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GAIN STABILISATION IN PROPORTIONAL COUNTERS

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In studying the sensitivity of the gain of flow gas counters to ambient conditions it is found that a simple model of the avalanche process can be adapted to give an excellent description of the dependence of the gas gain on pressure (P) and temperature (T) around ambient. Four types of detector are studied: the wire counter, the pin detector, the parallel gap detector and the gas microstrip detector. It is found that a simple linear servo equation using the variable P/T can be used to stabilise counters by adjusting the applied anode potential.

1. INTRODUCTION

It is often necessary to operate gas proportional counters with flowing gas. The requirement arises when the counters have large area, thin, foil windows (e.g. in particle physics applications), when internal counting of a beta source is required (e.g. in radio-immuno assay [1]) or when very high counting rates must be supported for long periods (as in proposed applications for X-ray detection on sychrotron radiation sources). In flow operation the gain of a gas counter is affected by both the ambient temperature and pressure and this, in turn, affects the counting efficiency of the device. Depending on the particular structure, the gain fluctuations can be very significant over the ranges of temperature and pressure routinely experienced in a laboratory situation namely:

$$950\text{mb} < P < 1050\text{mb} \quad \text{and} \quad 18\text{C} < T < 30\text{C}.$$

Since the addition of a pressure control system would add very substantially to the cost of the detector system (and still not solve the temperature dependence), attention turned to the option of using an electronic control system to servo the EHT and thus compensate for the pressure and temperature induced gain shifts. A systematic study of the gas gain of a single wire proportional counter was carried out while monitoring the ambient thermodynamic variables - pressure (P) and temperature (T). The expected inverse dependence of the gas gain on pressure was observed along with a direct dependence on temperature. Turning to the extensive literature on proportional counter gain [2-11] it was surprising to discover no formulation which makes explicit any temperature dependence. In order to derive useful parameterisations of the gas gain as a function of P and T, an experimental survey was instituted of the gain of an cylindical proportional counter, a pin detector (spherical anode), a parallel gap counter and a microstrip gas counter (MSGD) over the dynamic range of the variables experienced in the laboratory (940 < P < 1030mb and 18 < T < 24C). These results were analysed in terms of the simplest possible model and stabilisation algorithms developed which enabled the gains of the various devices to be controlled to within an error of around one percent.

2. THE GAIN MODEL

In a single wire proportional counter the gas gain is given by the expression:

$$\ln G = -\int_{r_0}^{a} \alpha \, dr \qquad (1)$$

where G is the gas gain, a the radius of the anode wire, α the first Townsend coefficient and r_0 the radius at which avalanching commences.

If we postulate for the time being only a single interaction of the drifting electrons with the counter gas (viz. ionisation) then we can write:

$$\alpha = \frac{1}{\lambda} \exp - \frac{W}{E\,\lambda} \qquad (2)$$

where W is the threshold energy for ionisation in eV, λ the electron's mean free path for the process and E is the local value of the electric field. If σ is the molecular cross-section for this process we also have:

$$\lambda = \frac{1}{N\sigma}$$

where
$$N = \frac{N_a P}{R\ T} \qquad \text{(the molecular density)}$$

(N_a is Avogadro's number and R is the gas constant).

Thus λ and therefore α are functions of the variable P/T (q).

The problem is that there are several inelastic scattering processes involved in the avalanche with cross-sections which vary with electron energy, and the experimentally observed α does not behave as (2) predicts when P is varied. The commonest approach to this problem is to parameterise in terms of the variables s = α/P and S = E/P and find an empirical fit or approximation to relate these two quantities and this has been done in various ways with various levels of success (see [10] for a comparative analysis). However, the temperature dependence is made implicit and so the results are not useful in the case of flow counters. (It will be noted that in the case of a sealed (rigid) counter the gain is independent of P and T since, by definition, N cannot change.)

Given the requirement of finding a gain expression valid only around NTP it seemed useful to proceed on the basis of expressions (1) and (2) and see if the non-ideal behaviour of α could be incorporated in a simple way which explicitly depended on P and T. As a further simplification r_0 was set to ∞. This removed an undefined constant from the gain equation while still providing an excellent fit. Integrating (1) with (2) substituted and using

$$E = \frac{V}{r \ln(b/a)}$$

gives:
$$\ln G = V/A \exp(-B/V) \qquad (3)$$

where
$$A = W \ln(b/a)$$

and
$$B = \frac{W \ln(b/a)\ a\ N_a \sigma\ q}{R}$$

V is the anode potential and a and b the anode and cathode radii. The other parameters are defined above.

As figure 1 shows this formula provides an excellent fit to the gain over a range of 10^2 to 10^4, the practical gain range of proportional counters. We see that (3) predicts a linear dependence of B on q. We shall see below that experiment confirms this expectation and the physical complexities of the avalanche processes show up simply as an offset on the B versus q curve.

Applying the same reasoning to the case of the pin detector with its spherical electrode where:

$$E = \frac{V}{r^2(1/a - 1/b)}$$

we get: $$\ln G = \sqrt{\pi}/2\ \sqrt{(V/A)}\ \mathrm{erfc}\sqrt{(B/V)}$$

where A and B are functions of a,b, W, λ.

This equation is very unfriendly for purposes of analysis and it was found that equation (3) fitted the pin detector gain curves just as well so permitting the same analysis to be performed for both detectors (with, of course, different fitting parameters).

The integration of (1) in the case of the parallel gap counter is simplified by the fact that E = V/d where d is the width of the amplifying gap. We have:

$$\ln G = A \exp(-AB/V) \qquad (4)$$

where $A = d/\lambda$ and $B = W$

In this case we expect A to be proportional to q.

3. EXPERIMENTAL RESULTS

Using a ^{55}Fe X-ray source (5.9keV) experimental gain measurements were carried out on four detectors:

1. A standard cylindrical wire counter with a gold-plated tungsten anode wire of 20μm diameter inside a brass tube of 20mm diameter.

2. A single pin detector as described in [1] with an anode consisting of a 2mm diameter sphere mounted on a coned shaft. The cathode structures are approximately 50mm from the anode.

3. A parallel gap counter consisting of a 10mm deep conversion space separated from a 1mm wide avalanche gap by a stainless steel mesh. The drift field was kept low (typically 30V across the 10mm gap) to minimise charge loss on the mesh which was kept at earth while positive EHT was applied to the back electrode.

4. A microstrip gas detector (MSGD) with 10μm wide anodes, 100μm wide anode-cathode gaps and 90μm wide cathode strips. The anodes and cathodes of this test device were connected together in groups of twenty, forming a counter of active area

6mm x 50mm. The pattern was formed with a Ni/Au process on S8900 glass [12]. The conversion space was defined by a drift electrode 9mm above the glass plate.

In cases 1 - 3 a flow of 100cc/min of argon + 7.5%CH_4 premixed gas was used. The MSGD (case 4) was flowed with a mixture of argon + 50%dimethylether supplied by a precision mass-flow controller.

Measurements were carried out over the range of ambient conditions obtaining in the laboratory which during the period of the experiment was $940 < P < 1030$mb and $18 < T < 24$C giving a range of approximately $3.25 < q < 3.5$ (mb/K).

As figure 1 shows, the fit of equation (3) for the gain of the wire counter is extremely good over the gain range of $70 < G < 17000$. (Equally good fits are obtained for all the detector types to the appropriate model.) As P and T varied the constants A and B were determined by a standard fitting procedure from the measured gain versus EHT curve for each q value. If unconstrained, A and B were both found to vary with q. However, it was found that no statistically significant change occurred in the fitting error if A was fixed at the average derived from the first six q values so that all the q dependence could be confined to the B parameter. After a few weeks a sufficient span of q values had been accumulated to allow a plot of B versus q. As figure 2 shows this gives a very reasonable straight line fit:

$$B = 219q + 307 \text{ (V)}.$$

The procedure was repeated with the pin detector. As noted above, the wire formula (3) was applied to the pin detector gain curves and found to fit as well as the formula derived from the spherical field description. Figure 3 shows the B versus q plot for this detector. Again a good straight line fit is observed:

$$B = 1915q + 663 \text{ (V)}.$$

The parallel gap counter was the most difficult device to obtain reproducible results from, due to its high sensitivity to gas purity as well as to q. However, eventually a consistent set was obtained. In this case the B parameter (equation 4) was averaged and a single parameter fit performed on the A parameter which was expected to dominate the q dependence. As figure 4 shows we again observe a straight line fit for A:

$$A = 916q - 91.4 \text{ (V)}.$$

Biassing is more complex in the case of the MSGD since the potential applied to the drift electrode (V_D) weakly influences the electric field above the anode, and hence the gain. For consistency the bias conditions on the MSGD were kept constant (V_D = -3200V, V_C = -690V) and the gain points measured over a few weeks fitted to the equation:

$$G = \exp\{V_C/A \exp(-(cq + d)/V_C)\}$$

The A parameter was evaluated from the gain versus V_C curve (equation (3)) to be 54.9V and all the q dependence is forced into the B parameter (cq + d).

Figure 5 shows the data and fit.

4. GAIN STABILISATION

As a result of the above measurements it is possible to have a complete description of the gain of a device in terms of q and V. Thus for the wire counter we have:

$$\ln G = V/74.0 \exp(-(222q+297)/V) \qquad (5)$$

If we now select a desired operating point for the counter such as: Po=990mb, To=20C, Vo=1330V (Go=3565.4) then the relation between V and q defined by the equation

$$\ln(3565.4) = V_S/74.0 \exp(-(222q+297)/V_S) \quad (6)$$

yields the anode potential (V_S) which keeps the counter gain set on G_0 at any ambient condition defined by q. Solving this equation numerically yields data that can be accurately fitted by the straight line:

$$V_S = 124q + 910.$$

Thus on any particular occasion when the counter is in use one obtains the ambient pressure and temperature, calculates q and thence the set value for the EHT from this relation. Figure 6 shows the measured gas gain of the wire counter over a reasonably wide range of q under (manual) servo control. A standard deviation of 0.8% is observed; without correction a gain change of 25% would occur over this range of q.

Similarly for the pin detector:

$$\ln G = V/60.0 \exp(-(1915q+663)/V)$$

Choosing a set point of V_0=3700V (G_0=7855) with P_0 and T_0 as above and solving the equivalent equation to (6) above we get:

$$V_S = 655q + 1485.$$

Applying this servo control to the usual range of ambient variation ($3.3 < q < 3.48$) the gain is held constant to a standard deviation of 1.27%. Over this range of q the gain, if uncorrected, would vary by a factor of 2.3:1.

Solving the equation for a range of set-points reveals the useful information that the coefficients of q in the equation for V_S are themselves linear functions of the set-point voltage V_0. Thus the servo relation can be calculated for any chosen bias (V_0) using the formula:

$$V_S = (0.116V_0+226)q + 0.586V_0 - 720$$

For the parallel gap detector the gain formula is:

$$\ln G = (91.6q-91.4)\exp(-23.864(91.6q-91.4)/V)$$

Choosing a set point of V_0=1520V (G_0=1218) with P_0 and T_0 as above and again solving the equivalent of equation (6) for the parallel gap case we obtain the servo equation for the set-point voltage:

$$V_S = 453q - 11.$$

Measurements show that this relation permits the gain to be stabilised to within a standard deviation of 4.15%. (The uncorrected gain variation over $3.3 < q < 3.5$ is 4.1:1).

If the ambient variables P and T are recorded at the same time as any experimental data then the gain formulae $G(V_C,q)$ can be used for off-line corrections. This approach was used in a long series of measurements on the aging and stability of MSGDs [12]. The data of figure 5 can be used as an example. The residuals of the data points with respect to the fitted curve show a standard deviation $\sigma = 0.62\%$ compared with a gain variation of 6% over the range of q covered ($3.45 < q < 3.5$).

5. DISCUSSION

The success of the simple model described above in predicting the behaviour of a range of gas avalanche detectors in response to ambient changes provides reliable characterisations of their gain variations. Thus because the gain can be written:

$$G = G(P/T)$$

it follows (by differentiation) that:

$$\partial G/\partial T = -P/T\ \partial G/\partial P$$

In the units in which the modelling is carried out ({P}=mb, {T}=K), $P/T \approx 3$, i.e. 1 degree K (C) change in T produces the same gain change as a 3mb change in P. The maximum likely excursion range of T in a laboratory is around 15C corresponding to about 45mb in P. Thus it is clear that temperature and pressure excursions have a comparable effect and must both be taken account of.

The full gain formula deduced for a detector G(V,q) {e.g. equation (5)} can be used to explore the gain sensitivity of the various detectors to ambient fluctuations. Figure 7 shows that the MSGD operating at V_C=-690V ($G \approx 1000$) exhibits a relative sensitivity (1/G dG/dq in K/mb) which varies between -1.08 and -1.115 over the range $3.3 < q < 3.5$ which one may expect in a laboratory. i.e. it is to first order constant.

Figure 8 shows the relative sensitivity of the same counter at q=3.4637 as a function of the MSGD gain. While the sensitivity rises sharply at low gains, in the practical working region (G>500) 1/G dG/dq settles to a value around -1.1 K/mb, again to first order constant.

The above results show that a simple modification to the simplest model for gas counter amplification gives algorithms which can describe the behaviour of the gains of the main types of flow gas counter accurately in the range of ambient conditions normally encountered in practical operation. The results show that (as the physics predicts) the key parameter for determining environmental effects is P/T (ambient pressure/ambient absolute temperature). It is relatively easy to adapt these algorithms to produce servo control formulae which permit the gain of the counter to be stabilised by appropriate adjustment of the counter voltage. The fact that these formulae are simple linear expressions in q (P/T) make the option of automatic electronic control of the gain very attractive and much cheaper to implement than stabilising the pressure and temperature of the detector.

The (perhaps) surprising fact that the solutions to equations such as (6) are so accurately linear is simply due to the limited range of q over which we must work. Differentiating (6) with respect to q shows that dV/dq is indeed approximately constant under these conditions. Given the knowledge that V_S is a linear function of q, the servo equation for any detector can obviously be measured directly as ambient conditions vary and the required function quickly obtained.

The results also show that the dependence of the gain on the ambient conditions is much more serious in the case of the pin detector and the parallel gap counter. In fact, differentiating the gain with respect to q for each of the four cases and substituting the measured parameters and typical running conditions gives the following results:

Detector	**1/G(dG/dq)** (K/mb)	**Error in Servoed Gain (σ)** 3.3 < q < 3.5
MSGD	-1.1	0.62%
wire counter	-1.4	0.8%
pin detector	-4.6	1.27%
parallel gap counter	-8.4	4.15%

The stabilisation accuracy of the servo process is determined by the interaction of the measurement errors of P and T, the accuracy with which the detector HT can be set and dG/dV for the detector at the operating point. With δP=0.5mb, δT=0.1K and δV=0.5V a combined error of 0.61% is calculated for the single wire counter which is dominated by the HT error. At the other extreme the predicted error for the parallel gap servo is 1.6% compared with the observed 4.15%. The poorer performance in practice is almost certainly due to the additional uncertainties present in the ambient parameters. Because of the thermal inertia of the detector housing it is unlikely that the gas temperature monitor was always in thermal equilibrium with the gas. Similarly, the small pressure fluctuations caused by the gas bubbler on the counter gas outlet were probably significant in this case. The parallel gap counter is so sensitive to ambient conditions that a significant gain shift is induced by doubling the counter flow rate and thus slightly increasing the back pressure from the outlet tube.

The different sensitivities exhibited by the various counters probably result from the differing number of mean free paths involved in the respective gain processes. In the case of the MSGD and the 20μm diameter wire the gain occurs almost entirely in about 20 mean free paths, in the pin detector there is probably of order 100 and in the parallel gap device the fit to equation (4) indicates some 220 mean free paths. Clearly, the best flow detector design for minimising the effects of ambient fluctuations is an MSGD with as small an anode width as possible.

The recently introduced Gas Electron Multiplier (GEM) [13] is a detector in which electrons released by an ionising event in a drift region are avalanched in the high electric field within a hole (50μm diameter) in a thin (50μm) plastic foil coated on either side with conducting material and across which a suitable potential (≈500V) may be established. The characteristic dimension of the avalanche region is 50μm, therefore one would expect that the stability of the gain against ambient conditions will be slightly worse that of a single wire counter.

The Micro-Dot Avalanche Chamber [14] reproduces the field geometry of the pin detector used for the present tests on a much smaller scale. Anode diameters are typically tens of microns which will result in an ambient sensitivity similar to that of the single wire counter and the MSGD.

The “Compteur a Trous” (CAT) [15] is simply a parallel gap avalanche counter. In its form with multiple holes it becomes indistinguishable from the parallel gap with a mesh drift-avalanche separator used for the tests described above. The CAT can therefore be expected to suffer from the poor environmental stability described above.

A new form of the parallel gap detector is recently reported in the form of the MICROMEGAS in which the avalanche gap is reduced to a dimension of 50 to 100μm [16] and operated near to gain saturation. Under these conditions the ambient sensitivity should be much reduced compared with the detector used for the present measurements.

The gain curve of each detector has been fitted to q and V with three parameters which clearly depend on both the detector dimensions and the filling gas. Separating out these dependencies would entail a further sequence of measurements which would eventually produce constants for the gas. The methods described above are simply intended to provide a convenient method for stabilising flow counters against ambient conditions in an *ad hoc* manner and not as a method for investigating the physics of the avalanche process. However, additional measurements with varying counter parameters would generate general formulae predictive of the gas gain of any cylindrical wire counter in conditions around the ambient range.

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FIGURE CAPTIONS

Figure 1 A fit of the gain formula proposed for a cylindrical wire counter over a wide range of gain (70 - 17000).

Figure 2 The fitted values of the parameter B in the cylindrical wire counter formula (3) as ambient conditions change (q = P/T).

Figure 3 The fitted values of the parameter B in the gain formula (3) applied to pin detector as ambient conditions change.

Figure 4 The fitted values of the parameter A in the gain formula (4) for the parallel gap counter as ambient conditions change.

Figure 5 The gain of an MSGD is plotted as a function of the environmental variable q.

Figure 6 The gas gain of the cylindrical wire counter as ambient conditions change while the anode potential is adjusted in accordance with the "servo" formula derived from the measurements shown in figure 2.

Figure 7 The ambient gain sensitivity 1/GdG/dq of the MSGD as a function of q at V_C=-690V (G=1000).

Figure 8 The ambient gain sensitivity 1/GdG/dq of the MSGD at q=3.4637 (typical ambient conditions) as a function of gas gain.

FIGURE 1

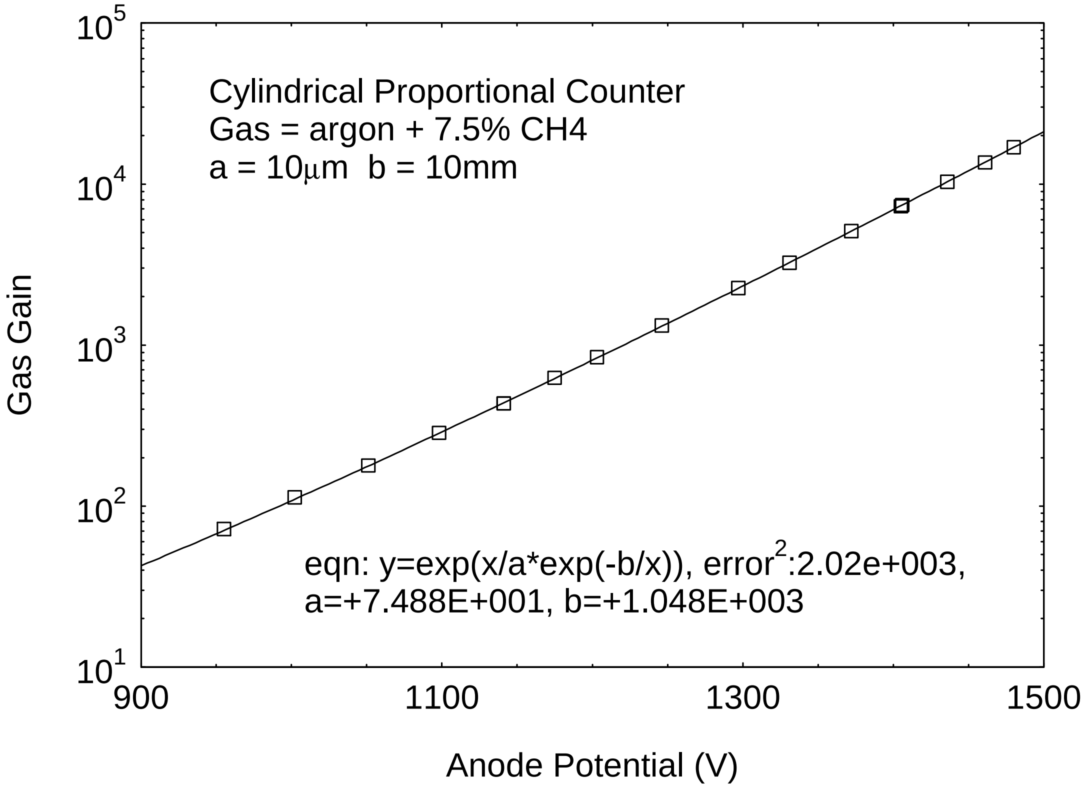

FIGURE 2

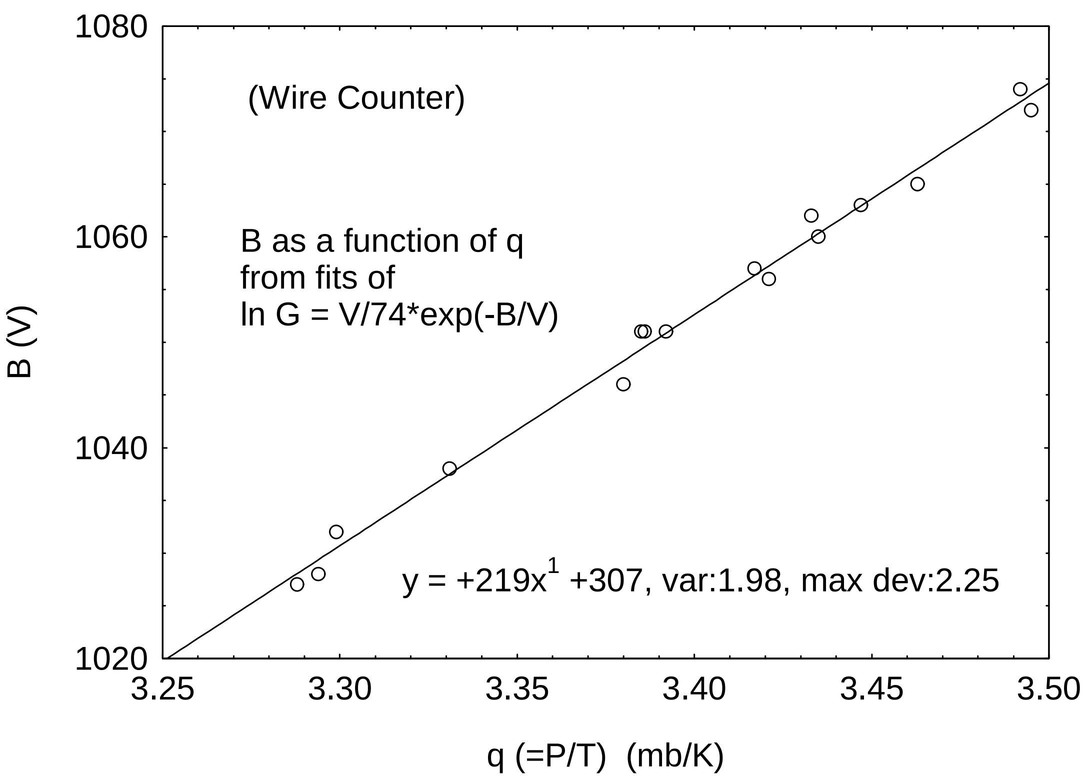

FIGURE 3

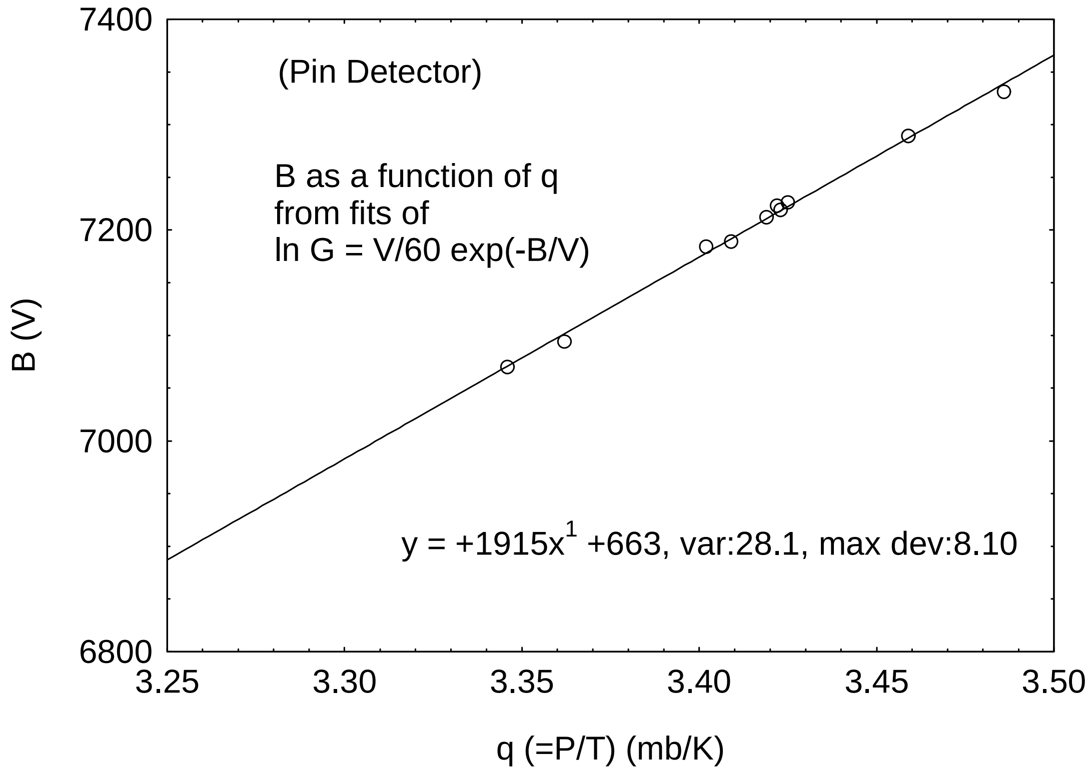

FIGURE 4

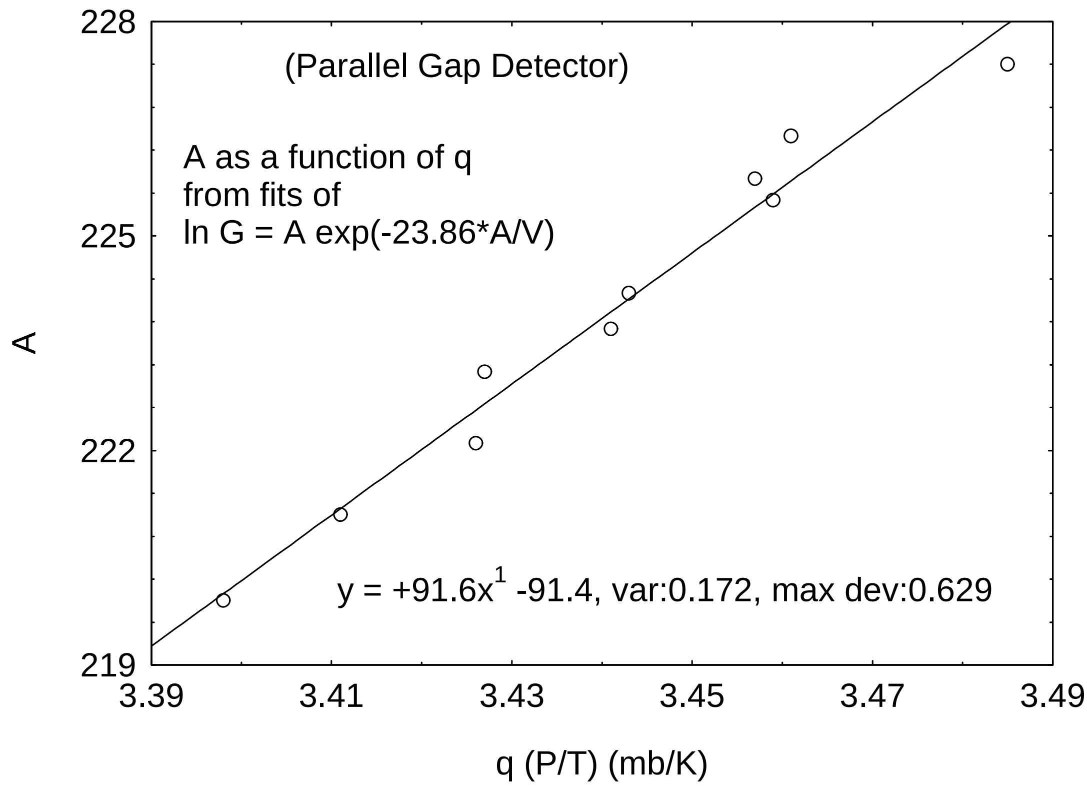

FIGURE 5

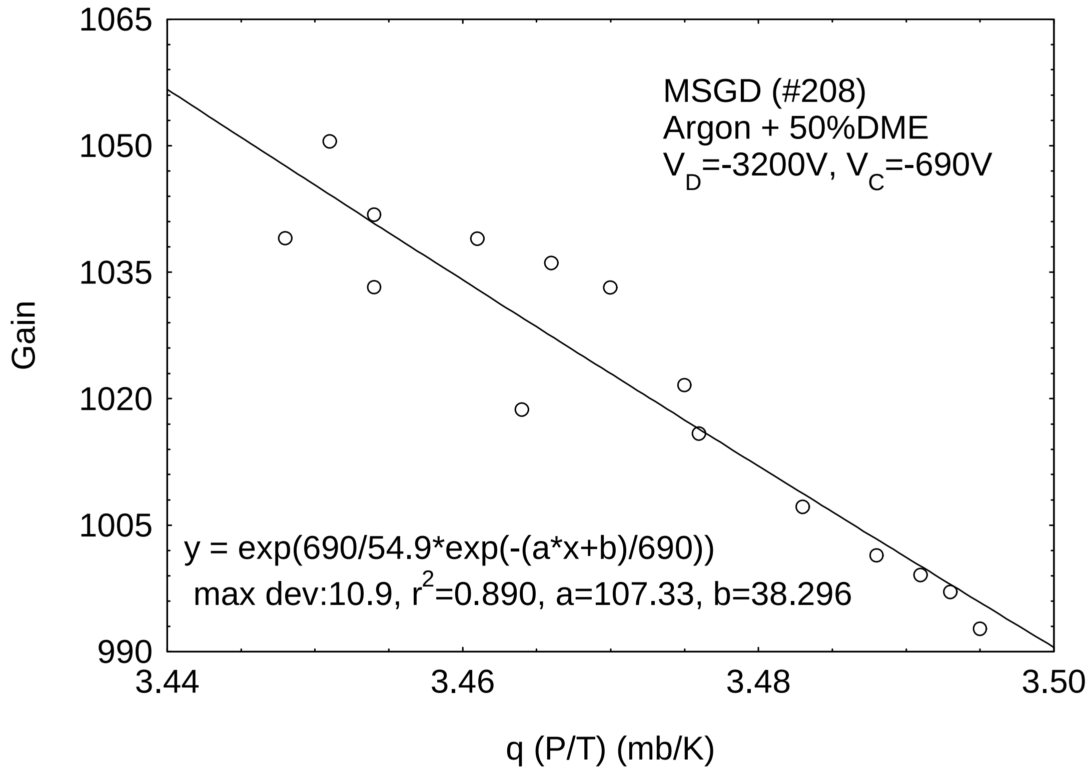

FIGURE 6

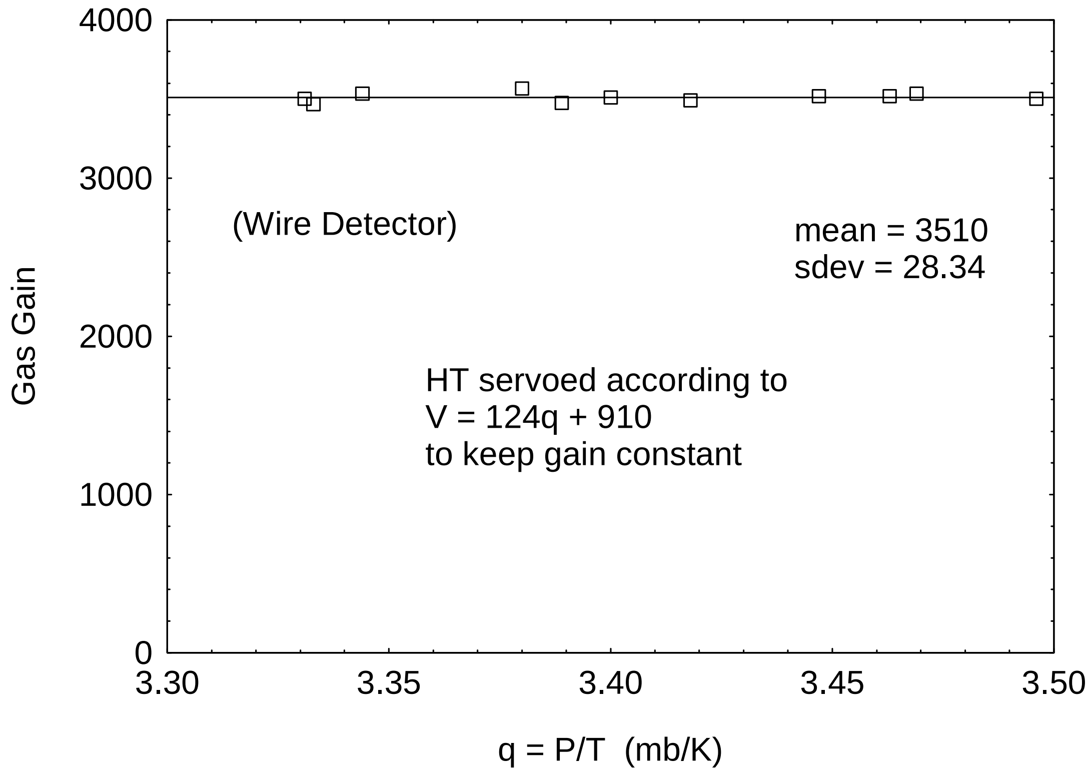

FIGURE 7

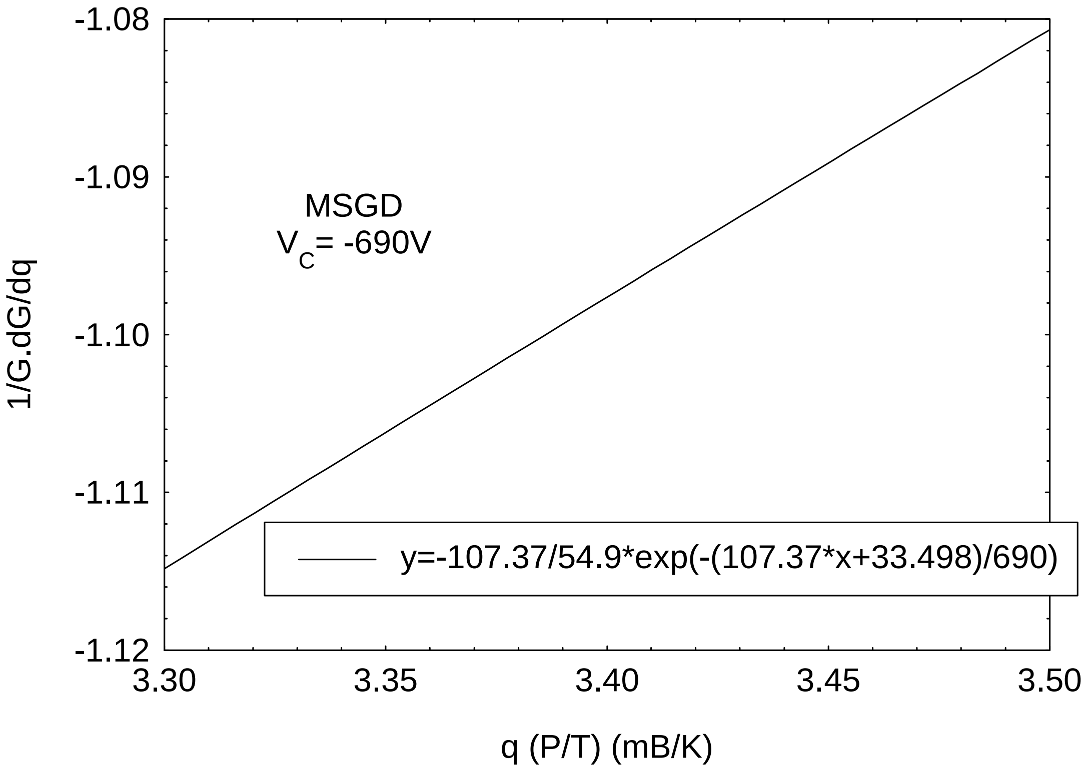

FIGURE 8