catch the light

technical reprint R/P079

metal ceramic photomultipliers for oil well logging

electron tubes

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A G Wright Electron Tubes Ltd, Bury Street, Ruislip, HA4 7TA, UK.

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1 application

Electron Tubes most rugged photomultipliers are constructed of metal and ceramic. Compared with conventional photomultipliers with glass envelopes, metal-ceramic devices offer far superior resistance to damage from shock and vibration. The Electron Tubes devices described in this document have established a reputation as the most rugged photomultpliers currently available from any manufacturer. In addition, the window is sapphire, a material free from naturally occuring ^{40}K, Uranimum and Thorium contaminants.

There are three types of metal-ceramic photomultipliers in the Electron Tubes range. The primary categorisation is with regard to photocathode diameter: ¾", 1" and 2" nominal diameters are available, which are designated 9224, 9223 and 9226 respectively. All photomultpliers include an integral voltage divider network and are encapsulated in a fibreglass housing. In this form they are referred to as assemblies.

Assemblies can be supplied for use up to 200ºC, guaranteed to specified operational levels of shock and vibration. The specification against which the product is supplied is agreed between Electron Tubes and the customer. A two digit suffix is added to the type number to identify each customer's confidential specification.

MWD and wireline applications demand high levels of performance and reliability. To meet these quality requirements, Electron Tubes include the following production screening procedures, applied during production:

- temperature cycling over the range 23ºC - TºC - 23ºC, at least twice for every tube
- random vibration to a prescribed level.

Where operating parameters are given in this technical note, they are intended as a guide to the user.

table 1 characteristics and ratings

tube type	9224	9223	9226
number of dynodes	12	12	14
effective cathode diammeter mm	20	25	45

window		
material	:	sapphire
index of refraction	:	1.76
photocathode		
type	:	high temperature bialkali
spectral range	:	140 – 600 nm
corning blue (23ºC) (typ)	:	6
QE at peak wavelngth (typ)	:	20%
dynodes	:	venetian blind, BeO
maximum ratings		
anode current	:	100 μA
temperature ºC	:	-30 to T (note 1)
voltage	:	(note 2)
shock and vibration	:	(note 3)

note 1 the maximum temperature at which performance is guaranteed is subject to specificification. Sustained operation above this temperature may affect performance and shorten tube life.
note 2 overall voltage is specified to attain a gain of 10^6 or as otherwise agreed and it will not exceed 3000 V
note 3 specified in Section 7.

table 2 typical performance information

tube type		9224	9223	9226
cathode sensitivity, CB	20ºC	6	6	6
	150ºC	4	4	4
	175ºC	3	3	3
^{137}Cs resolution at 100pC/MeV, %	20ºC	10	8	10
	150ºC	12	10	13
	175ºC	14	11	15
dark current at 100pC/MeV, μA	150ºC	1	1	2
	175ºC	3	5	10
noise edge keV	150ºC	10	15	20
	175ºC	25	25	40
operating voltage at 100pc/MeV	20ºC	1900	1900	1850
	150ºC	2300	2000	2050
	175ºC	2350	2150	2100

performance values listed are the medians for production distributions.

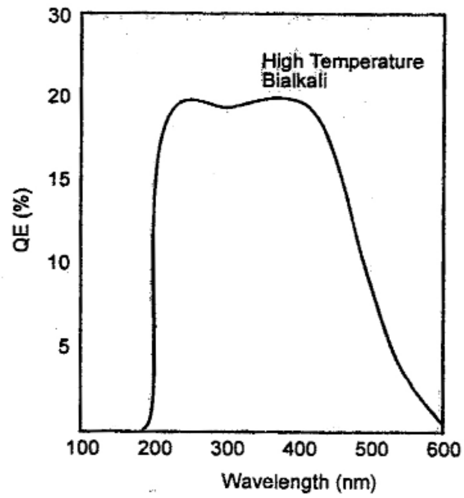


figure 1 typical photocathode spectral response at room temperature

2 voltage gain characteristics

Since the majority of applications involve a NaI(TI) crystal, it is practical to give the gain in terms of output charge per unit gamma ray energy absorbed in the crystal. For example, a gain of 5 x 10^5 corresponds to approximately 100 pc/MeV. The light output for a set of crystals with similar geometry will vary by about 50%, so the conversion from pC/MeV to absolute gain carries this degree of uncertainty.

The output from a photomultplier/NaI(TI) combination decreases with increasing temperature. Approximately equal contributions can be attributed to reduced light output from the scintillator and the remainder to loss of gain and photosensitivity in the photomultiplier. Performance with temperature is given in **table 2**. Note that the sensitivities of crystal and photomultiplier are restored on return to room temperature.

3 resolution and noise edge (NE)

Resolution is measured and specified using industry standard, high temperature crystals. The perferred isotope for test and specification is ^{137}Cs because it relates directly to oil well logging applications. ^{241}Am, which emits at 60 keV is sometimes specified. The loss in performance with increasing temperature is shown in **figure 3**. The spectra have beeen normalised to restore the peak to the same channel to illustrate the loss in resolution and the appearance of a noise-edge at low energies. The position of the noise-edge is defined by reference to the Compton peak, as shown.

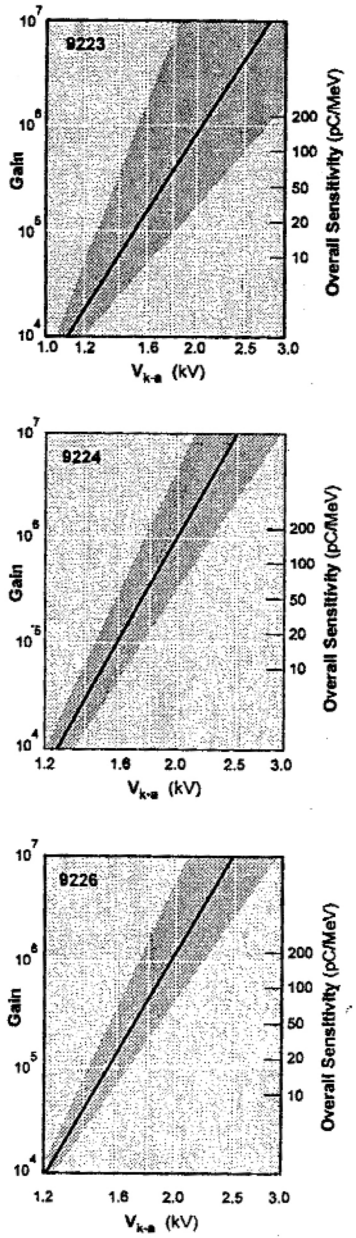


figure 2 gain as a function of overall voltage. The overall sensivity in units of pC/Mev is useful in predicting the output pulse height when the photomultiplier is used with a NaI(Tl) crystal. The hatched areas illustrate the typical production spread in gain from photomultipliers of the same type.

Alternatively, noise may be specified with reference to increased counts within a given energy window. This is illustrated in **figure 4** for a window spanning 30 to 80 keV.

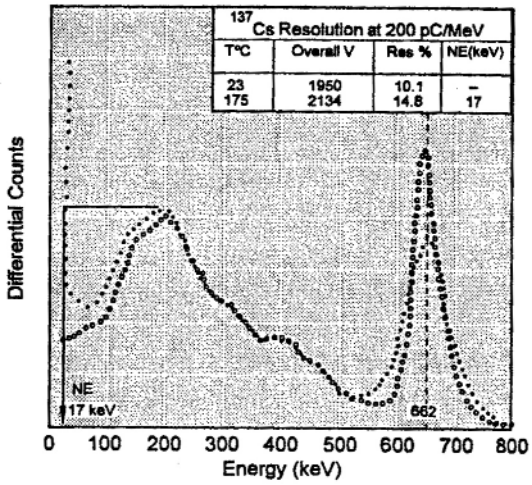


figure 3 effect of increasing temperature on resolution and noise-edge for a 9223. note that the operating voltage has been increased at high temperature to restore the peak position. The noise-edge (NE) is defined with reference to the Compton peak, as shown.

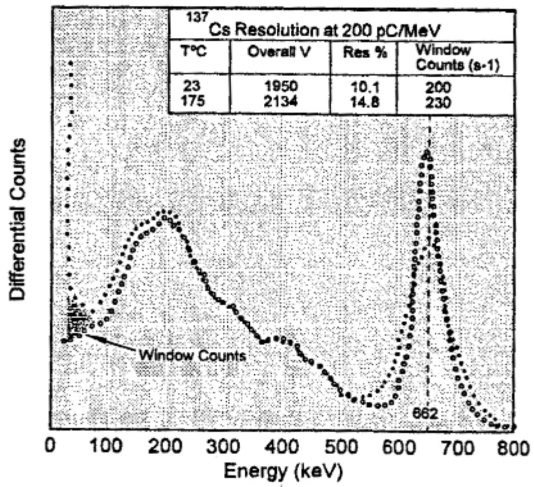


figure 4 effect of increasing temperature on the number of counts in a selected energy window for a 9226. Note that the operting voltage has been increased to restore the peak position.

4 dark current and noise edge

Dark current versus temperature has the profile shown in **figure 5**. Dark current affects the NaI(TI) spectrum in two ways: firstly, it boradens the resoltuion and secondly it reduces the dynamic range obscuring the low energy region of the spectrum. Note that it is not the dark current itself which has this effect, but the associated shot noise. Large statistical fluctuations about the mean dark current cause the exponential-like, low energy tail, shown in **figure 3**, which is a feature of all NaI(TI) spectra at high temperatures. These same statistical fluctuations also broaden the photopeak resolution of **figures 3** and **4**.

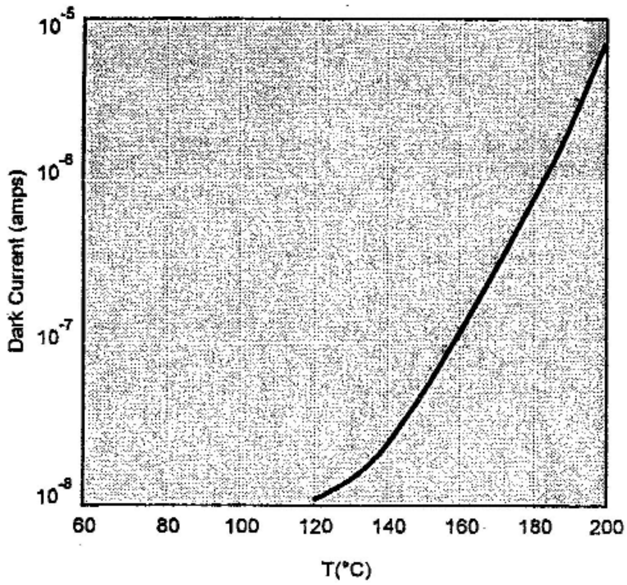


figure 5 dark curreent for a 9223 selection for 200ºC operation.

5 plateau characteristics

For gross counting applications, where spectral information is not required, photomultpliers can be supplied to a specifiction based on a plateau measurement. Using a NaI(TI) crystal and specified radio-isotope, the plateau curve is measured by recording the count rate above a fixed threshold, as a function of applied voltage. Referring to **figure 6**, at low applied voltage, and hence low gain, few events are of sufficient energy to trigger the threshold of the electronics and low counts are recorded. The curve shows signs of a plateau once the gain is sufficient to amplify the majority of events above the set threshold. As the high voltage is increased further, a small increment in counts is measured from contributions made by the low energy region of the spectrum. The curve breaks away from a plateau characteristic at high voltage, either because of contributions from the noise-edge or from the onset of photomultplier breakdown.

It is customary to set the specification in terms of the length of the plateau, measured in volts. No plateau characteristic is ever absolutely flat and it is the permitted tolerance on the slope which will define the plateau length. In the example illustrated in **figure 6**, the rectangular box specifices the voltage over which the count rate is constant, to within ±2.5%. To perform gross counting with this experimental arrangement, the recommended operating voltage is mid-way along the box at 1970 V. With the tube operated in this manner, the counts are essentially independent of temperature, and, to some extent, ageing.

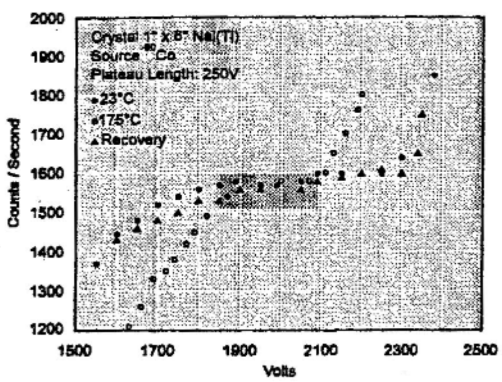


figure 6 plateau characteristics for a 9223 obtained by counting output signals that exceed a fixed threshold. In this example, the plateau is defined as the voltage over which the count rate is constant within ±2.5%. Note how the plateau length shrinks at high temperature because of the combined effects of gain loss and the onset of noise at high operating voltages.

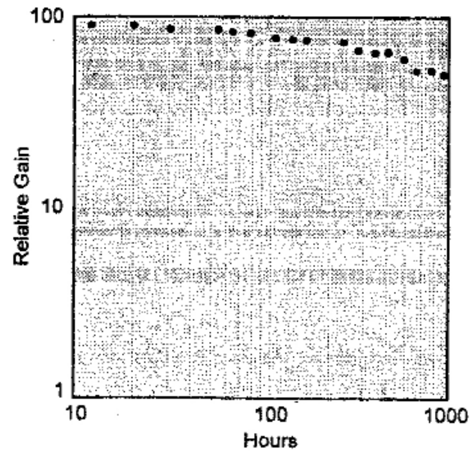


figure 7(a) illustrates change of gain with continuous operation at 175ºC. Initial sensitivity of the tube is 200 pC/MeV.

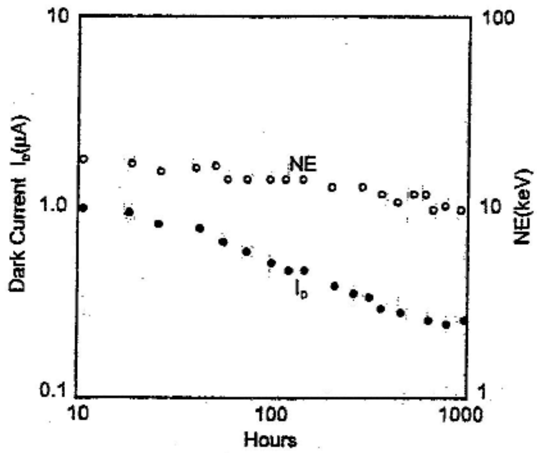


figure 7(b) illustrating how Noise Edge and Dark Current tend to improve with prolonged operation at high temperature, even allowing for the loss in gain.

6 high temperature performance

There are three critical photomultiplier parameters which are affected by temperature:

- cathode sensitivity
- gain
- dark current

Gain can be restored by increasing the high voltage. However, a loss of cathode sensitivity and increased dark current have a direct influence on performance at temperaturs above about 120ºC.

6.1 continuous operation at high temperature

After a prolonged period of continuous operation at high tempertaure, certain tube parameters will remain permanently affected. Photomultiplier gain and cathode sensitivity, and hence resolution, are degraded with the passage of time. The degree of performance loss depends on both the temperature and the duration of the exposure. The loss of overall sensitivity is shown in **figure 7**(a). The dark current, and hence the noise-edge, generally improve with operation at high temperature, are illustrated in **figure 7**(b).

7 shock and vibration

Electron Tubes have qualified photomultplier assembles to very high levels of shock and vibration. Routinely all photomultpliers undergo a production vibration test whilst operating.

7.1 shock

Assemblies have been qualified to the following lests (table 3). The shock impulse profile is a half sine wave of the state duration (base width), applied in each direction along all 3 axes. The definition of the orthogonal axes is the same as that used for magnetic effects. (See **figure 14**).

table 3 – shock levels - MR and MRL are defined in the text

type	shocks per axis	level	axis	level ĝ	duration ms
9223/4	30	MR	x,y	1000	0.5
	30	MR	z	350	2.0
	60	MRL	x,y	750	1.0
	60	MRL	z	250	2.5
9226	30	MR	x,y	850	0.5
	30	MR	z	350	2.0
	60	MRL	x,y	750	1.0
	60	MRL	z	250	2.5

7.2 vibration

Assemblies have been qualified under random vibration, applied in three directions in turn, at a level and for the duration stated. These specifications apply to all types in the range.

table 4 – vibration levels

Level	PSDL g^2/Hz	Roll ON/OFF dB/Octave	g(rms)	duration minutes
MR	2.0	6	36	10
MRL	1.0	6	26	60

An example of random vibration, power spectral density curve, illustrating the terms used, is shown in **figure 8**. PSDL refers to the power spectral density level applied; roll-on and roll-off describe the rate of application of the power as a function of frequency. The equivalent g(rms) is derived by integration of the curve in **figure 8**.

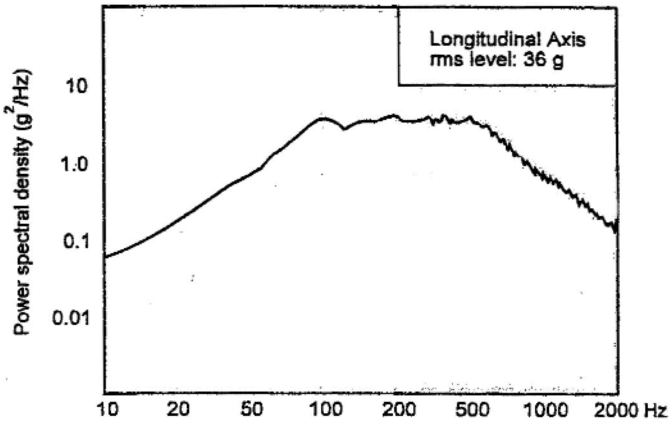


figure 8 an example of a random vibration power spectral density curve. The square root of the area under each curve is related to g(rms).

important

The maximum rating (MR) is the maximum level assemblies are designed to withstand – this level must not be applied continuously nor exceeded.

The maximum recommended levels (MRL) are the maximum continuous shock and vibration levels for the photomultiplier.

Performance may be affected during shock and vibration. The method of mounting, the operating conditions and the details of the associated electronics all contribute to the quality of performance.

All assemblies are subject to a production vibration test of 6.5 g(rms) along all three orthogonal axes, for three minutes per axis, while operating at an anode sensitivity of 100 pC/MeV.

8 voltage divider options

A range of divider networks based on the configuratio of **figure 9** is offered to suit particular customer requirements. Most applications are served by either the 'standard' or the 'high rate' variants, examples of which are shown in table 5. Decoupling capacitors are included to extend the dynamic range. The standard capacitance value is 2.2 nF. The standard divider is recommended where low power consumption is a major consideration. Applications involving variable or high count rate require a lower resistance divider. The high rate divider, with a total resistance of 7 MΩ, helps to minimise gain changes with increasing source counts.

important

Although photomultpliers may be operated with positive or negative high voltage, positive high voltage is always recommended. If negative high voltage must be used, then careful consideration must be given to the following.

- Any material in contact with the window, for example a NaI(TI) crystal, must be maintained at cathode potential.
- The interface between the crystal and the window must be shielded along the body of the housing. The shield, maintained at cath ode potential, should overlap the interface, covering approximately 15 mm on each side. This is illustrated in **figure 12**.
- Failure to follow these precautions will result in erratic performances and reduced tube life.

table 5 – typical voltage dividers

type	mode	R MΩ	R_k MΩ	Total MΩ
9223/9224	standard	3.9	7.8	56
9223/9224	high rate	0.5	1.0	7
9226	standard	2.4	9.0	43

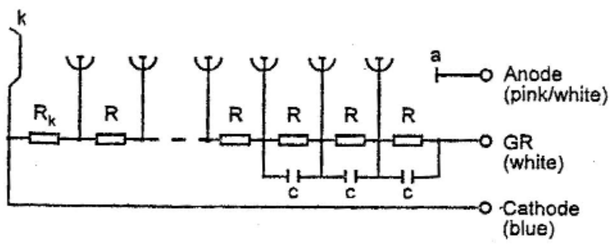


figure 9 voltage divider circuit diagram common to all photomultipliers.

9 operating precautions

9.1 positive high voltage operation

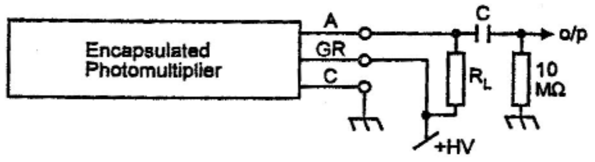


figure 10 the additional, external components that are added to the assembly for operation with positive high voltage.

The 10 MΩ resistor connected between output and ground is a safety precaution. This prevents the capacitor from charging to the high voltage rail in the event that the electronics is disconnected.

9.2 negative high voltage operation

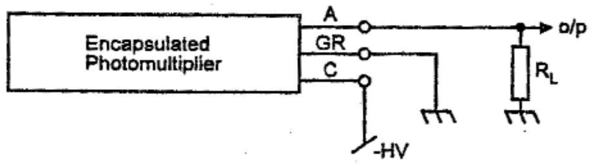


figure 11 this configuration offers the advantage of direct coupling to the anode. The precautions necessary when using this configuration, are illustrated in **figure 12**.

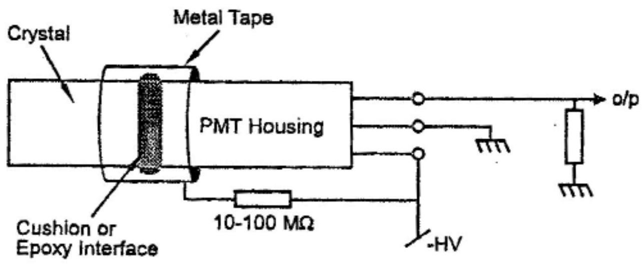


figure 12 stable performance with negative high voltage is assisted by eliminating potential gradients in the vicinity of the photocathode by using electrostatic shielding Note that the can of the crystal must also be mainted at cathode potential.

10 count rate effects

All photomultpliers exhibit gain shift with changing anode current. In spectral measurements, this manifests itself as a change in photopeak position with event rate. The importance of this phenomenon depends on the application: where a peak stabilisation circuit is used, rate effects will be corrected by the feedback circuitry, with the possible exception of short duration bursts. Applications based on a plateau characteristic are usually insensitive to rate effects.

The effect is intrinsic to the secondary emission process on the dynode surface. It is quantified as the relative change in gain produced by an increase in source rate from 1 kHz to 10kHz. The source is ^{137}Cs, with all counts above 20 keV included. **Figure 13** illustrates the variable magnitude of the rate effect from tube to tube and also its dependence on increasing gain. A marked decrease in rate effect occurs with increasing temperature.

Where gain stability is important, the recommendation is to operate the photomultplier at a gain < 1 pC/MeV, where the effect will be of the order of 1%.

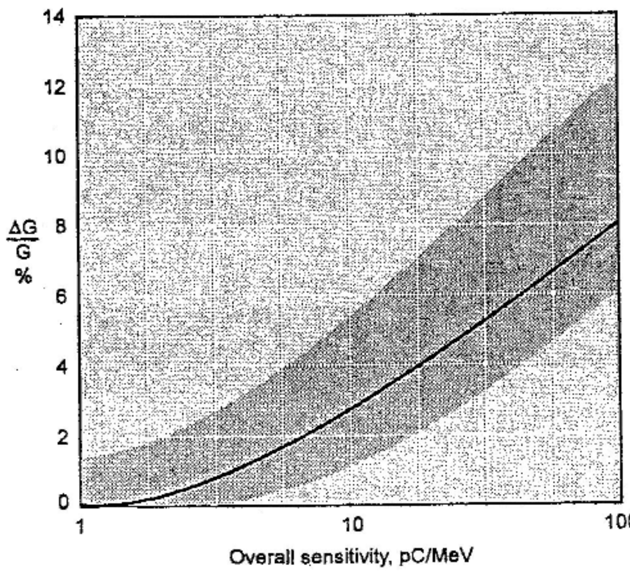


figure 13 gain shift versus gain for change in count rate from 1 – 10 kHz. The central curve represents typical behaviour and the performance of any particular tube will fall within the shaded band.

11 the effect of magnetic fields on performance

The gain of metal-ceramic photomultipliers is sensitive to magnetic fields, even of the order of the earth's field. This is shown in **figure 14**. A simple shield formed from 0.5 mm thick mu-metal sheet is sufficient to eliminate the effects of changing the photomultiplier's orientation in the earth's field. It also significantly reduced the variation due to static and low frequency fields from transformers, motors, switches and permanent magnets.

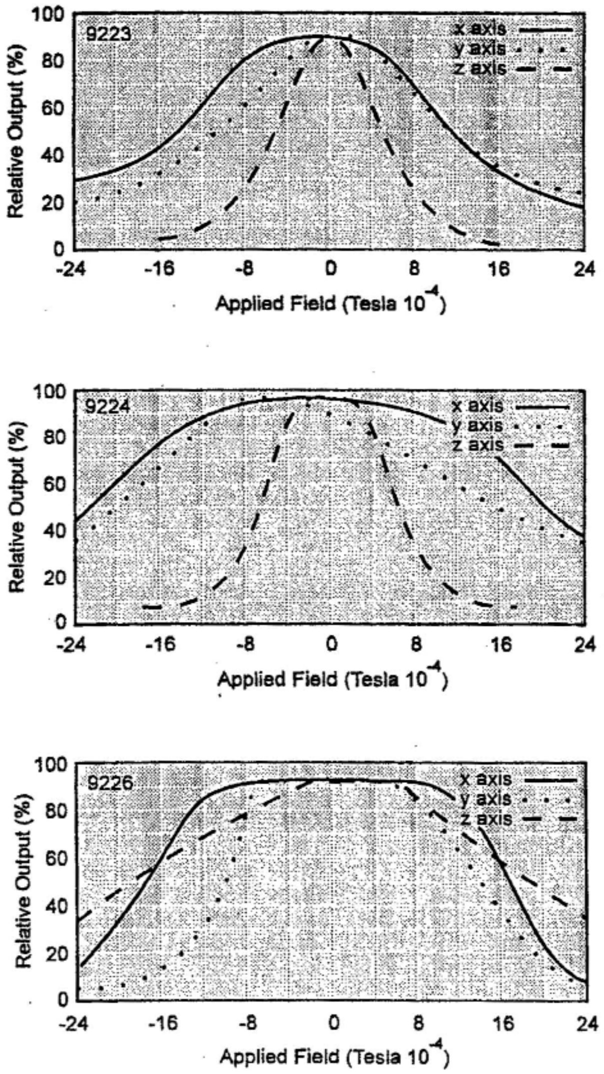
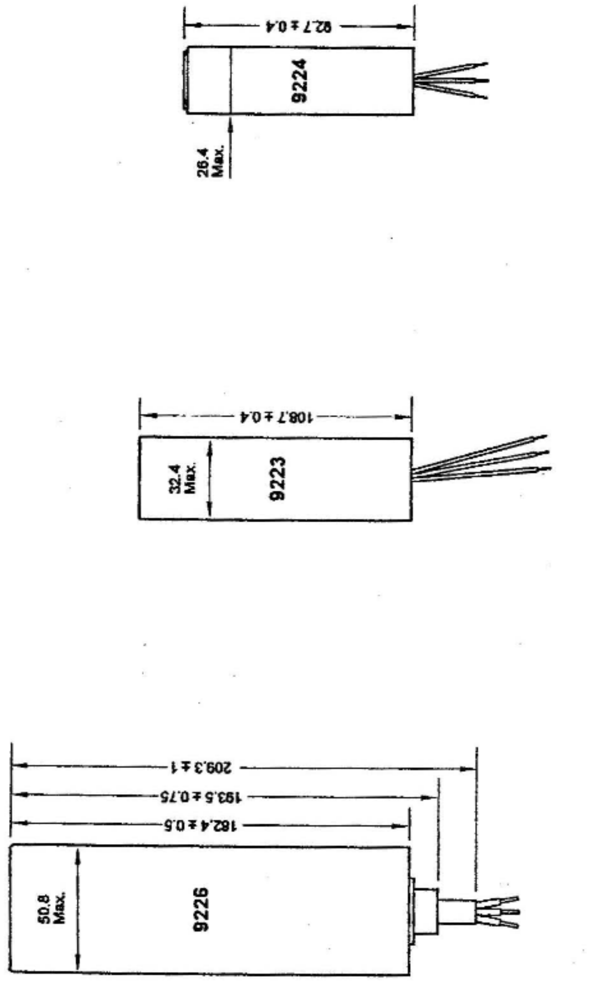


figure 14 the gain of metal-ceramic photomultipliers is sensitive to magnetic fields. The cordinate axes are defined as: x lies across the direction of the slats of the dynodes; y is parallel to the direction of the slats and z lies along the axis of the photomultiplier.

12 outline drawings (mm)

Metal-ceramic assemblies are shown in **figure 15**.

figure 15 all dimensions are nominal, unless otherwise stated. The wires are coded as follows: Anode : Pink/White, Cathode : Grey, GR : White.



Electron Tubes Limited
Bury Street, Ruislip
Middx HA4 7TA, UK
Tel: +44 (0)1895 630771
Fax: +44 (0)1895 635953
Email: info@electron-tubes.co.uk

Electron Tubes Inc.
100 Forge Way, Unit F
Rockaway, NJ 07866, USA
Tel: (973)586 9594
Toll free: (800)521 8382
Fax: (973)586 9771
Email: sales@electrontubes.com

www.electrontubes.com

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