A preamplifier for moving-coil cartridges

For those who prefer the sound of moving-coil cartridges, we present this fine preamplifier using ultra well-matched monolithic transistor pairs to achieve very low noise. The circuit can be battery operated or mains-powered with a plugpack.

by RON DE JONG

By far the most common cartridge currently in use is the moving magnet (or MM) cartridge. In this design, a tiny magnet mounted on the remote end of the cantilever provides a magnetic field cut by two fixed coils mounted close by.

When the magnet is set in motion, as occurs when the stylus tracks the record groove, the magnetic field moves and small electrical signals are generated by the two coils. These signals are subsequently fed to a phono preamplifier and to the tone control and power amplifier stages.

Over the last few years, however, there has been renewed interest in another type of cartridge – the moving coil (or MC) cartridge. Some dedicated hifi enthusiasts claim that the MC cartridge offers advantages in terms of transient response, frequency response, and phase response at high frequencies. Whether or not these claims are valid is a matter for some argument – suffice to say that we do not intend to enter the debate here.

So how does a moving coil cartridge differ from a moving magnet type? The answer is that the positions of the coils and magnets are reversed, although the principle of operation remains essentially the same.

In the moving coil cartridge, the magnet is held stationary while two miniature coils are mounted on the cantilever assembly and move as the stylus tracks the groove (hence the name "moving coil"). Since the coils are attached to the cantilever, they must be kept extremely small to keep the tip mass to a minimum. As a result, the output level of an MC cartridge is extremely low, typically around 200μV at a recording velocity of 5cm/s.

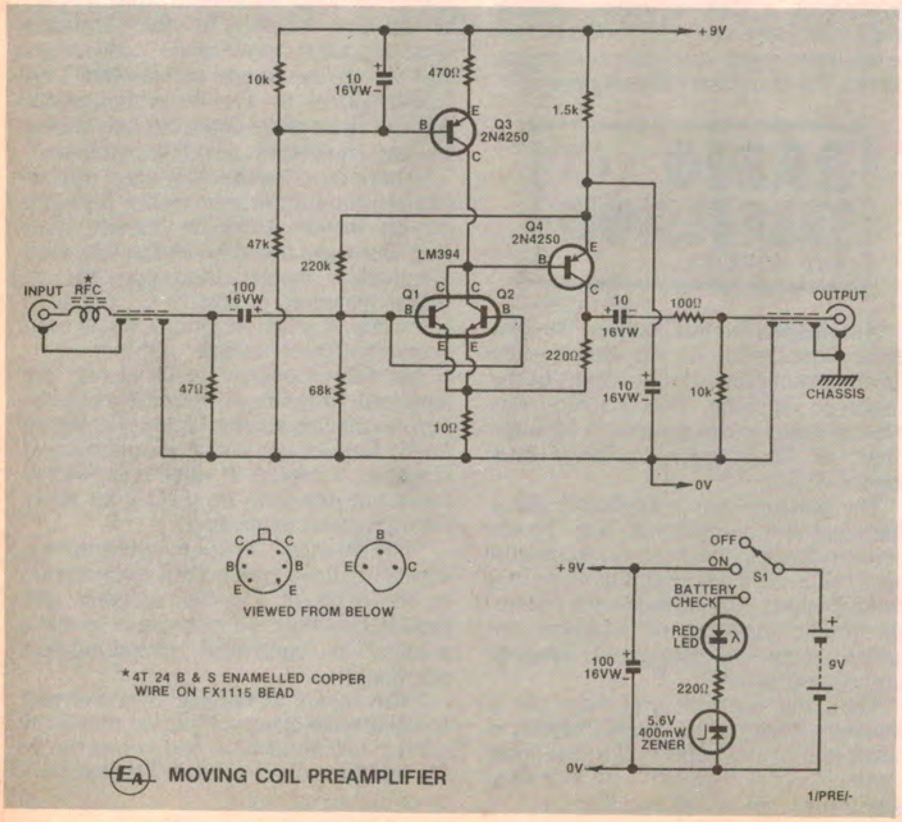
This is around 27dB below the output level of an MM cartridge, which is typically around 5mV (or more) at 5cm/sec.

Because the output of an MC cartridge is so low, considerable voltage gain is required before the signal is fed into the phono inputs of a conventional hifi amplifier. One solution is to use a transformer but these are quite expensive and difficult to manufacture. The alternative solution is to use an additional preamplifier stage, and the design presented here has performance equal to or better than most commercial units for a fraction of the cost.

Before taking a look at the circuit, however, it may be as well to point out that the requirement for a separate preamplifier is one reason why MC cartridges have not gained widespread popularity in the past. Commercial units tend to be expensive and this, coupled with the high cost of the cartridge itself ($100 or more), has been sufficient to deter most hifi enthusiasts. This project will help overcome that problem, at least as far as the cost of the preamplifier is concerned!

DESIGN CONSIDERATIONS

Perhaps the most important specification of an MC preamplifier is the signal-



MOVING COIL PREAMPLIFIER

SPECIFICATIONS

INPUT IMPEDANCE: 47Ω
FREQUENCY RESPONSE: 20Hz to 100kHz ± 0.25dB
CHANNEL SEPARATION: better than 80dB at 10kHz
GAIN: 27dB
NOISE: 64dB with respect to input level of 150μV unweighted over a 20Hz to 20kHz bandwidth
DISTORTION: .008% for 300mV output; unmeasurable at normal output levels.
MAXIMUM INPUT VOLTAGE: 20mV

to-noise ratio. Let's first take a look at the various sources of noise and find out how these may be minimised in a low noise preamplifier design.

There are four main sources of noise in a transistor amplifier: shot noise, emitter base voltage noise, 1/f noise and thermal noise. These individual noise sources are illustrated in Fig. 1 which shows a simplified model of a noisy transistor amplifier. Note that we only show noise generators at the input of the amplifier and not noise generated in later stages. In most cases this is quite valid since the amplifier is most sensitive at the inputs and following stages will operate at higher signal levels.

Looking at each noise source individually, "shot noise" or quantum noise occurs because of the discrete nature of electric current; ie the individual electrons comprising the current flow. The mechanism involved is analogous to rainfall in that individual raindrops striking a tin roof create noise. From this you can see that shot noise actually increases with collector current. Another feature of shot noise is that it is "white" ie, the noise amplitude is constant with frequency.

Referred to the input of the transistor this shot noise is called base current noise and is modelled by a current generator at the input (see Fig. 1). The formula for base current noise is given by equation (1) in Fig. 1.

Emitter-base voltage noise is modelled by a voltage source in series with the base and is given by equation (2). This is also a white noise source but, unlike base current noise, actually decreases with increasing collector current.

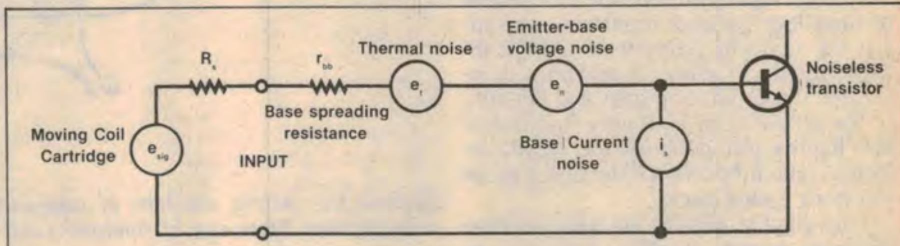
1/f or "flicker" noise is a significant source of noise at low frequencies because, as its name suggests, it has 1/f spectral characteristic and so noise voltage increases as the inverse of the frequency. There are no exact formulas for this and it is simply given by equation (3) where K and k are constants which depend on the actual device used.

The best known source of noise is probably the thermal or "Johnson" noise generated in a resistor. This also has a white noise distribution and is given by equation (4). We can minimise this source of noise by minimising the input resistance, and this has the added benefit of reducing input noise voltage due to base noise current.

Referring to Fig. 1, we can see that this input resistance consists of the source resistance and the "base spreading" resistance of the input transistor. The source resistance is the resistance of the MC cartridge and is about 3Ω, while the base spreading resistance is an inherent feature of the transistor.

Clearly, we can significantly reduce thermal noise by choosing a transistor with a very low Rbb – or base spreading resistance. Most audio transistors have an Rbb of around 100Ω while for some UHF transistors it can be as low 4Ω. In fact, some designs for MC preamps do use UHF transistors. We can also achieve low Rbb, however, by simply connecting a large number of transistors in parallel, thus dividing Rbb by the number of transistors used.

The outputs from the Moving Coil Preamplifier are fed into the "phono" inputs of a conventional hifi amplifier. Unit has built-in battery check function.



$i_s^2 = 2qI_c/h_{FE}\ A/\sqrt{Hz}$ ... (1)

$e^2 = K^2T^2 2/qI_c\ V/\sqrt{Hz}$ ... (2)

$i_f^2 = K.I^a/f\ A/\sqrt{Hz}$ ... (3)

$e^2 = 4kT(R_s + r_{bb})\ V/\sqrt{Hz}$ ... (4)

$e^2 = e^2 + e^2(R_s + r_{bb})^2 i_s\ V/\sqrt{Hz}$ ... (5)

$I_{c(opt)} = kT/q\sqrt{h_{FE}}/R_s + r_{bb}$ ... (6)

FIG. 1 $q = 1.6 \times 10^{19}$ Coulombs, $k = 1.38 \times 10^{-23}$ J/°K, T = 300°K

The approach we eventually took was to use an LM394 super-matched transistor pair. Each of these transistors actually consists of a large number of individual transistors connected in parallel, giving each device an Rbb of 40 or 20 when the two are connected together. These transistors also have very high Hfe of 500 and due to the large number of transistors, statistical variations are considerably reduced and 1/f noise is very low.

What has emerged so far is that we can minimise noise by reducing the input resistance, but so far we have not considered how to minimise the effect of base current noise and emitter-base voltage noise. Since one increases with collector current while the other decreases, there is an optimum collector current at which the overall noise is at a minimum. To work this out we have to sum all the noise sources into an "equivalent input noise voltage".

Since the various sources are statistically unrelated, we do not simply add the voltages together but take the square root of the sum of the squares as shown in equation (5). Differentiating this equation with respect to collector current reveals that the minimum noise occurs according to equation (6).

THE CIRCUIT

Let's now take a look at the actual circuit we have used. The basic configuration is one we have taken from the National Semiconductor Linear Applications Handbook and uses just four transistors. Briefly, Q1 and Q2 are connected in parellel as a common emitter amplifier with Q3 as a constant current load. This drives Q4, another common emitter amplifier, which in turn drives the output and the feedback network to Q1 and Q2.

Looking at the circuit in more detail now, we have included a small RF choke at each input. This consists of four turns of 28SWG wire on an FX1115 bead and, in conjunction with the 47Ω resistor following, prevents RF interference from being rectified by the input stage and passed to the amplifier Q5. A 100μF electrolytic capacitor couples the input signal to transistors Q1 and Q2.

Because of feedback to the emitters of Q1 and Q2, the input impedance of the stage is quite high at around 35kΩ. The recommended load for most moving coil cartridges is merely stated as being greater than 10Ω but if it is too high the leakage inductance of the cartridge will create unwanted bass boost. It is for this reason that we have included the 47Ω resistor on the input.

Incidentally, this is the standard input impedance of most MC preamplifiers.

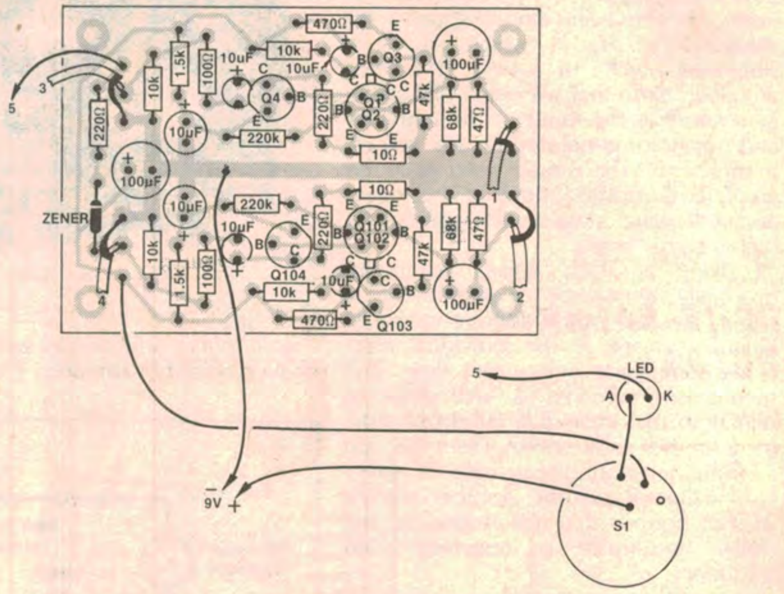
The collector load of Q1/Q2 is transistor Q3, used here as a constant current source delivering about 3mA. We have used this in preference to a simple resistive load because it permits us to adjust the collector current of Q1/Q2 independently of gain. In addition, it increases the open loop gain and linearity of the amplifier to give very low distortion figures and increases the supply rejection ratio (important if the unit is to be run from a plug pack).

Following Q1 and Q2 we have another common emitter amplifier consisting of transistor Q4. The emitter is decoupled to ground rather than to the supply which again improves the supply rejection, and the emitter voltage is used to bias Q1 and Q2 on. This arrangement is a variation on collector biasing since the emitter voltage of Q4 tracks the collector voltage of Q1 and Q2. However, it has an advantage over conventional collector biasing in that there is no loading effect.

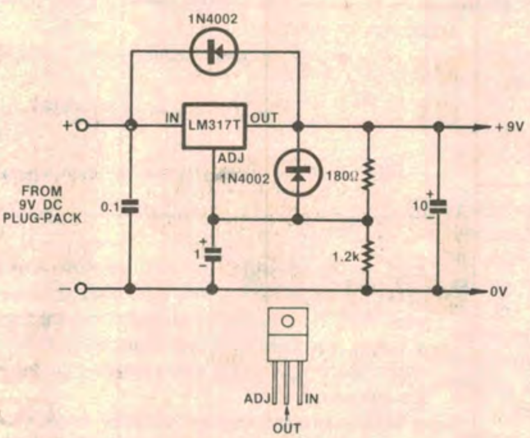
Collector load of Q4 is a 220Ω resistor which forms part of a voltage divider feedback circuit with the 10Ω emitter resistor of Q1/Q2. The voltage divider ratio sets the closed loop gain at 23 – or about 27dB – which is the gain required to bring moving coil cartridge output levels up to normal phono input levels.

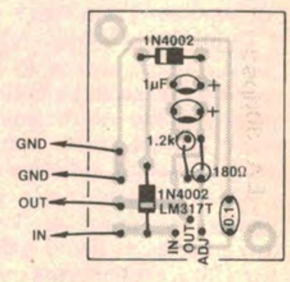
Output from the MC preamplifier is AC –coupled via a 10μF tantalum capacitor and a 100Ω resistor with a 10kΩ pulldown resistor after the capacitor to remove any DC voltage on the output. The purpose of the 100Ω resistor is to isolate the feedback loop from any loading effects of the following amplifier or shielded cable. If this is not done, any capacitive loading will introduce an additional "pole" or phase lag which could make the MC preamplifier unstable.

At this stage we can work out what the equivalent input noise voltage is and (hopefully) see if it matches the measured result. Using the formulae already given, the individual noise contributions are as follows: Emitter-base voltage noise = 0.327nV/(Hz)$^{1/2}$; Base current noise xR = .026nV/(Hz)$^{1/2}$; Thermal noise (including cartridge = 0.617nV/(Hz)$^{1/2}$.



Follow this wiring diagram in conjunction with the circuit when wiring up the preamplifier. Note use of shielded cable between the PCB and RCA sockets.





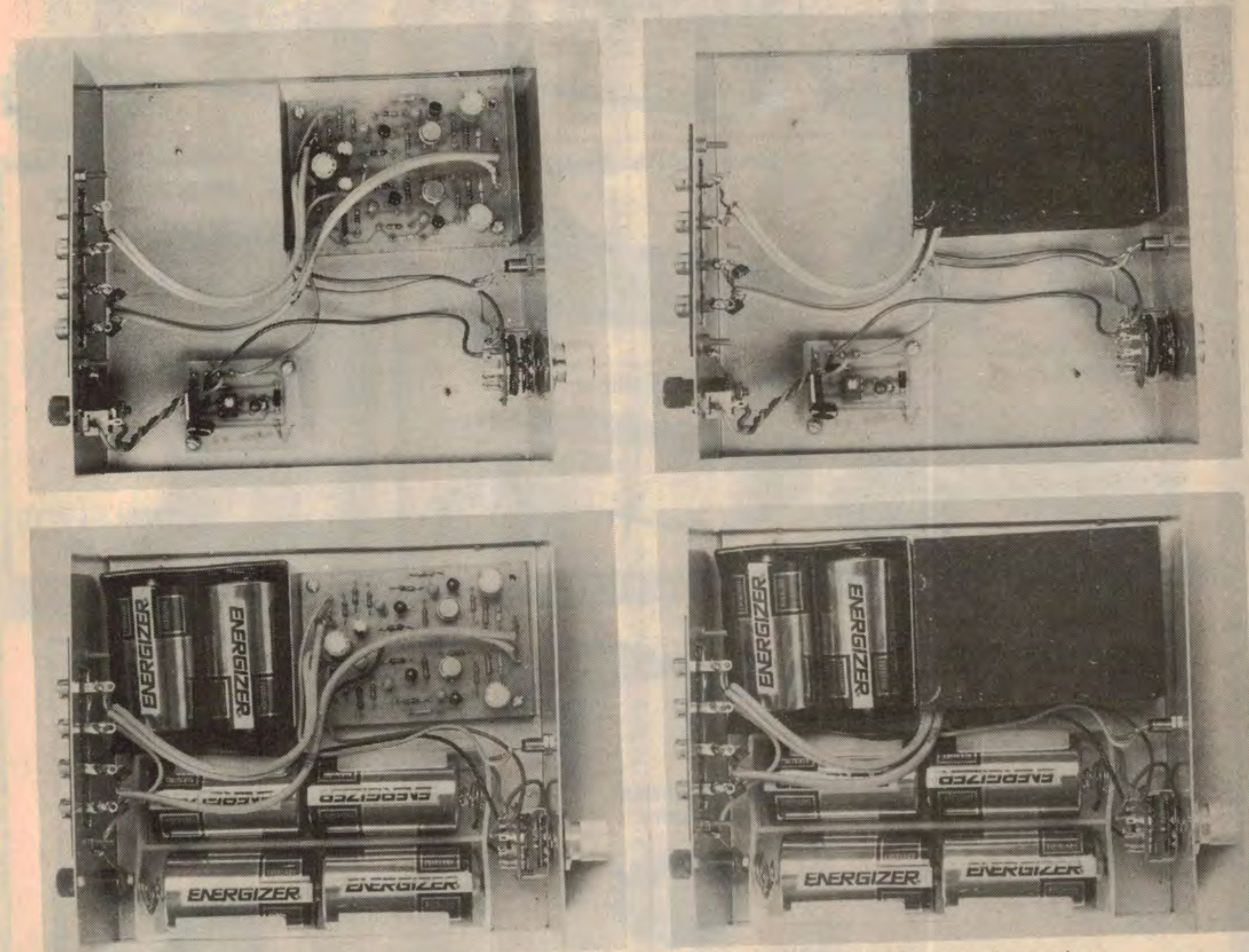
Optional voltage regulator circuit and PCB component overlay for plug pack operation.

Adding all of these vectorially gives 0.7nV/(Hz)$^{1/2}$ which taken over a 20kHz bandwidth gives a total input noise of 98nV. This gives a S/N ratio of 64dB with respect to a 150μV input signal, which is exactly the measured result.

One point which also emerges from this is that the base noise current is well below the other noise sources. Hence we could have increased the collector current of Q1/Q2 and thus reduced the emitter base voltage noise considerably. If we use the formula for optimum collector current for lowest noise we find that this current is around 20mA which is much greater than the 3mA we chose. We did this for two reasons however: lower distortion and lower power consumption.

Power for the unit can be obtained either from six 1.5V "D" size batteries or from a 9V DC plug pack and a small regulator circuit inside the unit. The regulator printed circuit board is one we have used before and is intended as a general purpose regulated supply. In practice we found that this arrangement was just as quiet as the battery operated version so long as the plug pack transformer is kept some distance from the unit.

We have also provided a battery check function consisting of a front panel LED, 220Ω resistor and 5.6V zener diode. When the front panel switch is set to "battery check" power is applied to this circuit. If the battery voltage exceeds the 5.6V drop across the zener and the 1.6V drop across the LED – ie 7.2V – then the LED will turn on. If the LED glows very



These internal views show the plug pack powered version (top) and the battery powered version (bottom).

feebly or not at all, a new battery is required.

CONSTRUCTION

Construction of the unit is straightforward. Most of the components are mounted on a single printed circuit board (PCB) coded 81mc7 and measuring 62 x 89mm. The optional regulator board is required for plug pack operation only. It measures 46 x 36mm and is coded 80gps3.

Mount the components on the main PCB according to the component overlay diagram included with this article. In particular note the orientation of the zener diode, transistors and electrolytic capacitors. We recommend that PC stakes be used for the various connections to the board, as these simplify connection and give a neat appearance.

We built our unit into a standard metal case measuring 184 x 70 x 160mm (D x H x W). This unit comes with a U-shaped steel cover and an aluminium base and, because the case is not all steel, trouble with hum fields from nearby power transformers may be experienced in some instances. Our solution was to mount the preamp board inside a separate small galvanised (more commonly referred to as galvanised iron) steel box. This gives excellent results and, because it is inside the main case, does not detract from the appearance of the unit.

You will have to fabricate the steel box yourself. It consists of two U-shaped pieces (which may be galvanised iron, Zincalume, Marviplate, etc) which form the base and the lid. Dimensions of the box should be 64 x 92 mm (ie, just large enough to accommodate the PCB), while the height should be around 40mm. The PCB is mounted inside the box using four 10mm tapped brass spacers, which also serve to hold the base of the box inside the main case.

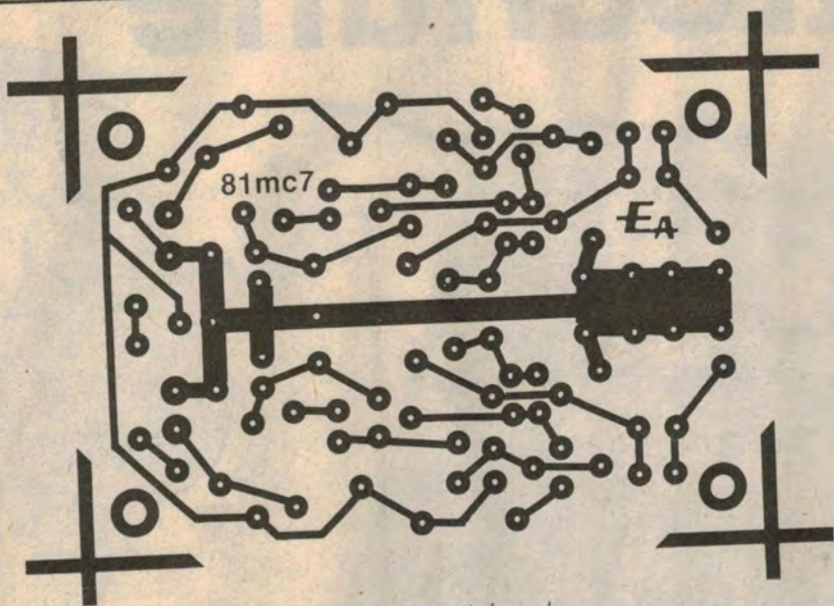
Before mounting the PCB, however, make a cutout on the back panel for the 4-way RCA connector and drill holes for the back panel earthing terminal and the front panel switch and LED bezel. Drilling centres can be obtained from the front panel artwork shown actual size in this article. This artwork can also be used to produce a Scotchcal front panel or you can obtain a finished panel from the usual sources shown on the last page of this magazine.

The back panel earth terminal must be connected to an earthed lug and thence

We estimate that the current cost of components for this project is about

$30

including sales tax.



Actual size reproduction of the printed circuit board.

to the earth terminal on one of the output sockets. The RF chokes at the inputs are made by passing four turns of 28 SWG enamelled copper wire through a small ferrite bead, type FX1115 from Philips. One end of each choke is soldered to an RCA input terminal and the other end to the inner conductor at the shielded cable. The outputs from the preamp are also connected via shielded cable.

If you are using batteries to power your unit then you will require one 4 x "D" cell battery holder and one 2 x "D" cell battery holder. These are wired up in series to give the requisite 9V. Alternatively, a plug pack power supply and the regulator board can be used.

Finally, check all wiring carefully and then switch to the "battery check" position. The front panel LED should come on to indicate that battery voltage is present. Now switch to the "on" position and check the preamplifier for correct operation simply by connecting it to an MC cartridge and amplifier and "trying it out".

If an MC cartridge is not immediately available, touch the input terminals with your finger. You should hear a loud hum from the loudspeakers. Happy listening!

Back panel view of the unit. The two output sockets are at left while the input sockets are at right.

PARTS LIST

- 1 metal case, 184 x 70 x 160mm (D x H x W)
- 1 printed circuit board, code 81mc7, 62 x 89mm
- 1 single pole 3-position rotary switch
- 1 small red LED
- 1 4-way RCA panel socket
- 1 terminal post
- 6 1.5V "D" cell
- 1 4 "D" cell holder
- 1 2 "D" cell holder
- 4 10mm tapped brass standoffs
- 2 FX1115 ferrite beads
- ½ metre of 28SWG enamelled copper wire
- ½ metre of twin shield cable

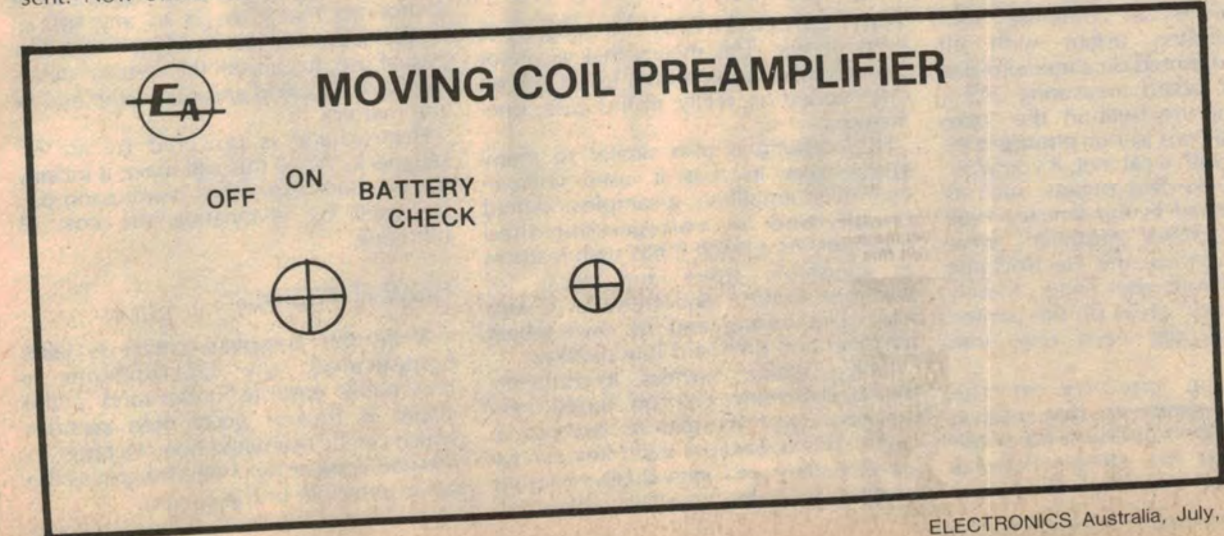
SEMICONDUCTORS
- 2 LM394 super match transistor pair
- 4 2N4250 PNP transistors
- 1 5.6V 400mW zener diode

CAPACITORS
- 3 100μF 16VW PC electrolytics
- 6 10μF 16VW PC electrolytics

RESISTORS (all ½W, 5%)
2 x 220kΩ, 2 x 68kΩ, 2 x 47kΩ, 4 x 10k Ω, 2 x 1.5kΩ, 2 x 470Ω, 3 x 220Ω, 2 x 100Ω, 2 x 47Ω, 2 x 10Ω

MISCELLANEOUS
Machine screws and nuts, hook-up wire, PC stakes etc.

ADD FOR PLUG-PACK OPERATION
- 1 9V DC plug-pack supply
- 1 printed circuit board, code 80gps3, 46 × 36mm
- 1 LM317T three-terminal regulator
- 1 3.5mm jack socket
- 2 1N4002 diodes
- 1 0.1μF metallised polyester capacitor
- 1 1μF 16VW tantalum capacitor
- 1 10μF 16VW tantalum capacitor
- 1 1.2kΩ resistor
- 1 180Ω resistor



Finished Scotchcal front panels will be available from the usual parts suppliers.