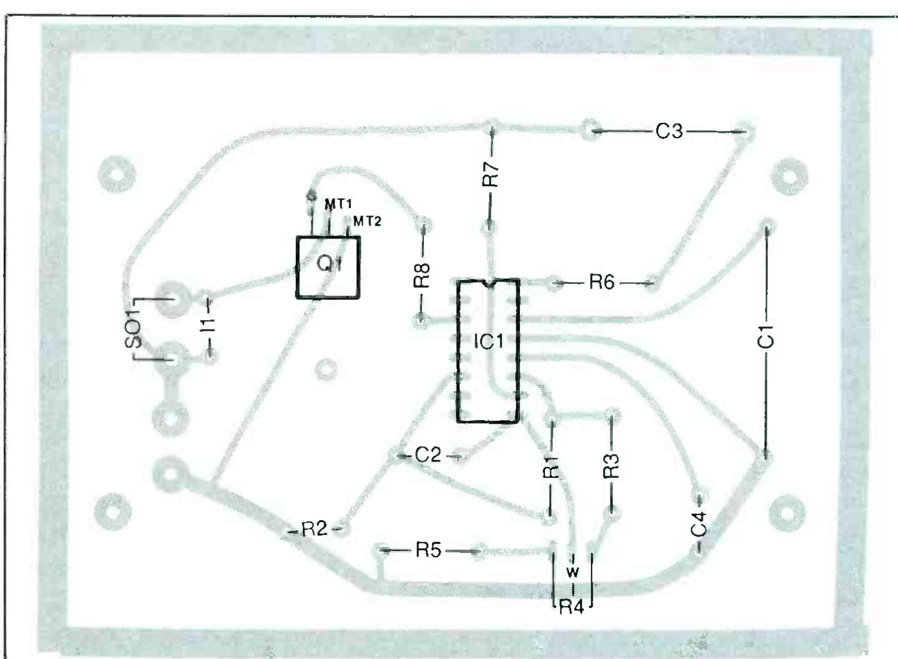


Fig. 8. The wiring diagram for the pc board. Use this layout as a guide to component placement if you wire the circuit on perforated board.

thermistor and the *R3/R4/R5* combination.

When the temperature of the water has reached 100 degrees, set *R4* so that the neon lamp is on for about half the period of each timing cycle. Give the system 15 minutes or so to stabilize and then check the temperature on the thermometer. If the temperature has strayed from 100 degrees, adjust the front panel control until it is brought into line. When all is working properly, mark the setpoint on the project's panel for future reference.

For best control, once the water heats up, the controller should operate within its proportional range, which means that the heater should never be on or off for an entire control cycle. Varying cycle duration may make a difference in how well the system exercises its control; so feel free to experiment with different values of capacitance for *C4*. (Halving the value of *C4* will halve the length of the control cycle.) Of course, the wattage rating of the immersion heater, how much water it is heating, room temperature and selection of setpoint all affect the controller's ability to maintain the desired temperature.

For super-accurate control, use a small electric fountain pump to agitate the water to keep layers of different temperatures from forming in the water. Keep in mind that every time you add a new bottle of chemicals to the tub that you will have to give the system time to heat them to the proper temperature before using them. How long it takes for the added bottles of chemicals to come up to optimum temperature will depend on how cool they are with respect to the water in the tub. The larger the temperature difference between the two, the longer the waiting time. However, you can considerably shorten the waiting time by immersing the chemicals in a basin of hot water for a few minutes to reduce the temperature differential. **ME**