Project 153

Temperature adaptor for your multimeter

This simple add-on project extends the functions of your multimeter to the measurement of temperature. It is particularly suited to digital multimeters. It can be used to measure temperature over the range from −55°C to +150°C with an accuracy of 0.5°C or better.

Geoff Nicholls

IT IS SURPRISING how useful an 'electronic thermometer' can be in an electronics workshop or laboratory. Temperature measurement is a rarely-included function on modern multimeters, however. Measuring temperature in a chemistry or physics lab is commonplace, and the same should be so in an electronics lab, but rarely is.

Component temperature rise, or the actual operating temperature of a device, can be an important parameter in a circuit — no matter whether the component's a resistor or a transistor. The performance of heatsinks can be assessed using temperature measurements.

When fault-finding or servicing equipment, thermal problems can be quickly sought out and identified by temperature measurement. And that's just a few applications!

Sensors

There are a number of ways to measure temperature electrically or electronically. Thermocouples, which consist of two dissimilar metal wires bonded together, have long been used. The junction of the metals generates a small voltage that is proportional to the junction temperature. The voltage output is non-linear with changing temperature. Thermocouples are generally used for temperature measurement at high temperatures and over extremely wide ranges.

The resistance of semiconductor material varies considerably with temperature and this is exploited in 'thermistors'. The variation is non-linear, but thermistors have been used for temperature measurement where accuracy and linearity are not important.

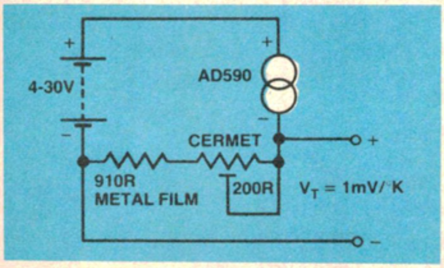


Figure 1. Simple thermometer with +/− 2°C accuracy.

Any semiconductor junction will exhibit temperature dependence of the forward conduction voltage. For silicon junctions, which have a forward conduction voltage of around 600 mV, the junction voltage will vary by typically −2.2 mV/°C at a forward current of around 250 uA, and this is generally linear over quite a wide range.

Silicon diodes and the base-emitter junction of silicon transistors are often used in temperature sensing and control applications. Accuracy and repeatability are generally very good. We described a digital temperature meter which employed a silicon diode sensor (ETI-589) back in the December 1977 issue.

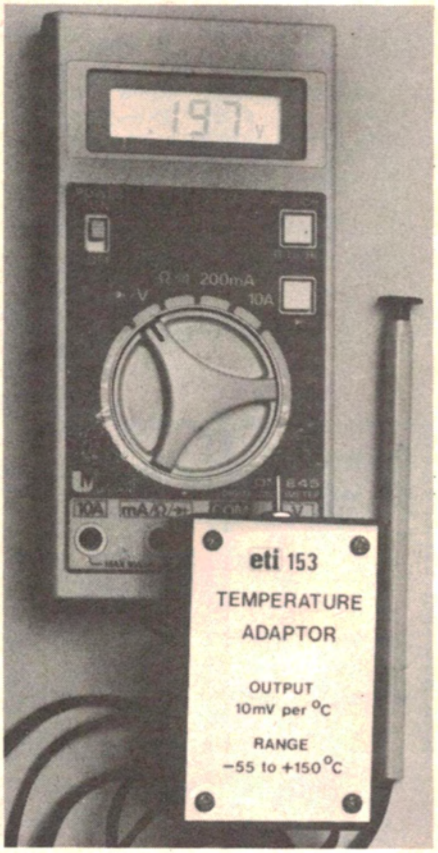
However, a number of specially-constructed ICs are available which have been designed to provide a highly accurate and linear temperature-to-current or temperature-to-voltage output over a wide temperature range. Such devices are unrivalled for accuracy, linearity and speed of response.

I chose the Analog Devices' AD590 which is available in two package styles — a TO-52 'can' and a tiny ceramic flat pack — and several accuracy grades. It is distributed by Parameters Pty Ltd, 41 Herbert St, Artarmon NSW 2064. (02)439-3288.

The AD590

The AD590 is a two-terminal integrated circuit temperature transducer which produces an output current proportional to absolute temperature. For supply voltages between +4 V and +30 V the device acts as a high impedance, constant current regulator passing 1 uA/°K. Laser trimming of the chip's thin film resistors is used to calibrate the device to 298.2 uA output at 298.2°K (+25°C).

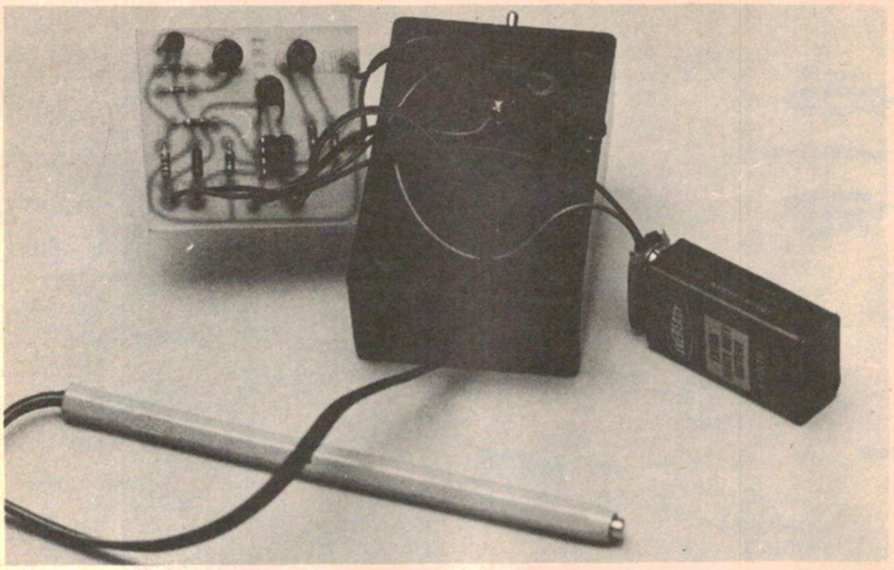
The device is particularly useful in remote sensing applications. The device is insensitive to voltage drops over long lines due to its high impedance current output. Any well-insulated twisted pair is sufficient for operation hundreds of feet from the receiving circuitry.



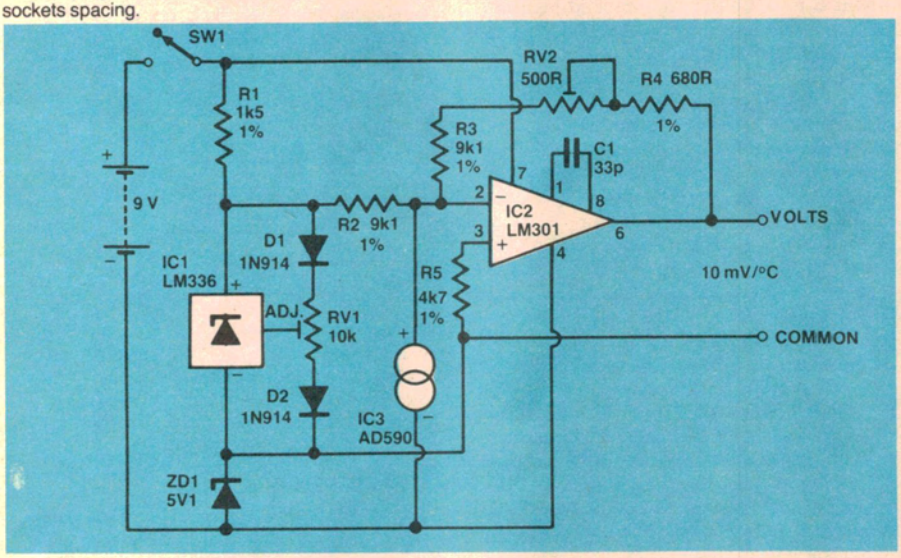
And it's 19.7°C! Our adaptor plugged into one of the lab. multimeters.

Superior interference rejection results from the output being a current rather than a voltage. In addition, power requirements are low (1.5 mWs @ 5 V @ +25°C), making the AD590 easy to apply as a remote sensor. The high output impedance (>10M) provides excellent rejection of supply voltage drift and ripple.

It is electrically durable, withstanding a forward voltage up to 44 V and a reverse voltage of 20 V. Hence, supply irregularities or pin reversal will not damage the device.



Simplicity. Construction is quite simple and all the electronics fits neatly in a small jiffy box. The tops of the banana plugs can just be seen. These are spaced at 19 mm ('GR' spacing) or to suit your multimeter input sockets spacing.



HOW IT WORKS — ETI-153

The AD590 temperature transducer, IC3, requires a voltage to be applied across it, developing a current that is directly proportional to absolute temperature with a precision sensitivity of 1 uA/°K. This is amplified by an op-amp, employed here as a current-to-voltage converter that provides an output of 10 mV/°C. As zero Kelvin is 273 degrees below zero Celsius, an 'offset' has to be provided for the output to be proportional to the Celsius scale. This is achieved by running the op-amp input at 'virtual ground' and supplying the AD590 sensor from a negative supply rail. Thus, at 0°C, the output will 0 V.

IC1 is a precision voltage reference (LM336) that maintains 2.49 V between its +ve and –ve pins. Two silicon diodes, D1 and D2, and a cermet (high stability) trimpot, RV1, allow the reference voltage to be 'trimmed'. This is normally done to minimise the temperature coefficient of the LM336, however, I have used it to provide trimming of the offset of Celsius zero from absolute zero.

Zener diode D3 provides a negative supply rail for the AD590 temperature transducer (IC3). The voltage obtained is around –4.5 V as the 5V1 zener is operated at a current of about 1 mA, set by the value of R1. The zener in the prototype was rated at 400 mW. If a 1 W type is used, R1 should be reduced to 1k.

IC2 is used in 'virtual ground' mode as a current-to-voltage converter. Its operation can be understood by remembering that IC2 is an op-amp and to a good approximation has infinite gain and infinite input impedance. A negative feedback path, formed by R3-R4-RV2, acts to maintain the inverting input (pin 2) at the same potential as the non-inverting input (pin 3). i.e: at 0 volts. Although very little current flows into pin 2 of IC2, it is kept at 0 V by the feedback action.

The AD590 connects to pin 2 of IC2 (inverting input) and acts as a current sink, passing 1 uA/°K. The reference, IC1, supplies a current of 273 uA through R2, which can be trimmed by RV1. Thus, the current through the feedback resistors is equal to the absolute temperature minus 273, in microamps, and results in an output voltage of 10 mV/°C when RV2 is set to provide the 'scale factor' required.

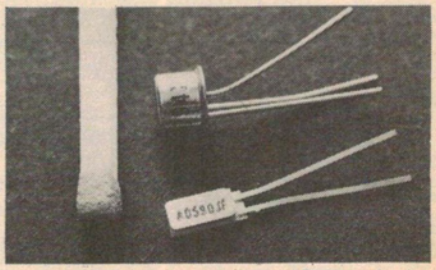
To ensure the appropriate accuracy, high stability 1% metal film resistors and cermet trimpots are used. Capacitor C1 provides compensation for the op-amp, to ensure stability.

The AD590 is available in a number of accuracy grades. The 'M grade' device will give better than ±0.05° accuracy from 0° to 100° Celsius. It costs around $60, however. For about $5, you can purchase the 'J grade' AD590 which will give an accuracy of ±0.3° from 0° to 100°C. The accuracy you get depends on a number of factors (discussed later) and the type of circuit.

The simplest circuit you could use is shown in Figure 1. This will give temperature directly in the Kelvin scale with a voltage/temperature relationship of 1 mV/°K. Thus at a typical ambient temperature of +25°C (298°K), the output will be 0.298 V. The output can be 'trimmed' to the correct temperature (calibrated) at one temperature point by the 200 ohm cermet trimpot. This is a 'one trim' circuit. With the AD590J, accuracy will be ±2° over the range from 0° to 100°C.

A circuit which provides for two trim, or calibration, points results in much better accuracy, Also, a more convenient voltage/temperature relationship is useful, which requires the output of the sensor to be scaled. An op-amp can be used for this to provide a stable gain. A figure of 10 mV/°C (or /°K) is suitable, and that's what I chose.

The accompanying photograph shows the two package styles compared to a match head. The TO-52 can (H package) is for general use. It has a longer time constant — the time taken to stabilise after changing the package's temperature — than the ceramic flat pack (F package). Typically, the H package will take four minutes to stabilise in still air, but the F package will only take about half that time. When applied to an aluminium block (e.g: a heatsink), the H package will typically take four seconds to stabilise, while the F package will take around half a second.



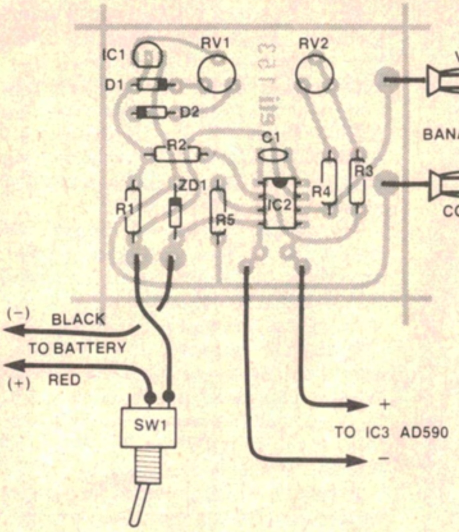
Tiny, what? The two versions of the AD590 packaging, compared to a match head. Above is the H package (TO-52); below is the ceramic F package.

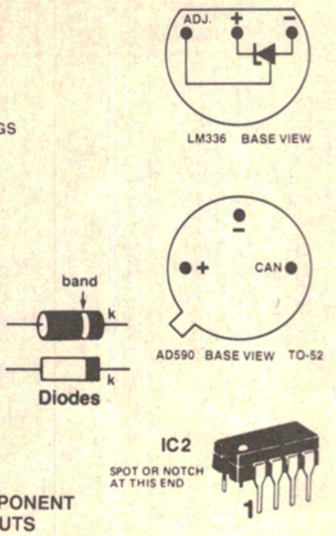
Construction

The project was designed to fit inside a small jiffy box with a metal lid having overall dimensions of 30 x 50 x 80 mm. They're common and low in cost.

All the electronics, except the AD590 sensor, are mounted on a small pc board. This can be assembled first. Just check your pc board before assembling the components, ensuring there are no broken tracks or shorts between tracks and that all holes are correctly drilled.

The components can be assembled to the pc board in any order, just watch that you put the two ICs, the two diodes and the zener the right way round. Don't take too long to solder the resistors as they are high stability types, but ensure that each joint is properly made. ▶





COMPONENT PINOUTS

I mounted the banana plugs in the box between the plastic pillars at one end so that the whole unit plugged straight into a normal multimeter. To do this, the plugs must be spaced ¾" (19 mm) which is known as 'GR' spacing. To make this easier, I have laid out the pc board with the output pads spaced exactly at 'GR' spacing. The board can be used as a template when drilling the holes for the banana plugs.

Remove the plastic body of each plug and solder about 10 cm of insulated hook-up wire to each. Using the pc board, drill pilot holes of about 1 mm diameter through the box near one end and enlarge them until the banana plugs will fit through the box.

Cut the plastic body of each plug in half and install the plugs, tightening the body from the inside for each plug.

Drill a hole for the switch, between the plugs, in the end of the box making sure that the switch will not foul the plugs.

If the switch you have will not mount as mine did then you may fit it into the lid of the box, but keep it near the end where the plugs are.

Also drill a hole, in the end of the box opposite the switch, for the cable from the sensor.

Wire up the battery connector, switch and plugs, following the overlay. Don't connect the AD590 yet. Plug the unit into your multimeter, set RV2 to the mid-position and set you multimeter to the 20 V range. Switch on and adjust RV1 to obtain a reading of −2.73 V.

The probe

I made the probe from the barrel of a BIC 'finepoint' pen. Discard the innards and cut back the pointed end by about 2 mm. Use a 7/32" drill bit to carefully enlarge the hole at the pointed end to a depth of 2 mm.

Cut the −ve lead of the AD590 back about 6-7 mm. This identifies the two leads. Now snip the tab off the AD590 and file the tab stump back to allow the device to slip into the pointed end of the modified pen barrel.

The lead between the sensor and the electronics is a convenient length of small figure-8 flex with one marked lead (i.e: 'light speaker wire'). I used a length about one metre long. Slip one end through the pen barrel and trim back the unmarked lead by about 6 mm. Solder the marked lead to the AD590 +ve lead, the unmarked (cut back) lead to the AD590 −ve lead.

It is important to keep moisture away from any exposed conductors, since only one microamp of leakage will cause a one degree error. Consequently, after soldering I coated all exposed conductors and the base of the AD590 with two coats of nail polish*, allowing drying time between coats.

Now seal the AD590 into the end of the pen barrel. I used a silicone sealant ('Silastic'), poking some down the pen barrel, in the pointed end first, then putting a blob on the base of the AD590 before pushing it in place. Wipe away any excess. Put a blob down the other end of the barrel, too.

Take the free end of the cable, strip and tin the two wires. Pass this end through the hole you drilled in the box for it and knot the cable on the inside leaving about 60 mm to the end. Solder the two wires to the pc board as per the overlay. Remember, the marked lead is from the +ve of the AD590.

PARTS LIST — ETI 153

Resistors	all 1% metal film, unless noted
R1	1k5
R2, R3	9k1
R4	680R
R5	4k7
RV1	10k cermet, horizontal pc mount trimpot
RV2	500R cermet, horizontal pc mount trimpot
Capacitor	
C1	33p ceramic
Semiconductors	
IC1	LM336 precision voltage reference
IC2	uA301, LM301 gen. purp. op-amp
IC3	AD590J precision temp. sensor (see text)
D1, D2	1N914 or 1N4148
ZD1	5V1, 400 mW zener (see note).

Miscellaneous
ETI-153 pc board; UB5 zippy box (28 x 54 x 83 mm); two banana plugs; hookup wire, cable, probe etc.

NOTE: A 5V6/1 W zener may be used but, if so, change R1 to 1k.

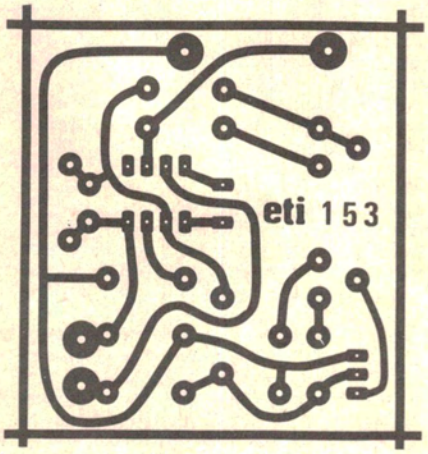
Price estimate $18 — $20

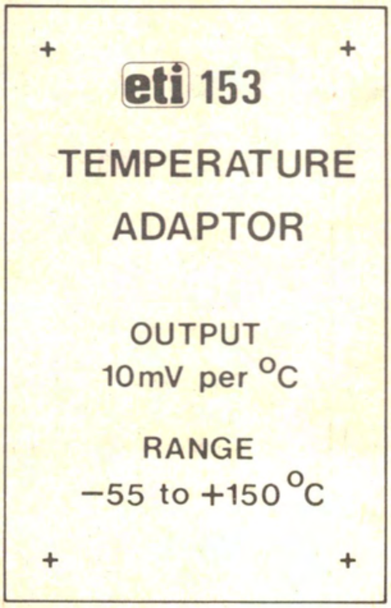
Switch the unit on and set the multimeter to the 2 Vdc range (unless it's an autoranging meter). You should get a reading of around 0.200-0.250 or so, depending on the ambient temperature. If not, reverse the leads from the AD590 and try again. If you still get no result, there's a fault which you'll have to track down and correct.

If all's well, you can now calibrate the unit for maximum accuracy.

Calibration

There are three main methods of calibration; I shall describe them in order of increasing





Artwork. Full size artwork for the pc board and front panel. You can obtain a 1:1 negative or positive, for making your own pc board and/or Scotchcal, for $1.00 each, post paid, ($2.00 the pair) from **ETI-153 Artwork, ETI Magazine, P.O. Box 21, Waterloo NSW 2017.** Make your cheque or money order out to 'ETI Artwork Sales'. Ensure you ask for a **positive** or **negative,** as you require.

accuracy.

The simplest way is to leave RV2 set in the mid-position and adjust RV1 to read a known temperature. This requires a thermometer to be placed in the same thermal environment as the AD590 sensor. This method will result in accurate readings over a range of 10 to 20 degrees, depending on the resolution of the reference thermometer.

The second calibration technique involves adjusting RV1 to obtain a reading at 0°C with the sensor immersed in melting ice, then placing the sensor in steam and adjusting RV2 for a reading at 100°C.

For this method, a good ice bath is a tall glass (but a vacuum 'Thermos' flask is better) filled with pure crushed ice which is then allowed to melt until the liquid level about two-thirds fills the glass.

Place the sensor about 20 mm below the water surface, wait for the multimeter reading to stabilise, then adjust RV1 to obtain a reading of 0.000 V.

Next, surreptitiously borrow a small saucepan from the kitchen and half an hour of kitchen time. Boil up a litre or two of water so that it's boiling rapidly with plenty of steam emitting. Place the sensor in the steam cloud, allow a few seconds for the reading to stabilise, then adjust RV2 for a reading of 1.000 V. Note that the boiling point of water depends on altitude so this method is strictly only accurate at or near sea level, unless you can borrow a reference thermometer of sufficient accuracy.

The most accurate calibration is obtained by using a laboratory grade thermometer and immersing it and the AD590 in a stirred liquid bath — first one bath at a temperature low in the desired range, then in another at a temperature high in the range. For best accuracy, you need to repeat the procedure several times, adjusting RV1 at the lower temperature and RV2 at the higher temperature, until the desired accuracy is reached.

With the calibration completed, you can complete the assembly. Cut a rectangle of thin cardboard the same size as the box lid, then cut off the corners. The pc board goes in the box with the components facing down, the battery going in first. The cardboard goes between the copper side of the pc board and the lid, preventing shorts.

I dressed up the box lid with a Scotchcal label. If you want to do the same, apply the Scotchcal to the lid before screwing it to the box. Peel off the backing at one end and carefully align it against the edge of the panel. Smooth it down and then continue peeling off the backing, smoothing the label in place as you go. Any air bubbles can be removed by rubbing them towards the nearest edge.

That's it!

For improved thermal coupling under some circumstance, a small heatsink can be slipped over the AD590. I used a Thermalloy No. 2224B. Note that this slows down the thermal response. When measuring the temperature of solid objects, particular metal objects (transistor cases, heatsinks, resistor bodies, etc), use a little thermal paste to improve thermal coupling. ●

ACCURACY

The overall accuracy of the ETI-153 is determined by three main factors: (i) *calibration error and overall accuracy* of the AD590 sensor; (ii) the *thermal environment* in which it is used, and (iii) *drift in the electronics* due to changes in the ambient temperature.

1. Calibration error and non-linearity of the AD590. This factor is easily calculated by referring to the table from the Analogue Devices applications note (Table 1), reproduced here. The 'Number of Trims' column refers to the type of circuit used with the AD590J. For the ETI-153, use the 'Two Trims' data. For the simple Kelvin circuit (Figure 1) use the 'One Trim' data.

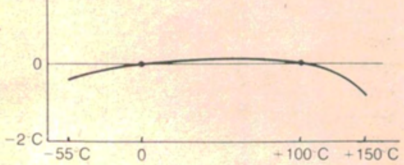
To obtain the error after calibrating at 0°C and 100°C, look down the row where the temperature span is 100°C until you find the column under 0°C, which is the lowest temperature in the span. The error is found to be ±0.3°C. If you calibrate the instrument at 0°C and 50°C, the error is ±0.1°C. These figures exclude any trim errors due to the calibration technique, of course.

2. Thermal environment. The AD590 dissipates a tiny amount of power owing to the voltage across it and the current flowing through it. This power causes self-heating of the sensor and must be allowed for so as to obtain maximum accuracy.

The rise in sensor temperature due to self-heating is given by:

$$T_J - T_A = P(\theta_{JC} + \theta_{CA}).$$

Where T_J is the junction temperature of the AD590.
T_A is the ambient temperature
p is the power dissipated
θ_{JC} is the chip-to-case thermal resistance
θ_{CA} is the case-to-medium thermal resistace



Typical two-trim accuracy.

J GRADE Number Of Trims	Temperature Span (°C)	Lowest Temperature In Span (°C)							
		-55	-25	0	+25	+50	+75	+100	+125
None	10	4.2	4.6	5.0	5.4	5.8	6.2	6.6	7.2
None	25	5.0	5.2	5.5	5.9	6.0	6.9	7.5	8.0
None	50	6.5	6.5	6.4	6.9	7.3	8.2	9.0	–
None	100	7.7	8.0	8.3	8.7	9.4	–	–	–
None	150	9.2	9.5	9.6	–	–	–	–	–
None	205	10.0	–	–	–	–	–	–	–
One	10	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.3
One	25	0.9	0.6	0.5	0.5	0.5	0.6	0.8	0.9
One	50	1.9	1.5	1.0	1.0	1.0	1.5	1.9	–
One	100	2.3	2.2	2.0	2.0	2.3	–	–	–
One	150	2.5	2.4	2.5	–	–	–	–	–
One	205	3.0	–	–	–	–	–	–	–
Two	10	0.1	*	*	*	*	*	*	0.1
Two	25	0.2	0.1	*	*	*	*	0.1	0.2
Two	50	0.4	0.2	0.1	*	*	0.1	0.2	*
Two	100	0.7	0.5	0.3	0.7	1.0	–	–	–
Two	150	1.0	0.7	1.2	–	–	–	–	–
Two	205	1.5	–	–	–	–	–	–	–

*Below 0.05°C

Table 1.

Typical values of $\theta_{JC} + \theta_{CA}$ are given in Table 2.

Using this information, the temperature rise at 25°C (= 298°K) due to a power dissipation of approximately 298 uA by 4.5 V = 1.3 mW (in still air, without a heatsink), is given by:

$$T_J - T_A = 1.3 \times 10^{-3} \times 480$$
$$= 0.62^\circ C.$$

Note however, that $T_J - T_A$ is directly proportional to the absolute temperature and hence, if the ETI-153 is calibrated with the AD590 in the same medium as it will be used, then the adjustment of the scale factor, with RV2, will compensate for the self-heating effect. In any case, the error is reduced by better thermal coupling to the medium.

The other main environmental effect is the thermal time constant, or the speed of response of the sensor to temperature changes. The column, τ, in Table 2 gives the time required to reach 63.2% of a step temperature change. The response is given by:

$$T(t) = T_{initial} + (T_{final} - T_{initial})(1 - e^{-t/\tau})$$

3. Drift in the electronics due to ambient temperature changes. There are three error terms here. *Thermocouple errors* are introduced by dissimilar metal junctions being at different temperatures. This can only be seen in the AD590 end of the circuit, since all the electronics in the jiffy box can be assumed to be at the same temperature.

Since the AD590 has a power supply rejection of 0.5 uA/V and the maximum possible thermocouple voltage is far less than 20 mV, the effect on the output is negligible.

The electronics in the jiffy box operates at *ambient temperature* which introduces errors when it varies from what it was during calibration of the instrument.

The major contribution to this error comes from the two ICs. Using the worst-case figures for temperature changes over a 0° — 70°C ambient range results in a maximum error of less than 1°C in the output. In practise, the drift from this cause should be much less.

I subjected the prototype to a blast from a hair dryer for about one minute which resulted in a temperature change of 0.1°C. Few multimeters would have better stability than the ETI-153 under these conditions.

Over normal ambient temperature changes ranging from about +15° to +35°, the output change caused by drift in the electronics should not degrade the accuracy of the AD590.

MEDIUM	$\theta_{JC} + \theta_{CA}$ (°C/watt)		τ (sec)	
	H	F	H	F
Aluminium block	30	10	0.6	0.1
Stirred oil	42	60	1.4	0.6
Moving air				
with heatsink	45	—	5.0	—
without heatsink	115	190	13.5	10.0
Still air				
with heatsink	191	—	108	—
without heatsink	480	650	60	30

Table 2