A thermister-governed fan control printed circuit board

Circuit description

The Fan Control Board is a small self-contained printed circuit board which provides rudimentary temperature control for any enclosure in which it is mounted. It is constructed on a board about 2½” x 2” in size, which can be mounted anywhere convenient on the inside of the enclosure. The circuit and the fan which it controls are powered by a single 12Vdc supply. The temperature at which the fan turns on can be set within the range 20°C to 40°C by adjusting a trim potentiometer mounted on the board.

The prevailing temperature is sensed by a thermister. When the temperature experienced by the thermister is greater than a preset, adjustable level, the circuit closes a relay. The relay’s contacts control the power delivered to the fan. The relay’s contacts are rated to 8A at 30Vdc. The logic circuit, the relay coil and the relay contact circuit are all powered by a single external 12Vdc source, which connects to the board through a screw terminal strip. This circuit runs completely independently from anything else inside the enclosure. In fact, it can be run off its own power supply if desired.

Reference is made to Schematic #1 in the attached Appendices.

The thermister (labeled Th in the schematic) is wired as one quadrant in a Wheatstone bridge. The reference side of the bridge is comprised of two 10KΩ resistors (R2 and R3), which provide a 6V reference voltage to the positive input (pin 5) of a precision differential comparator (U1). The sensor side of the bridge has the thermister in the lower quadrant and a variable, but preset, resistance in the upper quadrant. The preset resistance is determined by the setting of a 50KΩ linear potentiometer (RV) in series with a 22KΩ fixed resistor (R1). By adjusting the turns on RV, the series resistance in this quadrant can be varied from 22KΩ to 72KΩ. The midpoint of the sensor side of the bridge is connected to the negative input (pin 6) of comparator U1. Note that U1 is a dual comparator, only one of which is used. The potentiometer used (Digikey part number CT94EW503-ND) is an 18-turn PCB-mounted trimpot with its adjustment screw on the top, which allows the trigger temperature to be fine-tuned. Resistors R1, R2 and R3 are 1% tolerance precision resistors.

For the purpose of a preliminary analysis, ignore 150KΩ resistor R6, which provides hysteresis in the trigger temperature. For the time being, let us treat it as infinite.

When the temperature-controlled voltage on input pin 6 goes below the reference voltage on input pin 7, the output transistor of the comparator becomes active. The comparator used (Digikey part number 296-10285-5-ND) is an N-channel device with an open-drain output. When U1 becomes active, its output line is held at ground potential. On the other hand, when U1 is not active, the output transistor is cut off and the voltage at the output line is allowed to float.

When the comparator is active, its output line is grounded. Current equal to $I = V / R = 12V / 1K\Omega = 12mA$ will flow through 1KΩ resistor R4. Transistor Q1 will be cut off and there will be no voltage drop over resistor R5 and no current flowing through it. Since no current flows through the collector-emitter pathway of Q1, the relay contacts will be open and the fan will not run.

Now, consider the case when the comparator is not active. Its output line will float. Q1’s base is connected to the 12V supply through the series combination of R4 (1KΩ) and R5 (10KΩ). Q1 will turn on. The datasheet for Q1 states that the base-emitter voltage will be in the range 0.75V – 0.95V. In order to determine the minimum current which will flow into Q1’s base, let us assume a base-emitter voltage of 1V, at the high end of the range. Then, the current flowing into Q1’s base will be at least equal to $I = V / R = (12V - 1V) / (1K\Omega + 10K\Omega) = 1mA$.

Let us assume first that Q1 operates in its linear region when forward-biased. Q1’s datasheet also states that it has a minimum forward current gain of 80 when operating in its linear region. With a base current of 1mA, current of at least 80 × 1mA = 80mA will flow through Q1's collector-emitter pathway. Since the relay's coil is in series with Q1's collector, this current will flow through the relay's coil, too. This current should be enough to close the relay's contacts. The datasheet for the relay used (Digikey part number PB450-ND) states that the resistance of the relay coil is 360Ω. When current of 80mA flows through this resistance, the corresponding voltage drop will be equal to $V = I \times R = 80mA \times 360\Omega = 28.8V$. This is not possible, of course, because it exceeds the power supply voltage.

What is at fault is the assumption that Q1 operates in its linear region when forward-biased. Let us therefore make the alternative assumption, that Q1 operates in its saturation mode. In saturation mode, the voltage drop over Q1's collector-emitter pathway will be close to zero, and the current flowing through the collector-emitter pathway will be determined by the other components in series with the collector. In our case, the relay coil will be subject to a 12V voltage drop and the current flowing through it will be equal to $I = V / R = 12V / 360\Omega = 33.3mA$. Q1's base current will still be 1mA, as determined by the other components in the base circuit.

The logic of the circuit is summarized in the following table.

Input voltage	U1	Output voltage	Q1 mode	Relay	Fan
Pin 6 greater than Pin 5	Active	Ground	Cut off	Open	Off
Pin 6 less than Pin 5	Not active	+5V	Saturation	Closed	Powered

Let me say a word diode D1 (a common 1N4001 diode). It provides a bypass route for the current which must flow when transistor Q1 turns off. When Q1 is in its saturation mode, current flows through the relay's coil. The magnetic field generated by this current pulls the metals contacts into the closed position. When Q1 is then cut off, that current is (supposed to) stop flowing. However, there is the magnetic field to take into account. The magnetic field constitutes a form of energy, and that energy must go somewhere when the magnetic field collapses. It does go somewhere. As the magnetic field collapses, it forces current to flow through the circuit containing the coil. The collapse takes place at a rate which "tries to keep the current flowing" in the same direction and at the same magnitude that it was flowing before. If there are resistances in the circuit containing the coil, voltage drops will build up over those components in whatever magnitude is required to allow the current to flow. Those voltage spikes can damage the other components. D1 exists to provide an alternative path for the discharge current. It will direct the current forced out by the collapsing magnetic field back into the coil, where the resistance of the wire in the coil will burn the energy off as heat. D1 is rated for 1A continuous current and can easily handle the occasional release of energy when a cooling cycle is concluded.

The description above has focused on the comparator and how it controls the relay. We have not looked at the role temperature plays in process. To do that, we will now turn our attention to the thermister.

Thermister characteristics

The thermister used (Digikey part number KC005T-ND) has a nominal resistance of 50K at 25°C. It has a negative temperature coefficient (NTC) so its resistance increases as the ambient temperature decreases. The datasheet for Th – the material used in this particular device is MS120 – gives the following information:

Ambient temperature	$R / R_{25°C}$	Thermister resistance
15°C	1.648	82.4KΩ
20°C	1.279	64.0KΩ
25°C	1.000	50.0KΩ
30°C	0.7879	39.4KΩ
35°C	0.6251	31.3KΩ
40°C	0.4993	25.0KΩ
45°C	0.4014	20.1KΩ

The thermister's resistance is quite sensitive to temperature. For example, between 20°C and 30°C, its resistance changes by 64.0KΩ – 39.4KΩ, or 24.6KΩ, which is an average rate of change of about 2.5KΩ per degree.

The values of R1 (22KΩ) and RV (0 – 50KΩ) are such that the trigger temperature can be set anywhere within the following range:

minimum when $R_{thermister}$ = 72KΩ → R / $R_{25°C}$ = 1.44 → temperature ≈ 18°C, and
maximum when $R_{thermister}$ = 22KΩ → R / $R_{25°C}$ = 0.44 → temperature ≈ 42°C

To do an analysis, let us assume that the potentiometer RV is adjusted so that its resistance is equal to 28KΩ. The total resistance of RV in series with R1 is then equal to 50KΩ. This resistance is equal to the thermister's resistance at 25°C, a widely-used value for "room temperature". If the ambient temperature is below 25°C, then the resistance of the thermister will be greater than 50KΩ, the resistance of its quadrant in the Wheatstone bridge will be greater than the resistance of the RV-R1 branch, and the voltage applied to pin 6 of comparator U1 will is greater than 6V. This exceeds the 6V reference voltage at pin 5 of the comparator. The comparator will become active, its output line (pin 7) will be low, transistor Q1 will be cut off, the relay will be open and the fan will not be powered.

On the other hand, when the ambient temperature is greater than 25°C, the thermister will have a lower resistance than the RV-R1 branch, the pin 6 voltage of U1 will be less than the reference voltage at pin 5, and the downstream components will be such that the fan is powered.

Hysteresis

Now let us examine resistor R6 (150KΩ). It provides feedback from the output of U1 back to its inputs. The analyses done above assumed that this resistor did not exist (had an infinite value), so there was no feedback of U1's output.

R6 provides some hysteresis to eliminate chattering near the trigger temperature.

Let us examine first the effect of R6 when the comparator is active and its output voltage is low. From an electrical point of view, resistor R6 would be in parallel with resistor R3 in the bottom quadrant of the reference side of the Wheatstone bridge, both of which connect U1's pin 5 to ground. The top quadrant remains resistor R2 by itself. With R6 in parallel with R3, the relative resistances of the top and bottom quadrants of the reference side of the bridge is not 50:50. Instead, it is R2:R3||R6 = 10KΩ:10KΩ||150KΩ = 10KΩ:9.375KΩ. The reference voltage will not be 6V; it will be equal to 12V × [9.375KΩ / (10KΩ + 9.375KΩ)] = 5.806V.

Now, let us examine the effect of R6 when the comparator is not active. We determined above that the current flowing through R4 and R5 when the comparator was not active was approximately equal to 1mA. The voltage drop over R4 will be equal to V = I × R = 1mA × 1KΩ = 1V. This will put the voltage at U1's output line (pin 7) equal to 12V – 1V = 11V. From an electrical point of view, resistor R6 is (almost) in parallel with resistor R2, connecting U1's pin 6 to the 12V supply. More precisely, 10KΩ resistor R2 connects pin 6 to +12V, 150KΩ resistor R6 connects pin 6 to +11V and 10KΩ resistor R3 connects pin 6 to ground. One can combine the three branches to calculate[1] that the voltage at their common node (pin 6) is equal to 6.161V.

So, when the comparator is not active, and the fan is off, the reference voltage is equal to 5.806V. When the comparator turns off, and the fan powers up, the reference voltage increases to 6.161V.

[1] Let I_2, I_6 and I_3 be the currents flowing through resistors R2, R6 and R3, respectively. Let $V_{pin\ 6}$ be the voltage at their common node. Then, the three voltage drop equations are: $V_{pin\ 6}$ = 12V – (10KΩ × I_2), $V_{pin\ 6}$ = 11V – (150KΩ x I_6) and $V_{pin\ 6}$ = 10KΩ × I_3. The net current flowing into the common node must be equal to zero, so that $I_2 + I_6 = I_3$. These four equations can be combined to give a single equation in $V_{pin\ 6}$, being: $V_{pin\ 6} = 10 \times \{[(12 - V_{pin\ 6}) / 10] + [(11 - V_{pin\ 6}) / 150]\}$. This equation can be re-arranged to be: $31 \times V_{pin\ 6} = 191$.

We can calculate the temperatures at which the thermister's resistance is such that the voltages on the sensor side of the Wheatstone bridge equals these two reference voltages. We refer again to the thermister's datasheet, which states that its resistance changes by 4.84% at a temperature of 25°C. (This is a more exact value for the rate of change than the average 2.5KΩ/°C we calculated above by looking at a 10°C change in temperature.) We can write down the following two equations:

The voltage at the negative input of the comparator (pin 6) is given by:

$V_{negative\ input} = 12V \times [R_{Th} / (R_{Th} + R1 + RV)]$ (1)

The thermister's resistance at a temperature ΔT in the neighbourhood of 25°C is given by:

$R_{Th} = 50K\Omega \times [100\% - (\Delta T \times 4.84\%/°C)]$ (2)

At the lower reference voltage, $V_{negative\ input} = 5.806V$, we get:

$5.806V = 12V \times [R_{Th} / (R_{Th} + 50K\Omega)]$, which can be solved to give $R_{Th} = 46.868K\Omega$ and, then

$46.868K\Omega = 50K\Omega \times [100\% - (\Delta T \times 4.84\%/°C)]$, which can be solved to give $\Delta T = +1.29°C$.

At the lower reference voltage, $V_{negative\ input} = 6.161V$, we get:

$6.161V = 12V \times [R_{Th} / (R_{Th} + 50K\Omega)]$, which can be solved to give $R_{Th} = 52.757K\Omega$, so that

$52.757K\Omega = 50K\Omega \times [100\% - (\Delta T \times 4.84\%/°C)]$, which can be solved to give $\Delta T = -1.14°C$.

Conclusion: When the comparator is active, and the fan is powered up, the trigger temperature is adjusted 1.29°C upwards to 26.29°C. When the temperature reaches 26.29°C, the comparator will turn off and the fan will start running. The adjustment is now 1.14°C downwards, which means that the fan will not stop running until the temperature has decreased to 23.86°C.

R6 therefore causes a 1.29°C + 1.14°C = 2.43°C difference between the temperatures at which the fan turns on and turns off. This ensures that the circuit does not switch on and off too quickly near the desired temperature. Values lower than 150KΩ for R6 would increase the amount of hysteresis. Values greater than 150KΩ for R6 would give less.

The sensitivity of the comparator

The above calculations were carried out to more decimal places of precision than is common. One may ask: how sensitive is the comparator? Or, in other words, how finely can it distinguish changes of temperature? The datasheet for the comparator used states that it has a typical input offset voltage of 2mV, with a guaranteed maximum of 5mV. For analysis purposes, let us ignore R6 and the hysteresis it introduces. Suppose that the trigger temperature is set to 25°C by setting potentiometer RV to 28KΩ. At the trigger temperature, the voltage at both input lines of the comparator will be 6V. Now, suppose the temperature changes by such an amount that the voltage on the sensor-side of the Wheatstone bridge rises by 5mV to 6.005V, the smallest change we are guaranteed that the comparator can detect. We can calculate the thermister resistance in this condition, as we did above, in two steps:

$V_{negative\ input} = 12V \times [R_{Th} / (R_{Th} + R1 + RV)]$
→ $6.005V = 12V \times [R_{Th} / (R_{Th} + 50K\Omega)]$, which can be solved to give $R_{Th} = 50.083K\Omega$

$R_{Th} = 50K\Omega \times [100\% - (\Delta T \times 4.84\%/°C)]$
→ $50.083K\Omega = 50K\Omega \times [100\% - (\Delta T \times 4.84\%/°C)]$, which can be solved to give $\Delta T = -0.034°C$

So, the comparator can detect a change in temperature as small as 0.034°C.

The fan

I often use a 12V cooling fan which is Digikey part number P9729-ND. It has a square housing 60mm on each side. When mounted with a screen (Digikey part number CR373-ND) and finger guard (Digikey part number CR221-ND), it makes a fine-looking finished product. The fan requires current of 155mA when running. The power it consumes when running is equal to $P = I \times V = 155mA \times 12V = 1.86W$.

Power considerations

The power consumed by the relay coil is equal to $P = I \times V = 33.3mA \times 12V = 400mW$.

The datasheet for Q1 states that it can handle a collector current of 600mA. This is well in excess of the 33.3mA which flows through the relay coil and the collector-emitter pathway of Q1 when the fan is running.

The reference side of the Wheatstone bridge is comprised of two 10KΩ resistors in series. Each resistor will draw current equal to $I = V / R = 6V / 10K\Omega = 0.6mA$ and will dissipate power equal to $P = IV = 0.6mA \times 6V = 3.6mW$. Standard quarter-watt ratings will easily suffice for them.

Consider the sensor-side of the Wheatstone bridge. The worst thermal condition for R1 and potentiometer RV occurs at extremely high temperatures, when the resistance of the thermister falls close to zero. The current through the series combination of R1 and potentiometer RV would be at its maximum, equal to $I = V / R = 12V / 50K\Omega = 0.24mA$. R1 would dissipate power equal to $P = I^2R = (0.00024A^2)(22K\Omega) = 1.3mW$. A quarter-watt resistor will also suffice for R1. RV would dissipate power equal to $P = I^2R = (0.00024A^2)(28K\Omega) = 1.6mW$. The datasheet for potentiometer RV states that it is rated to 500mW, far in excess of what is needed here.

At very low temperatures, on the other hand, the resistance of the thermister increases. At a temperature of -50°C, the thermister's resistance ratio ($R / R_{25°C}$) reaches about 100, so that its resistance reaches about 5MΩ. The power the thermister would dissipate in this condition is equal to $P = V^2 / R = (12V)^2 / 5M\Omega = 0.03mW$. However, this is not the worst case for the thermister.

The worst case for the thermister occurs at mid-range temperatures. At a trigger temperature of 25°C, for example, the thermister would dissipate power equal to $P = V^2 / R = (6V)^2 / 28K\Omega = 1.3mW$. It should be noted that the thermister's datasheet gives the thermal dissipation constant as 1.4mW/°C. We should interpret this to mean that, near the trigger temperature, the thermister's own power dissipation will raise its temperature by about 1°C. This is not an important issue if the trigger temperature is set using the potentiometer while the Fan Control Board is mounted in the location where it is to be used and under operating conditions. The designer can choose to set the temperature at which the circuit turns the fan on or the temperature at which it turns the fan off.

One last note: It would be possible to use potentiometer RV as the only resistive component in its quadrant of the Wheatstone bridge. Fixed resistor R1 was put in series with the potentiometer in order to limit the current flowing through the thermister if the potentiometer is inadvertently set to its lowest limit.

Printed circuit board

The silkscreen side and copper trace side of the printed circuit board are set out separately in the attached Appendices. Both the schematic and the PCB layout were prepared using ExpressPCB's drafting software, which is available as a free download on the internet.

Jim Hawley
July 2012

An e-mail setting out errors and omissions would be appreciated.

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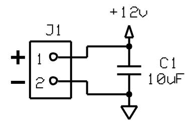
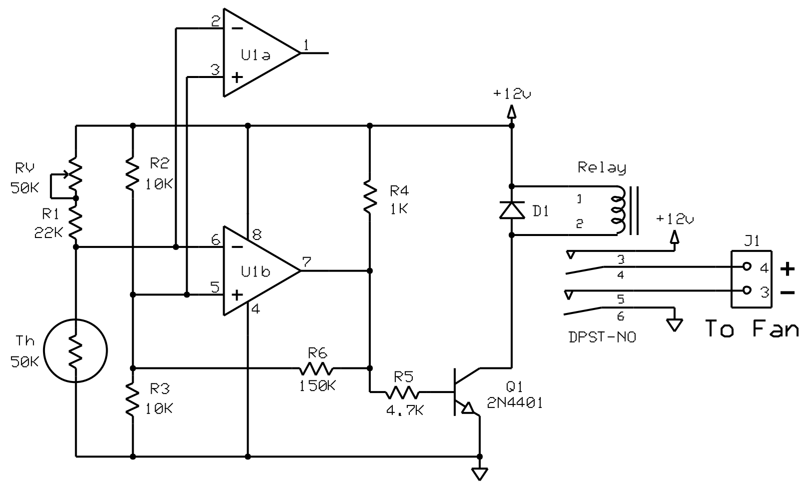


Power Supply



Fan control circuit

Digikey parts numbers

Th = KC005T-ND thermister 50K 1%
U1 = 296-10285-5-ND dual precision differential comparator
RV = CT94EW503-ND 50K 10% 18-turn trimpot with top adjustment
Relay = PB450-ND 12V DPST 8A at 277Vac
Q1 = 2N4401-ND general purpose NPN transistor 600mA
D1 = 1N4001-E3/54GICT-ND general purpose 1V 50V diode
J1 = 281-1437-ND 4-screw terminal strip 0.2" spacing
C1 = 478-1842-ND 10u 10% 35V tantalum round bud
R1,R2,R3 = PxxxxKCACT-ND Panasonic precision (1%) 1/4W resistors

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Schematic #1		
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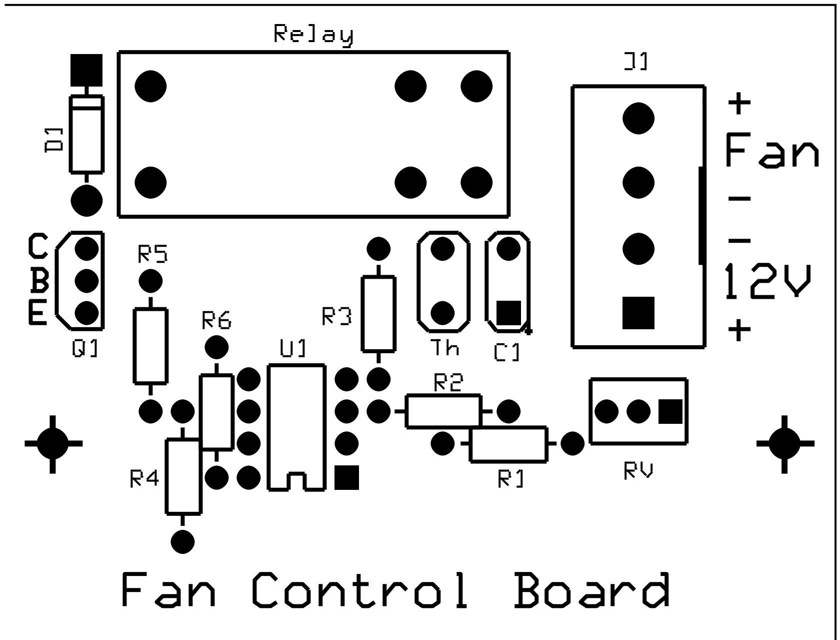

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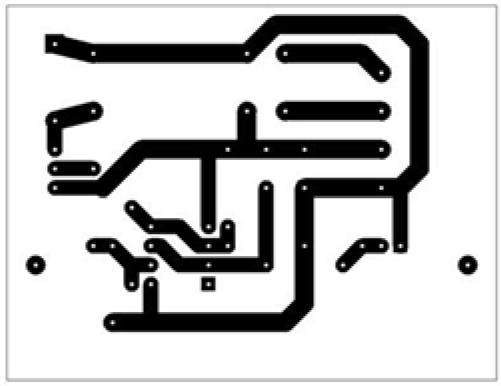

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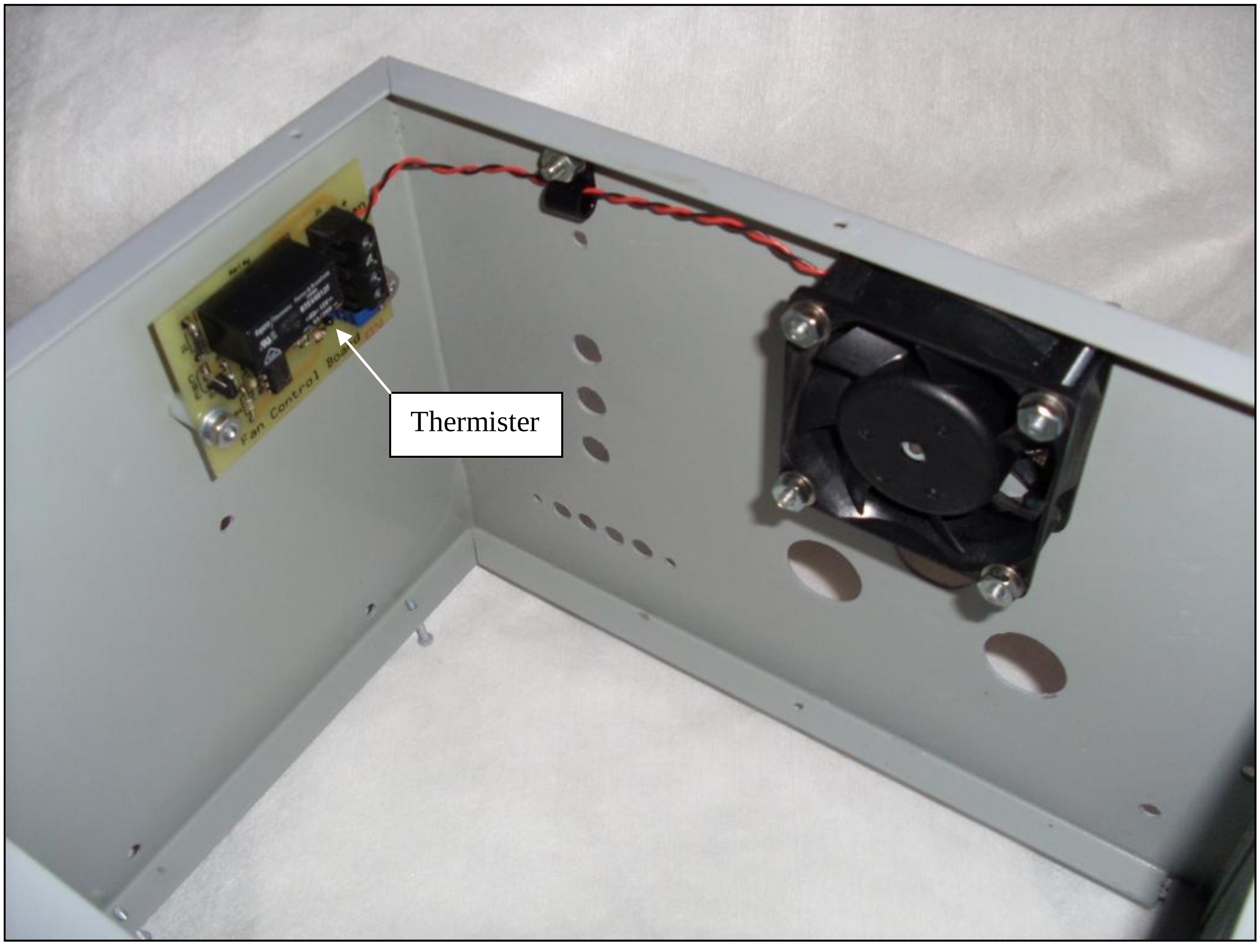

The photograph shows a complete Fan Control Board mounted on the left-side wall of the enclosure. The fan it controls is mounted on the back wall. The bud of the thermister can be seen peeking out just below the bottom edge of the relay. The thermister is a bud with two radial leads about an inch long. The thermister is soldered to the printed circuit board in such a way that the bud is about three-quarters of an inch above the surface of the board. This gets the sensor away from the board and closer to the prevailing temperature inside the enclosure which it is intended to monitor. The details of the thermister's mounting can be seen a little more clearly in the following photograph.