LONG-TERM BEHAVIOUR OF THREE PROTOTYPE VACUUM PHOTOTRIODES OPERATED WITH HIGH PHOTOCURRENTS

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Abstract

Accelerated burn-in measurements have been performed on three prototype 1" vacuum phototriodes, (VPT), for the CMS ECAL Endcaps. The response of a Hamamatsu VPT was monitored for seven days in the laboratory, (B = 0 T), while drawing a cathode photocurrent of 200 nA, followed by a further eight days with the same photocurrent in an axial 4.7 T field. This corresponds to approximately 320 days of LHC operation at full luminosity for a VPT situated in the high background region of the Endcap. An Electron Tubes' VPT was operated for eight days in the laboratory, (B = 0 T), at reduced bias, with constant illumination giving an initial photocurrent of 200 nA, followed by a further fourteen days at the same illumination, but with normal operating bias. A second Electron Tubes' VPT was operated in the laboratory for eight days, with constant illumination producing an initial photocurrent of 200 nA. The results are discussed and suggestions made for minimising the long-term deterioration of VPTs operating with high photocurrents.

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1. Introduction

During past few months, the RAL and Brunel groups have been studying the long-term behaviour of prototype Endcap VPTs operating with substantial cathode currents. Background estimates indicate that, in the forward region of the Endcaps, each VPT will operate with a standing photocurrent of approximately 10 nA at full LHC luminosity, as a result of charged particle and gamma ray background absorbed in its associated lead tungstate crystal. Ten years' operation at full LHC luminosity will require the photocathodes of these VPTs to deliver more than 1 C of photoelectrons.

In order to study the long-term behaviour of VPTs operating with substantial photocurrents, accelerated ageing tests have been carried out with a photocurrent of 200 nA, twenty times larger than the expected Endcap worst case. A typical VPT operates normally at a photocurrent of 200 nA; the gain falls by a no more than a few percent as the photocurrent is increased from 1 nA to 200 nA. The voltage drop across the photocathode could be appreciable if the photocathode resistance were as high as 10^{10} ohms/□, [1], but no effects attributable to a significant photocathode voltage drop have been observed with prototype Hamamatsu or Electron Tubes' VPTs, even when operating at reduced anode-cathode voltage. Using 200 nA of photocurrent implies that two years' operation at full LHC luminosity for VPTs exposed to the highest levels of background may be compressed into a period of about 15 days.

Initial ageing tests, [2], indicated that, with a photocurrent of 200 nA, prototype VPTs showed a rapid reduction in anode pulse height, typically over a period of 8 – 24 hours, followed by a slower deterioration for the remainder of the test. In some cases, the total reduction was more than 30% over a ten-day period. Practically all of the deterioration was due to a reduction in the quantum efficiency of the photocathode. The gain typically remained constant to within a few percent for the duration of the measurement. The large, rapid reduction in photocathode response is tentatively ascribed to the bombardment of the photocathode by energetic heavy ions produced by ionisation of the residual gas in the VPT. One of the aims of the present series of measurements was to investigate the hypothesis of ion-impact damage to the photocathode, and, if it was confirmed, to attempt to minimise its effect.

2. Residual Gas Ionisation

When a vacuum phototube is manufactured, the residual gas pressure is reduced to as low a value as possible, by outgassing the tube envelope at high temperature and pumping for an extended period before sealing off the stem. A getter may also be incorporated to maintain the vacuum at a low value during the operational life of the tube A lower limit for the residual gas pressure, for tubes with caesiated photocathodes and dynodes, is presumably the saturated vapour pressure of Caesium, ~2 x 10^{-9} at., at 25 C. However, analyses of the composition of residual gas in photomultipliers show that it consists principally of a mixture of the common atmospheric gases, and hydrogen which is used in the production process.

Photoelectrons and secondary electrons with energies above about 50 eV can ionise residual gas molecules in the VPT and the resulting positive ions will be attracted to any internal surfaces that are at low potential, where they have a high probability of attachment. As a result, the tube may self pump and the internal pressure will be substantially reduced. In a VPT operating under normal bias, positive ions produced in the cathode-anode space will be attracted to the photocathode, where they will impact with energies up to 800 eV, depending on the tube bias.

The damage produced by high-energy ion impacts, or contamination of the photocathode, may be responsible for the observed deterioration of the photocathode.

It is straightforward to obtain an order-of-magnitude estimate of the clean-up effect of the VPT current on the residual gas. The mean free path for ionisation of an electron travelling in the residual gas is given by $1/n\sigma$, where n is the molecular density of the gas, and σ is the ionisation cross section. Although the composition of the residual gas is unknown, the ionisation energies and cross sections of common residual gases are quite similar. For example, the ionisation potential, (the threshold electron energy for ionisation), is 15.4 eV for H_2, 12.6 eV for H_2O, 15.6 eV for N_2 and 12.1 eV for O_2 [3]. In general, the ionisation cross section rises quickly from threshold, has a broad maximum in the region of 100 eV and falls slowly as the electron energy increases through 500 eV. For N_2, for example, the single-electron ionisation cross section is 2.5 at 50 eV, 3.3 at 100 eV, and 2.1 at 400eV [4]. The cross sections are measured in units of πa_o^2, ($= 0.88 \times 10^{-20}$ m^2), where a_o is the Bohr radius of hydrogen, 0.53×10^{-10} m. The values of the ionisation cross sections for other residual gases are similar, except for H_2, for which the peak cross section is only 1.1 at 100 eV. To obtain a rough estimate of the size of the effect, I assume $\sigma = 2.2 \times 0.88 \times 10^{-20}$ m^2 at all electron energies, for all molecules in the residual gas. If the residual gas pressure is 10^{-8} at., the corresponding electron mean free path for ionisation is about 200 m at 20^{o}C.

I assume that all electrons in the VPT are capable of initiating ionisation (ie I ignore the fact that photoelectrons are accelerated from an energy of only 1 or 2 eV and will not ionise effectively until they reach ~20 eV. Secondary electrons, too, are typically emitted with an energy of several eV and do not ionise during the first fraction of a millimetre of their path, but I assume ionisation occurs throughout their path. Estimating the total electron path length associated with each photoelectron is not completely straightforward. Approximately half the photoelectrons liberated by the photocathode are collected by the anode. The remainder pass through the anode mesh and impact on the dynode where they produce secondary electrons. Of these, about half are collected by the anode. The other half pass through the anode mesh, come to rest in the cathode-anode space, and are attracted back to the anode. Approximately half are again collected and the remaining secondary electrons travel back to the dynode, where they are assumed to be lost. The production of tertiary electrons is neglected in this simple approach. The average electron path length associated with the production of a single photoelectron is therefore

$$z \cong z_a + 0.5z_d + s(0.125z_a + 0.625z_d).$$

Here, z_a is the cathode-anode separation, about 4 mm, z_d is the anode-dynode separation, about 2 mm, and s is the dynode secondary emission coefficient. For $s = 16$, z = 33 mm, and the chance that a given photoelectron is responsible for the ionisation of a residual gas molecule is about 1.6×10^{-4}.

If there are p photoelectrons produced per second, $p = I/q$, where I is the photocurrent and q the electron charge. The density of residual gas atoms is also more conveniently expressed as $n = N/V$, where N is the total number of residual gas atoms in the VPT, and V the total VPT volume.

In time dt, the number of residual gas atoms ionised is:

$$-dN = p\, z\, n\, \sigma\, dt$$

Substituting for p and n gives:

$$-dN = (I\, z\, \sigma / q\, V)\, N\, dt$$

and integrating gives: $N(t) = N_o \exp(-t/\tau)$

with time constant, τ, given by $\tau = (q\ V/I\ z\ \sigma)$.
Taking I = 200 nA and assuming a VPT volume of 11.4×10^{-6} m^3, results in $\tau = 1.4 \times 10^4$ s.
ie if every ionising collision produces a trapped ion, the residual gas pressure should be reduced to a negligible value in a time of the order of $3\tau = 4.3 \times 10^4$ s, or about 12 hours.

Of course, this is only a very rough estimate of the clearing time, and fails to take account of the fact that the envelope and electrodes will outgas, which will presumably lead eventually to an equilibrium between the number of atoms per second removed by ionisation and the number of new residual gas atoms appearing in the vacuum.

3. Measurements

Measurements were performed in two of the standard Brunel test set-ups. For all measurements, except those at high field, the VPT was clamped in an insulating holder inside a light-tight box, and, normally, held with its faceplate in contact with a 20mm diameter aperture in a printed circuit board. The face of the PCB adjacent to the VPT faceplate was copper-covered and grounded. The VPT faceplate was uniformly illuminated by four hyperbright blue LEDs [5] connected in series with a 470 ohm resistor and a precision dc power supply with digital readout of voltage and current. A fifth, hyperbright blue LED provided pulse illumination.

Measurements in a 4.7 T axial magnetic field were performed with the VPT mounted vertically in a grounded aluminium cup with a 20 mm diameter hole bored in the centre of its base. The VPT was held axially in the cup with insulating screws and periphery of the faceplate was in contact with the edges of the 20 mm hole. DC illumination was provided by two hyperbright blue LEDs connected in parallel, mounted outside the magnetic field, light being piped to the VPT through two 1mm diameter polystyrene fibres. A third LED, mounted in a similar manner outside the field, was optically connected to a further polystyrene fibre and provided pulse illumination.

Unless specifically mentioned, the VPTs were operated with photocathode grounded and positive bias voltages of 800 and 600 V on anode and dynode, respectively.

3.1 Hamamatsu XA0566

The first measurements were carried out on a Hamamatsu VPT, serial XA0566. In order to try to remove the residual gas without affecting the photocathode, the VPT was burnt-in for 43 hours with the anode at –20 V and the dynode at –600 V. The DC LEDs were adjusted to produce 200 nA from the photocathode, measured with normal bias at the start of the operation, and not altered thereafter. With reverse bias, both anode and dynode acted as weak photoemitters; the dynode photocurrent was about 7 nA and the anode current about 10 nA. However, only the photoelectrons from the dynode gained sufficient energy to ionise residual gas atoms efficiently, and the effective path length was only ~6 mm. Substituting these values in the expression obtained above for the clean-up lifetime, $\tau = (q\ V/I\ z\ \sigma)$, gives $\tau = 1.6 \times 10^6$ s, or about 440 hours, two orders of magnitude longer than with normal bias. It is clear that a routine burn-in of a large number of VPTs using such a procedure is not feasible and that the 43 hour burn-in might be expected to have only a minor effect on the residual gas pressure.

The VPT was then operated for a total of more than 10,000 minutes, (7 days), in zero field with normal bias (Va = 800 V, Vd = 600V) and a photocurrent of approximately 200 nA. In this test the DC LEDs were adjusted from time to time to keep the photocurrent to within a few percent of 200 nA as the photocathode deteriorated. Apart from a substantial, 12-day break after the test

had been in progress for 256 minutes, the illumination of the photocathode was continuous, except for infrequent breaks of a few minutes' duration to enable accurate measurements to be made with the pulsed LED. During the 12-day stop, the bias voltages and LEDs were turned off and the VPT was kept in the dark.

Figure 1 shows the variation with time of the mean anode pulse height (using the pulsed LED). The data have been normalised to the mean pulse height at the start of the measurement. There is a rapid fall in pulse height, of about 9%, during the first 500 minutes of illumination. The long interruption in the measurement after 256 minutes resulted in a small recovery in the pulse height, of about 1%, but this was rapidly eclipsed by a further rapid deterioration when the high-level illumination was resumed. After 500 minutes the rapid fall in anode signal ceased and was replaced by a slower decrease, of about 0.5% per 1,000 minutes.

Figure 2 shows the time dependence of the photocurrent (measured with the constant illumination provided by the pulsed LED). Once again, the data have been normalised to illustrate more clearly the fractional loss in signal. It is clear that the anode signal and the photocurrent behave very similarly, confirming that the loss in VPT performance is primarily due to a loss in photocathode quantum efficiency.

Figure 3 shows the variation of the current gain, measured as the ratio of anode and cathode currents produced by the DC LEDs. As expected from the strong correlation seen in Figs. 1 and 2, the gain was approximately constant throughout the measurement. There was a small initial fall in the gain, a recovery when the device was switched off for an extended period, followed by a very rapid gain decrease after switch on. Thereafter, the gain increased slowly until, after about 2,000 minutes it reached a stable plateau. The peak-to-peak gain excursion over the complete measurement is only ~2%.

Following the above measurements, the VPT was transferred to the high-field set-up, where, following an initial 0 T calibration, it was placed in an axial 4.7 T field for a further 11,000 minutes, (~8 days), with a 200 nA photocurrent.

Figure 4 shows the behaviour of the anode mean pulse height in the 4.7 T field. The data have been normalised to the anode pulse height with B = 0 T at the start of the test and show clearly the 30% fall in the anode signal due to the high field. Immediately following the VPT's introduction into the field, the normalised anode signal showed a small, rapid fall from a value of about 0.72 to 0.70. This was followed by a slow rise to a plateau of approximately 0.75. Figure 5 shows that the normalised photocurrent similarly recovered after an initial rapid fall, but after reaching a maximum of 1.01 at ~9,000 minutes, it began to decrease again. The changes in anode pulse height and the photocurrent are quite small. Figure 6 shows that the gain actually increased slightly, (~2.5%), throughout the high field measurement. The most encouraging feature of these measurements is the fact that the VPT parameters varied slowly, and by only a few percent, following the initial zero-field burn-in.

3.2 Electron Tubes ET39

Figures 7 and 8 show the behaviour of the photocurrent of the first Electron Tubes VPT tested, serial 39. The VPT was burnt-in at 0 T, and the illumination provided by the four DC LEDs was kept constant at the value required to produce an initial photocurrent of approximately 200 nA. The output of the 15 V power supply supplying the DC LEDs was held constant to ±5 mV in 15 V, sufficient to restrict fluctuations in the light output to below ±0.2% for the duration of the measurement, but variations in ambient temperature may have resulted in additional, slowly-varying fluctuations in the light output of about -0.5% K^{-1}.

For the first 25 minutes of the measurement the bias voltages were Va = 800 V and Vd = 600 V. Thereafter, the bias was reduced to Va = 50 V, Vd = 20 V, for a period of about 7,000 minutes. Then, for the final part of the measurement, a further 13,000 minutes, the bias was restored to Va = 800 V, Vd = 600 V. The figures show that the photoelectron collection efficiency is slightly greater when Va = 800 V than when Va = 50 V, and this accounts for the step changes observed in the photocurrent at 25 and 7,000 minutes. In addition, the photocurrent reduces rapidly at normal bias, both initially and when normal bias is restored after 7,000 minutes of low bias operation. The photocathode response declines by about 11% in the first 1,500 minutes after normal bias is restored, for example. By contrast, at low bias the photocathode deteriorates far less rapidly and the loss of sensitivity occurs at about same rate as the long-term rate at normal bias. There appear to be two sources of photocathode damage. The first occurs relatively rapidly – it can reduce the photocathode efficiency by more than 10% in a few hours at a photocurrent of 200 nA, and requires high energy electrons for its occurrence. The second process is much slower, and appears to be independent of VPT bias.

Figure 9 shows the behaviour of the gain at normal bias of ET39 during this sequence of measurements. Between 25 minutes and 7,000 minutes, when the VPT was operated at reduced bias, the gain is close to unity and is not shown on the graph. However, it is apparent that the low bias operation caused a small reduction in the gain, which is much accelerated when normal bias is applied after 7,000 minutes. Overall, the change in the gain is quite small, of the order of 4%.

Figure 10 shows the behaviour of the normalised anode current during the experiment. Although the shape of the curve is superficially similar to the gain curve of Fig. 9, it is important to note that the anode signal decreases by about 24% over the measurement, confirming that the major contributor to VPT deterioration is damage to the photocathode.

3.3 Electron Tubes ET35

One of the motivations for testing this VPT was to investigate whether the deterioration depended on the grounding of the envelope of the VPT. For both of the previous tests, the edge of the VPT faceplate was somewhat fortuitously connected to ground by being pressed up against a grounded, conducting aperture. The VPT itself was supported in an insulating clamp and the outer surface of the glass envelope was allowed to float. In measurements carried out on ET35, the VPT envelope was wrapped tightly with aluminium foil and grounded by direct connection to the photocathode pin. The VPT was slid backwards in its clamp through about 1 mm, so that there was no electrical connection between the faceplate and the front aperture.

The VPT was tested in the laboratory, B = 0 T, with normal 800 V/600 V bias. It had been rejected for CERN beam tests because of its high leakage currents, and, for the first 45 minutes of operation with 200 nA photocurrent, the photocurrent fluctuated rapidly at the nA level. However, the cathode dark current fell abruptly after 45 minutes and thereafter short term fluctuations in the photocurrent dropped to ~ ±0.01 nA in 10 seconds. As a result, measurements taken between t = 0 and 45 minutes have been omitted from Figs. 11 and 12.

Figure 11 shows the behaviour of the normalised anode current, photocurrent and gain, all measured with the high-illumination DC LEDs. The illumination was adjusted to provide a photocurrent of 200 nA at the start of the measurement and left undisturbed thereafter. As indicated above, the stability of the illumination is expected to be limited by the temperature dependence to about -0.5% K^{-1}. The laboratory temperature was monitored throughout the measurement and varied between 17.0 and 20.5 C.

The pattern of deterioration observed in this VPT was very similar to that observed with the other VPTs – a rapid reduction during the first 1,000 minutes, followed by a slower decrease thereafter. Damage occurred predominantly to the photocathode, but there was also a steady reduction in the gain. By the end of the measurement the gain had fallen by about 8%, but the photocathode response was only 65% of its initial value, with the result that the relative anode current had fallen to below 60%. Although not shown, the reduction in mean anode pulse height with time, obtained with the pulsed LED, is very similar to the reduction in the anode current shown in Fig. 11.

Figure 12 compares the normalised photocurrent with a simple double exponential fit. The agreement between the data and fit is reasonably good, except at 9,000 minutes, where the laboratory was exceptionally cold following the weekend, with the result that the LED illumination may have been a few percent above average. 0.22 of the fall in normalised photocathode response is accounted for the fast component of the fit, whose time constant is 1.2 $x10^4$ s, quite close to the value of 1.4 x 10^4 s estimated for the clean up of residual gas by ionising collisions using a 200 nA photocurrent. The time constant for the slow component is 5.4 x 10^6 s. For a photocurrent of about 140 nA this corresponds to a charge delivered by the photocathode of about 0.75 C.

4. Conclusions

VPTs deteriorate significantly if they are required to deliver substantial photocurrents for extended periods of time, both at 0 T, and in a 4.7 T axial field. There is no evidence for excessive damage occurring when a device is transferred to a high field following an initial burn-in at zero field. The measurements show no significant differences in the damage due to different grounding arrangements for the VPT envelope.

Damage occurs to both the dynode and the photocathode, but is primarily associated with the photocathode. Photocathode damage shows two distinct time dependencies, the faster of which, with a time constant of, typically, 1.2 x 10^4 s using a burn-in photocurrent of 200 nA, (equivalent to the production of 2.4 mC of photoelectrons) is compatible with that expected from positive ions produced by the ionisation of residual gas atoms. It does not occur if the VPT is operated at very low bias voltages.

The fast component may result in a reduction in photocathode sensitivity of up to 25%, but the fact that the Hamamatsu VPT showed only a 9% loss indicates that the extent of the damage can be limited by appropriate fabrication techniques, possibly by the control of residual gas pressure through the use of getters, or by adopting a burn-in procedure that minimises the number of high energy ions reaching the photocathode. More work is needed on burn-in procedures. It may be useful to burn-in the VPT with a relatively high anode voltage and a small voltage between anode and dynode, say Va = 1000 V, Vd = 900 V, in an effort to restrict the penetration of high energy secondary electrons into the photocathode – anode space. However, it is difficult to believe that this will reduce photocathode damage by more than a factor of two. Investigation of the burn-in behaviour of VPT prototypes fitted with a getter is clearly vital.

The slow component has a damage constant of about 0.75 C of photoelectrons. As this appears to occur with both slow and fast photoelectrons, it is tempting to believe that it represents a deterioration of the photocathode efficiency proportional to the number of photoelectrons delivered by the surface. As such, it may prove difficult to avoid.

The results with the Hamamatsu VPT also demonstrate that long-term operation with elevated currents is not necessarily bad. Electron/ion impacts can enhance the behaviour of sensitive surfaces. Both the photocurrent and the gain increased with time when the Hamamatsu VPT was in the high field, and, as a result, the anode pulse height was a few percent higher at the end of the high field test than at its start.

References

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2. K. W. Bell and M. Sproston, Private Communication.
3. Handbook of Chemistry and Physics, 76th Edition 1995-96, section 10-210.
4. Tables of Physical and Chemical Constants, G. W. C. Kaye and T. H. Laby, 15th Edition, Longman 1986, ISBN 0-582-46354-8, p301.
5. RS Components, 5 mm, 'hyperbright' blue LED, cat. no. 284-1392.

Figure captions

1. Burn-in behaviour of Hamamatsu VPT XA0566 in zero field with a constant photocurrent of 200 nA. Normalised mean anode pulse height measured with a pulsed blue LED as a function of time. Va = 800 V, Vd = 600 V, Vk = 0 V. The fluctuation at about 250 minutes shows where the experiment was interrupted for a period of 12 days during which the VPT was stored in the dark with bias voltages off.

2. Burn-in behaviour of Hamamatsu VPT XA0566 in zero field with a constant photocurrent of 200 nA. Normalised photocathode response to a pulsed blue LED as a function of time. For further information, see caption to Fig. 1.

3. Burn-in behaviour of Hamamatsu VPT XA0566 in zero field with a constant photocurrent of 200 nA. Gain as a function of time. For further information, see caption to Fig. 1.

4. Burn-in behaviour of Hamamatsu VPT XA0566 in a 4.7 T axial field with a constant photocurrent of 200 nA Mean anode pulse height as a function of time, normalised to 1.0 with field off.

5. Burn-in behaviour of Hamamatsu VPT XA0566 in a 4.7 T axial field with a constant photocurrent of 200 nA. Normalised photocathode response to a pulsed blue LED as a function of time. The scatter of the data reflect the fact that the photocurrent was below 1 nA and affected by fluctuations in the photocathode dark current, which, typically, amounted to ~0.3 nA and was subtracted from the raw current measurements.

6. Burn-in behaviour of Hamamatsu VPT XA0566 in a 4.7 T axial field with a constant photocurrent of 200 nA. Gain as a function of time.

7. Burn-in behaviour of Electron Tubes VPT ser. 39, in zero field, with constant photocathode illumination adjusted to provide an initial photocurrent of approximately 200 nA. Photocurrent as a function of time for the first 200 minutes of the measurement. The bias was reduced from Va = 800 V, Vd = 600 V to Va = 50 V, Vd = 20 V after the first 25 minutes.

8. Burn-in behaviour of Electron Tubes VPT ser. 39, in zero field, with constant photocathode illumination adjusted to provide an initial photocurrent of approximately 200 nA. Photocurrent as a function of time. Fig. 7 shows the extreme LH portion of this curve. The bias was increased back to Va = 800 V, Vd = 600 V from Va = 50 V, Vd = 20 V after 7,000 minutes.

9. Burn-in behaviour of Electron Tubes VPT ser. 39, in zero field, with constant photocathode illumination adjusted to provide an initial photocurrent of approximately 200 nA. Gain as a function of time. The period when the bias was Va = 50 V, Vd = 20 V, and for which the gain was approximately unity, is not shown. Note that the fall in gain over the whole period of the measurement is only about 4%.

10 Burn-in behaviour of Electron Tubes VPT ser. 39, in zero field, with constant photocathode illumination adjusted to provide an initial photocurrent of approximately 200 nA. Anode current as a function of time. The period when the bias was Va = 50 V, Vd = 20 V, and the anode current correspondingly low, is not shown. The anode current at constant illumination falls by about 24% during the measurement.

11. Burn-in behaviour of Electron Tubes VPT ser. 35, in zero field, with constant photocathode illumination adjusted to provide an initial photocurrent of approximately 200 nA. Normalised gain, photocurrent and anode current as functions of time.

12. Burn-in behaviour of Electron Tubes VPT ser. 35, in zero field, with constant photocathode illumination adjusted to provide an initial photocurrent of approximately 200 nA. Normalised photocurrent and double exponential fit:
$I = 0.221 \exp(-0.00492\ t) + 0.746 \exp(-1.12 \times 10^{-5}\ t)$, with t in minutes.

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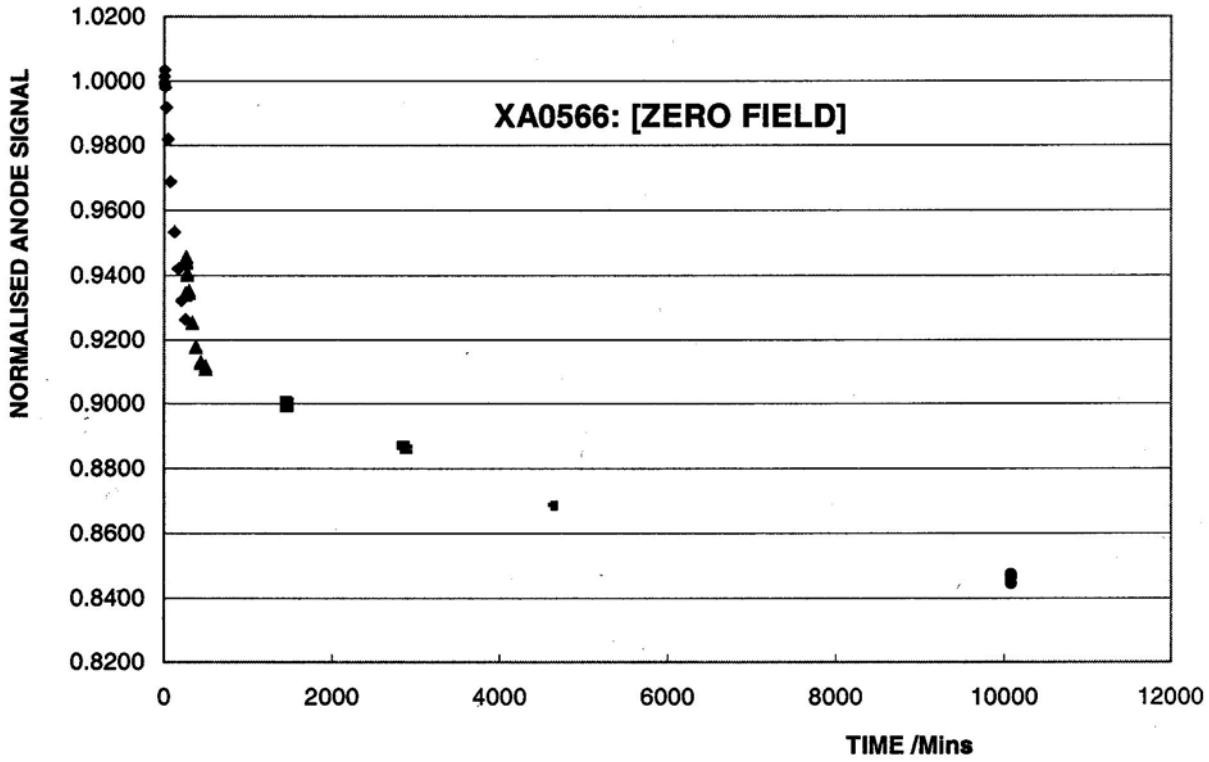


Figure 1

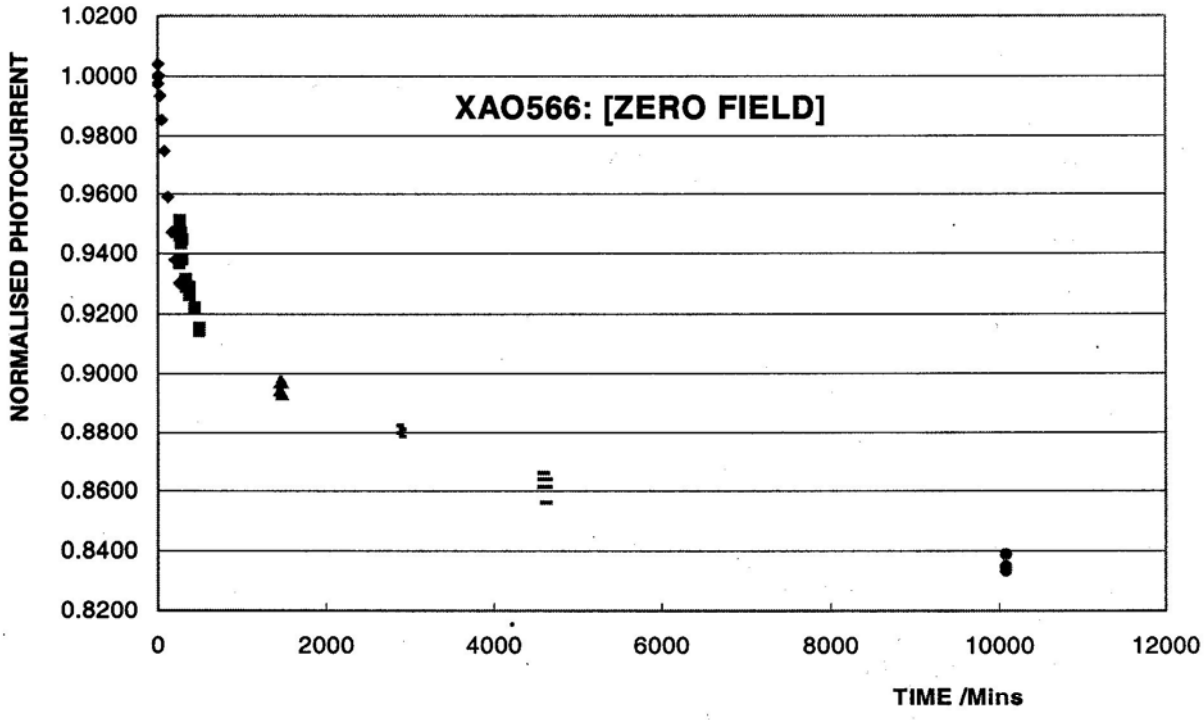
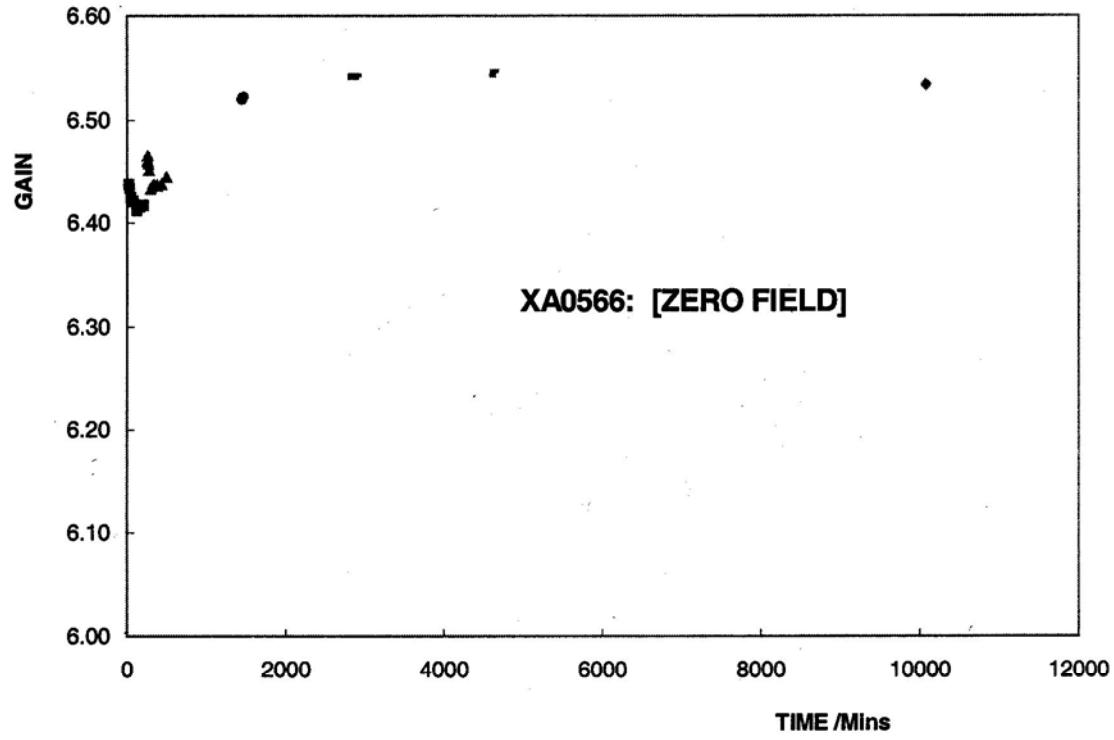


Figure 2



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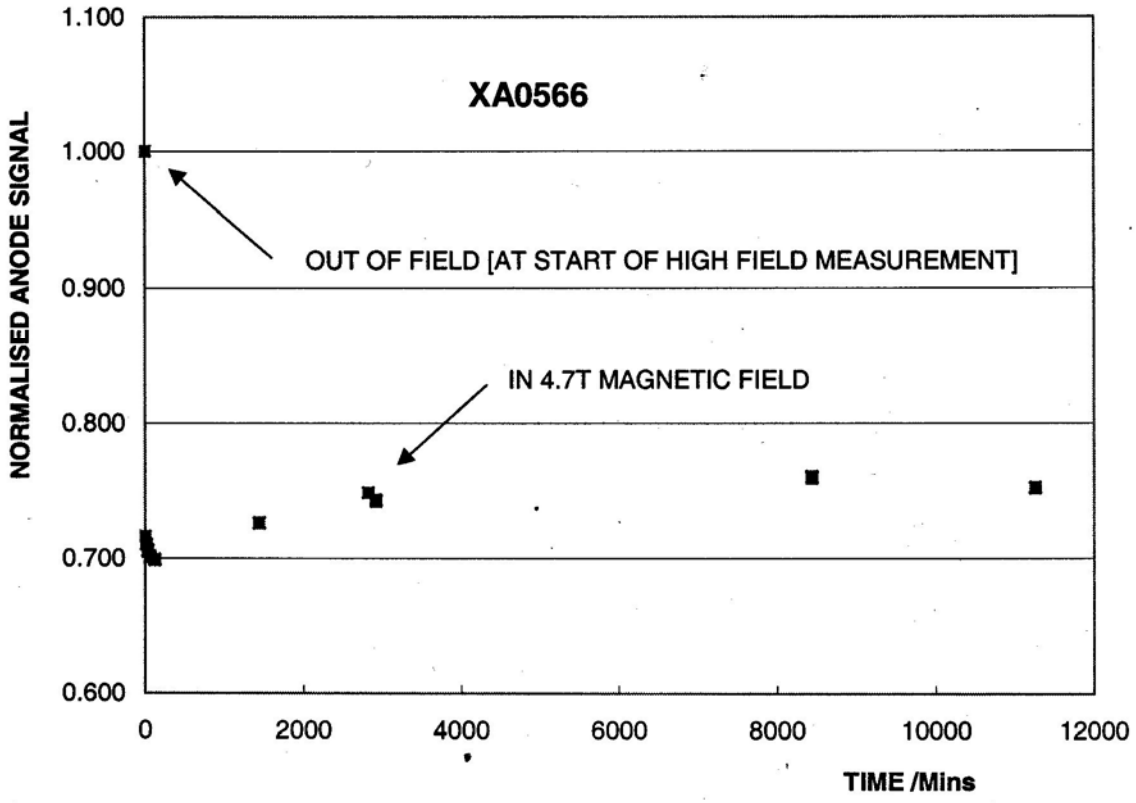


Figure 4

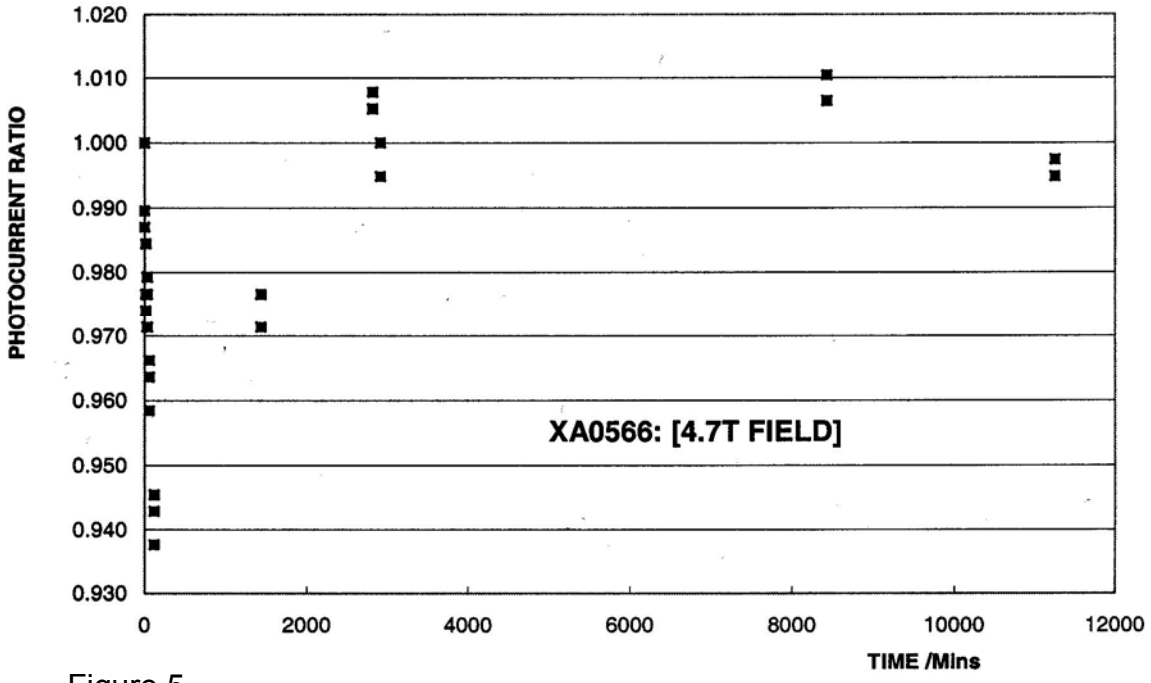


Figure 5

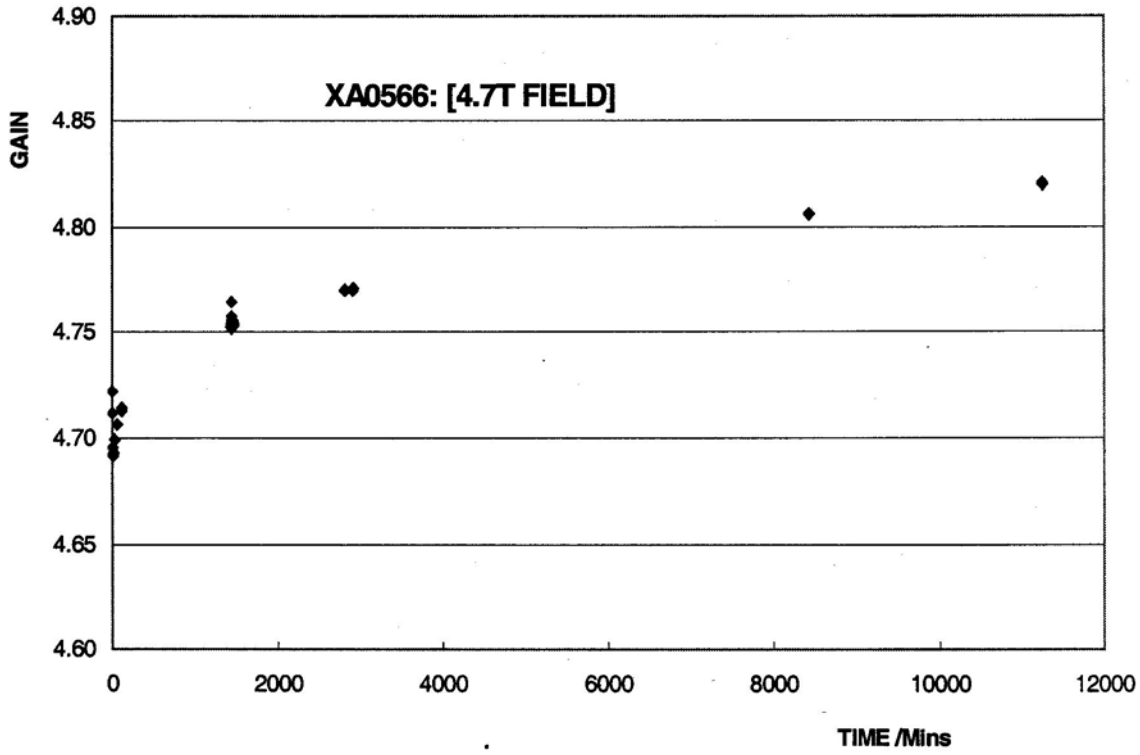


Figure 6

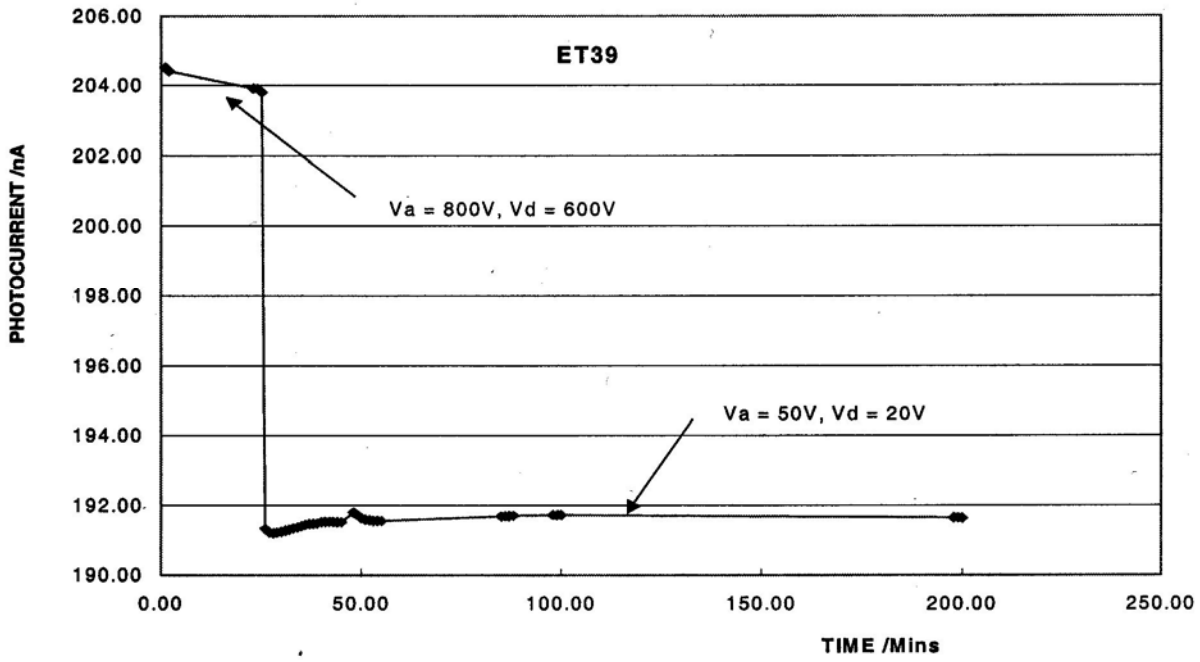
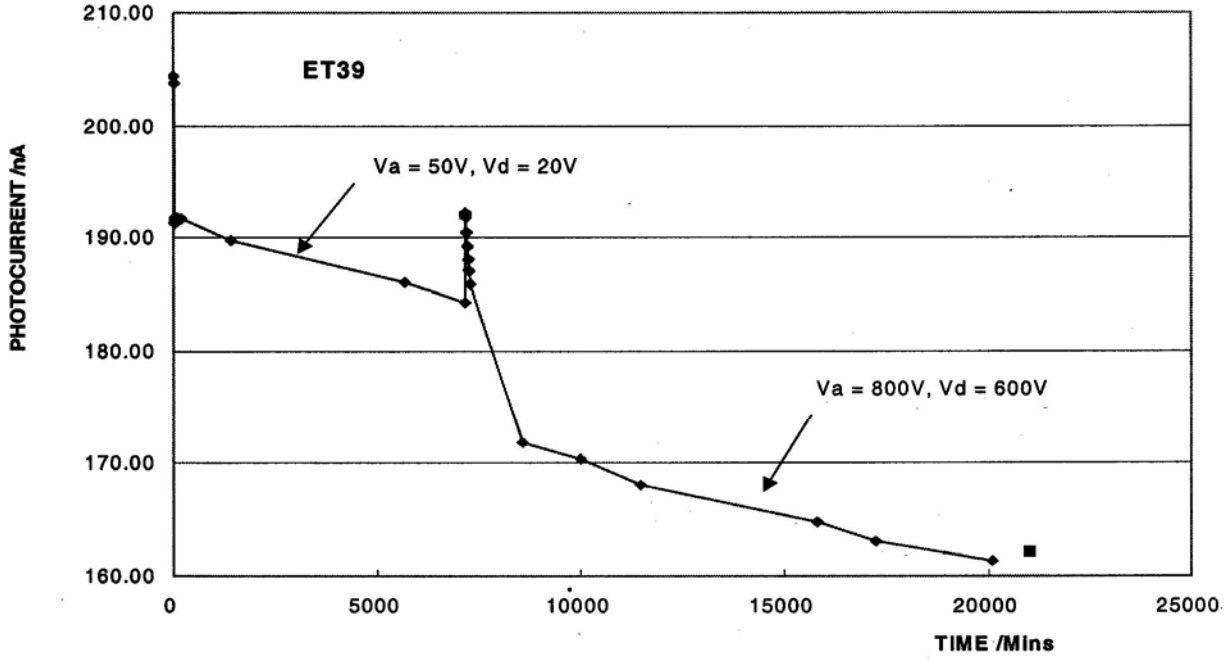


Figure 7



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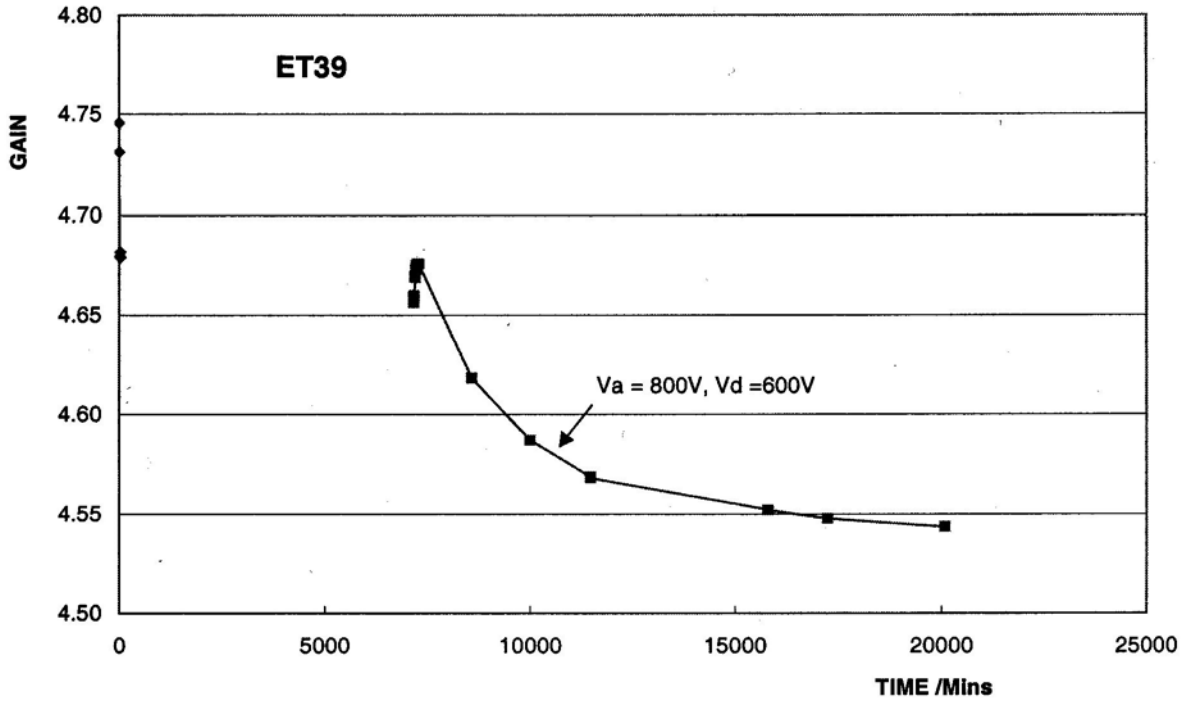

Figure 9

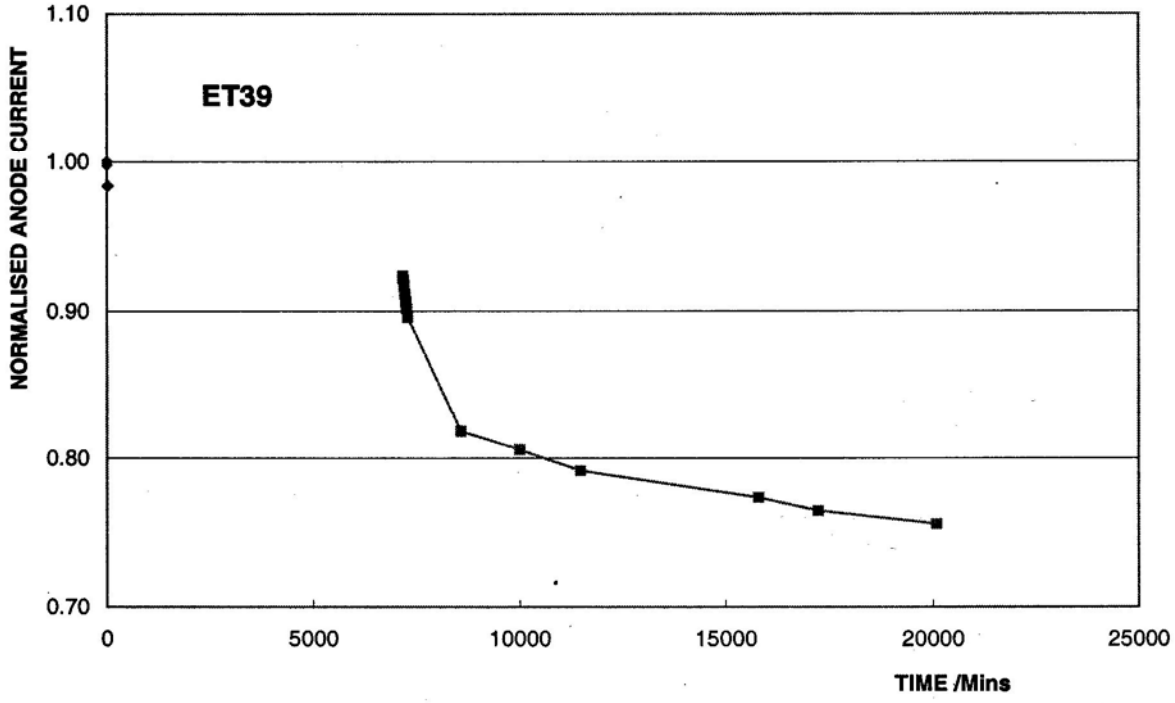

Figure 10

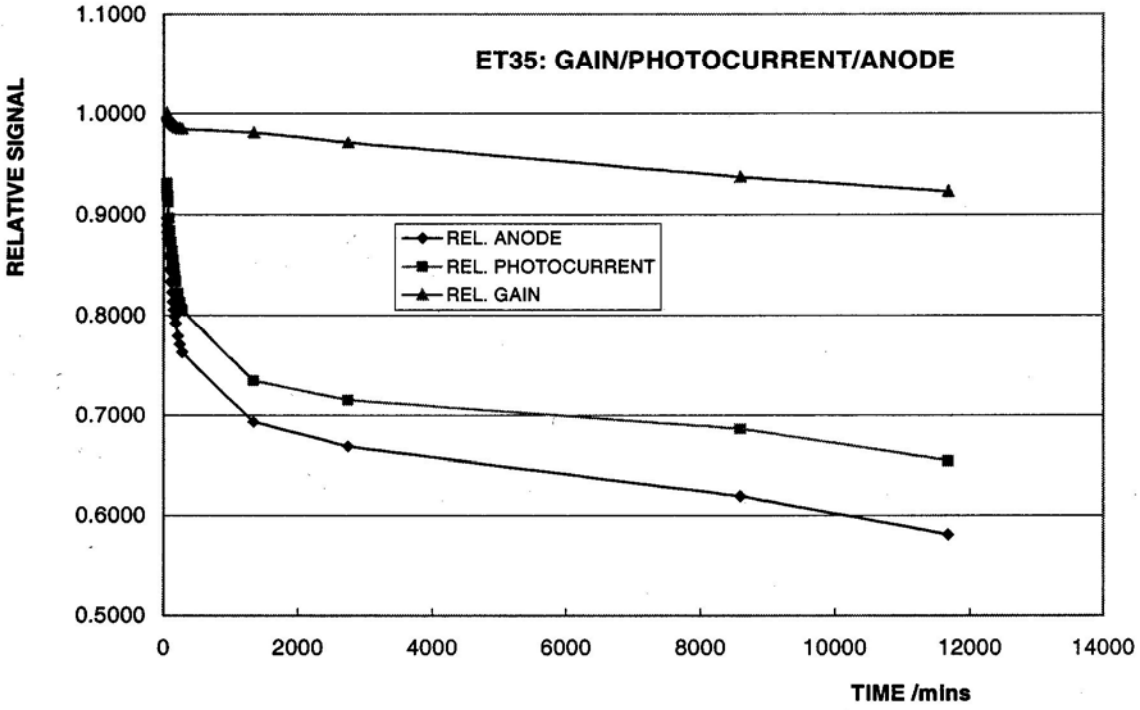

Figure 11

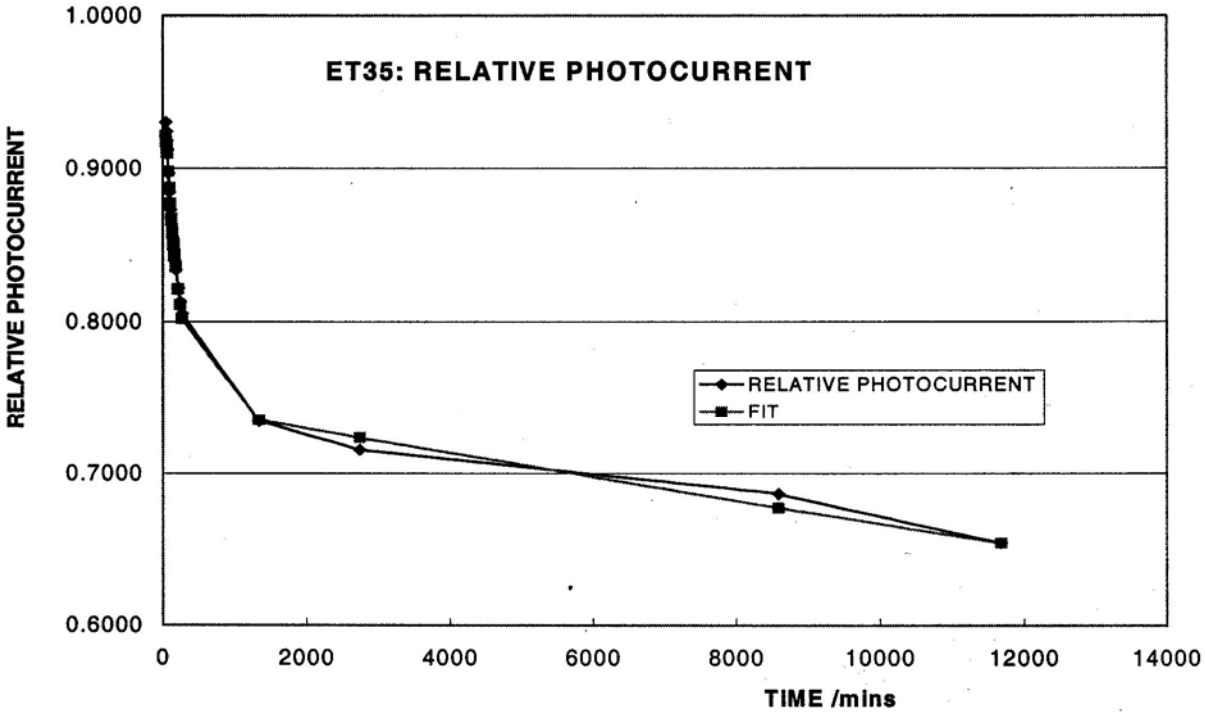

Figure 12