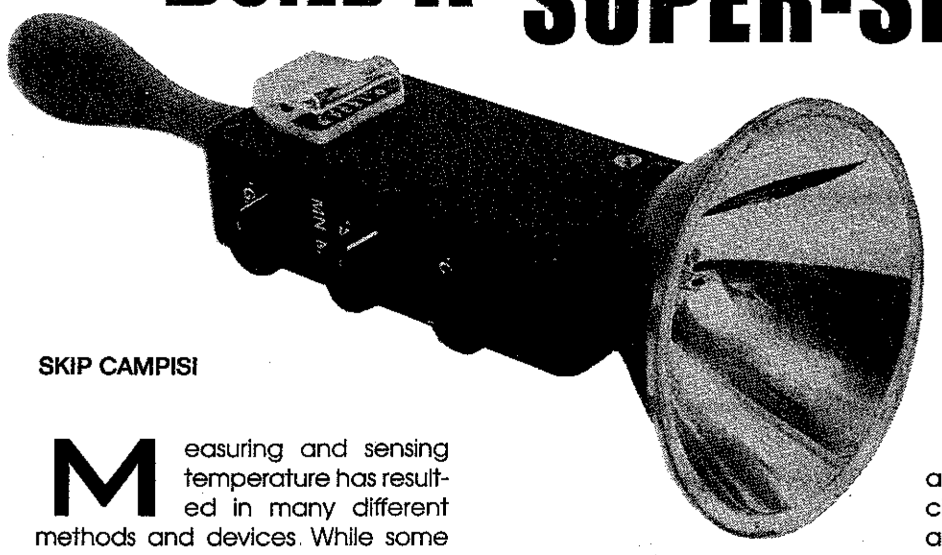
BUILD A SUPER-SENSITIVE HEAT DETECTOR



Detect hot or cold objects remotely with this ultra-sensitive infrared-sensing device

SKIP CAMPISI

Measuring and sensing temperature has resulted in many different methods and devices. While some of the solutions developed meet certain requirements such as temperature range and accuracy, most have some sort of characteristic that makes them unsuitable for the average home hobbyiest.

Sensors such as thermocouples, thermistors, and exotic ICs usually require their own "flavor" of circuitry in order to use their outputs. The outputs are also usually non-linear and change only slightly in relation to the temperature change. The result is a system that can easily be inaccurate because of circuit noise being interpreted as temperature change.

Fortunately for the home experimenter, materials and components are readily available for building an inexpensive non-contact type of temperature sensor that overcomes the limitations listed above. Such a device is presented here. The unit actually indicates the temperature *difference* between the temperature of an object and an arbitrary "ambient" temperature reference that can be set at any time.

A gain control is used to adjust the sensing range from 1° C down to an incredible 0.01° C between the sensor and the ambient reference temperature! While that specification might sound like "design overkill," it is really quite essential for remote sensing. For example, a match flame can be detected up to a distance of one foot at the 1° C gain setting. With the gain increased to detect a difference of 0.1° C, the heat from the palm of your hand can be detected at the same distance. At the maximum gain setting, that same match flame can be detected from across a room!

Obviously, those objects are all more than 1° C hotter than room temperature, so why is such a high gain needed? The culprit is, of course, the "column" of air between the object and the sensor. As the air absorbs and dissipates some of the heat, the apparent temperature falls off rapidly in an inverse-square relationship with the distance—double the distance, and the heat energy drops by a square-root function. By the time the heat reaches the sensor, we are probably sensing convection currents more than the actual direct heat from the object.

The implication is that any air flow will disturb the readings. When using the device at higher gains, still air is the biggest requirement for consistent results. Avoid fans, heat vents, and the like when experimenting. Of course, that "disadvantage" can also become an advantage, especially when using the unit to *detect* air flow such as "leak" testing.

About the Circuit. As you can see on the schematic diagram in Fig. 1, the actual circuit for the Heat Detector is a deceptively simple design. Remember, however, that the signals involved with sensing a heat source at a distance are very low in amplitude. Low-amplitude signals always run the risk of being lost in the normal background noise that they are sitting in, so all of the components were selected for low-noise performance. For example, notice that all of the fixed resistors are 1% metal-film units. Those types of resistors perform extremely well when low noise is important. What is interesting in the overall design is that the actual values of the resistors are *not* critical—any value within 5% or even 10% of those given should work well. However, the metal-film composition of the resistor is mandatory!

The circuit is a "current mirror" stretched to the ultimate degree. The current mirror itself is built around Q1 and Q2, a pair of surface-mount transistors. The tiny mass of the SOT-23 transistor package lets the circuit respond extremely fast to temperature changes.

A standard current-mirror circuit would only have Q1 and Q2 with their bases and emitters connected in parallel and the base of Q1 shorted to its collector, forming a diode-connected transistor. The current

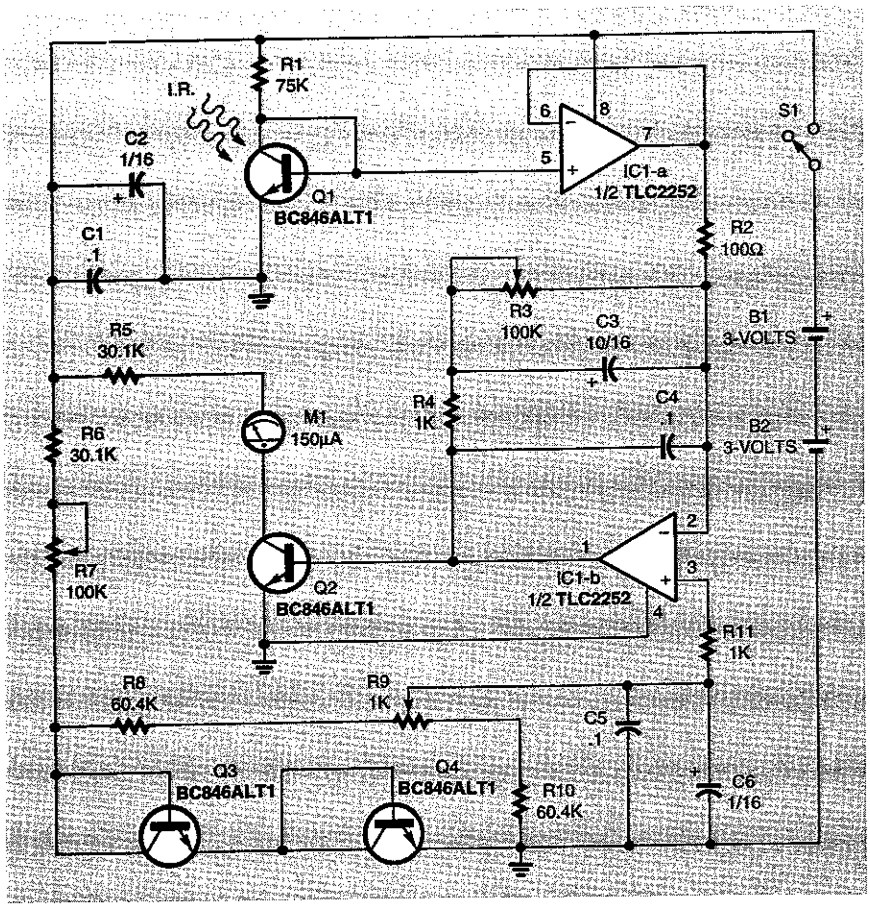


Fig. 1. The Heat Detector is built around a simple current-mirror circuit When one transistor is heated up, the change in its current flow is reflected in a parallel circuit

flowing through R1 would then be "reflected" in Q2's collector. For both currents to be equal in size and temperature tracking, Q1 and Q2 are normally a matched pair in a single package. However, the characteristic that we are looking for is the temperature *difference* between Q1 and Q2; that is why individual units are used. For every 1° C increase in the junction temperature of a silicon transistor at a fixed bias current, its forward-bias voltage decreases by about 2 millivolts. By holding Q2 at a fixed ambient temperature, its collector current will decrease as Q1's temperature rises.

A change of only 2 millivolts is not a lot to work with in a remote-sensing circuit, especially if we are interested in displaying a difference of 0.01° C. Besides, an *increase* in current for an increase in temperature would be very desirable.

Placing Q1 outside of the cabinet at the focal point of a standard parabolic flashlight reflector makes the sensor very directional and extremely sensitive to infrared energy focused by the reflector. The rest of the components are located inside a fully-enclosed cabinet that is used as an ambient-temperature reference.

Between Q1 and Q2, a two-stage inverting variable-gain amplifier made up of IC1-a and IC1-b provides the high gain needed for remote sensing. The first stage (IC1-a) is a unity-gain buffer that drives the second stage (IC1-b) The second stage is an inverting amplifier with a gain that can be adjusted between about −10 and −1000 with R3. The audio taper of R3 makes adjusting easy; the most useful gain setting, −100, is at about the center of its rotation

A 1 2-volt reference, built around Q3 and Q4, tracks temperature changes within the case at a rate of −4 millivolts per degree C The reference is divided exactly in half, using R8–R10, to a 0 6-volt reference tracking at −2 millivolts per degree C. That output is applied to the reference input of IC1-b Note that the bias resistors for the transistors have been chosen so that Q1–Q4 all operate at the same current level That will help ensure that their forward voltages are approximately equal, assuming that they are at the same temperature

The 0.6-volt reference acts as a "ground" reference for the input signal from Q1. When Q1 heats up by 1° C, its forward voltage decreases by 2 millivolts. With the reference set by R3 to its minimum gain of −10, the voltage appearing at Q2's base and emitter increases by 20 millivolts, which about doubles its collector current. The result is a full-scale display on M1 At a gain of −1000, a 0 01° C increase results in a 20 *microvolt* signal giving a full-scale display! With Q1 at ambient, Q2 conducts enough current for a 50%-of-full-scale display on M1

As you might suspect, setting the operating levels of the transistors is crucial in order to get any meaningful results out of the instrument. That is done by leaving Q1's current fixed and varying the current to Q3 and Q4 with R7 When adjusting the 1 2 volt reference, R7 can be considered as a "coarse" adjustment Any "fine" adjustments are then done with R9

The collector of Q2 directly drives M1, an analog current meter. Although the circuit uses a 150-microamp unit, you can use any analog meter that has a full-scale display between 50 and 250 microamps. Keep in mind that the markings on the meter do *not* indicate any particular temperature reading, just the relative change If you are going to use a meter of a different capacity, R1, R5, and R6 must be changed in order for the circuit to work The different values for those components are shown in Table 1 for several different types of meters. Those resistors have been selected to provide current through the transistors so that they all operate at about 50% of M1's full-scale current The meter is protected from excess current by R5

The total current drain of the circuit is only about 300 microamperes when M1 is a 150-µA unit A simple unregulated power supply is quite suitable in that case Two 3-volt lithium coin cells are connected in series for a 6-volt supply. With a rating of about 200 milliamp-hours, they will last a long time They also have a very "flat" discharge voltage curve, simulating a regulated power supply at those low currents

One final consideration for this type of circuit is the concern over external noise pickup, such as 60-Hz hum and radio-frequency interference (RFI) Capacitors C1–C6 were specially selected to filter out as much noise as possible while still keeping response times very fast. Tantalum capacitors are highly recommended If you have noise problems the values of the capacitors can be increased You can even connect the parabolic reflector to ground through one of its mounting screws if necessary.

Construction Tips. The Heat Detector's circuit is simple enough that it can be built on perfboard using standard construction technuques One area that will be a bit more difficult is connecting the tiny surface-mount transistors to the circuit. The simplest method is to attach separate leads directly to the units, converting them to through-hole-like devices They can then be mounted to a perfboard like any other standard leaded part The technique is shown in Fig. 2 Use 30-gauge wires that are at least 1-inch long for the leads—the excess length can be trimmed off after the unit is mounted to the board. In order to help protect the transistor from heat-related damage during soldering as well as making it easier to handle the tiny parts, hold the transistor case with a "micro-gator" clip such as a RadioShack 270-373. That particular clip has flat jaws rather than serrated teeth.

Using small tweezers, carefully bend the transistor leads out flat from the case Wrap a turn or two of wire around the unit's leads with the tweezers Put the clip in a bench vise and attach another clip to the free end of the wire so that it acts as a weight, stretching the wire. Using very fine solder and a very fine tip on your iron, carefully solder the wire to the lead Use as little heat as possible for a very brief time in order to avoid damaging the transistor. Repeat the procedure for all three leads on all four transistors Once the solder joints are cool, check the transistors with an ohmmeter to verify that the transistors were not damaged during soldering

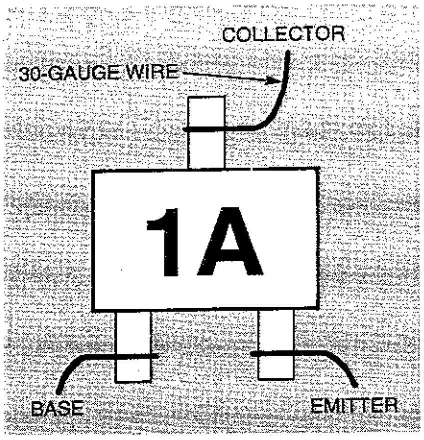


Fig. 2. Surface-mount transistors can be converted to use with perfboard with some careful work.

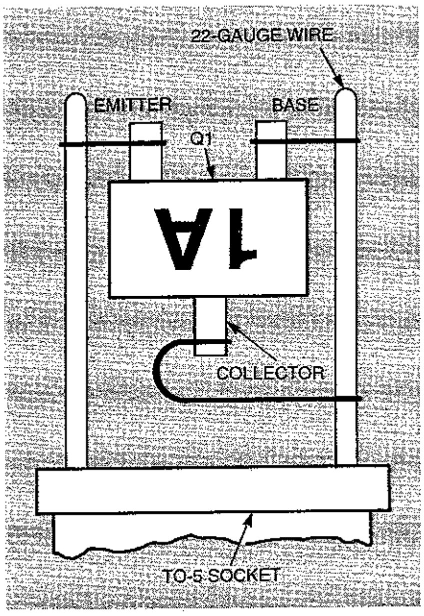


Fig. 3 Transistor Q1 is mounted to a TO-5 socket so that it can be moved to the focal point of a parabolic reflector.

The BC846ALT1 transistors specified for Ql–Q4 are general-purpose NPN small-signal units. Any similar type of device can also be used Examples of alternate part numbers include BC848ALT1, MMBT3904LT1, and MMBT4401LT1 Note, however, that it is important that all of the transistors are the same device type in order for the correct matching of transistor characteristics In other words, don't mix and match when selecting parts for Q1–Q4.

When laying out the components on the perfboard, it is a good idea to place R3, R7 and R9 along one side so that their controls point in the same direction Since R7 and R9 are 20-turn units having only a small adjustment screw, it would be convenient to use some sort of panel-knob adapter for them. Such a device is available from Spectrol for their line of multi-turn potentiometers Other manufacturers might have similar devices available The adapters should be mounted to the potentiometers according to the manufacturer's instructions.

Transistors Q3 and Q4 should be installed between R7 and R9 with their cases sitting about ¼-inch above the board for good air circulation around the transistors Mount Q2 in a similar fashion Remember that Q1 will not be mounted on the board; it will be discussed later.

Next, select a plastic cabinet that is large enough to hold M1, S1, and the completed circuit board Cut an appropriate hole for M1; locate and drill the three mounting holes for R3, R7, R9, and S1 The board will be supported by the three potentiometers

A parabolic reflector from a flashlight or lantern will be used for the collector. Although the size can vary depending on what you have available, a 3-inch-diameter reflector from a 6-volt lantern is a very effective size for the intended use

Select a transistor socket that will fit through the light-bulb hole at the base of the reflector. A standard TO-5 or TO-39 socket should be fine in most cases However, it might be necessary to use a smaller TO-18 socket. Install the socket in a hole centered in one end of the cabinet, using silicone sealant to hold it in place if necessary.

Drill a couple of clearance holes through the base of the parabolic reflector on either side of the light-bulb hole for a pair of 2-56 or 4-40 mounting screws Place the reflector over the transistor socket and mark and drill the screw holes

Using Fig. 3 as a guide, insert two 1-inch lengths of 22-gauge tinned solid-bus wire into the two widest-spaced holes in the transistor socket Install Q1 by carefully wrapping its wire leads from its base and

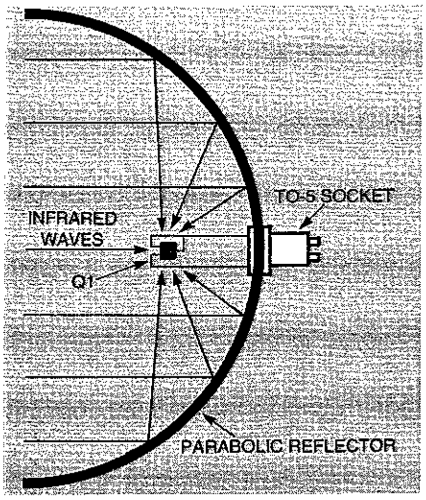


Fig. 4 When Q1 is at the focal point of a parabolic reflector, all of the gathered heat energy will strike the transistor. The size of the reflector will increase the ability of the Heat Detector to collect energy from the source of heat increasing the gain of the system.

PARTS LIST FOR THE HEAT DETECTOR

SEMICONDUCTORS

IC1—TLC2252 CMOS dual op-amp, integrated circuit (Texas Instruments)
Q1-Q4—BC846ALT1 Surface-mount general-purpose transistor, NPN (see text)

RESISTORS

(All resistors are ¼-watt, 1% metal-film units, unless otherwise noted.)
R1—75,000-ohm (see text)
R2—100-ohm
R3—100,000-ohm potentiometer, audio-taper
R4, R11—1000-ohm
R5, R6—30,100-ohm (see text)
R7—100,000-ohm potentiometer, 20-turn (Spectrol)
R8, R10—60,400-ohm
R9—1000-ohm potentiometer, 20-turn (Spectrol)

CAPACITORS

C1, C4, C5—0.1-µF, monolithic ceramic
C2, C6—1-µF, 16-WVDC, electrolytic
C3—10-µF, 16-WVDC, electrolytic

ADDITIONAL PARTS AND MATERIALS

B1, B2—3-volt lithium battery (CR2032 or similar)
M1—Analog panel meter, 150-µA (see text)
S1—Single-pole, single-throw switch
3-inch parabolic flashlight reflector, enclosure, battery holder, wooden or plastic handle, knobs, shaft adapters for R7 and R9, hardware, etc.

emitter around the 22-gauge wires as shown—do not solder the connections just yet

Carefully slide Q1 on its leads to about the center of the 22-gauge bus wires Attach the reflector to the case without disturbing Q1 With everything assembled, Q1 should be at a point close to the focal point of the reflector, similar to the arrangement shown in Fig. 4 It does not have to be exact at this point; we will next be adjusting the assembly's focus Set the reflector assembly down on a table or bench so that you can look directly down the "business" end of the reflector at Q1.

Starting at a distance of about a foot or two away from the reflector, look at the "image" of Q1 in the reflector You should see a black "ring' somewhere around the reflector's inside circumference, either towards the front or rear The black ring is the focused image of Q1's case. If you don't see the ring try sliding Q1 further in or out and look again; it might take a little practice. What you see should look similar to the view shown in Fig. 5

Once you see the black ring, move farther away from the assembly while keeping the ring in sight. What you want to end up with is the black ring just about filling the forward (widest) section of the reflector from a distance of around 8 to 10 feet. That is a good focal point for indoor use of the Heat Detector Slide Q1 in and out a little at a time to achieve that focus

You can confirm a good focus by pointing the reflector directly at a diffuse light source across the room such as a lamp with a shade or a sun-lit window curtain. Peek over the edge of the reflector, and you should see Q1 glowing like a lamp as the focused light shines on it DO NOT point the unit directly at the Sun or you might melt or severely damage the transistor!

Once you have a good focus, carefully remove the reflector and solder the base and emitter wire leads of Q1 to the 22-gauge wires. Wrap the collector wire lead of Q1 around the 22-gauge wire connected to Q1's base lead and solder that connection also Re-check the focal point; if everything looks good cut off the excess 22-guage wires.

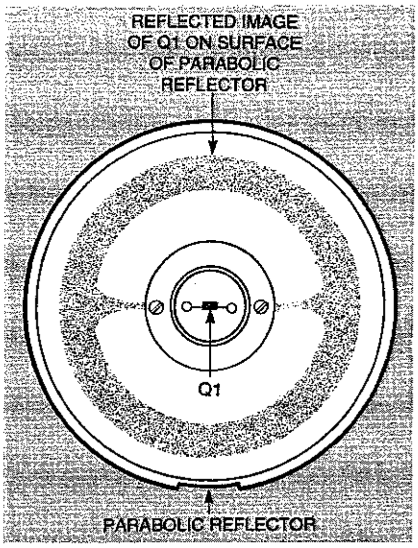


Fig 5. When focusing Q1, you should see a black band around the surface of the reflector. Careful adjustment of Q1 can vary the apparent size of the reflector to the rest of the circuit.

TABLE 1

ALTERNATE RESISTORS FOR M1

M1	R1	R5	R6
50-mA	215k	90.9k	100k
100-mA	110k	45.3k	49.9k
150-mA	75k	30.1k	30.1k
200-mA	53.6k	22.1k	20k
250-mA	43.2k	18.2k	15k

Select a non-metallic handle, such as a plastic or wooden one, and mount it to the opposite end of the case. It is important that the handle not conduct any heat from your hand, or the accuracy of the unit will be affected. If you use a handle from a wood file, the threads in the handle will make it easier to mount the handle to the case

Now you can finish up assembling the Heat Detector. Install the board, S1, and M1, and then wire up the rest of the circuit If you want to label any of the controls, that should be done before installing any other parts When wiring Q1 into the circuit, pay careful attention to the polarities of that component.

Install the reflector, the handle, and close up the case Install the knobs on the potentiometers and set the unit aside for at least 15 minutes to let the temperature inside stabilize after all of the handling it just received You are now ready to test.

(Continued on page 50)

to know how to program in QBasic, but it's very easy to modify the code and see what happens. Many budding programmers start gaining hands-on experience by modifying a program to achieve a particular goal. Just make sure that you have a backup copy of the program before you start experimenting. The program is well documented and will stand alone to act as a guide for those who are familiar with QBasic.

One example of a need to modify the program has to do with distinctive-ring service. The program will detect and count a normal ring cycle (two seconds of ringing followed by four seconds silence). Distinctive ringing might cause the Phone Troll to count each burst of rings, indicating two or three rings for each actual ring. Simply divide the variable *ringct* by two or three, or rewrite the program to indicate which sequence of rings was received.

Like any good servant, your troll awaits. Ω

HEAT DETECTOR

(continued from page 41)

Using the Heat Detector. There are a few points to consider whenever using the Heat Detector to obtain consistent readings: always grasp the unit by the handle only, keeping your body heat as far away from the cabinet as possible. For critical operation, attaching the unit to a camera tripod would be an excellent method.

Unless you are actually leak-testing and looking for circulating air, any air that blows across Q1 will cause temperature drift in your readings. Still air is the priority here.

The parabolic reflector used is very directional and will take some practice in aiming. Pointing a standard flashlight at an opposite wall will give you an idea of the area of coverage to be expected.

Hold the unit by the handle and set R3 to its *minimum* gain setting. Set R7 and R9 to their mid-positions. Turn on the power and point the reflector at a blank wall.

Adjust R7 for a display of about half of full scale on M1. That is the most sensitive area, although any region between 20% and 80% will work well. If R7 won't get you on scale, it might be necessary to adjust R6's value. An increase in value lowers M1's reading, and vice versa.

Advance R3 slowly while watching the display—it will probably move off-scale in one direction or the other as you arrive at the maximum gain setting. That is due to inherent offset voltages in the components. Adjusting R7 should give full-scale coverage in either direction at the highest gain setting. If not, adjust R6's value as mentioned above.

Note that making any settings with R7 becomes more difficult as the gain is increased. That is where R9 becomes very useful. For best results, always adjust R7 first to get as close as possible; then use R9 as a "fine" adjust for a 50% of full-scale indication on M1.

Set R3 back down to its minimum gain setting and adjust R7 for a 50% reading on M1. Now that you have an ambient-temperature set-point from the blank wall, point the unit at a match or candle flame about 6 to 12 inches away. You should immediately "peg" M1. Return to the blank wall and the display will return to 50%.

Rotate R3 to mid-position, and adjust R7 for a 50% reading on the blank wall. Hold the palm of your hand about 6 to 12 inches in front of the reflector and M1 should go full-scale again. Hold an ice cube in front of the reflector and M1 should drop to its minimum reading.

Rotate R3 to its maximum position, and adjust R7 (followed by R9) for a 50% reading on the blank wall. Now you can "sweep" slowly around the room. A hot spot such as a sun-lit window or a lamp will probably peg M1 at full-scale. You will now note that any breeze, even one caused by rapid movement of the Heat Detector, will cause display drift!

Going Further. You will by now have realized that the parabolic reflector plays a critical role in the sensitivity and area of coverage of the Heat Detector. A 3-inch-diameter reflector is an excellent size for general-purpose use. However, it can be difficult to aim accurately at distant objects.

The solution to that problem is to use a larger reflector. Any photographic supply store will carry larger-diameter reflectors. Of course, the sensitivity of the instrument increases with the square of the diameter in addition to the coverage.

Some applications such as remote testing of circuit boards for hot spots might have the opposite requirement—miniature parabolic reflectors. A 1-inch-diameter reflector would be highly directional. The Heat Detector has sufficient gain to compensate for the decreased gain from the reflector. A miniature flashlight would be a good source for smaller reflectors.

Of course, you still have to make sure that Q1 is focused properly. An adjustable focus arrangement would be a great help in close-up work, where the focal point moves further away from the rear of the reflector. One method that can be used to make the Heat Detector more versatile would be to use a TO-5 transistor socket with female pins that are spring-loaded and completely hollow through their length. That would allow you to slide Q1 back and forth to achieve any focus position.

The Heat Detector is an easy-to-build precision instrument that shouldn't cost more than about $25 to put together even using all new parts. Any salvaged or surplus components will drop the cost of the project to the point where it becomes an almost trivial matter to add such an instrument to your bench or tool kit. Build one yourself and have hours of educational fun, or even put it to some practical use! Ω