Versatile radiation meter

Disappointed with current Geiger-tube circuits, Darren Heywood set about designing a more versatile meter with voltage, 4-20mA and audio outputs.

Designs for geiger counters that I have seen published tend to be crude. For example, the HT power supply powering the geiger tube is not regulated and of extremely high impedance. Moreover, the output is usually just a simple series of audio clicks. Assuming that a geiger tube costs £30 or more, providing it with such a basic output method is a waste.

The reason for my interest in Geiger counters was to find out if a high voltage flash over produced gamma radiation. This idea seemed plausible since a spark gap radiates electromagnetic radiation in the hf band, light and ultra violet rays, and perhaps X rays. Gamma radiation is just above ultra violet and X-rays in the electro magnetic spectrum.

Features of my finished design are given in the panel.

Features of the radiation meter

- HT continuously variable between 0-1100V
- HT can source 1mA continuously at 1000V
- The instrument is portable, powered by 12V batteries
- Five calibrated outputs, namely:
  - 0-5V output
  - 4-20mA output for chart recorders, etc, calibrated for 0-1mrad/h
  - Direct frequency output
  - 0-1mA moving coil meter output, calibrated in two ranges
  - 0.5W variable audio output
- Can accept a variety of different tubes
- Excellent accuracy
- Low battery indicator
- Simple to calibrate if tube data is available
- Two meter ranges
- All parts easily obtainable and cheap

Geiger tube selection

I spent a while looking for a suitable tube. Langrex Electronics was helpful in supplying data on the *MX* series. From that data, it seemed obvious that the most sensitive tube would have the following properties:

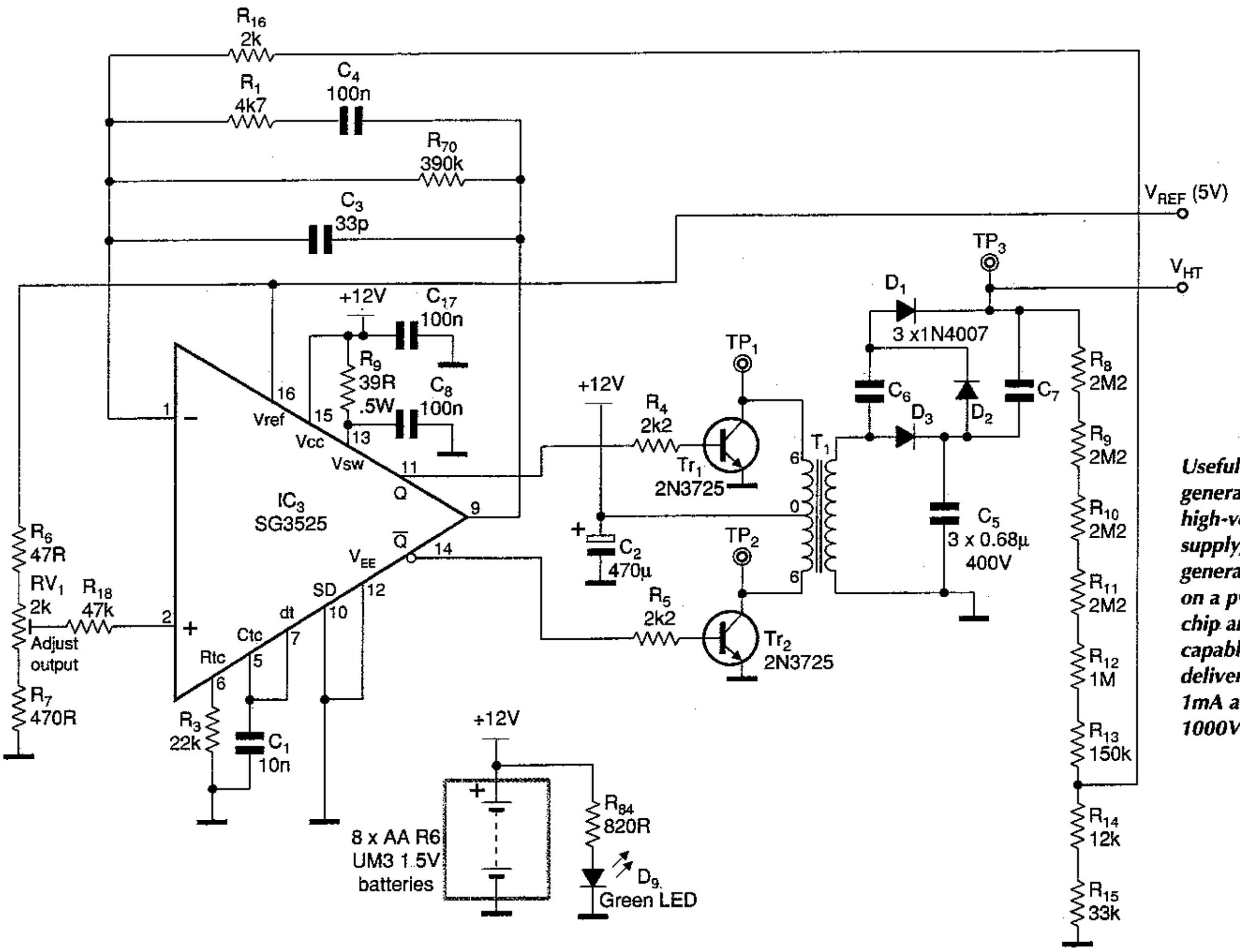
- Highest counts/min for 1mrad/h (good resolution)
- Lowest background counts (low noise)
- Lowest dead time

The *MX178* seemed to the most suitable candidate, but I was quoted £350 for it. Out of the suppliers I contacted, Colomor Electronics gave the best deal, offering an *MX120/01* for £35 inclusive. This tube is robust and measures around 20mm diameter by 160mm long.

For the price, the gain of this particular tube is good. At 1millirad/hour, it outputs 113.3Hz. Maximum background count averages around 1.5Hz, so resolution is 1.5/113.3, which equates to 13.24µrad/hour. This means that if the tube was exposed to 13.24µrad/h, it wound be unlikely that any pickup would be detected. In other words, you would not be able to tell difference between background radiation and this dose level.

Gain of the *MX120/01* is simply 113.3Hz/mrad/h. In contrast, the *MX178* has a gain of 146.7Hz/mrad/hour with a resolution of 1/146.7, which is 6.82µrad/hour. Clearly this is a better choice if you can afford it.

Dead time for the *120/01* is approximately 250µs measured on a *TEK475* oscilloscope. This is the time span that the tube is ionised or active. Once the tube has been activated by ionising radiation, it will take it about 250µs to return to its normal state.



Useful also as a general-purpose high-voltage supply, this HT generator is based on a pwm driver chip and is capable of delivering up to 1mA at 0 to 1000V.

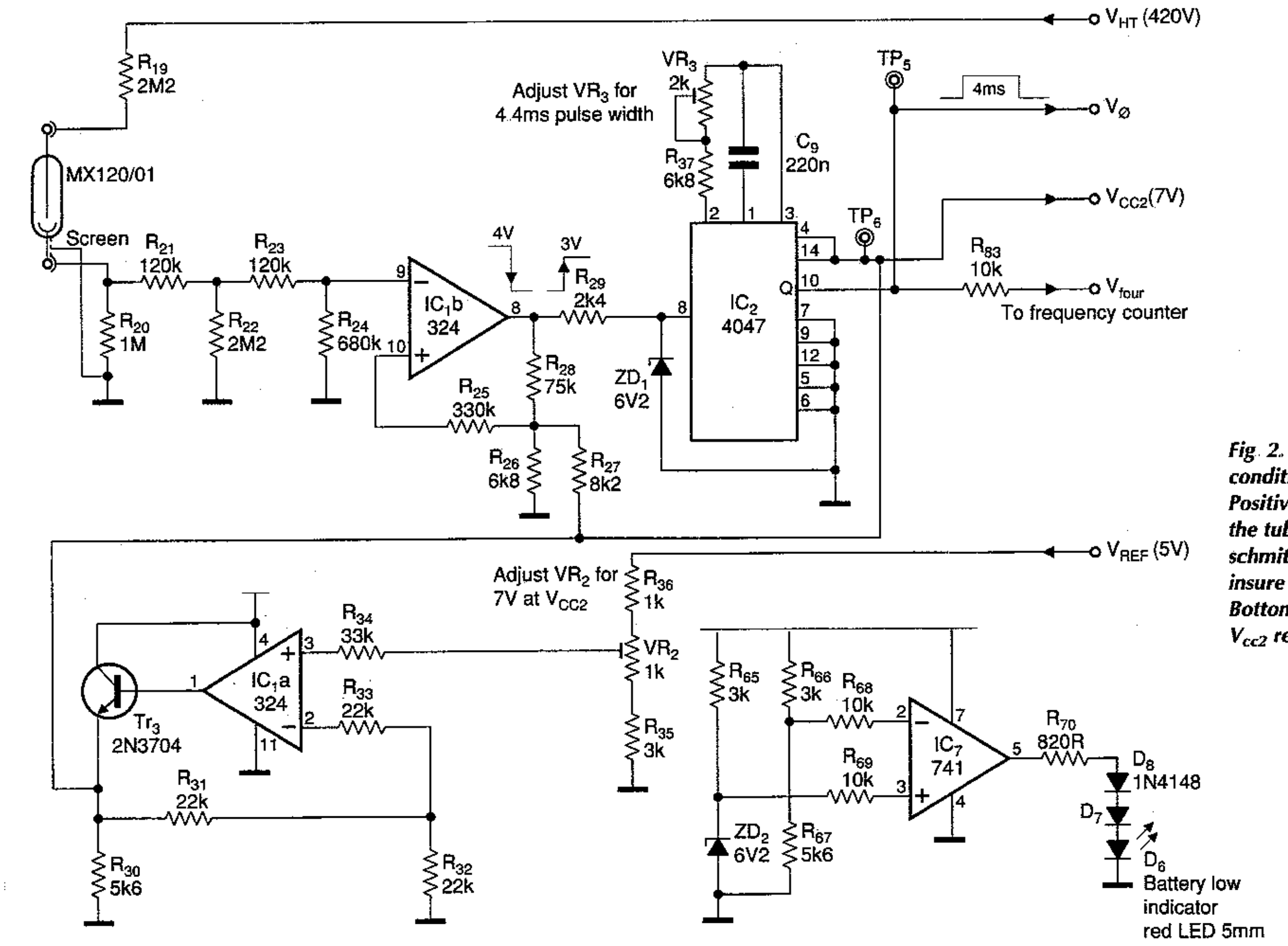
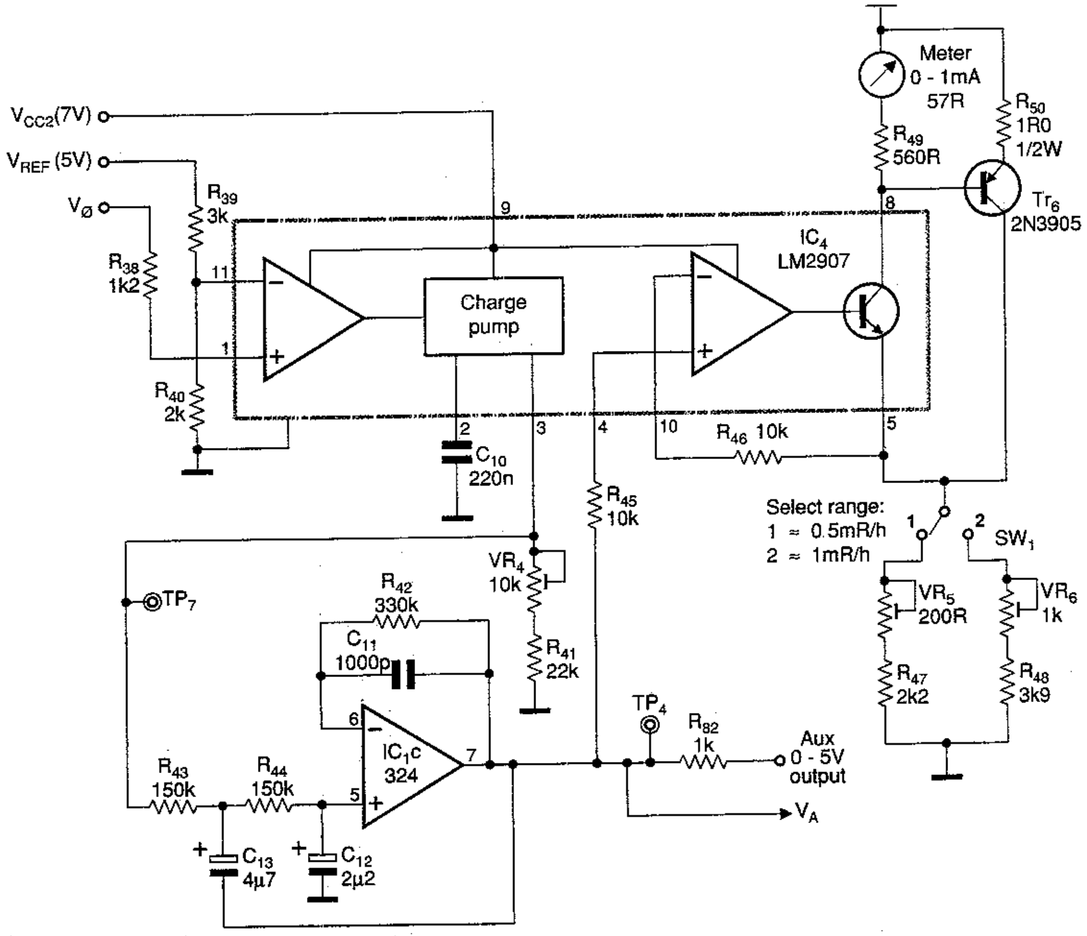


Fig. 2. Input conditioning circuits. Positive pulses from the tube feed a schmitt trigger to insure integrity. Bottom left is the 7V V_{cc2} regulator.



Heart of the radiation detector is this frequency-to-voltage converter. In addition to providing meter drive, this circuit also has a 0 to 5V auxiliary output.

Generating 1kV at 1mA

One of the most efficient methods of transferring energy across a transformer is via pulse width modulation

As you can see from **Fig. 1**, I have exploited the *SG3525* pwm chip. Potentiometer RV_1 allows the output voltage to be adjusted anywhere between 0 and 1100V, the output having very little ripple. At 1000V, the output, is capable of sourcing 1mA continuously and hence a power of 1W is delivered. This figure may be increased by reducing resistor values R_4 and R_5.

The manufacturer guarantees 400mA sourcing/sinking at output pins 11 and 14 I tried this on breadboard, only to find that the chip became excessively hot. For this reason, two 2N3725 moderate power switches were added. These are superior to the more common 2N2219As and faster. While on, these transistors conduct approximately 250 to 300mA.

In conjunction with R_3, pins 6, 5 and 7 and C_1 set the free running oscillator to 3.570kHz. Pin 7 is the dead time pin but is not used in this application since turn on/off times of $Tr_{1\,2}$ are very fast.

Transformer T_1 is a standard 6VA 240V primary with 6-0-6 secondary type for pcb mounting. Mine came from Rapid Electronics, part No 88-0150. Components $D_{1\text{-}3}$ and $C_{5\text{-}7}$ form the voltage tripling and smoothing of the output.

You will notice that R_{14}+R_{15}+R_{16} is equal to R_{18} so the two op-amp input currents are about balanced. This helps reduce offset and drift inherent in the op-amp It is good design practice to balance the differential inputs no matter what the circuit application is I have endeavoured to do this throughout this design,

It is common knowledge that the first stage op-amp on the front end of any pwm chip provides the majority of the open-loop or system gain. Consider the output divider $R_{8\text{-}15}$ which attenuates the output by as much as 46.2dB. This means the closed-loop gain will be around 46dB or approximately 200.

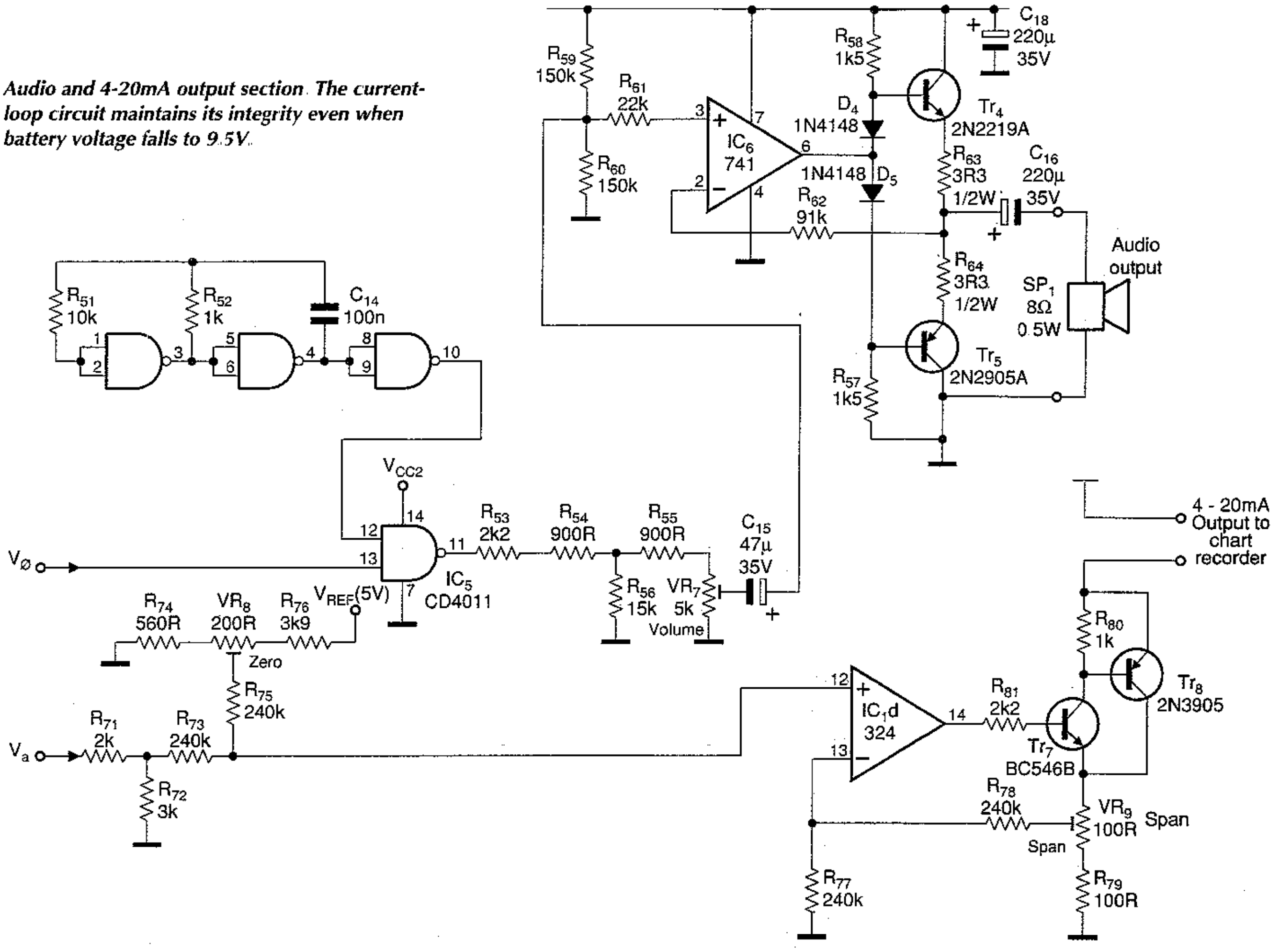
Since the closed-loop gain requirement is so high and the loop gain is only 80dB or 10000, I was slightly worried about the overall accuracy.

For example, the error between the two differential inputs will be about 10mV This disregards offsets and drift etc. As a result, it would be desirable to have an open-loop gain of say 100dB. This would reduce the closed-loop error by a factor of 10. Now, an error of 1mV would exist between the differential inputs This is of course without R_{17} being in circuit

Loop tuning components consisted of C_3, R_1. Capacitor C_4 and R_7 were included at a later stage To check the loop performance, I injected a variable frequency signal on pin 2 and noticed the natural frequency of the loop was in the order of 25Hz – and it was almost oscillating

At this point, I had two choices. I could either increase C_4, thus increasing the phase margin, or I could reduce the overall gain. I was reluctant to do the former since this would slow the loop response down Consequently I strapped a resistance decade box across pins 1 and 9 and adjusted the box until good stability was achieved at 25Hz This is the main reason for including R_{17}.

Overall, the stability is excellent, the loop being reasonably fast. The output stays within 1V anywhere in range 0 to 1100V Pin 16 outputs a stable 5.1V reference voltage capable of supplying 20mA or more. This reference voltage is used throughout the instrument.



Audio and 4-20mA output section. The current-loop circuit maintains its integrity even when battery voltage falls to 9.5V.

Geiger input action

As you can see from **Fig. 2**, the tube is fed from the HT via a 2.2MΩ resistor The cathode end of the tube connects to a 1MΩ resistor to ground. This ensures that positive only pulses are dropped across R_{20} and are approximately 12V in amplitude

rom here the signal passes through a –3dB attenuator and on to schmitt trigger, IC_{1b}. The output switches low at about 4V and returns when the input pulse is around 3V.

Output of IC_{1b} feeds a monostable pulse stretcher in non-retriggerable mode, via R_{29}/ZD_1, which limits the pulse output presented to IC_2 to 6.2V. This is done because IC_2's supply line is fed from V_{cc2}, which is 7V. Pulse width from IC_2 may be advanced or retarded I recommend that you set this pulse at around 4ms, which corresponds to a little over 113.3Hz – full span for the *MX120/01*.

Note that IC_{1a} is designed to generate a stable 7V supply, V_{cc2}, for powering $IC_{2,4,5}$. The reasoning behind this was that the *LM2907* frequency-to-voltage converter includes V_{cc2} in its transfer equation. This makes it essential that V_{cc2} be kept constant at all times.

Another benefit of this scheme is that since the instrument is powered by batteries, the effect on accuracy of the gradually falling supply voltage is minimised.

Supply V_{cc2} is capable of sourcing more than 50mA and its output impedance is quite low. However the circuit draws nowhere near this amount of current under normal conditions Stability of V_{cc2} depends on V_{ref} output of the *SG3525* m chip, so its drift is very low

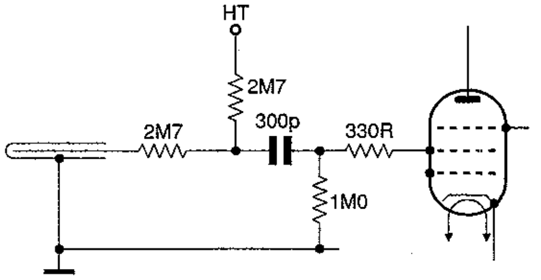
I included a low-voltage indicator in the form of a 5mm red led. This led is designed to switch when the battery discharges to around 9.5V. Once this led comes on, the 4-20mA accuracy begins to be affected. Diodes $D_{7,8}$ were included because IC_7 does not swing all the way to ground. Without these diodes, the led will not turn off properly.

Frequency to voltage conversion

The *LM2907* is the heart of the instrument. It converts the varying frequency from the tube converted to a varying dc level.

National Semiconductor guarantees a basic linear transfer of ±0.3%, which is a very good figure. In fact, on calibrating the instrument, non-linearity is not noticeable. The chip is versatile and easy to use Its transfer equation is simply,

$$\frac{dV_{out}}{df_{in}} = V_{cc2} \times C_{10} \times R$$



Recommended connections from the MX120/01 tube data sheet. This halogen-quenched Geiger-Müller tube has a working voltage of 420V, threshold voltage of 375V and a 200µs dead time. Its maximum background figure is 90 counts a minute.

where $R=RV_4+R_{41}$. Voltage V_{cc2} is fixed at 7V but may be varied to accommodate other configurations. For the *MX120/01* tube,

$$\Delta V_{out} = 0 \text{ to } 5\text{V}$$

$$\Delta f_{in} = 0 \text{ to } 113.3\text{Hz}$$

$$\frac{\Delta V_{out}}{\Delta f_{in}} = 0.044\text{V/Hz}$$

Capacitor C_{10} is 220nF and, $0.044=7\times220\times10^{-9}\times R$. As a result, R is 28647.8Ω. Hence potentiometer RV_4 is used to trim the output on pin 7 of IC_1 to 5V at 113.3Hz. The only component that you may have to change to accommodate a different tube is R_{41}.

For an in depth discussion on exactly how the *LM2907* charge pump operates, refer to National's Linear Applications Handbook 1994, Application Note AN162, p. 345.

Output of the charge pump is injected into a Butterworth type second-order low-pass filter which has a break frequency of about 0.33Hz. Its output will be around 40dB down at 3.3Hz. The output of the filter feeds the 0-1mA meter drive circuitry within the *LM2907* converter.

There are two ranges to choose from. The first is 0-500μrad/h and the second 0-1000μrad/h.

Transistor Tr_6 was included simply to redirect meter current should it exceed about 1.2mA, thus meter protection is incorporated in the design. Should a 0-5V output be required for external purposes, R_{82} provides suitable output.

Voltage V_{ref}, from the pwm chip supplies R_{39} and R_{40}. The hysteresis span on the input amplifier is about 0.6V.

I thoroughly recommend the use of an analogue meter as opposed to a digital type. The output of the tube is a continuously varying frequency being largely dependent on the nature of radiation. Although the low-pass filter does a good job at averaging or integrating, the output still varies according to the intermittent bombardment of the tube.

4-20mA output

Here, output from IC_1 is fed directly to R_{71}/R_{72} which drops it from 0-5 to 0-3V full scale. This allows a greater voltage drop to occur in the 4-20mA output loop. Again, V_{ref} from the *SG3525* is used, affording a stable low drift zero setting via RV_8. This potentiometer is used in conjunction with RV_9, which sets the span.

Transistors $Tr_{7,8}$ form a compound or current feedback structure. The inclusion of Tr_8 greatly increases the input impedance of Tr_7, allowing IC_{1d} to exercise its maximum gain. This increases overall accuracy.

The 4-20mA output easily drives a standard 250Ω, 0.1 % resistor – even with the battery supply as low as 9.5V.

Unfortunately, I do not, have access to a chart recorder, but I thoroughly recommend this output since the peaks and troughs would be exposed for further analysis.

Audio output

The audio section of the instrument is straight forward. Running at 5kHz, oscillator IC_5 is gated with the output of the 4047 monostable (pin 10).

Maximum output at RV_7 is about 3V pk-pk of 5kHz 'packets'. Potentiometer RV_7 may be adjusted for a comfortable audio output.

In conjunction with $Tr_{4,5}$, IC_6 makes up a low impedance buffer amplifier. It is capable of outputting around half a watt into an 8Ω speaker. The audio output is a convincing series of 5kHz clicks

Setting up

Set a frequency generator on square wave and adjust this signal for 0-12V peak. Set the frequency generator for 113.3Hz – assuming you are using the *MX120/01* – and inject this signal between ground and negative terminal of the tube connection on the pcb. The tube is obviously removed at this stage. Adjust RV_7 for comfortable audio output. Connect a volt meter between ground and TP_6 and adjust VR_2 for V_{cc2} of 7V exactly.

Next, with the aid of an oscilloscope, connect the probe between ground and TP_5 and adjust the pulse width for 4ms. With the function generator precisely set to 113Hz, adjust RV_4 for 5V exactly at TP_4. With S_1 on range 2, adjust RV_6 for 1mA reading on the moving coil meter.

With a current meter connected between the 4-20mA terminals, adjust the span potentiometer RV_9 for 20mA, then switch off the function generator (0Hz) and adjust RV_8 zero for 4mA. Switch the generator back on and re-adjust the span pot RV_9 for 20mA. Repeat this procedure until you get satisfactory results.

Once the above has been completed, set the frequency generator for 113/2=56.5Hz, switch S_1 to range 1 and adjust RV_5 for full span on the moving coil meter, i.e. 1mA. Connect a volt meter across ground and HT and adjust RV_1 for 420V, again assuming you are using the *MX120/01*. Your instrument is now ready for use

How do I know if it works?

Elsewhere in the article, I mentioned that HT flash over perhaps radiates gamma radiation. Sadly this is not the case. Further to this, I picked up no appreciable radiation reading from house bricks, luminous watches, uv lamps or television screens. In fact, television screens probably emit low level X-rays instead of gamma radiation.

What I found to worked extremely well was the mantle as used in Calor gas lamps. This is that little piece of material that covers the flame and glows, emitting light. These are available in abundance at the local ironmonger.

With three of these mantles wrapped around the *MX120/01* tube, it is possible to obtain a reading of between 250μrad/h and 300μrad/h rising to sometimes to 400μrad/h. I have no idea what the safe permitted dose actually is.

Other thoughts

With regards to the various op-amps used in the instrument, only one exhibited hf on its output, namely IC_{1c}. This is why C_{11} is strapped across its input/output terminals. I suspect the reason for this is the high source/feedback resistance used. I expected hf on the 4-20mA amplifier, IC_{1d}, but it was stable. This leads me to think that the *LM324* quad op-amps are well compensated internally.

The *LM324* quad op-amp will swing all the way to ground and its common mode input range includes ground. I recommend that the tube connection be of twin screened audio cable, the screen being connected to ground.

The *MX* series of tubes are old Mullard types. I believe that tube performance has changed little over the years. Also, the new unit for radiation is the gray, I have used millirads per hour to quantify absorbed dose throughout this article but, 1mrad/h is simply 0.01mGy/h. ■

Technical support

Linear Applications Specific ICs databook 1993, National Semiconductor

Linear Applications Handbook AN-162, p. 345, 1994, National Semiconductor

1990 Linear Databook, Linear Technology Corp. Page 5-97, (*SG3525* data sheet).

Langrex, 0181 684 1166, fax 0181 684 3056

Colomor, 0181 743 0899, fax 0181 749 3934.