DEVELOPING THE SOFT X-RAY PERFORMANCE OF CsI-COATED MICROCHANNEL PLATE DETECTORS

by

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A thesis submitted to the University of Leicester for the degree of Doctor of Philosophy

May 1987
To my parents and Cherith
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LIST OF PUBLICATIONS

Many of the experimental results presented in this thesis have been reported in the following papers:

Fraser G.W., Barstow M.A., Whiteley M.J. and Wells A.
"Enhanced soft X-ray detection efficiencies for imaging microchannel plate detectors"
Nature 300 (1982) 509

Fraser G.W., Barstow M.A., Pearson J.F., Whiteley M.J. and Lewis M.
"The soft X-ray detection efficiency of coated microchannel plates"

Whiteley M.J., Pearson J.F., Fraser G.W. and Barstow M.A.
"The stability of CsI-coated microchannel plate X-ray detectors"

Fraser G.W., Whiteley M.J. and Pearson J.F.
"Developments in microchannel plate detectors for imaging X-ray astronomy"
Proc. SPIE 597 (1985) 343

Pearson J.F., Fraser G.W. and Whiteley M.J.
"The variation of microchannel plate resistance with temperature and applied voltage"
Accepted for publication in Nuc. Instr. Meth. (March 1987)

(For the abbreviations used see pages 272-3)
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CHAPTER 1

THE RÔLE OF MICROCHANNEL PLATES IN IMAGING SOFT X-RAY ASTRONOMY

1.1 Imaging soft X-ray and extreme ultraviolet astronomy

Until this century, all observations of the Universe were made in the visible spectral region. This region, however, is only a small part of the whole electromagnetic spectrum (see Table 1-1).

During the last sixty years, technological advances have enabled observations to be made in the other spectral regions. Two partially overlapping wavebands that are relevant to the work reported in this thesis are the soft X-ray waveband (1.2 to 120 $\AA$ (10 to 0.1 keV)) and the extreme ultraviolet (EUV) waveband (100 to 1000 $\AA$ (120 to 12 eV)). The earth's atmosphere is opaque to these photons (see Table 1-1), and, therefore, observations can only be carried out from sounding rockets or satellites.

Very sensitive detectors are required to observe cosmic sources of EUV and soft X-ray photons; general sensitivity considerations (see ref.(2) for example) suggest the need of a photon counting detector. In recent years, the development of grazing incidence X-ray optics [3] has enabled cosmic soft X-radiation to be imaged directly. A typical grazing incidence soft X-ray telescope consists of a nest of paraboloidal-hyperboloidal mirrors that are confocal and co-axial. The mirror assembly focusses photons into a conical shell, producing an image at the focal surface (see Figure 1-1). The photons are incident at angles in the range, $\theta_x \pm \delta \theta_x$ to that surface. The limiting resolution of such a telescope, which is due to geometrical aberrations and scattering, may be quantified by the r.m.s. blur circle radius, $\sigma_{\text{telescope}}$. High resolution soft X-ray images can be obtained by placing a position-sensitive X-ray detector at the telescope focus; the detector should have a spatial resolution, $\sigma_{\text{detector}}$, that is better than that of the telescope (i.e. $\sigma_{\text{detector}} < \sigma_{\text{telescope}}$), and, preferably, a high photon detection efficiency and energy (spectral)
<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>$\nu$ or $h\nu$</th>
<th>Type of Radiation</th>
</tr>
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<tr>
<td>$10^{-4}$ Å</td>
<td>12.4 MeV</td>
<td>Gamma rays</td>
</tr>
<tr>
<td>$10^{-3}$ Å</td>
<td>12.4 keV</td>
<td>X-rays</td>
</tr>
<tr>
<td>$10^{-2}$ Å</td>
<td>124 eV</td>
<td>Ultra-violet</td>
</tr>
<tr>
<td>$10^{-1}$ Å</td>
<td>1.24 eV</td>
<td>Visible</td>
</tr>
<tr>
<td>$1 = 10^{-10}$ m</td>
<td>0.012 eV</td>
<td>Infra-red</td>
</tr>
<tr>
<td>10 Å</td>
<td>30000 MHz</td>
<td>Radar</td>
</tr>
<tr>
<td>100 Å</td>
<td>300 MHz</td>
<td>UHF</td>
</tr>
<tr>
<td>1000 Å</td>
<td>3 MHz</td>
<td>FM</td>
</tr>
<tr>
<td>10000 Å = 1 μ</td>
<td>300 kHz</td>
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</tr>
<tr>
<td>10 μ</td>
<td>30000 MHz</td>
<td>Long wave</td>
</tr>
</tbody>
</table>

Table 1-1 The electromagnetic spectrum [1].
Figure 1-1 Schematic diagram of a soft X-ray telescope showing the relative position of the mirrors (a nest of three in this case) and the detector. The mean X-ray angle of incidence $\theta_X$ is also shown.
resolution.

A variety of position sensitive detectors, including imaging proportional counters [4], gas scintillation proportional counters [5], charge-coupled devices [6], negative electron affinity devices [7], and microchannel plate (MCP) detectors, has been developed for EUV and soft X-ray astronomical use. It is the continuing development of MCP photon counting detectors that is the subject of this thesis.

1.2 Microchannel plates

Microchannel plates [8,9] are high gain electron multipliers. A typical MCP is a thin glass disc, of diameter 25-60 mm (although larger plates have been manufactured), perforated by a large number (upto $1.25 \times 10^6$ per cm$^2$ detection area) of very narrow tubes, or microchannels. (See Figure 1-2). The channels of a particular MCP have a common diameter which is normally in the range, 8-50 microns. The thickness of an MCP (of the order of 1 mm) is determined by the desired channel length-to-diameter ratio (L/D): L/D values range from 40:1 to 175:1. When the channels are evacuated, the application of a large electric field along their length causes each one to behave as an independent.

Figure 1-2 Schematic diagram of a microchannel plate.
continuous-dynode electron multiplier. The development of such multipliers (both single-channel channel electron multipliers (CEMs) and MCPs) is described in several recent reviews [8,10,11,12].

If an electron, ion, or ultraviolet or X-ray photon strikes the wall of a channel at the more negatively biased end, one or more electrons may be ejected from the wall into the channel. An electron avalanche can be initiated resulting in the issue of a cloud of electrons from the more positive end of the channel. The position of such a cloud can be detected with an electronic position-sensitive readout.

It is this ability to convert the energy of an incident photon or charged particle into a precisely located, detectable charge cloud that is the principal characteristic of MCPs. Very high spatial resolution (of the order of the inter-channel separation) can be attained. This, together with both high gain capability and compact size, have led to the use of MCPs in many applications (see Table 1-2).

1.3 Imaging soft X-ray astronomical satellite experiments

MCPs have been extensively used in the field of X-ray astronomy as high spatial resolution focal plane detectors. MCP detectors will be included on at least three future satellites.

The development of a particular focal surface instrument is dependent on the design of the focussing optics. For example, the range of photon incidence angles at the focal surface of a grazing incidence telescope is small (typically being several degrees only), and, therefore, the response of a detector that is to be positioned at the focus needs to be optimized only for incidence angles in that range.

The first satellite that had a soft X-ray imaging capability was the Einstein observatory (also known as the High Energy Astrophysical Observatory, HEAO-B) [21]. This satellite had an X-ray telescope [22] consisting of a nest of four mirrors, giving a field of view of 25 arc-minutes with angular resolution of better than 2 arc-seconds at the centre of the field. The focal plane instrumentation
<table>
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<th>Application</th>
<th>Uses</th>
<th>Refs.</th>
</tr>
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<td>Military night sights</td>
<td>[13]</td>
</tr>
<tr>
<td></td>
<td>High speed photography</td>
<td></td>
</tr>
<tr>
<td>X-ray image intensifier</td>
<td>Medical topography</td>
<td>[14,15]</td>
</tr>
<tr>
<td>Transmission and scanning electron microscope</td>
<td>High magnification, high brightness microscopy with minimum effect on the specimen</td>
<td>[16]</td>
</tr>
<tr>
<td>Field ion microscopy</td>
<td>Atomic resolution of solid surfaces</td>
<td>[17,18]</td>
</tr>
<tr>
<td>Neutron radiography</td>
<td>Non-destructive testing</td>
<td>[19]</td>
</tr>
<tr>
<td>Ultra-high speed cathode ray tube</td>
<td>Real time observations of very fast single events</td>
<td>[20]</td>
</tr>
</tbody>
</table>

Table 1-2 Some applications of microchannel plates.
included three high resolution imaging detectors (HRIs). Each HRI [23] comprised a "tandem-pair" assembly of MCPs (see Section 2.5.3.1), together with a crossed-wire grid charge encoder.

The Einstein observatory, which was launched in November 1978, added hundreds of sources, ranging from individual stars to quasars with very large red shifts, to the X-ray catalogues until it ceased operating in 1981.

The European X-ray Observing Satellite (EXOSAT) [24] was launched in May 1983 and carried a variety of instruments including two low energy imaging telescopes (LEITs) [25]. Each LEIT consisted of a grazing incidence X-ray telescope and two associated detectors, namely a position-sensitive proportional counter and an MCP detector (known as a channel multiplier array (CMA)). There were some technical problems with the LEIT detectors but data continued to be acquired until the satellite ceased operation on 10th April 1986.

To date, most X-ray astronomical observations have been made in the 0.5-20 keV energy band. The German Roentgensatellit (ROSAT) [26] is due to be launched in 1991. The main ROSAT telescope is designed to carry out an all-sky survey in the 0.15-2 keV band. One of the focal plane instruments will be a High Resolution Imager (HRI); this will be essentially the same as an Einstein HRI except that it will bear a CsI, rather than a MgF$_2$, photocathode. Such CsI photocathodes were developed at Leicester and a number of the developments are reported in this thesis (see Chapters 4 and 5). The ROSAT HRI will be coated at Leicester.

It is intended to make the first all-sky survey in the 0.04-0.2 keV energy band with the ROSAT Wide Field Camera (WFC) which will be carried alongside the main ROSAT telescope. The WFC [27] will consist of a nest of three grazing incidence mirrors. Two identical MCP tandem-pair detectors will be mounted on a turret assembly positioned at the focus. The MCPs will be curved in order to match the optimal focal surface. Filters, which will be mounted on a wheel in front of the detector, will provide broadband energy information.
A consortium of U.K. research groups is building the WFC. The detectors, which are the responsibility of the X-ray Astronomy Group of Leicester University, are currently under development. Indeed, part of the work reported in this thesis, especially the lifetest work reported in Chapter 6, was a part of the WFC detector development programme.

Looking further into the future, a proposal [28] by an Anglo-American consortium for the inclusion of a high resolution camera (HRC), utilizing large area Mullard\* MCPs, as one of the four focal plane instruments on the Advanced X-ray Astronomical Facility (AXAF), has been accepted by NASA. AXAF, which is to be NASA's principal X-ray astronomy satellite until the turn of the century, is scheduled for launch in the 1990s. The proposal describes the detector as having both high spatial resolution and high time resolution over the entire field of view. The detector will also have a high X-ray quantum detection efficiency and modest energy resolution in the 0.1-8 keV energy band. Some of the work that is reported in this thesis is particularly relevant to the AXAF HRC. In Chapter 7, we report our investigation of detectors that incorporated MCPs with 8 micron diameter channels. ("Standard" MCPs have 12.5 micron diameter channels.) These MCPs are important for a number of reasons. For example, they have a smaller channel pitch than "standard" MCPs; channel pitch is the factor that limits spatial resolution in MCP detectors. We also present the results of our investigation into the Fe\(^{55}\) (5.9 keV) response of several MCP detectors.

The main parameters of all the above mentioned satellite instruments are summarized in Table 1-3.

1.4 Programme of research

Satellite-borne MCP detectors, such as those carried on the Einstein observatory, have operated very successfully, but, in several respects, they were inferior to the other soft X-ray position sensitive detectors mentioned in Section 1.1. First, the intrinsic soft X-ray quantum

\*Mullard Ltd., New Road, Mitcham, Surrey CR4 4XY
<table>
<thead>
<tr>
<th></th>
<th>Einstein HRI</th>
<th>EXOSAT CMA</th>
<th>ROSAT WFC</th>
<th>AXAF HRC</th>
</tr>
</thead>
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<tr>
<td><strong>Energy range (keV)</strong></td>
<td>0.15-3.0</td>
<td>0.04-2.0</td>
<td>0.04-0.2</td>
<td>0.1-8.0</td>
</tr>
<tr>
<td><strong>Field of view (arc min)</strong></td>
<td>25 x 25</td>
<td>132 x 132</td>
<td>300 x 300</td>
<td>32 x 32</td>
</tr>
<tr>
<td><strong>Spatial resolution on axis (arc secs)</strong></td>
<td>2</td>
<td>10</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>MCP size diameter</strong></td>
<td>36 mm</td>
<td>46 mm</td>
<td>55 mm</td>
<td>100 x 100 mm²</td>
</tr>
<tr>
<td><strong>Intrinsic energy resolution</strong></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>E/ΔE &gt; 1 at 1 keV</td>
</tr>
</tbody>
</table>

Table 1-3 Comparison of the characteristics of four instruments.
detection efficiency (QDE) of an uncoated MCP is low, being typically less than 10 percent at most X-ray incidence angles [29]. Detectors that utilize an MCP as the photon to photo-electron converter, therefore, have low quantum detection efficiencies. Secondly, MCP detectors such as the HRIs have no intrinsic energy resolution.

In an attempt to enhance the QDE of the Einstein HRIs, a MgF₂ photocathode was deposited onto the front face of the front MCP. The front surface thickness and channel penetration depth of the photocathode were chosen to give the highest detector QDE over the incident angle and energy ranges appropriate. Nevertheless, the enhanced HRI QDEs were still low (the maximum value being approximately 30 percent at a photon energy of 0.86 keV) compared to the almost 100 percent QDEs of those other detectors listed at the end of Section 1.1.

The initial aim of the work presented in this thesis was to further enhance the soft X-ray QDE of an MCP detector by the use of a superior deposition photocathode (see Chapter 4). Caesium iodide was chosen as the candidate photocathode material. The research with CsI photocathodes at Leicester was a co-operative effort; the initial work was performed by M.A. Barstow, G.W. Fraser, and myself. This work was undertaken as a part of the ROSAT WFC detector development programme. For this reason, the deposition geometry of the CsI photocathodes was optimized for radiation incident on the detector at an angle of 30° to the detector normal. The stability of these photocathodes was then investigated; the results are presented in Chapter 5.

In the initial work with the CsI photocathodes, photon energies were less than 2 keV. In later work, enhanced QDEs were measured at photon energies up to 6 keV by the use of thicker photocathodes.

The usual method, albeit crude, of achieving some spectral information from an MCP detector is to position bandpass filters in front of it. The EXOSAT satellite did have and the ROSAT satellite will have, bandpass filters. As a consequence of the initial work with CsI photocathodes, we realized that some intrinsic energy resolution might be attainable under specific operating conditions from
detectors incorporating CsI-coated channel plates. The initial work to investigate this possibility was performed by J.F. Pearson at Leicester. Further research, including the testing of MCPs having channel diameters of only 8 microns, and the use of electron-retarding interplate bias voltages, is reported in Chapter 7. As the AXAF proposal [28] specifies an MCP detector having some energy resolution, the test detectors were optimized specifically for AXAF evaluation, i.e. for radiation incident at an angle of 4° or less.

There is one other feature of MCP operation that is undesirable. If a large total amount of charge is abstracted per unit area from an MCP, gain degradation is observed. A series of lifetests have been carried out on a number of MCP detectors and the characteristics of gain degradation have been investigated. One method of minimizing the rate of gain depression in MCPs was tested. This required an MCP to be treated with a solution of CsOH. Chapter 6 gives the details of all the lifetests performed by us.

The research reported in this thesis was carried out on a CASE award supported jointly by the Science and Engineering Research Council and Mullard Ltd, who were primarily interested in the photocathode stability tests and in the phenomenon of MCP gain degradation.
CHAPTER 2

PHOTON DETECTION IN AN MCP TANDEM-PAIR DETECTOR

2.1 Introduction

All of the work reported in this thesis was performed with soft X-ray, imaging, tandem-pair MCP detectors. (Tandem-pair MCP detectors are described in Section 2.4.1.3.) In this chapter, it will be shown why such detectors are usefully employed in the field of imaging X-ray astronomy by discussing the physical processes involved both in the detection of, and in the determination of the position of, an incident photon.

2.2 Imaging requirements of a soft X-ray astronomical MCP detector

In principle, an imaging detector for soft X-ray astronomical use could consist of a single MCP and a position sensitive readout, the former being utilized to convert the incident photon flux into electron avalanches, the latter being used to encode the position of those avalanches. Ideally, the readout has to be capable of encoding the position of an individual avalanche with an uncertainty of less than the inter-channel separation (the pitch) of the MCP. If the readout is for a satellite-borne detector, it is also a requirement that the processing electronics be lightweight and compact. As the soft X-ray flux observed from astronomical sources is, all too often, low (for example the maximum expected event rate from the Rosat WFC telescope is 200 counts per second [26]), a high count rate capability is not required from either the MCP or the readout.

2.2.1 Principles of position encoding

One method of encoding the position of an electron cloud emanating from the exit face of the MCP is to use a readout with discrete anodes, one for each pixel of the image field,
together with associated electronics (see ref. (30) for an example). Other readouts, which effectively combine the individual anodes but still allow high precision event location to be realized, have been designed. With such readouts, a number of which are described in the summary by Fraser [12], the signals appearing at a small number of terminals are used to obtain event positions.

Two types of position encoder were employed in the detectors that are reported in this thesis, namely resistive anode (RA) readouts and graded density (GD) readouts. The actual encoders used will be described in Chapter 3. Both types are analogue devices; they encode the centroid position of a single incident electron cloud. Apart from their electrical simplicity and robust construction, these readouts also have the advantage that radial spreading of the incident charge clouds in the gap between the MCP and the readout does not affect the spatial resolution attainable. Indeed, the GD readout relies on charge spreading for correct operation.

2.2.1.1 The RA encoder

Parkes et al [31] showed that a 1-dimensional resistive strip had a position resolution at least equal to the channel pitch limited resolution (the channel pitch was 20 microns) when using zero-cross timing electronics. The capacitance to ground of such a strip causes it to behave as an RC transmission line. A position related time signal, \( t^p \), can be obtained by measuring the difference in the zero-cross times, \( t_1^p \), \( t_2^p \), of the doubly differentiated waveforms at each line-end terminal. \( t^p \) gives the displacement of a charge cloud from the centre of the strip. Parkes et al obtained 18 micron r.m.s. resolution at the centre of a 20 mm long resistive strip (i.e. \( \Delta X/L_s = 1100 \) where \( \Delta X \) is the positional uncertainty and \( L_s \) is the encoder length). Fraser and Mathieson [32, 33] showed that a 2-dimensional resistive anode should be capable of similar position resolution.

A two-dimensional RA is a four terminal device. It performs the combined functions of resistive charge division
and charge collection. An electron cloud incident on the anode partitions between the electrodes in such a manner that the charge appearing at a particular electrode is proportional to the proximity of the cloud to that electrode. Relatively simple electronics can be connected to the terminals to determine the position co-ordinates of an event. Position signals, X and Y, can be found by calculation as follows:

\[
X = \frac{V_1}{(V_1 + V_3)}
\]

\[
Y = \frac{V_2}{(V_2 + V_4)}
\]

where \( V_1, 2, 3, 4 \) are the peak output voltages at the terminals (see Figure 2-1).

The spatial resolution that can be attained with an RA is determined by the signal-to-noise ratio at its terminals. As an RA can only encode the position of a single event at any one time, the signal is the charge in a single electron cloud. The noise signal is due to the Johnson noise of the resistive component of the output impedance of the RA. The

![Figure 2-1 A square resistive anode with electrodes central to the sides [32]. The electrodes are assumed to be connected through charge-sensitive pre-amplifiers to shaping filters.](image)
noise charge, $Q_{\text{noise}}$, is approximately given by

$$Q_{\text{noise}} = (4kT\gamma/R)^{1/2}$$

where

- $k$, Boltzmann's constant $= 1.38 \times 10^{-23} \text{ J K}^{-1}$
- $T$ = the temperature of the anode in degrees Kelvin
- $\gamma$ = the time constant of the shaping amplifiers in seconds
- $R$ = the surface resistance of the anode in ohms.

With an amplifier time constant of 2 $\mu$s, and an anode resistance of 240 k$\Omega$, (values pertinent for the WFC MCP detector [27]), the noise contribution is of the order of 2300 electrons r.m.s. Thus, if 10 microns spatial resolution is required over a detection area that has a diameter 25 mm, the charge cloud must contain more than $5.8 \times 10^6$ electrons (a charge of approximately 1 pC).

### 2.2.1.2 The GD readout

Readouts based on wire grids have been investigated by various authors (e.g. capacitively coupled grids [34], resistively coupled grids [35,36]). The GD encoder is just one particular type of grid readout. The wires in a single grid are electrically connected together into two groups, $X_1$ and $X_2$ say, in such a way that the number density of $X_1$ varies almost linearly with position, $X$, across the electrode whilst the number density of $X_2$ varies in the same manner but in the opposite sense (see Figure 2-2). If the charge cloud has a large extent compared to the interwire separation, the charges, $Q_{X_1}$, $Q_{X_2}$, collected by the two groups of wires, are also linearly related to the position, $X$, of the cloud. The event centroid position can be found from

$$X = \frac{Q_{X_1}}{Q_{X_1} + Q_{X_2}}.$$

Two-dimensional position sensing is achieved by having two orthogonal grids, one behind the other. A small potential difference (approximately 0.1 volts) has to be applied between the two grids in MCP applications to ensure equipartition of the charge between them [37]. If the amount of charge impinging on the readout has to be measured, a reflector plate, which is held at a potential that is
Figure 2-2 A graded density wire plane. The wires are connected in two groups, X1 and X2. The electrodes are assumed connected through charge-sensitive pre-amplifiers to shaping filters. The position signal, X, is given by

\[ X = \frac{V_2}{V_1 + V_2} \]

where \( V_{1,2} \) are the peak output voltages at the electrodes.
several hundred volts more negative than the grids, is positioned behind the grids. This plate repels any electrons that pass through both grids back onto them and ensures that all charge is collected.

It has been claimed that graded density readouts are superior to RAs, as far as spatial resolution is concerned, because of the absence of Johnson noise, but this still has to be shown in practice. There are two main causes of noise in a GD readout. One is the preamplifier noise due to the capacitative loads presented to the preamplifiers. This has been measured to be approximately 2600 electrons FWHM (1100 electrons r.m.s) \cite{3d} under a 110 pF load. The collected charge was 2.5 pC, which is equivalent to $1.5 \times 10^7$ electrons. The second component of noise is due to the partitioning of charge between a number of wires. This component exceeded the preamplifier noise component in ref.\cite{38}. This source is not present in a continuous RA.

If an RA or a GD readout (or one of a number of similar readouts, such as the wedge and strip anode \cite{39}) is to be used as the readout element of an MCP detector, then, in order for the detector spatial resolution not to be compromised by the noise component of the readout, the MCP must produce charge clouds of at least $10^7$ electrons for every detected incident photon. As we will show shortly, a single MCP cannot achieve this satisfactorily. First, though, the process of MCP manufacture is described.

2.3 The MCP manufacturing process

MCPs are usually fabricated from a glass mixture whose composition includes PbO, SiO$_2$ and various alkali oxides. The compositions of four common types of channel plate glass are given in Table 2-1. It is the modification of such a glass mixture by the subsequent manufacturing processes that produces the "active" glass which is both the photon-to-photoelectron conversion medium and the electron multiplication medium. The manufacturing process \cite{42} is shown schematically in Figure 2-3. The channel glass is formed into a cylinder and a rod of a soluble glass is fitted inside it. The soluble glass is chosen so as not to
<table>
<thead>
<tr>
<th>Glass Type</th>
<th>Composition by weight</th>
<th>Pseudo-molecule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phillips 3502 [40]</td>
<td>49.4% SiO$_2$; 7.6% K$_2$O 27.4% PbO; 4.5% Na$_2$O 11% Bi$_2$O$_3$; 0.05% BaO</td>
<td>Si$<em>5$O$</em>{12}$Pb.K.Na$^*$</td>
</tr>
<tr>
<td>M102 [28]</td>
<td>similar to type 3502</td>
<td>as above</td>
</tr>
<tr>
<td>Corning 8161 [41]</td>
<td>39.0% SiO$_2$; 5.1% K$_2$O 51.5% PbO; 0.2% Na$_2$O 2.0% Rb$_2$O; 1.5% BaO</td>
<td>Si$<em>6$O$</em>{17}$Pb$_2$K</td>
</tr>
<tr>
<td>GE-821 [41]</td>
<td>37.0% SiO$_2$; 5.5% K$_2$O 58.5% PbO; 0.5% Na$_2$O 2.5% Al$_2$O$_3$</td>
<td>Si$<em>5$O$</em>{13}$Pb$_2$K</td>
</tr>
</tbody>
</table>

Table 2-1 Bulk compositions of various MCP glasses.

$^*$ Obtained by ignoring the barium content and treating the high-Z bismuth and lead atoms as equivalent.
Figure 2-3 The MCP manufacturing process (adapted from ref. (43)).

1) The etchable core is assembled into the channel glass.
2) The cladded glass is drawn into a fibre.
3) The fibre is cut, and the elements are stacked and fused together.
4) The first stack is drawn into a multifibre.
5) The multifibre is cut, and the elements are stacked and fused together.
6) The ingot is sliced.
7) The wafer is ground and polished.
8) The polished wafer is etched and reduced in a hydrogen atmosphere.
9) The electrodes are deposited onto the wafer giving the finished MCP.
interact with the channel glass. The composite rod is drawn into a fibre, which is cut into lengths. These are stacked into a hexagonal block and the individual elements are fused together using a third glass mixture.

The multifibre so formed is itself drawn and cut. Once again, the cut lengths are stacked and fused together. The result is a boule of glass which contains a microchannel matrix whose channels are filled with the soluble glass mixture. Individual MCPs are cut from such a boule.

After an MCP has been cut, the flat faces are usually polished. MCPs which are to have a curved surface, such as those for the ROSAT WFC detector, are shaped prior to this stage. The channel cores are etched away with a suitable etchant to produce the microchannel array which is then baked in a hydrogen furnace. Lead oxide that is present in the surface layers of the channel walls is chemically reduced to metallic lead; water is also produced. The majority of this water is driven off, but some remains in the MCP structure. This latent water had to be removed before an MCP could be coated with CsI (see Chapter 4). The reduction causes a semiconducting lead layer to be formed just below the surface of the channel walls. Further details of the physical processes that occur during the hydrogen reduction will be given in Section 4.3.2.1.

The hydrogen bake gives an MCP its desired semi-conductive properties, together with its characteristic black colour. Electrical connection to an MCP is made via vacuum deposited electrodes; either Nichrome (Ni$_7$Cr$_2$Fe$_3$) or Inconel (Ni$_{10}$Cr$_2$Fe) is usually used. It is usual to deposit the electrodes so that they extend one or two channel diameters into the channels. This penetration is known as electrode end spoiling.

The reduction process is usually controlled so that the resultant MCP has an "in vacuo" resistance between its electroded faces of a few hundred MΩ. MCPs, however, have been fabricated so that they have a corresponding resistance of only tens of MΩ [44].

The manufacturing process is very flexible and MCPs can be fabricated with unconventional cross-sections; for example, rectangular MCPs have been made [45].
2.4 The interaction of a soft X-ray photon with an MCP

At soft X-ray wavelengths, the predominant process involved in the interaction of a photon with matter is the photoelectric effect. A soft X-ray, incident on a channel wall, interacts within approximately 100 Å of the channel surface. During the hydrogen reduction process, this layer is depleted of lead and enriched with potassium (see Chapter 4). When a photon is absorbed by an atom, a photoelectron, together with either a fluorescent photon or one or more other (e.g. Auger) electrons, is ejected from that atom. As these primary electrons travel through the MCP glass, they can lose kinetic energy via scattering processes and produce low energy secondary electrons. One or more of these primary and secondary electrons may escape from the surface of the channel wall. In this way, the energy of a soft X-ray photon can be converted into the kinetic energy of a number of free electrons.

Without any multiplication, the number of electrons liberated by a single photon interaction is too small to be detected by the electronic position sensitive readouts that are currently available for satellite-borne detectors. Thus, the number of electrons in an initial batch has to be augmented. In an MCP, this is achieved through the phenomenon of electron multiplication.

2.4.1 The gain characteristics of a single MCP

When a large voltage (of the order of kilovolts) is applied between the electroded faces of an MCP that is in a vacuum of better than $10^{-5}$ torr, each channel behaves as an electron multiplier. The semiconducting layer, which is present just under the surface of each channel wall, enables a potential gradient to be established along the channels. A photon interaction at the entrance of a channel may result in a batch of one or more photoelectrons being ejected into the channel as described above (see Figure 2-4). As a particular electron travels across the channel, it is accelerated down the channel under the effect of the applied voltage and gains energy. Eventually, the electron will
collide with the channel wall. If the collision energy of that electron is sufficient, secondary electrons can be created; these can also be ejected into the channel.

On average, if the number of electrons ejected from the channel wall per incident electron is greater than unity (i.e. if the secondary electron emission coefficient (SEEC) of the channel wall material is greater than one), electron multiplication is achieved. Multiplication can continue along a channel with the result that a cloud of electrons emerges from the more positive end of that channel. Those electrons that are abstracted from the channel have to be replenished, and this is achieved through the semiconducting layer.

The amount of electron multiplication (the gain) of a channel is dependent on both the channel geometry and the potential difference applied between its input and output. A higher potential difference increases the electron collision energy and, in the range of collision energies encountered in the channels (upto approximately 200 eV), this leads to an increase in the SEEC of the channel wall glass [46,47].

![Diagram of electron multiplication in a single channel](image)

Figure 2-4 Electron multiplication in a single channel. A photon interaction at the channel entrance (the more negatively biased end) can result in the initiation of an electron avalanche.
The increased collision energy is a result of the electrons travelling further down the channel before colliding. The average number of collisions occurring in a channel from entrance to exit is therefore reduced. This is an important effect for a channel plate that is operated in the low-gain (also called the linear or current) mode, but not for one being operated in the high gain (or saturated or pulse counting) mode.

2.4.1.1 The low gain régime

When a moderate voltage (upto approximately 1000 volts for an MCP with an L/D ratio of 120:1) is applied across an MCP, each channel acts as a series of equally spaced dynodes. The output cloud resulting from a single photon interaction may contain upto $10^4$ electrons. With thousands of interactions occurring every second, the MCP output current is proportional to the photon flux. This property is exploited in, for example, image intensification devices.

If a pulse height distribution (PHD) - a histogram of the number density of events versus output charge level - is recorded, it has a negative exponential form [48,49]. Such a distribution is a consequence of the statistics of the multiplication process.

If the incident photon flux is increased to the point at which the output current would be greater than approximately 10 percent of the MCP strip current (the bias current due to the application of the applied voltage), the output current is limited. This leads to a loss of contrast in an image intensifier. An MCP can, however, produce an output current that is proportional to the flux which greatly exceeds the approximately 10 percent linear limit if the incident flux occurs in sufficiently short bursts. This feature is utilized in MCP photomultipliers [49]. The charge that is abstracted in an output pulse is stored in the capacitance to ground of the channel walls. The pulse repetition rate, however, is limited because stored charge can only be replenished through the low conductivity channel walls.

When a low flux of photons has to be imaged, individual photon detection can be usefully employed. It has been
observed [50] that the output PHD of a curved-channel CEM changes dramatically as its gain is increased. At a gain of the order of $10^6-10^7$, the output PHD is peaked rather than being quasi-negative exponential in form. The CEM is said to be operating in the saturated mode. This change in the nature of the output PHD is beneficial when photon counting because it allows for discrimination of noise events and minimizes the dynamic range of the pulses to be processed by the readout electronics.

If it is attempted to operate a single MCP with a gain greater than approximately $10^8$ (this is achieved by increasing the MCP bias voltage), the phenomenon of ion feedback occurs before the output PHD becomes saturated.

2.4.1.2 Ion feedback

Ion feedback occurs when positive ions drift, under the effect of the applied voltage, along a channel towards the channel entrance. As MCPs are also sensitive to positive ions (the detection efficiency for positive ions with energy up to 1 keV may be as high as 40 percent [51]), then, if an ion collides with the channel wall, an electron avalanche may be initiated resulting in an output pulse. Thus, if the gain of a single MCP is raised by increasing the bias voltage, the signal-to-noise ratio decreases as the number of ion feedback induced events increases.

There are two sources of positive ions: either they are desorbed from the channel walls due to electron bombardment, which is greatest at the output of the channels, or they are produced by the ionization of residual gas molecules. The latter mechanism can be suppressed by decreasing the ambient pressure. (MCPs should only be operated in a vacuum of better than approximately $10^{-5}$ torr.)

The number of ion feedback induced events can be minimized by introducing a break in the channels. This reduces the distance that an ion can move up a channel before colliding with the wall, and, therefore, reduces the gain that an ion initiated event can attain. If photon counting is being performed, low gain events can be discriminated out electronically.
2.4.1.3 High gain configurations

There are two common methods of introducing a break into the channels of an MCP detector. In tandem-pair detectors, two MCPs are positioned close together and face to face with their channel axes at some small angle to one another, as indicated in Figure 2-5. Detectors for astronomical use usually have a front plate with a $0^\circ$ bias angle (i.e. with the long axis of the channels perpendicular to the (flat) MCP input face) combined with an MCP with, for example, a $13^\circ$ bias angle. This creates a $13^\circ$ bend in the path of any positive ions drifting towards the front MCP from the rear (see Figure 2-6).

Another method of reducing the effects of ion feedback is to curve either the whole of the channel or only the output region, where the electron density is greatest during a pulse. Such curvature results in the so-called "C" or "J"

![Diagram of tandem-pair MCP configurations](image)

Figure 2-5 Tandem-pair MCP configurations. (a) The standard configuration for an astronomical detector; the front MCP has a $0^\circ$ degree channel bias angle, $\theta_B$; (b) A standard configuration for a test detector.
Figure 2-6 The bend in the channels of a tandem-pair detector inhibits those positive ions that are created in channels of the rear MCP from colliding near to the front face of the front MCP.
plates. Detectors utilizing these types of channel plates only require one MCP. Such an MCP, however, has a maximum gain of only several times $10^6$, and, therefore, it cannot be usefully employed with those position-sensitive readouts, such as an RA or GD, that generally require gains an order of magnitude greater.

2.4.1.4 The high gain régime

Curved channel MCPs can produce pulses containing approximately $10^6$ electrons, whereas tandem-pair detectors can give gains of greater than $10^7$ without ion feedback effects. At gains as high as these, the output PHD becomes quasi-Gaussian. A typical PHD is shown in Figure 2-7. Such a PHD can be characterized by its peak gain, $G_C$, and its (normalized) full width at half maximum (FWHM), $\Delta G_C / G_C$. The cause of this "saturated" behaviour is positive wall charging, which is a consequence of the high resistance through which the abstracted charge is replenished. The strip current per channel is typically $10^{-11}$ amps (equivalent to approximately 60 electrons per microsecond). A typical output pulse has a duration of up to a few hundred nanoseconds [52] and contains $10^7$ electrons. This charge cannot be replenished instantaneously. Thus, the channel wall charges positively during the passage of a pulse and the channel electric field is modified. This produces a reduction of the collision energy of the electrons. Eventually, the SEEC of the channel wall falls to unity and a dynamic equilibrium is set up. At this stage, the magnitude of the charge in the pulse stabilizes (saturates).

Calculations [53] have shown that the output peak charge, $Q_C$, that can be attained in the high gain mode is related to the bias voltage, $V_0$, the channel length, $L$, and diameter, $D$, as follows:

$$Q_C \sim V_0 D (L/D)^{-1}$$

In a tandem-pair detector, the two MCPs are usually separated by a hundred microns or so. An electron cloud that leaves a single channel of the front MCP spreads out as it crosses the interplate gap. This is due to the radial component of the electrons' velocity. The effect of space
Figure 2-7  A typical output pulse height distribution from an MCP tandem-pair detector; peak gain, $G_C$, full width at half maximum, $\Delta G_C$. The FWHM value is given by $\Delta G_C / G_C$. 
charge repulsion is not significant. The electrons from a single channel of the front MCP, therefore, can illuminate a number of channels in the rear MCP. The almost simultaneous entry of a large number of electrons into a channel of the rear MCP drives that channel hard into saturation. By assuming that a cloud of \( G_F \) electrons partitions uniformly between \( N_C \) channels of the rear MCP, Fraser et al [54] have derived an expression for the peak gain of a tandem-pair detector, in terms of the single electron gains of the individual MCPs, as follows:

\[
G_C = G_F^{1-\beta} G_R \beta
\]

where

- \( G_F \) is the front MCP single electron gain,
- \( G_R \) is the rear MCP single electron gain,
- \( \beta \) is an empirical parameter obtained by considering the variation of \( G_C \) with interplate gap voltage, \( V_G \) (0 < \( \beta \) < 1).

It has also been shown [54] that the voltage required to induce saturation in an MCP, \((V_0)_S\), is given empirically by

\[
(V_0)_S = (V_0)_T + 450 \text{ volts}
\]

with \((V_0)_T\) being given by

\[
(V_0)_T = (4.0_1/2 \times 0.2) \text{ volts}
\]

where

- \( 0_1 \) is the first crossover potential for MCP glass; it is estimated to be 20 volts.

Thus

\[
(V_0)_S = 8.94 \times 0.2 + 450 \text{ volts.}
\]

### 2.4.1.5 Tandem-pair detector operation

The gain of a tandem pair detector is dependent on the voltage difference applied across the front and rear MCPs \((V_F \text{ and } V_R \text{ respectively})\), as well as on the interplate gap voltage difference, \( V_G \). The FWHM of the output PHD is also a function of these voltages. For imaging applications that employ photon counting techniques, it is desirable for the FWHM to be as small as possible and the peak gain to be as high as possible. A high gain increases the signal-to-noise
ratio at the terminals of the position encoder. A narrow FWHM imposes less strict requirements on the dynamic range of the position encoding electronics and also enables improved discrimination of desired events from noise events (which are described in Section 2-5). It is important, therefore, to optimize the settings of $V_F$, $V_R$ and $V_G$ in order to obtain an optimized output PHD.

Once saturation has set in, increasing $V_F$ increases the average gain of individual events but the fraction of low charge events is reduced. Increasing $V_R$ also increases the gain but the fraction of high charge events is reduced. Thus, an increase of either $V_F$ or $V_R$ both effectively reduces the FWHM and increases the peak gain of the output PHD. Unfortunately, the number of noise events with a gain greater than a fixed gain level also increases.

The other voltage that can be varied usefully is $V_G$. As the FWHM of a distribution reflects any spread in the factors affecting the detector gain, such as the number, $N_C$, of channels in the rear MCP illuminated by electrons from a single channel of the front MCP. In an attempt to reduce $N_C$ and, consequently, the PHD FWHM, it was usually the practice to apply an interplate voltage difference that accelerated electrons across the gap. (The greater the voltage difference, the smaller the area of the rear MCP illuminated by electrons from a single channel of the front MCP.) As $V_G$ is increased above approximately 100 volts, the number of channels of the rear MCP illuminated reaches a minimum and no further FWHM decrease is observed with increased $V_G$. In practice, an electron accelerating voltage difference of a few hundred volts is usually applied across the gap. In Chapter 6, however, we will report our use of an electron retarding electric field.

2.5 MCP detector dark noise

When it is not being illuminated, it is observed that a typical tandem-pair MCP detector still produces an output count rate of the order of 1 count cm$^{-2}$ sec$^{-1}$. This count rate can increase greatly if a "hotspot" is present. A hotspot is a localized area of increased dark noise count.
rate (up to several hundred counts sec$^{-1}$ over a detection area of tens of mm$^2$). Such a hotspot mimics a real external source of illumination. A hotspot is often caused by a dust particle or fibre on the front surface of the detector. Hotspots can also be induced by the local evolution of trapped gas or imperfections in the MCP. The clean handling and assembly of MCPs and the provision of adequate outgassing pathways in the detector bodies aids in the elimination of hotspots.

A number of mechanisms have been proposed as explanations of MCP dark noise. Unlike photomultiplier dark noise, MCP dark noise is not thermally generated [35]. The passage of cosmic rays through the MCP has also been discounted as a major noise component [35]. Field emission from channel defects is normally held to be the dominant mechanism on the basis of two experimentally observed facts. First, the output PHD due to noise events alone has a negative exponential form; this indicates that the noise source is spread along the whole length of the channels. Secondly, as the voltage applied across an MCP increases, the noise count rate above a fixed discriminator setting rises rapidly. It is because of this that high gain MCP detectors are operated at voltages that are high enough to induce saturation but low enough for the noise count rate not to be excessive. As the output PHD of noise events is a negative exponential, a low noise rate allows all but a small number of higher charge noise events to be discriminated out (see Figure 2-8).

We present some results in Chapter 7, obtained from detectors that incorporated 12.5 and 8 micron MCPs, which can be interpreted as eliminating field emission from channel defects as being the dominant mechanism. If MCP manufacture results in a constant probability of defect production (a) per channel or (b) per unit channel surface area then, if field emission from channel defects is the dominant source of noise, the noise count rate from these detectors should be dependent on (a) $1/D^2$ or (b) $1/D$. Neither of these dependencies was observed.

The remaining noise mechanism is internal radioactivity, which is usually discounted on the basis of results
Figure 2-8 Comparison of the output pulse height distribution due to noise events (lower distribution) and that due to signal events (upper distribution - shown displaced along the Y-axis). The dashed line indicates a possible output charge level at which to set an electronic threshold.
presented in ref. (35). From a knowledge of MCP composition, the noise contribution from this source can be calculated [55]. As can be seen from Table 2-1, a typical MCP contains approximately 5 percent by weight of potassium. The radioactive isotope $^{40}$K, which has a half-life of $1.28 \times 10^9$ years, has an abundance of 0.0118 percent in the naturally occurring element. In an MCP of diameter 36 mm and thickness 1.5 mm, it can be estimated that there are approximately 10 disintegrations per second (equal to 1 count cm$^{-2}$ sec$^{-1}$). Almost 90 percent of the disintegrations occur by the emission of a 1.31 MeV beta particle, the rest being by 1.46 MeV gamma emission. The efficiency of an MCP to an external source of gamma rays is 2 percent [56], whilst the efficiency of an MCP to an external source of 2 MeV electrons may be as high as 59 percent [57]. As the number of output counts per internally generated gamma ray is not likely to be greater than the number of counts per incident gamma ray from an external source, internal photon emission can be discounted as the dominant source of noise. The "self-efficiency" of an MCP to 2 MeV electrons could be of a similar magnitude to the "external source" efficiency, say 50 percent. The range of 1.31 MeV electrons in lead glass is about 5 mm.

It can be seen that a noise count rate of $0.45 \text{ counts cm}^{-2} \text{ sec}^{-1}$ can be expected from the beta decay of K$^{40}$ atoms in an MCP. Such a count rate is of the correct order to account for the observed noise count rates. Investigations are continuing in our laboratory [58].

2.6 Factors affecting the output PHDs of a tandem-pair MCP detector

The form of the output PHD reflects divergences in the various gain parameters. Under certain conditions, a sharply peaked output distribution cannot be realized. One occasion when this occurs is when the photons are incident at small angles to the long axis of the channels. At such small angles, photons can penetrate further down a channel (upto a distance $D \cdot \cot \theta_x$, where $\theta_x$ is the angle of incidence) before interacting with the channel wall. An event that is
initiated away from the channel entrance has, on average, a lower gain than an event initiated near to the channel entrance because of the reduced distance over which electron multiplication can occur. This causes the output PHD to be broadened towards lower charge levels.

At very small incidence angles ($\theta_X < \arccot L/D$), an MCP becomes partially, geometrically transparent. Thus, a fraction of the incident photons can pass straight through the MCP without interacting. This reduces the quantum detection efficiency of the detector.

At angles of incidence approaching the critical angle of reflection, $\theta_C^X$ for MCP glass, the incident photons can be reflected further into the channel. Reflection can occur for X-rays incident at an angle upto approximately $2.0\theta_C^X$ because of the geometry of a photon interaction with a cylindrical channel, as indicated in Figure 2-9. The grazing angle, $\gamma$, the angle of incidence, $\theta_X^X$, and the polar angle, $\psi$, are related by

$$\sin \gamma = \sin \theta_X^X \cos \psi.$$

Another factor that affects the peak gain of an output distribution is the input count rate. At relatively high illumination levels, individual channels do not have sufficient time to fully replenish abstracted charge before they are re-excited. The lack of available charge, combined with the resultant, altered channel electric field, causes subsequent pulses to have a decreased gain. Thus, at high input count rates (greater than approximately 0.01 counts channel$^{-1}$ sec$^{-1}$), the PHD peak gain is reduced.

The photon flux level required to induce gain depression in a detector that incorporates conventional, high resistivity MCPs is sufficiently high that it is not a problem for imaging, soft X-ray astronomical detectors. Care has to be taken, however, when testing detectors in the laboratory to ensure that the test beam is of a low enough flux so as not to induce (unwanted) gain depression.

2.7 MCP intrinsic soft X-ray detection efficiency

When a soft X-ray strikes an MCP, it can interact with either the electrode material or the surface layers of a...
Figure 2-9  a) Plan view of a cell of a hexagonally-packed MCP. Channel radius, \( r \), channel pitch, \( p \), minimum septal thickness, \( S_{\text{min}} \) [28].

b) Vertical section through the central channel along the line AB, at polar angle, \( \Psi \). X-rays incident at \( \theta_X \) degrees to the MCP normal illuminate the channel to a depth \( D \cos \Psi \cot \theta_X \), where \( D \) is the channel diameter. Note that this figure illustrates an MCP with bias angle \( \theta_B = 0^\circ \).

c) Geometry of the X-ray interaction with the channel wall. \( k \) is the vector in the direction of the MCP surface normal and \( n \) is the normal to the channel wall at the point of incidence, C. \( \theta_X \) is the photon incident angle, \( \alpha \) is the grazing angle and \( \alpha' \) is the refraction angle.
channel wall; the latter is a region that is composed of lead-depleted silica [46,59]. The resultant soft X-ray QDE lies typically in the 1-10 percent range for most combinations of X-ray energy and X-ray incidence angle. (The QDE of a detector is defined as the number of output counts per incident photon.) Under our standard detector operating conditions (described in Chapter 3), in which the front face of the front MCP is held at a large negative potential, any photoelectron emitted from the front interchannel web is repelled away from the channels and hence cannot be detected. The maximum attainable QDE of an MCP, with its front surface held at a large negative potential, is limited, therefore, to the open area fraction. For MCPS with hexagonally-packed circular channels and a zero degree channel bias angle this fraction is approximately 63 percent, calculated from

\[ A_{\text{open}} = \frac{2\pi r^2}{\sqrt{3}} \]

where

- \( r \) is the channel radius and
- \( p \) is the channel pitch.

MCP quantum detection efficiency is a function of both X-ray energy and X-ray angle of incidence. When a soft X-ray, of given energy, enters a particular material, the probability of it being absorbed between a depth, \( z \), and a depth, \( z + dz \), is

\[ \mu \exp(-\mu z) dz \]

where

- \( \mu \) is the linear absorption coefficient of the material to photons of the given energy.

Similarly, the primary and secondary electrons that are created by the absorption of the photon also have a probability of travelling a particular distance (and hence of escaping into the channel). Thus, the nearer to the channel wall that an interaction occurs, the higher the probability of one or more photoelectrons escaping into the channel and, hence, the higher the probability of the event being registered. The smaller the X-ray incidence angle, the nearer to the channel wall surface interactions occur. If the angle of X-ray incidence is reduced, so that it is of
similar magnitude to the critical angle of X-ray reflection, the detector QDE decreases as more and more events have a gain below the electronic discriminator level. At very small incident angles, the QDE is further reduced as the MCP becomes partially, geometrically transparent. A plot of quantum efficiency versus X-ray angle of incidence for a particular X-ray energy has a maximum value near to the critical angle of reflection and tends to zero for both very small incidence angles and incidence angles approaching $\pi/2$. Figure 2-10 shows a typical QDE curve. The main feature of such curves is that, except for a narrow range of angles, the intrinsic efficiency of an MCP is less than 5 to 10 percent.

![Figure 2-10 Typical variation of quantum detection efficiency with C K X-rays, Q(\theta_X, 44.7 Å) with X-ray angle of incidence, \theta_X.](image-url)
CHAPTER 3

THE TEST FACILITIES

3.1 Introduction

The results presented in this thesis were obtained from eight tandem-pair MCP detectors. In this chapter, we describe both the detectors and the experimental test facilities in which they were operated.

3.2 The detectors

The principal components of our tandem-pair MCP detectors were two MCPs, their associated electrodes and a position sensitive readout. These were assembled, together with any ancillary components, in a detector body. Three detector bodies have been fabricated at Leicester. Body 1 was used to test detectors in Vacuum Test Facility 1 (VTF 1) and Body 2, which is shown schematically in Figure 3-1, was used for MCP tests in VTF 2. (See Section 3.4 for descriptions of VTF 1 and VTF 2.) Body 3, which could also be mounted in VTF 1, was designed to a standard that allowed it to be flown on sounding rockets. Table 3-1 lists the MCP parameters for our eight test detectors.

3.2.1 A detector frame of reference

It is useful to define a detector frame of reference, characterized by three orthogonal axes, $X_d$, $Y_d$ and $Z_d$. Figure 3-2 illustrates such a co-ordinate scheme. In this frame, the origin is positioned at the centre of the front face of the front MCP. The $X_d-Y_d$ plane is the plane containing the front face of the front MCP, which is assumed to be flat (as was the case for all eight of our test detectors), of the front MCP. The $Y_d$ axis is the axis of rotation for a detector placed in either VTF 1 or VTF 2.
Figure 3-1 Schematic diagram of a tandem-pair MCP detector. The detector body shown is Body 2 [60].
<table>
<thead>
<tr>
<th>DETECTOR BACK</th>
<th>DETECTOR BODY</th>
<th>FRONTAL MCP</th>
<th>REAR MCP</th>
<th>MCP DIAMETER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No.</td>
<td>L/D</td>
<td>D (μm)</td>
<td>θθ</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>F1</td>
<td>120:1</td>
<td>12.5</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>F2</td>
<td>120:1</td>
<td>12.5</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>F3</td>
<td>120:1</td>
<td>12.5</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>F4</td>
<td>120:1</td>
<td>12.5</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>F5</td>
<td>40:1</td>
<td>12.5</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>F6</td>
<td>175:1</td>
<td>8.0</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>F7</td>
<td>175:1</td>
<td>8.0</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>F8</td>
<td>80:1</td>
<td>25.0</td>
</tr>
</tbody>
</table>

Table 3-1 The MCP parameters of the eight test detectors.
Figure 3-2 The detector frame of reference, showing the $X_d$, $Y_d$ and $Z_d$ axes. The origin is positioned at the centre of the front face of the front MCP.
3.2.2 The MCP-electrode assembly

In order to operate a tandem-pair MCP detector, a potential difference has to be applied across each MCP. In all three of our detector types, the voltages were applied through annular electrodes. These electrodes also provided the mechanical support for the MCPs. Various electrode designs were used.

3.2.2.1 Electrode shape

All of the electrodes were basically annular (see Figure 3-3); some castellated electrodes (shown in Figure 3-3(b)) were also fabricated. Castellated electrodes were used to

![Figure 3-3 MCP detector electrode designs.](image)

(a) Annular design. The tab helps with the positioning of the electrode in the detector body.
(b) Castellated design.
facilitate the outgassing of the detector. By staggering the
castellations of the electrodes on either side of a
particular MCP, the number of channels covered over at both
ends was minimized.

In order to minimize the effects of noise produced at
the electrode edges, the inside diameter of successive
electrodes was reduced, going from the front electrode to
the rear [61]; any noise produced at an electrode edge
should have been masked by the next electrode down the
chain. This technique was extended by fabricating a special
rear electrode with an insert to mask a severe noise source
in Detector 4.

3.2.2.2 Electrode fabrication

All electrodes were fabricated from copper clad kapton
(which is an insulator). The first stage in the fabrication
of an electrode was that the desired designs, magnified by a
factor of two, of both the front and rear views of the
electrode were drawn in ink. Care had to be taken to ensure
that no pinholes were left in the electrode area. The
drawings were photographically reduced to produce a pair of
positive masks of the correct dimensions. The copper clad
kapton board was prepared by coating it in photoresist and
baking it. After the treated board had been baked, the front
and rear masks were carefully positioned on either side of
it and the whole assembly was exposed to UV radiation. The
exposed photoresist was removed by rinsing the board in a
solution of NaOH. Finally, the board was submerged in an
etching solution to etch away any copper and/or kapton that
was not protected by (unexposed) photoresist. The etching
process was terminated when the etchant began to eat into
the desired electrode structure. After rinsing in water, all
copper surfaces were gold plated.

3.2.2.3 Interplate gap electrodes

The thickness of the electrode(s) placed between the two
MCPs defined the interplate gap (in the absence of any
additional spacers). This gap ranged from 40 to 160 microns
for all eight of our test detectors. The larger gaps were defined by "double-sided" electrodes; these electrodes had two independent conductive surfaces separated by a thin layer of insulator. When placed between two MCPs, such a double-sided electrode enabled a potential difference to be set up across the gap. Gap voltage differences ranging from an electron accelerating voltage of 300 volts to an electron retarding voltage of 100 volts were used by us.

It is not essential to have a gap between the MCPs; there are reports in the literature concerning detectors having two or three MCPs physically in contact [49, 62].

3.2.2.4 The positioning of the MCPs in the detector body

The MCPs were positioned correctly between their respective electrodes, in planes parallel to the $X_d-Y_d$ plane, by being placed in insulating rings (shown as MCP spacers in Figure 3-1), each ring being slightly thinner than the MCP it surrounded (in order to allow good electrical contact between the MCP and its electrodes). In Body 1, fibre-glass rings were used whereas PTFE rings were used in Body 2. In both of these bodies, the rings were loose fitting. In Body 3, which could be flown on sounding rockets, tight-fitting PTFE rings were used. These had to be warmed in the hands before an MCP could be inserted. Upon cooling, the PTFE contracted, gripping the MCP.

In contrast to most other MCP applications, MCP detectors for X-ray astronomy usually have a front MCP with a channel bias angle of $0^\circ$ (i.e. the channels are parallel to the detector $Z_d$ axis). The orientation of such an MCP about the $Z_d$ axis does not have to be considered. Several of our test detectors (namely Detectors 1, 2 and 5), however, had front MCPs with non-zero channel bias angles. These MCPs had to be assembled in their detector bodies in such away that a $0^\circ$ angle of X-ray incidence with respect to the channel axes could be attained when the detector was mounted in the test chamber; i.e. each channel had to lie in a plane parallel to the $X_d-Z_d$ plane. This alignment procedure was not easy, especially when the operation had to be carried out in a dry nitrogen ($DN_2$) atmosphere, and often resulted
in a non-zero minimum X-ray incidence angle. Occasionally, the MCP was rotated about the \( Z_d \) axis from its desired orientation after assembly by as much as \( 30^\circ \).

When a front MCP with a non-zero channel bias angle was incorporated in a detector, the rear MCP was orientated to give the maximum possible angle between the channel axes of the two MCPs. It is uncertain if there is an optimum (in terms of PHD quality and/or gain) value of this angle [63]. Indeed, an adequate PHD has been obtained from a detector having its front and rear channels parallel [63].

3.2.3 The detector readout

The type of readout encoder used both in Body 1 and Body 2 was a 2-dimensional graded density readout consisting of two orthogonal grids and a reflector plate. The readout used in Body 2 is shown schematically in Figure 3-4. It had three field-defining electrodes in the gap between the rear of the rear MCP and the front GD grid and two field-defining electrodes in the gap between the rear GD grid and the reflector plate. Normally, the rear face of the rear MCP was held at a voltage of -100 volts, the reflector plate was held at -500 volts and the two grids were held at approximately ground potential. The potentials of the various

![Diagram of the graded density readout of detector Body 2.](image)

Figure 3-4 Schematic diagram of the graded density readout of detector Body 2.
field-defining electrodes were defined by resistor chains.

The readout encoder used in Body 3 was a resistive anode. It was 54 mm square and had a resistance per square of approximately 0.7 MΩ. It had been manufactured by depositing a resistive ink onto a ceramic substrate. Along each side there was a 36 mm long electrode.

### 3.2.4 Other detector components

For many of our measurement sequences, a carbon-coated stretched polypropylene window was positioned in front of the front MCP. Such a window prevented charged particles from impinging upon the detector. We used polypropylene because it can easily be stretched to produce a window as thin as 1 micron and because it has a high transmission for soft X-rays (see Figure 3-5). Each window was coated with a thin layer of carbon to prevent it from charging up. Transmissions for such a composite window varied from approximately 75 percent at C K (0.28 keV) to almost 100 percent at Si K (1.74 keV). The presence of a window of non-unity transmission in front of the test detector had to be taken into account when quantum detection efficiencies were being calculated (see Chapter 4).

When we used an uncollimated source, such as the mercury discharge lamp (described in Section 3.4.1.3), we replaced the polypropylene window with a copper-beryllium mask. One or more apertures in the mask defined the areas of the detector that were illuminated. A mask with a 5 mm diameter aperture was used in the tests reported in Chapter 6.

### 3.3 MCP handling techniques

Apart from the sources of noise listed in Section 2.5, noise events can also be induced by poor electrical contact, local high ambient pressure (due to gas trapped in channels, for example) or marks, such as a scratch or crack, on the plate [64]. Noise sources due to electrical contact problems can be minimized by appropriate electrode design and those sources due to trapped gas can be reduced both by providing adequate outgassing paths and by the use of castellated
Figure 3-5 The soft X-ray and EUV transmission of three thicknesses of polypropylene. The increased transmissions at the extreme right-hand side are due to the C K edge.
electrodes.

Noise can also be induced by foreign bodies, such as fibres or dust particles, coming into contact with the MCPs. As the front surface of the front MCP of our detectors was always held at a large negative potential, such particles could have induced hotspots through the mechanism of field emission. This source of noise [64] was kept to a minimum by the careful handling and assembly of the MCPs and detector components.

First, all detector parts were kept as free of foreign bodies as possible. All detectors were assembled either in a laminar flow cabinet or in a clean room. A jet of DN₂ was used to remove any particle observed on a detector component. Gloves (nylon or plastic) were worn when handling any detector part in an effort to keep all surfaces free from grease. It has been found that the safest method of manipulating a channel plate is with plastic tweezers. It is very easy to scratch MCP glass and, therefore, great care was needed. Small diameter plates were picked up by gripping the plate on opposite edges (see Figure 3-6(a)). Both thin MCPs (0.5 mm or less), which had a tendency for flakes to break off, and larger diameter MCPs were picked up by gripping them as shown in Figure 3-6(b).

3.4 The vacuum test facilities

An MCP detector can only be safely operated if the ambient pressure is less than 10⁻⁵ torr. Thus, two vacuum test facilities have been constructed at Leicester for detector development.

3.4.1 Vacuum Test Facility 1 (VTF 1)

Figure 3-7 is a schematic diagram, and Figure 3-8 a functional diagram, of VTF 1. The test chamber, which is cylindrical with a diameter of 0.7 metres and a height of 0.4 metres, is fabricated from aluminium. Aluminium is a poor material with which to construct a vacuum system because it absorbs water vapour when exposed to the atmosphere and subsequently outgasses it when pumped. As
Figure 3-6  The two methods of handling MCPs with tweezers.
(a) The method of handling small diameter (25 mm or less) MCPs.
(b) The method of handling both large diameter and thin MCPs.
Figure 3-7 Schematic diagram of Vacuum Test Facility 1.
Figure 3-8 The VTF 1 vacuum system.
1) The vacuum chamber.
2) Pneumatically operated quarter-swing baffle valve.
3) Cold trap.
4) Oil-filled diffusion pump.
5) Backing line valve.
6) Oil-sealed rotary pump.
7) Pirani gauge head (backing line pressure).
8) Pirani gauge.
9) Roughing line valve.
10) Dry nitrogen inlet valve.
11) Penning gauge head.
12) Penning gauge.
much of the work reported later required the presence of as little water vapour as possible, the interior of the chamber was kept dry by letting it up to atmospheric pressure with DN₂.

The VTF 1 chamber is pumped by a diffusion pump / rotary pump system [65] In order to reduce oil backstreaming [66] into the chamber, a liquid nitrogen (LN₂) cooled cold trap, shown in Figure 3-7, had been fitted. Typically, the chamber pressure could be reduced to 8-10 x 10⁻⁶ torr with the proportional counter (see Section 3.4.1.2) in position.

The test apparatus in the vacuum chamber of VTF 1 is shown schematically in Figure 3-9. The MCP detector under

Figure 3-9 The arrangement of the test apparatus inside the vacuum chamber of VTF 1 (seen from above). The MCP detector is mounted on a turntable. A manually operated gate determines whether the left-hand or the right-hand side of the MCP detector is illuminated by the collimated and filtered X-ray beam; the former option is shown. The proportional counter can be moved into the path of the beam.
test was mounted on the turntable and could be rotated about a vertical axis (the detector $Y_d$ axis) which passed through the front face of the front MCP. By rotating the detector, the X-ray angle of incidence, $\theta_x$, could be varied. The construction of detector Body 1 meant that X-rays could only impinge on the detector within $30^\circ$ either side of normal incidence.

3.4.1.1 The X-ray source

The VTF 1 test X-ray beam was obtained from a collimated, filtered, electron bombardment source (see Figure 3-10). Various X-ray lines could be excited by choosing suitable combinations of anode coating and anode voltage. Lower energy (bremsstrahlung) radiation was

![Figure 3-10 An electron bombardment X-ray source. Electrons, emitted from the filament, are accelerated by the anode voltage and bombard the water-cooled anode producing X-rays. The source is operated in vacuo.](image-url)
attenuated with an appropriate filter. Table 3-2 lists the anode coating / anode voltage combinations that were used to excite particular test X-ray lines. A relatively narrow X-ray beam (approximately 0.5° FWHM in extent) was produced by collimating the output flux from the source. This was done with a pair of collimating holes (shown in Figure 3-9). The beam could be manually switched, by means of a "gate" on the collimator, to illuminate a spot on either the left-hand or the right-hand side of the MCP detector. To do this, though, required a vacuum break.

3.4.1.2 The proportional counter

In order to perform quantum detection efficiency measurements, it was necessary to know the absolute flux of X-rays falling on the test detector; the efficiency measurement calculations are detailed in Chapter 4. To measure this flux, we used a pill box type proportional counter (PC) [67] which was positioned in the test chamber. This was also mounted on a turntable and could be swung into the path of the X-ray beam (in front of the MCP detector).

The gas used in the PC was P10 (a 10:90 mix of methane and argon). Leakage through the PC window was the main source of residual gas inside the chamber. With the PC in place, the limiting chamber pressure was 8-10 x 10⁻⁶ torr.

<table>
<thead>
<tr>
<th>X-ray Line</th>
<th>Wavelength (Å)</th>
<th>Energy (keV)</th>
<th>Anode Coating</th>
<th>Anode Voltage (V)</th>
<th>Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>B K</td>
<td>67.6</td>
<td>0.18</td>
<td>BN</td>
<td>300</td>
<td>None</td>
</tr>
<tr>
<td>C K</td>
<td>44.7</td>
<td>0.28</td>
<td>SiC</td>
<td>600</td>
<td>Lexan</td>
</tr>
<tr>
<td>O K</td>
<td>23.6</td>
<td>0.53</td>
<td>MgO</td>
<td>1000</td>
<td>Lexan</td>
</tr>
<tr>
<td>Mg K</td>
<td>9.89</td>
<td>1.25</td>
<td>MgO</td>
<td>2500</td>
<td>20µm Al</td>
</tr>
<tr>
<td>Al K</td>
<td>8.34</td>
<td>1.49</td>
<td>Al₂O₃</td>
<td>2500</td>
<td>20µm Al</td>
</tr>
<tr>
<td>Si K</td>
<td>7.1</td>
<td>1.74</td>
<td>SiC</td>
<td>2300</td>
<td>1µm Ag</td>
</tr>
</tbody>
</table>

Table 3-2 The anode coating and anode voltage combinations for the test X-ray lines.
...and it was approximately $3 \times 10^{-6}$ torr with the PC window blanked off.

The windows for the VTF 1 PC were produced by glueing a piece of stretched carbon-coated polypropylene onto a wire mesh. When assembled in the PC, the mesh was towards the vacuum; it supported the window when the PC was pressurized with gas. The transmission of the composite carbon-coated stretched polypropylene and wire mesh window to the X-ray wavelength of interest could be easily found. The stretched polypropylene had to be taken from a larger sample. From this larger sample, another piece was taken and this was glued to a sample of the PC wire mesh. This composite filter was attached to the filter wheel in the vacuum chamber. By comparing the PC output count rate with and without the composite filter in the path of the X-ray beam, the transmission of that filter, and hence the PC window, could be calculated.

3.4.1.3 The ultraviolet source

For those lifetest measurements reported in Chapter 6 that were performed in VTF 1, the VTF 1 X-ray source was not used because it did not produce an intense enough beam to enable the lifetests to be performed in a reasonable length of time. Thus, VTF 1 was modified to allow a mercury discharge lamp to be used as the source. Such a lamp emits 4.89 and 6.7 eV (2537 and 1850 Å respectively) photons in the ultraviolet region of the spectrum. The arrangement of the UV source on VTF 1 is shown in Figure 3-11. A quartz glass window was fitted into one of the perspex viewports in the lid of the vacuum chamber. Quartz glass transmits UV radiation (see Figure 3-12). Pieces of wire mesh could be put into the collimator to reduce the flux.

Inside the chamber, the X-ray source collimator was replaced with a mirror to reflect the photons from the source onto the face of the test detector.

3.4.2 Vacuum Test Facility 2 (VTF 2)

The main disadvantage with VTF 1 was that there was only
Figure 3-11 The arrangement of the UV source and collimator. To enable UV photons to enter the vacuum chamber, a quartz-glass window is fitted into one of the perspex windows in the lid of the VTF 1 chamber. Inside the vacuum chamber, the X-ray collimator is replaced by a mirror.
Figure 3-12 The UV, visible and IR transmission of quartz-glass. The 4.89 (0.254 microns) and 6.7 eV (0.185 microns) emission lines of mercury are shown by the dashed vertical lines.
one pumped volume. Thus, for example, if the source anode had to be re-coated, everything in the chamber had to be let up to atmospheric pressure.

The second test facility, shown schematically in Figure 3-13 and functionally in Figure 3-14, was designed with separate chambers for the test detector and the X-ray source. It was constructed from stainless steel, a
Figure 3-14 The VTF 2 vacuum system.
1) The vacuum chamber.
2) Manually operated gate valve.
3) Cold trap.
4) Turbo-molecular pump.
5) Backing line valve.
6) Oil-sealed rotary pump.
7) Pirani gauge head (backing line pressure).
8) Pirani gauge.
9) Roughing line valve.
10) Penning gauge head (chamber pressure).
11) Penning gauge.
12) Ion gauge head (chamber pressure).
13) Ion gauge.
preferable material to aluminium (from which VTF 1 was constructed), as it does not absorb water vapour as readily. Both of the VTF 2 chambers were designed to be as free from oil contamination as was economically practicable. Details of the design philosophy behind, and the construction of, VTF 2 can be found in ref.(60).

3.4.2.1 The test chamber

The test chamber is pumped by a turbomolecular pump (TMP) [65] backed by a rotary pump. An LN₂-cooled cold trap was fitted to minimize oil backstreaming. The chamber can be evacuated from atmospheric pressure to a pressure of approximately 10⁻⁶ torr in only several minutes. The ultimate pressure attainable was 2-3 x 10⁻⁷ torr.

The detector mount and transport system (see Figure 3-15) enables an attached detector to be both rotated about the detector Y_d axis (which is horizontal in VTF 2) and translated along that axis.

Figure 3-15 The VTF 2 detector mount and transport system [60].
The VTF 2 test chamber also contains a PC (shown in Figure 3-16). This can be lowered, by means of a pneumatic cylinder, into the path of the X-ray beam. Depending on the photon energy, either P10 or P50 (a 50:50 argon/methane mix) gas was used in the PC.

3.4.2.2 The VTF 2 source

Two sources were used in VTF 2, namely an X-ray source and an Fe\textsuperscript{55} source. The VTF 2 X-ray source is an electron bombardment type, and is similar to that in VTF 1. It is situated in a chamber pumped by an ion pump [65]. A stretched polypropylene window separates the source chamber from the test chamber and enables X-rays from the source to enter the test chamber. The by-pass valve arrangement, shown

![Diagram of the VTF 2 source setup](image)

Figure 3-16 The VTF 2 proportional counter. X-rays enter the counter chamber through the carbon-coated polypropylene window [60].
in Figure 3-17, enables either chamber to be let up or pumped down irrespective of the state of the other whilst maintaining as small a pressure difference as possible across the window. During the lifetests performed in VTF 2 (see Chapter 6), the source anode was repeatedly recoated without having to remove the voltages applied to the test detector.

The only X-ray lines produced by the VTF 2 source for the measurements reported in this thesis were C K and Si K. The beam is collimated by two 2 mm diameter apertures separated by a distance of 460 mm. One of these apertures, together with the low energy filter, is mounted on the filter wheel that is situated in the test chamber. The X-ray spot can be scanned across the test detector by translating the detector along the $Y_d$ axis with the transport system.

![Diagram of VTF 2 by-pass valve arrangement](image)

**Figure 3-17** The VTF 2 by-pass valve arrangement; this is situated between the test chamber and the X-ray source chamber [60].
The construction of Body 2 only allowed X-rays to impinge on a detector within ±40° of normal incidence.

We used an Fe\textsuperscript{55} source instead of the VTF 2 X-ray source to illuminate detectors with higher energy (5.9 keV) photons. This source, which has a strength of 20 millicuries (equivalent to $7.4 \times 10^3$ disintegrations per second), can be mounted onto a flange which enables it to be attached onto the test chamber in place of the X-ray source chamber. With both of the X-ray beam collimating holes in position, the Fe\textsuperscript{55} source could only just be detected above the detector background level. Thus, one of the collimating holes had to be removed when using this source, resulting in almost the whole face of the MCP detector being illuminated.

3.5 The test system electronics

We used two sets of processing electronics, one for each of the test facilities. For both the RA and GD readouts, four pre-amplifiers were required, two being connected to each position sensing axis. VTF 1 was designed to accommodate detectors whose imaging capabilities were to be investigated, and, therefore, in order to reduce noise signals due to capacitive pickup, the charge sensitive pre-amplifiers had to be positioned as close as possible to the readout terminals. Thus, pre-amplifiers were built into Bodies 1 and 3. Conversely, the pre-amplifiers for the VTF 2 detector body (Body 2) are mounted outside the test chamber. The signals from the readout are routed through vacuum feedthroughs to the pre-amplifiers, which are positioned close to them. Having the VTF 2 pre-amplifiers outside the vacuum system makes them accessible at all times in contrast to the pre-amplifiers in VTF 1. The pre-amplifier outputs are connected to combined imaging and photon counting electronics.

3.5.1 The photon counting electronics

The photon counting electronics, which are the same for both sets of equipment, are shown schematically in Figure 3-18. The four pre-amplifier signals are summed in a
Figure 3-18 The photon counting electronics.

PA - pre-amplifier;
FSA - fast summing amplifier;
FA - filter amplifier;
SCA - single channel analyser;
T - interval timer;
C - counter chain;
PHA - pulse height analyser.

The SCA outputs a reset pulse to the imaging electronics (shown in Figure 3-19). It also outputs a strobe pulse to the oscilloscope.
fast summing amplifier (FSA). The resultant FSA output signal is shaped by a filter amplifier (FA), its output peak amplitude being proportional to the total charge collected by the readout encoder. The FA output signal can be fed into a pulse height analyser (PHA). In order to perform photon counting, the signal from the FA is passed to a single channel analyser (SCA). This device outputs a trigger pulse to the counter chain if the peak amplitude of the signal at its input is greater than a (manually) preset lower level threshold (LLT). By setting the lower level threshold to a suitable charge level, say 0.1 pC, many of the detector noise events, together with all the counts due to noise in the electronics, can be rejected from the counter chain.

3.5.2 The imaging electronics

Both sets of imaging electronics calculate the position dependent quantities $\frac{Q_1}{Q_1 + Q_2}$ for each axis dimension, $Q_1$, $Q_2$ being the charges collected at the readout terminals of that axis. As an example, the VTF 2 imaging electronics are shown in Figure 3-19. For one axis, say the X-axis, each pre-amplifier output is fed into an FA. The peak amplitude of the FA outputs are stretched in a stretcher (S) and both of the X-axis stretched amplitudes are passed into a sum-and-inverter (S+I). As its name suggests, this unit outputs the sum, with its sign reversed, of the two inputs. One of the inputs into the first S+I is also fed into a second S+I, resulting in its sign being inverted. The inverted summed signal, together with the other inverted signal, is fed into a ratio unit (D) (which requires negative input signals) which outputs the quotient, $\frac{Q_1}{Q_1 + Q_2}$. This signal is used to control one axis of an oscilloscope operated in the X-Y mode. By using a storage oscilloscope, a two-dimensional detector image can be built up.
Figure 3-19 The VTF 2 imaging electronics.

PA - pre-amplifier;
FA - filter amplifier;
S - stretcher unit;
S+I - sum-and-inverter unit;
D - divider unit;
CRO - oscilloscope.
CHAPTER 4

ENHANCED MCP SOFT X-RAY DETECTION EFFICIENCY

As discussed in Section 1.4, MCPs that are received directly from the manufacturer have two major limitations. First, they have a low QDE (typically less than 10 percent) for all $\theta_X$. Secondly, detectors incorporating such MCPs possess no intrinsic photon energy discrimination. In this chapter, we describe a method of enhancing the soft X-ray QDE of bare MCPs by means of a superior deposition photocathode. This technique has been previously described [68,69].

4.1 The intrinsic soft X-ray QDE of MCPs

The variation of MCP QDE as a function of $\theta_X$ had been measured by various authors [70,71]. As we mentioned in Section 2.7, the efficiency peaks at an angle of incidence that is correlated with the critical angle of reflection and tends to zero as $|\theta_X|$ tends to both 0 and $\pi/2$. Several models have been produced that describe this behaviour both qualitatively and quantitatively [29,70]. For an MCP that is operated such that the electric field in front of the MCP acts to repel electrons away from the MCP surface, these models suggest that the QDE is totally determined by the detection efficiency, $Q_\text{det}$, of the open area fraction of that MCP. There is no contribution from the interchannel web. A significant response can be obtained from the interchannel web under UV [44], EUV [72], soft X-ray [73] and electron [74] bombardment, by preceding the MCP with a high transparency mesh which is biased to a slightly more negative potential than the MCP front face. Photoelectrons that are released from the interchannel web are returned to the plane of emission where they may initiate an output pulse. (Our eight test detectors were operated with the front face of the front MCP held at a high negative potential but no mesh was used.)

The models suggest that there is little scope for increasing the intrinsic open area contribution without
drastically altering the chemical composition of the MCP. In the field of soft X-ray astronomy, therefore, the usual method to increase MCP photon detection efficiencies is to deposit a photocathode — a material of relatively high photoelectric yield — onto the MCP front surface and channel walls. It is this method that is further investigated in this chapter.

4.2 X-ray photocathodes

There are two distinct modes of operation of a photocathode, namely the transmission mode and the reflection mode.

4.2.1 Transmission photocathodes

Operation of a transmission photocathode is shown in Figure 4-1. The photocathode material is usually deposited onto either a thin substrate or a fine wire mesh [75]. The substrate is placed towards the X-ray source. This enables secondary electrons, produced in the photocathode material, to escape and be detected. They have too low an energy (the mean emission energy of electrons from CsI is 1.4 eV [76]) to penetrate the substrate material. An externally applied electric field accelerates any electrons that emerge from the rear face of the photocathode towards the MCPs.

A model of transmission photocathode behaviour has been developed [77]. For photon counting applications, it is the pulse quantum yield, \( X_p \) counts per incident photon, which must be maximized. It is found that, because of the relation between the average photon absorption depth and the escape length of the secondary electrons, there is an optimum photocathode thickness for each X-ray wavelength. If the photocathode is too thin, too few photons are absorbed. If it is too thick, the majority of the secondary electrons are produced too far from the rear of the photocathode to escape. One method of increasing the photocathode thickness without increasing the amount of material through which the secondary electrons have to escape is to reduce the density of the photocathode material.
Figure 4-1 (a) Schematic diagram of a transmission photocathode, thickness $T$, showing the reflected and refracted components of the incident X-ray beam, intensity $\Gamma_0$ photons cm$^{-2}$ sec$^{-1}$. $R(\omega)$ is the reflection coefficient. When a refracted photon is absorbed in the photocathode material, the primary and secondary electrons generated may be emitted from the back surface (after Fraser [77]).

(b) Transmitted electrons are accelerated towards the MCP assembly by an applied potential difference. The fraction of photons not absorbed by the photocathode can also excite electron avalanches in the MCP assembly (after Fraser [77]).
4.2.1.1 Low density transmission photocathodes

Low density, or "fluffy", CsI photocathodes (5-10 percent of bulk density), 0.35 mm thick, have been investigated by Bateman et al [14,15] for the purpose of detecting high energy (1-50 keV) photons. Low density photocathodes have to be thicker than normal density photocathodes in order to increase the probability of photon absorption.

We had considered using low density transmission photocathodes as a method of MCP efficiency enhancement, especially at photon energies as high as several keV. There are a number of reasons why we pursued alternative methods. One reason is that problems had been encountered in the production of these low density photocathodes [15]. Once produced, they exhibited temporal stability on timescales of only a few seconds [78]. It has also been found that, except for very thin photocathodes, which have low values of $X_p$ (approximately 1 percent or less), the most probable number of electrons emitted from the rear of a low density photocathode is unity. It is because of this that transmission photocathodes cannot be employed in conjunction with MCP assemblies to provide any intrinsic detector energy resolution (see Chapter 7). Finally, the MCP efficiency enhancement obtained with low density CsI photocathodes at photon energies as high as 6 keV (of interest for the AXAF detectors) is no better than the enhancement obtained with the alternative normal density photocathodes investigated below [79].

4.2.2 Reflection photocathodes

The reflection mode of operation of a photocathode is shown schematically in Figure 4-2. The photocathode material is deposited onto the MCP front surface (and, therefore, onto the input region of the channel walls). No additional substrate is required. This technique, which can enhance both the open area and the interchannel web components of efficiency, is not a new one.

As reported by Fraser [80], the best choice for a
Figure 4-2 (a) Schematic diagram of a reflection photocathode, thickness $T$, showing the reflected and refracted components of the incident X-ray beam, intensity $I_0$ photons cm$^{-2}$ sec$^{-1}$. $R(\omega)$ is the reflection coefficient. When a refracted photon is absorbed in the photocathode material, both primary and secondary electrons may be generated and some may escape from the photocathode.

(b) These reflected electrons cross the channel and interact with the channel wall again to initiate an avalanche.
photocathode material is that material which maximizes the MCP QDE in the desired waveband and over the desired range of X-ray incidence angles. From an experimental viewpoint, the material has to be easily deposited, it has to be both photoelectrically and mechanically stable after deposition at detector working pressures, and its photoelectric properties have to remain unchanged after periods at atmospheric pressure. It is also desirable if the photocathode material is stable under X-ray and electron bombardment for a period at least as long as the projected lifetime of the detector. Finally, the electrical conductivity of the photocathode must not impair the gain and count rate characteristics of the MCP.

4.2.2.1 MgF$_2$: the "standard" X-ray photocathode material

MgF$_2$ has commonly fulfilled the role of a reflection photocathode in XUV and X-ray astronomy [35,81], resulting in efficiencies that are a factor of 1.1 (C K illumination at $\theta_X = 45^\circ$) to 1.6 (Al K illumination at the same incidence angle) times greater than the bare MCP efficiencies [35]. The adoption of MgF$_2$ as a "standard" photocathode material, however, derived from its relative photoelectric stability in a normal laboratory atmosphere [67,82] and not because it provided the optimum photoelectric yield in any absolute sense.

4.2.2.2 Optimum reflection photocathode materials

A detailed study of X-ray photocathodes was undertaken by Fraser [80,83] in order to identify truly optimum coating materials. Materials are characterized by means of three secondary electron parameters, $\xi$, $L_S$ and $P_S(0)$. $\xi$ is the energy required to excite one secondary electron in the material. $L_S$, the secondary electron escape length, and $P_S(0)$ are related by the equation that defines the probability, $P_S(z)$, of a secondary electron reaching the photocathode surface from a depth, $z$, namely

$$P_S(z) = P_S(0).\exp\left(-\frac{z}{L_S}\right)$$

CsI was one of the materials investigated in the above
cited [80,83] study. It was investigated because it had been shown to have a secondary electron emission coefficient, $\delta$, of up to 14 when used in the transmission (bulk density) mode [84,85], while a $\delta$ of approximately 20 has been reported for thin layers of CsI that were operated in the reflection mode [86,87]. The photocathode study [83] confirmed the use of CsI in previous work and predicted it to be an optimum photocathode material for soft X-ray detectors provided that it fulfilled the further requirements of stability, etc. These latter requirements had ruled out the use of many materials, including CsI, in an earlier investigation [67].

We decided to investigate the use of CsI photocathodes in the hope that it could be handled in a manner that maintained its photoelectric stability.

CsI had previously been employed as a coating for far UV astronomical detectors [68,69]. It is easy to deposit by means of vacuum evaporation (see Sections 4.5 and 4.6 for details) because its boiling point is 1280°C (MgF$_2$ boils at 2239°C) [88]. It is mechanically stable at pressures of 10$^{-5}$ torr. CsI, however, is hygroscopic; its solubility in cold water is 44 grammes per litre [88]. This is much greater than the solubility in water of MgF$_2$, which is 0.076 grammes per litre [88]. We thought that a probable source of photoelectric instability in a hygroscopic material, such as CsI, was the absorption of water vapour [89], and, therefore, we decided to minimize all sources of water vapour when depositing, handling and storing CsI photocathodes.

4.3 MCP preparation

During the baking of an MCP matrix in hydrogen, some of the PbO in the surface regions is reduced to metallic lead and water. Thus, new MCPs copiously outgas water vapour when exposed to vacuum. In an attempt to reduce the possible contamination of CsI photocathodes from this source, we decided to vacuum bake all MCPs that were to be incorporated into a detector that was to include a CsI photocathode. If a coating was deposited onto an MCP that already bore a coating (for examples of multiple coatings see Chapter 7),
that MCP was not baked again prior to the re-coating because it has been shown that CsI photocathodes exhibit a decreased yield when baked at temperatures in excess of approximately 300°C [90].

It appears that the CEMs that were used in the early photocathode survey of Smith and Pounds [67] were not pre-baked. The relative QDE of their CsI-coated CEM fell rapidly (down to one third of the initial value) over a period of approximately ten days storage [91]. Similarly, the far UV QDE, reported by Weiser et al [68], for a tandem-pair CsI-coated MCP detector that was mounted at the focus of a prism spectrograph decreased with time. This decrease proceeded with a fixed, but wavelength dependent, time constant. The apparatus used by Weiser et al had been baked but it appears that their MCPs had not.

It may be that, in both of the above-mentioned cases, poisoning of the CsI deposition photocathodes by products, especially water vapour, that were outgassed by the substrate was at least partially responsible for the observed QDE degradation.

4.3.1 The vacuum bakeout apparatus

The MCPs and detector parts were baked in a vacuum bakeout rig. This is shown functionally in Figure 4-3. The bakeout chamber was cylindrical with a diameter of approximately 300 mm and a height of approximately 500 mm. It was constructed from stainless steel. The chamber was sealed with an indium wire seal. When under high vacuum (a pressure of less than $10^{-5}$ torr), the chamber was pumped by an ion pump which could reduce the pressure inside the chamber to below $10^{-10}$ torr. The chamber was pumped down from atmospheric pressure with a diffusion pump / rotary pump combination. The pressure in the chamber was monitored with an ion gauge. A Vacuum Generators' * "Micromass" residual gas analyser could be used to monitor the partial pressure of gases in the chamber. Both of these devices could only be used when the chamber was under high vacuum.

* Vacuum Generators Ltd, Hastings, TN34 1YQ
Figure 4-3  Functional diagram of the vacuum bakeout rig.
1/ The vacuum chamber;
2/ Valve;
3/ Ion pump;
4/ Dry N₂ inlet valve;
5/ Pneumatically operated baffle valve;
6/ Oil filled diffusion pump;
7/ Backing line valve;
8/ Roughing valve;
9/ Rotary pump.
The bakeout chamber was heated by electric elements. The desired chamber temperature was dialled up and a feedback control circuit caused the chamber temperature to be raised to, and then maintained at, the set value. The chamber temperature was monitored by the feedback circuit using a thermocouple.

4.3.2 The vacuum bakeout procedure

Before MCPs were to be baked, the bakeout chamber, with the MCP holders (see below) inside it, was sealed, pumped out, and baked to a temperature in the range 300-320°C for about 48 hours. After this time, the pressure in the chamber having stabilized, the heaters were switched off and the chamber was allowed to cool to room temperature. Typically, the chamber pressure fell to less than 10^{-11} torr after cooling.

The MCPs to be baked were placed into the specially constructed holders. Each holder supported a single MCP at three points only, as indicated in Figure 4-4, and allowed all of the channels to outgas during bakeout.

The MCPs, in their holders, were placed into the bakeout chamber which was then sealed and evacuated. They were vacuum baked at 275-300°C for 48 hours. Such temperatures are fairly typical of those used industrially [41] and in laboratory experiments [44] to prepare sealed MCP detectors. The duration of our bakeout procedure was, however, rather greater than the 8-10 hours typical for image tube processing.

![Diagram](image)

Figure 4-4 Showing how a holder supported an MCP in the bakeout chamber.
4.3.2.1 The outgassing effects of a vacuum bakeout

In order to observe the amounts and species of outgasing products produced during a bakeout, we performed a trial bakeout of ten MCPs. Initially, the bakeout chamber was sealed and pumped out. When the system was being pumped by the ion pump, a mass spectrum of the chamber atmosphere was obtained at a chamber pressure of $2 \times 10^{-6}$ torr and a chamber temperature of 23°C. This spectrum is shown in Figure 4-5(a). Sixteen hours later, when the chamber pressure had been reduced to $3 \times 10^{-7}$ torr, another mass spectrum was obtained; this is shown in Figure 4-5(b). The predominant mass/charge ratios observed in both spectra were 18 and 17, with 28, 16 and 44 being the next most intense peaks. Peaks at 18, 17 and 16 are characteristic of water vapour. The 28 peak is characteristic of both $N_2$ and CO and the 44 peak is characteristic of $CO_2$.

The chamber heaters were then switched on. The chamber pressure rose as material was outgassed from the vessel. This rise was sufficiently great to require the use of the diffusion pump to pump the system. It took approximately two hours to raise the temperature in the chamber to 295°C and a further six hours to reduce the chamber pressure by enough to enable the ion pump to be used again to pump the system.

Another mass spectrum, shown in Figure 4-5(c), was obtained when the chamber pressure had been reduced to $9 \times 10^{-7}$ torr (the temperature was still at 295°C). 48 hours after the chamber first reached 295°C, the chamber pressure was $4 \times 10^{-8}$ torr and the mass spectrum was as shown in Figure 4-5(d). The heaters were switched off at this point. After cooling to 21°C, the pressure was below the threshold of detection of the ion gauge (approximately $10^{-9}$ torr). Another mass spectrum was obtained at this point. It is shown in Figure 4-5(e).

Examining this last figure, it can be seen that the water vapour peaks had almost disappeared; the most intense peaks were 28 and 44. Some CO and $CO_2$ is evolved as a by-product of the operation of an ion gauge and it may be that these peaks were totally caused by this. Thus, it seems that the baking of the chamber in our manner resulted in a
Figure 4-5  Mass spectra of the bakeout chamber atmosphere at various times during the bakeout of the chamber plus MCP holder. The filled bars represent measured values and the unfilled bars represent measured values multiplied by 10.

(a) Temperature = 23°C,
    pressure = 2 x 10^{-6} torr.
(b) Temperature = 23°C,
    pressure = 3 x 10^{-7} torr.
(c) Temperature = 295°C,
    pressure = 9 x 10^{-6} torr.
(d) Temperature = 295°C,
    pressure = 4 x 10^{-8} torr.
(e) Temperature = 21°C,
    pressure < 10^{-9} torr.
reduction to below the threshold of detection of the level of all outgassing products, with the probable exception of those products produced by the ion gauge itself.

At this point, the chamber was valved off from the ion pump and it was let up to atmospheric pressure with dry $N_2$. A flow of dry $N_2$ through the chamber was maintained for the whole time that it was at atmospheric pressure.

The ten test MCPs, which were supported in a holder that was purpose-built for these tests, were transported in a dry $N_2$-filled bag to the bakeout chamber in which they were placed. The chamber was evacuated and the MCPs were baked at $275^\circ C$ for 50 hours. Mass spectra of the chamber atmosphere were recorded at intervals; these are shown in Figures 4-6(a-e). The chamber was let up to atmospheric pressure with dry $N_2$ and the MCPs were removed.

Comparison of Figures 4-6(a-e) with Figures 4-5(a-e) indicates that the major products outgassed during the bake of the MCPs were essentially the same, and in the same proportions, as previously observed with the bakeout of the chamber alone. As the total surface area of the ten MCPs was approximately $1 \text{ m}^2$, which was comparable to the surface area of the chamber, it can be inferred either that nothing was outgassed from the MCPs (unlikely) or that the principal products outgassed from the MCPs were the same as those outgassed by the chamber alone, namely water vapour, CO, $N_2$ and $CO_2$.

It has previously been reported [92] that baking an MCP at $300^\circ C$ for 10 hours resulted primarily in the evolution of water vapour; CO and $CO_2$ were produced at about one tenth of the rate of that of the water vapour. It has also been shown [93] that when an unbaked MCP was operated, the amount of CO and $CO_2$ evolved increased with the applied voltage but that the amount of water vapour outgassed was independent of the applied voltage. This indicated that water vapour was not desorbed by electron bombardment. Similarly, the operation of a pre-baked MCP also resulted in CO and $CO_2$ being outgassed but water vapour was not seen to be outgassed [92].
Figure 4-6  Mass spectra of the bakeout chamber atmosphere at various times during the bakeout of the chamber plus the ten MCPs. The filled bars represent measured values and the unfilled bars represent measured values multiplied by 10.

(a) Temperature = 25°C,
    pressure = 4 x 10^{-7} torr.
(b) Temperature = 20°C,
    pressure = 2 x 10^{-8} torr.
(c) Temperature = 275°C,
    pressure = 4 x 10^{-6} torr.
(d) Temperature = 275°C,
    pressure = 2 x 10^{-8} torr.
(e) Temperature = 23°C,
    pressure < 10^{-9} torr.
4.4 The physical effects of a high temperature bake on an MCP

There are a number of reasons why the characteristics of an MCP might be different before and after a vacuum bake. If the conductive layer of the channels is altered, the MCP resistance might change. If the electron emissive region is altered, the gain at a fixed bias voltage might alter, as might the QDE. These possibilities are now explored.

4.4.1 Resistance changes

The variation, if any, of MCP resistance was investigated using the ten 36 mm diameter MCPs reported above (see Section 4.3.2.1). These were obtained from Mullard's Ltd. and had been discarded during quality control because they did not have a uniform gain when illuminated by an electron beam. The MCPs had a channel diameter of 12.5 microns and an L/D ratio of 40:1. The ten MCPs were arbitrarily grouped into five pairs. Prior to the bakeout, each pair in turn was assembled into Body 1 in the conventional configuration. Voltages were applied to the front and rear faces of each MCP and the current drawn by each MCP (the strip current) was measured. All measurements were made at a VTF 1 chamber pressure of less than $10^{-5}$ torr and at room temperature.

When all five pairs of MCPs had been tested, the ten MCPs were vacuum baked at a temperature of $275^\circ C$ for 50 hours, after which they were allowed to cool to room temperature. After they had cooled, the MCPs were put into dry $N_2$ filled bags. The plates were retested in the same configurations as previously. The MCPs were exposed to the laboratory atmosphere for the shortest possible time (a few tens of seconds at most) before re-testing.

The variation of the resistance of the MCPs as a function of the applied potential difference, both before and after the bake, is shown in Figures 4-7(a,b). Prior to the bake, the MCP resistances varied from 130 to 230 M$\Omega$. After the bake, the range of resistances was 160 to 280 M$\Omega$. The ratio of the post-bake resistances to the pre-bake
Figure 4-7 (a)  In vacuo resistance at room temperature versus applied voltage for the ten unbaked MCPs.

(b) The corresponding in vacuo resistance at room temperature versus applied voltage for the ten MCPs after being baked at 275°C for 48 hours. Note the non-ohmic variation of resistance with applied voltage.
resistances is tabulated in Table 4-1. It can be seen that this ratio is approximately constant as a function of the applied voltage difference for seven of the MCPs. The post-bake values for these seven MCPs are some 10-30 percent greater than the pre-bake values.

Siddiqui [41] baked MCPs (characterized by $D = 12.5$ microns, $L/D = 44:1$) that had been fabricated from both Corning 8161 type glass and GE-821 type glass (see Table 2-1) at temperatures of up to $370^\circ C$ for a minimum period of eight hours. The strip current of the MCPs was measured during the heating up and cooling down periods. When baked below a transition temperature, which was in the range $210-250^\circ C$ for these MCPs, the variation of resistance with temperature was reversible. When the MCPs were baked above the transition temperature, however, irreversible changes occurred. The resistance of these MCPs at room temperature increased by 38-50 percent after the bake.

Siddiqui's MCP resistances were measured in a separate chamber from the bakeout chamber and, therefore, the MCPs would have been exposed to the laboratory atmosphere for some period after the bake.

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Table 4-1 The ratios of the post-bake MCP resistances to the pre-bake MCP resistances at the five named bias voltage differences.
Rager et al [94] baked a Mullard Q 40-25 MCP at 200°C for two hours. This procedure resulted in an increase of the MCP resistance at room temperature. When exposed to the laboratory atmosphere for a period of two months, though, the MCP resistance recovered to its pre-bake value. It was shown that this MCP behaved in the same manner after baking it and exposing it to the atmosphere as it had before being baked.

For all of the measurements of Rager et al, the bakeout and test chambers were combined ensuring that there should have been no contact of the MCPs with the atmosphere after the bake.

Both Siddiqui and ourselves baked MCPs in a similar way and at temperatures in excess of 250°C and observed an increase in the MCP resistances at room temperature. Our resistance increases ranged from 12-31 percent compared to the 38-50 percent increases reported by Siddiqui. Below the transition temperature, a bakeout might just result in the desorption of material from the channel surfaces which can be re-adsorbed when those surfaces are exposed to the atmosphere. Above the transition temperature, though, a bakeout probably causes changes to the conduction layer (see Section 4.4.4).

4.4.2 Gain variations

As well as the changes in MCP resistance, Siddiqui [41] also reported slight gain variations (less than 20 percent) for all of his test MCPs, whether baked up to the transition temperature or beyond. In contrast, however, Rager et al [94] reported substantial decreases in gain for their MCP which was baked at 250°C - the gain decreased by 40 percent and by 20 percent respectively after the first two bakes; the third bake did not alter the MCP gain. When this MCP was exposed to the atmosphere, no gain recovery occurred.

After showing a 40 percent decrease after baking, the gain of the MCP that was baked at 200°C recovered to its pre-bake value after exposure to the atmosphere. This recovery was complete, the MCP behaving as it had done before the bake.
The only comparable data obtained at Leicester was acquired from Detector 4. This detector showed no appreciable alteration in its gain characteristics after being baked for 48 hours at 275°C [60]. The five pairs of 40:1 MCPs were not used to obtain any gain data because they were known to have a non-uniform gain over their detection area having been discarded by the manufacturer for this reason.

4.4.3 QDE variations

The third property of an MCP that could be affected by a vacuum bake is its QDE. The only data available was obtained from Detector 4. No significant change in the efficiency versus X-ray incidence angle curve was observed after the bake [60].

4.4.4 Explanation of the bakeout effects

According to Siddiqui, it appears that a vacuum bake above approximately 250°C causes some irreversible changes to occur to an MCP. With bakes up to lower temperatures, any changes are reversible when the MCP is exposed to the atmosphere. One possible mechanism is that, below 250°C, material, possibly water vapour, is simply desorbed from the surface of the channel walls and, upon exposure to the atmosphere, it is re-absorbed. Another possible mechanism is the dissociation of alkali oxides at the surface during the bake and the re-oxidation of the subsequently formed alkali ions on exposure to the atmosphere.

It also appears that the factors affecting MCP resistance are different from those affecting MCP gain and QDE. It will be recalled that soft X-ray photons are absorbed in, and secondary electrons emitted from, a surface layer which is at most 100 Å thick. For lead glass, $L_s$ is only 33 Å [46], equivalent to about ten atomic diameters. This surface layer consists primarily of the oxides of silicon and potassium. The semi-conductive layer, which consists primarily of lead, alkali ions and SiO$_2$, lies approximately 1000 Å below the channel surface and extends
for several thousand Angstroms into the bulk of the channel wall.

When baked at a high enough temperature (greater than approximately 250°C), ions in the MCP bulk composition are free to move. It is reasonable to assume that the bulk of the glass behaves in the same manner during a vacuum bake as it does during the hydrogen reduction process. The absence of hydrogen during a vacuum bake, however, causes the surface regions to behave differently during the hydrogen reduction process. In a bake, there is no further reduction of any PbO that appears at the surface. Possible results of this are the further agglomeration of the atomic lead formed during the reduction process or, more probably, the diffusion of these lead atoms from the semiconductive layer into the bulk. This last mechanism would cause the MCP conductance to decrease (and hence the MCP resistance increases) in the manner observed by us. Any modification to the MCP glass would be permanent as long as the MCP is not re-baked above the temperature at which the bulk atoms become mobile.

It is also possible that the presence of hydrogen during the reduction process may cause some ion species to migrate towards or away from the surface that would not ordinarily do so in a normal bake. If such a migration does not take place during a high temperature bake, the surface layers should remain unaltered after a bake and hence the gain and QDE of the MCP should also remain unaltered.

At all temperatures, a vacuum bake should cause some material to be outgassed from the surface layers. Such behaviour would account for the reversible changes in resistance reported by Rager et al. Perhaps a momentary exposure to the atmosphere is all that is required to reverse any change to the resistance (as was observed by Siddiqui).

4.5 Preparation for coating

After MCPs had been baked, and the bakeout rig had been cooled to room temperature, it was flushed with dry $N_2$ and the MCPs were removed. The MCPs were sealed into dry $N_2$. 
filled polythene bags. The MCP to be coated was transferred to the coating apparatus which was an NGN type 12 SG evaporator with a 12" diameter bell jar. The bell jar was pumped through an LN\textsubscript{2} - cooled cold trap by a diffusion pump / rotary pump combination.

Prior to the installation of the MCP into the coating rig, the evaporation chamber was pumped down to its ultimate pressure (approximately $10^{-6}$ torr) and the MCP holder was heated to 100°C. The chamber was then exposed to an HT glow discharge, using dry N\textsubscript{2}, for a period of ten minutes. After this, the chamber was let up to atmospheric pressure with dry N\textsubscript{2}. Dry N\textsubscript{2}, rather than air, was used in order to reduce the amount of the atmospheric water vapour absorbed by the chamber. While the MCP was being installed in the chamber, the chamber was flushed with dry N\textsubscript{2}.

The MCP to be coated was positioned in a holder and a mask was placed over the MCP face to be coated. Two types of mask were used. One type had a circular aperture, and was used for full-face coating, and the other had a semi-circular aperture so that one half of the MCP could be coated while the other half remained uncoated (see Figure 4-8).

The CsI that was to be evaporated was sprinkled into a molybdenum boat which was itself placed between a pair of electrodes in the evaporation chamber. The chamber was then pumped down to a pressure of approximately $10^{-5}$ torr. The MCP and holder were heated to 100°C. This was followed by performing another glow discharge in the chamber. Immediately afterwards, the evaporation of the CsI took place. During the coating, the MCP was slowly rotated to ensure uniformity of coating within individual channels. A large direct current (40-50 A) was passed through the boat, causing it to heat up and its contents to be evaporated. The rate of coating was kept low (less than 50 Å per second) in order to eliminate cracks from forming in the deposited layers [95].

Substrate heating was adopted in an attempt to improve the durability of the CsI layer. It has been noted that heating of the substrate to a temperature in the range 100-300°C was necessary [95,96] in order to produce highly efficient thin
Figure 4-8 The two types of photocathode deposition.
(a) Full-face coating.
(b) Half-face coating.
film CsI(Na) and CsI(Tl) scintillators. More directly related to our application was the report that substrate heating in the 160-200°C range increased the secondary electron yield of CsI layers and improved their stability under prolonged electron bombardment [97].

A limited investigation of substrate heating was carried out by J.F. Pearson [60] with CsI films deposited onto pre-baked glass blanks. Although these tests failed to find any clear advantage, either mechanically, or in terms of storage characteristics, a degree of substrate heating was retained for the deposition of our photocathodes, if only to improve the cleanliness of the MCP at the time of the coating.

4.6 Optimization of the coating geometry

MCP coating geometry has been investigated [73] in order to maximize the QDE of a detector over particular ranges of X-ray incidence angle and wavelength whilst minimizing the variations of QDE over the detection area. The essential constraint was that all incident X-rays had to interact within the deposited layer. The working ranges of θ and wavelength encountered at the input of an astronomical detector input are determined by the optical system.

4.6.1 Coating penetration depth and uniformity of coating

For an MCP (plate radius, \( R_m \), channel bias angle, \( \theta_B = 0^\circ \)) mounted a height, \( h_m \), above a point evaporation source, S, with its centre, O, laterally displaced by a distance, \( d_m \) (see Figure 4.9(b)), the central coating angle, \( \hat{\omega}_0 \), is defined by

\[
\hat{\omega}_0 = \arctan \left( \frac{d_m}{h_m} \right)
\]

For a particular channel, C, situated at a radial distance \( r_m \) from the MCP centre, O, and stationary at an angle, \( \hat{\phi} \) to the line S'O, only one half of the channel circumference (shown shaded in Figure 4.9(b)) can be coated with the channel fixed in this position. Rotating the MCP about O many times during the coating (see Figure 4.9(c)) alleviates this problem but necessarily introduces a
Figure 4-9 Schematic MCP coating geometry [73].

(a) $S$ is the evaporant source and $S'$ is its vertical projection onto the plane of the MCP front face. The coating angle to a channel $C$ is $\hat{\alpha}$. $l_o$ is the distance down a channel from the input end. The arrow represents the direction of the evaporated material. The channel entrance (shown by the thick lines) is shown greatly enlarged compared to the coating dimensions.

(b) $r_m$ is the radial distance of the channel $C$ from the MCP centre $O$. In this position, only the channel wall (shown shaded) within $\pi/2$ of the beam direction can be coated. Rotation of the MCP (varying $\hat{\phi}$) ensures that all points on the channel circumference can be coated.

(c) Rotation of a channel about the MCP centre. $\hat{\gamma}$ is the angular co-ordinate of a point $T$ on the channel circumference.
variation in the coating penetration depth with angular position, $\gamma$.

The coating penetration depth, $H(r, \gamma)$ is given by [73]

$$H(r, \gamma) = D \cot \gamma \left[1 + A^2 - 2A \cos \gamma\right]^{-1/2}$$

where $A = \frac{r}{d}$.

At the MCP centre, where $r = 0$, the penetration depth around any particular channel is uniform. Off axis, $H$ varies in such a manner that the ratio of its maximum to minimum values, $F(r_m)$, is given by

$$F(r_m) = \frac{(1 + A)}{(1 - A)}$$

$F$ is a useful figure of merit to quantify coating uniformity, tending to unity as the source-to-MCP separation increases.

4.6.2 Coating thickness on the channel wall, $t_c(l_c)$

The coating thickness on the channel walls, $t_c$, had to be large compared to $L_e$, the secondary electron escape length of the photocathode material, and comparable to $(\mu \cosec \theta_x)^{-1}$, the mean X-ray absorption depth. The actual thickness deposited on the channel walls is a function of $r_m$, $\gamma$, and $l_c$, where $l_c$ is the distance down a channel from the input end. The wall coating thickness is linearly related to the thickness, $t_F$, of material deposited onto the MCP front surface interchannel web by

$$t_c = G(r_m, \gamma, l_c) \cdot t_F$$

In our coating system, $t_F$ was measured using a calibrated, quartz-crystal film thickness monitor placed close to, and parallel with, the MCP face to be coated. Both an Edwards* Hi-vacuum Model 1 and an Edwards FTM 4 monitor were used in the work reported here.

4.6.3 Experimental coating geometries

Detectors 1 and 8 were used to investigate the initial use of CsI photocathodes. All four of the MCPs were vacuum baked for 48 hours at 275°C. CsI photocathodes were vacuum evaporated onto one half of the front face of each front

* Edwards High Vacuum Ltd., Crawley, Sussex
MCP. For both detectors, 6000 Å of CsI was deposited at a central coating angle of 15°. The coated MCPs were assembled into their respective detector bodies, together with the respective rear MCP. On entry into the vacuum chamber of VTF 1, the CsI coatings had been exposed to the atmosphere for only a few tens of seconds.

One of the aims of this initial work was to produce an optimized focal plane detector for a wide-field XUV sounding rocket telescope. The grazing incidence optics were similar to those that will be flown on the ROSAT WFC. Photons impinge on the MCP detector at large angles ($22° < \theta_X < 30°$). The coating geometry, therefore, was chosen so as to maximize the QDE of the detector over this range of angles. The details of this optimization can be found in [61].

Before we used it for measurements reported later, Detector 4 was initially used by J.F. Pearson for preliminary investigations into the characteristics of thicker CsI photocathodes; these are required to produce a useful wall coating thickness at small central coating angles. Such coating geometries are appropriate for high resolution, long focal length X-ray telescopes, in particular the telescope proposed for AXAF. Thus, one half of MCP F4 was coated with CsI. The coating was characterized by $t_F = 14000$ Å, $\theta_0 = 4°$. Assuming that the evaporation was from an ideal point source, the thickness of CsI deposited onto the channel walls was approximately 310 Å. At central coating angles as small as this, the actual extent of the molybdenum boat has to be taken into effect. An upper limit to the thickness deposited was 550 Å when this was done.

4.7 The assembly of coated MCPs

Initially, after an MCP had been coated, it was the practice to let the coating chamber up to atmospheric pressure with dry $N_2$ and then to allow the MCP to cool. Later, though, the MCP was allowed to cool in vacuo. This was done because it was thought that this minimized the opportunity for water vapour to be absorbed by the CsI. When the MCP was at a temperature of approximately 35°C, the
holder assembly was removed from the coating rig, placed into a dry N₂ filled bag, and transported to the detector assembly area. All detector assembly was performed in a dry N₂ tent if a coated MCP was to be incorporated.

4.8 Experimental results

4.8.1 The quantum detection efficiency measurement method

The measurement technique for the determination of detector quantum detection efficiencies was essentially that of Bjorkholm et al [70]. The output count rate from the MCP detector, due to an X-ray beam falling completely on it, was measured. A proportional counter was then moved into the path of the beam in such a manner that it intercepted the whole beam. The output count rate from the PC was measured. After correcting for the noise count rates of the two detectors and for the (known) QDE of the PC at the chosen wavelength, the open area QDE, $Q_{OC}(\theta_X, \lambda)$ of the MCP detector could be calculated from

$$Q_{OC}(\theta_X, \lambda) = \frac{T_m(\lambda), T_w(\lambda)}{T_d(\lambda) \sec \phi} \cdot \frac{[N_{MCP}(\theta_X, \lambda) - n_{MCP}], Q_{PC}(\lambda)}{\frac{[N_{PC}(\lambda) + N_{PC}(\lambda)]}{2} - n_{PC}}$$

where

$T_m(\lambda)$, $T_w(\lambda)$, and $T_d(\lambda)$ are the transmissions, at the X-ray wavelength, $\lambda$, of the PC support mesh and the PC and MCP detector carbon-coated polypropylene windows respectively. $\theta_X$ is the angle of X-ray incidence with respect to the long axis of the channels of the front MCP and $\phi$ is the angle between the X-ray beam and the normal to the MCP detector window (see Figure 4-10). The factor sec $\phi$ accounts for the greater thickness of window in the path of the beam for all angles $\phi$ greater than 0°. $\phi$ was equal to $\theta_X$ except when a front MCP with a non-zero bias angle was incorporated into the MCP detector.

$N_{MCP}(\theta_X, \lambda)$ is the count rate of the MCP detector at a photon incidence angle, $\theta_X$ and a wavelength, $\lambda$. $N_{PC1}(\lambda)$ and $N_{PC2}(\lambda)$ are the PC output count rates both immediately before and immediately after the MCP count was made. The two values were averaged in an attempt to minimize the (slight)
Figure 4-10  The relationship between the incident X-ray beam, and the components of an MCP detector. Note that the thickness of the window is highly exaggerated. If the channel bias angle is non-zero, the angle of X-ray incidence with respect to the channels is different from the angle of incidence with respect to the normal to the window. As the value of $\phi$ is increased, the thickness of window material that the X-ray beam has to penetrate increases.
variations in the count rate from the source. It was assumed that the PC counts were obtained with the PC window perpendicular to the X-ray beam.

\( n_{\text{MCP}} \) and \( n_{\text{PC}} \) are the dark noise count rates of the MCP detector and PC respectively. The PC noise count rate was obtained by averaging four consecutive 100 second noise counts (the source was off). For those MCP detectors that had a relatively low noise count rate compared to the count rate when illuminated, \( n_{\text{MCP}} \) was determined by taking four consecutive noise counts both before and after the efficiency measurement sequence, and by finding their mean value. If, however, the MCP detector noise rate was greater than 10-20 percent of the count rate when illuminated, a noise reading was taken after every measurement of \( n_{\text{MCP}} \).

\( Q_{\text{PC}} \) is the QDE of the PC at the wavelength \( \lambda \) and has been calculated for the wavelengths appropriate for our measurements [60].

### 4.8.2 Initial detector calibration

After an MCP had been coated and assembled into a detector body, the gain characteristics of that detector were studied in order to establish appropriate bias voltages. Figures 4-11(a,b) show the variation of peak gain, \( G_c \), and FWHM, \( \Delta G_c / G_c \), as a function of \( V_F \) for the coated half of Detector 1. Al K X-rays were incident at 16°. Also shown is a set of measurements obtained with C K X-rays (\( V_R = 1400 \) volts) at the same incidence angle. The peak gain observed under C K illumination was lower than the corresponding peak gain observed under Al K illumination. From this result, it appears that this detector showed a degree of energy discrimination. As will be seen in Chapter 7, this was a real effect.

It can be seen that the FWHM values stabilized at values of \( V_F \) greater than approximately 1400 volts, showing that the detector was in the saturated mode of operation above this voltage. As a result of these measurements, we decided to make further measurements on Detector 1 with a voltage difference of 1400 volts applied across both the front and
Figure 4-11 (a) The variation of peak gain, $G_C$, with front MCP voltage, $V_F$, for Detector 1. The Al K measurements (filled circles) lie below the corresponding Al K measurements. All measurements were made at an incidence angle of $16^\circ$.

(b) The variation of FWHM, $\Delta G_C / G_C$, with front MCP voltage for Detector 1. Note how the FWHM stabilize at values of $V_F$ greater than 1400 volts.
rear MCPs. Higher values of either of these voltages led to an excessive noise count rate (tens of counts per second).

Figure 4-12 shows the variation of $G_c$ with the interplate gap voltage difference, $V_g$. For gap voltages in excess of 50 volts, the peak gain was stable at 4.5 pC and the FWHM was 43 percent. This behaviour is well understood [54].

After initial detector calibration, we decided to operate Detector 1 with the following voltages:

$V_F = 1400$ V, $V_G = 4-600$ V, $V_R = 1700$ V.

Similarly, we decided to operate Detector 8 with the following voltages:

$V_F = 1400$ V, $V_G = 50$ V, $V_R = 1700$ V.

Figure 4-12 The variation of peak gain, $G_c$, as a function of the interplate gap voltage difference, $V_g$, for Detector 1.
### 4.8.3 Initial QDE measurements

X-ray QDEs were measured for a range of X-ray incidence angles and energies on both the Csl-coated and the uncoated halves of Detectors 1 and 8. Figure 4-13 shows the variation of QDE with X-ray incidence angle for both halves of Detector 8 when illuminated by Al K X-rays. The deposition of the Csl photocathode greatly increased the detector QDE at all incidence angles. Figure 4-13 also shows measurements, which were made at Leicester, on a detector that incorporated an MgF$_2$-coated MCP [98]. The coating geometry of MCPs F1, F8 and the MgF$_2$-coated MCP were identical, although their pre-coating histories and the QDE of the bare MCPs differed somewhat. Figure 4-14 is analogous to Figure 4-13 but for C K X-rays.

Figure 4-15 shows the variation of detection efficiencies as a function of X-ray incidence angle for the Csl-coated half of Detector 1 when it was illuminated by Al K, Mg K, O K, C K and B K X-rays in turn. Small angle efficiencies have been omitted for clarity. Some spectral

![Graph](image)

**Figure 4-13** The open area QDE, $Q_c(\theta_X, 8.34 \text{ A})$ as a function of X-ray incidence angle. Al K X-rays. Filled circles - measurements on the Csl-coated half of Detector 8. Open circles - measurements on the uncoated half of Detector 8. Filled squares - measurements on an MgF$_2$-coated detector.
Figure 4-14 The open area QDE, \( Q_{\text{DE}}(\theta_X, 44.7 \, \text{A}) \), as a function of X-ray incidence angle. C K X-rays. Filled circles - measurements on the CsI-coated half of Detector 8. Open circles - measurements on the uncoated half of Detector 8. Filled squares - measurements on an MgF\(_2\)-coated MCP.

Figure 4-15 The open area QDE of the CsI-coated side of Detector 1. Mg K and Al K X-rays (left hand scale), O K, C K and B K X-rays (right hand scale).
contamination was possible with the source-filter arrangement used when O K X-rays were being generated.

4.8.4 Discussion of the initial results

In Figure 4-16, the measured and calculated open area efficiencies, \( Q_C(\theta_x, 8.34 \, \text{Å}) \) for the uncoated, reference half of Detector 8 are compared. All of the theoretical calculations presented in this thesis were made by G.W. Fraser. The calculated and experimental results for the CsI-coated half of the same detector are compared in Figures 4-17(a,b).

![Figure 4-16 Comparison of the measured (after a vacuum bake) and calculated open area QDE, \( Q_C(\theta_x, 8.34 \, \text{Å}) \), of the uncoated half of Detector 8. Filled circles - \(+\theta_x\) data. Open circles - \(-\theta_x\) data. Full curve - calculated assuming a test beam with zero angular divergence. Broken curve - calculated assuming a 0.5° FWHM beam divergence.](image)
Figure 8-17 Comparison of the measured and calculated open area QDE, $Q_c(\theta_x, \lambda)$ of the coated half of Detector 8 [73]. All of the theoretical curves refer to a CsI-coated MCP characterized by $D = 25$ microns, $L/D = 80:1$, $V_0 = 1300$ V. Filled circles - $+\theta_x$ data; open circles - $-\theta_x$. Squares represent additional data from a CsI-coated MCP characterized by $D = 25$ microns, $L/D = 120:1$, $V_0 = 1900$ V. Full curves - composite CsI/lead glass response for three characteristic CsI coating thicknesses; $d = 370$, 450 and 550 Å. Broken curves - CsI contribution. Hatched curve - lead glass contribution. Vertical lines - critical angles of X-ray reflection for CsI and MCP glass. The central coating angle, $\alpha_0$, is 15°.

(a) $\lambda = 8.34$ Å.
(b) $\lambda = 44.7$ Å.
The broken curves of Figure 4-17 represent the calculated contribution of the CsI, for $0^\circ_X < \theta_0^\circ$, and the hatched curve is the MCP-glass contribution smoothed with a $1^\circ$ wide top hat function (representing the angular divergence of the VTF 1 test X-ray beam). With Al K illumination, it can be seen that the measured efficiencies were somewhat higher than the predicted values, especially at small incidence angles. The model, however, does account for the relatively flat response of the detector over the incidence angle range, $1^\circ < \theta_X < 15^\circ$ in terms of separate MCP-glass and CsI contributions, peaked at $\theta_X = 1.5^\circ$ and $12^\circ$ respectively. The measured efficiencies with C K X-rays were in quite good agreement with the model at all angles.

Data obtained from an MCP, characterized by $D = 25$ microns, $L / D = 120:1$, $V_0 = 1900$ V, which had been coated identically [61], is also shown in Figure 4-17. The electron collision energies for this configuration were almost the same as those for Detector 8. At low X-ray energies and large incidence angles, where $Q_C$ is independent of both $D$ and $L / D$ [28], the efficiencies of the two MCPs should have been similar. Inspection of Figure 4-17 confirms that this was the case.

### 4.9 Conclusions

In this chapter, we have shown how the open area soft X-ray QDE of a tandem-pair MCP detector can be enhanced by the deposition of a CsI photocathode. CsI had previously been shown theoretically [83] to be an optimum photocathode material.

CsI is a hygroscopic material and, therefore, precautions were taken to minimize its contact with water vapour both when depositing it and when handling the coated MCPs. As MCPs outgas water vapour when put under vacuum, then, in order to reduce the possibility of contamination from this source, all MCPs in a detector that was to have a photocathode were vacuum baked at $275^\circ$C for a minimum of 48 hours. Such a bakeout caused the resistance of our MCPs (measured between the flat faces) to increase from between 10 and 30 percent. Their gain and QDE, however, appeared to
remain unchanged. We think that the bakeout decreased the
density of atomic lead in the semi-conductive layer.

After an MCP had been baked, it was always transported
and handled in a dry atmosphere. Prior to being coated, our
MCPs were heated to approximately 100°C. At the very least,
substrate heating should have improved the cleanliness of
the MCPs at the time of coating, although it is now doubtful
as to whether it actually has any benefits, either
mechanically or in terms of storage characteristics.

For both of the detectors investigated for this chapter,
6000 Å of CsI was deposited at a central coating angle of
15° onto one half of the input face of the front MCP. A
study of detector gain and noise count rate was made for
each detector. Acceptable noise count rates and peak gains
were achievable. Efficiency measurements on both the coated
and uncoated halves of the detectors were performed. The CsI
enhanced the QDE over the energy range 0.18 (B K) to 1.5 keV
(A1 K). The peak efficiency attained was 48 percent at C K.
These results compared well with the model of Fraser [83].

In the next two chapters, the stability of the CsI
photocathodes is investigated. Finally, in Chapter 7, the
energy resolving capability of CsI-coated detectors is
investigated.
CHAPTER 5

THE REPRODUCIBILITY AND STABILITY OF CsI PHOTOCATHODES

5.1 Introduction

In the previous chapter, we demonstrated that the soft X-ray QDE of MCPs can be greatly enhanced by the deposition of a CsI photocathode onto the MCP input face. Such a coating can also confer a limited degree of energy resolution to an MCP detector (as we will show in Chapter 7). These developments have important applications for imaging X-ray astronomy provided that the stability and reproducibility of the X-ray response of the photocathodes can be quantified.

In this chapter, the changes in the X-ray QDE of coated MCPs resulting from

1) deliberate exposure to a laboratory atmosphere
2) long term storage in poor vacuum, high vacuum and dry air or dry nitrogen

and

3) prolonged X-ray bombardment

are examined. The reproducibility of our CsI coating technique is indicated by comparing efficiency data from six coated MCPs.

5.2 Reproducibility of CsI deposition photocathodes

Figure 5-1 indicates the reproducibility of our coating technique. The QDE for C K X-rays of six CsI coated MCPs, each operated as the front MCP in its detector, is shown as a function of X-ray incidence angle, $\theta_X$. The data refers to freshly-prepared photocathode surfaces. Table 5-1 lists the geometric (channel diameter, D, length to diameter ratio, L/D, and channel bias angle, $\theta_B$), electrostatic (operating voltage, $V_0$ and mean electron collision energy, $eV_C$) and photocathode parameters (coating angle $\phi_0$ and thickness of CsI on the MCP front surface, $t_F$) for all six test MCPs.

The model [73] described in the previous chapter states that those MCPs with the thickest CsI coating on the channel
Table 5-1 CsI-coated MCP characteristics.

<table>
<thead>
<tr>
<th>MCP</th>
<th>L/D (μm)</th>
<th>D (μm)</th>
<th>θ_B (°)</th>
<th>V_0 (kV)</th>
<th>e.V_C (eV)</th>
<th>θ_0 (°)</th>
<th>τ_F (μs)</th>
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</thead>
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<tr>
<td>F1</td>
<td>120</td>
<td>12.5</td>
<td>4</td>
<td>1.4</td>
<td>24.3</td>
<td>15</td>
<td>6000</td>
</tr>
<tr>
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<td>12.5</td>
<td>0</td>
<td>1.6</td>
<td>31.7</td>
<td>15</td>
<td>6000</td>
</tr>
<tr>
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<td>0</td>
<td>1.4</td>
<td>24.3</td>
<td>4</td>
<td>14000</td>
</tr>
<tr>
<td>F5</td>
<td>40</td>
<td>12.5</td>
<td>13</td>
<td>0.55</td>
<td>33.8</td>
<td>4</td>
<td>30000</td>
</tr>
<tr>
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<td>8</td>
<td>0</td>
<td>1.8</td>
<td>40.2</td>
<td>4</td>
<td>14000</td>
</tr>
<tr>
<td>F8</td>
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<td>25</td>
<td>0</td>
<td>1.3</td>
<td>47.0</td>
<td>15</td>
<td>6000</td>
</tr>
</tbody>
</table>

Figure 5-1 Reproducibility of MCP open area QDE, Q_C(θ_X, 44.7 Å). Data from six MCPs newly coated with CsI, numbered as in Table 5-1. For those three MCPs that were half-coated with CsI, equivalent efficiencies on the uncoated, reference half are also shown.
walls and the highest values of collision energy should exhibit the highest efficiencies at large X-ray incidence angles. This is confirmed by the superiority of MCP number 5. Of more importance, however, is the fact that the efficiencies of all six coated MCPs lie well above the corresponding curves for the uncoated MCPs.

5.3 The effects of exposure to laboratory air on the QDE of a CsI-coated MCP

It was considered essential to quantify the effects of normal laboratory air on CsI-coated MCPs. Vacuum breaks are inevitable in the development of windowless MCP X-ray detectors. Even if detector assembly is carried out in enclosures that are flushed with dry N₂, as was our standard practice, contact of normally humid air with the hygroscopic photocathode surface cannot be totally excluded.

We subjected Detector 8 to a series of deliberate exposures to laboratory air. The chamber of VTF 1, in which the detector was mounted, was repeatedly opened to the atmosphere until the accumulated exposure time had reached eight hours. Figure 5-2(a) shows the variation in the open area QDE, Q_C, measured with C K radiation at three different angles of X-ray incidence, as a function of exposure time. These measurements were made on the CsI-coated half of MCP F8. Figure 5-3(a) is the corresponding figure for Al K illumination. Within measurement error, no overall decrease in efficiency was observed. Figures 5-2(b) and 5-3(b) show the corresponding variations of the peak gain and FWHM of the detector output PHD.

All of these air exposures were made while the relative humidity (RH) was in the range 44-56 percent and while the laboratory temperature was between 22 and 25°C. Our results can be compared with previously published accounts of the stability of CsI in air.

According to Scott [99], CsI photocathodes are indefinitely stable in dry air but are ruined by exposures to air with an RH greater than approximately 50 percent. Premaratne et al [100] have reported that \( \chi_C \), the X-ray photocurrent, is unaffected by 30 minutes exposure to air
Figure 5-2 (a) Variation of the open area efficiency, \( Q_C(\theta_X, 44.7 \text{ Å}) \), of the CsI-coated half of Detector 8 with accumulated air exposure time.
(b) Variation of the peak gain, \( G_C \) (open circles - left hand scale), and FWHM, \( \Delta G_C / G_C \) (filled circles - right hand scale), of Detector 8 with accumulated air exposure time.
Figure 5-3  (a) Variation of the open area efficiency, $Q_c(\theta_x, 8.34 \text{Å})$ of the CsI-coated half of Detector 8 with accumulated air exposure time.

(b) Variation of the peak gain, $G_c$ (open circles - left hand scale), and FWHM, $\Delta G_c / G_c$ (filled circles - right hand scale) of Detector 8 with accumulated air exposure time.
with an RH of 63 percent. Three hours under the same conditions, however, resulted in a significant decrease in \( X_C \). On longer timescales, Saloman et al [101] have reported \( X_C \) values unchanged after 18 hours in "humid" air (RH unspecified) and Verma [102] has reported a halving of the CsI secondary electron yield coefficient after 24 hours exposure to air with an RH of 60 percent at a temperature of 27°C.

If any consensus view emerges from examination of all of the data now available it is that the sensitivity of CsI X-ray photocathodes and dynodes will not degrade as a result of the kind of brief contact with laboratory air encountered in the detector developments described in this thesis, provided that very high humidities are excluded.

Figure 5-4 shows the variation in detector noise count rate, \( N_n \), with accumulated air exposure time. The test chamber used for these measurements, namely that of VTF 1, incorporated a perspex viewing port approximately 20 cm in diameter. We recorded noise counts both with the port covered by an opaque screen and with it open to the light. Figure 5-4 shows that the noise count rate in both measurement configurations was steady at about four counts per second, except for one measurement, which was made with the viewing port uncovered, after the first five-minute long air exposure. This increased noise count rate was associated with the CsI-coated half of the test MCP as can be clearly

![Figure 5-4](image)

**Figure 5-4** Variation of the noise count rate, \( N_n \), of Detector 8 with accumulated air exposure time. Open circles - perspex port covered; filled circles - perspex port uncovered.
seen from Figure 5-5(a) which is a photograph of the image recorded on the storage oscilloscope. Figure 5-5(b) was obtained immediately after Figure 5-5(a), but with the perspex window covered over, i.e. with the detector in the dark. There was no such differential brightening on any other noise image recorded during the sequence of air exposures.

The most straightforward interpretation of this noise data is that the initial five-minute air exposure "sensitized" the CsI photocathode to visible blue light and that further exposure "killed" this sensitivity. The QDE of freshly-coated MCPs is known to be a steeply falling function of wavelength longward of 1800 Å, with a value of 0.01 percent at a wavelength of 2000 Å [103].

Figure 5-5 (a) Noise image from Detector 8. The noise count is uniformly higher on the CsI-coated side (left hand side). The perspex port was open to light.
(b) The corresponding figure to Figure 5.5(a) but with the perspex port covered.
Light related noise enhancements have been intermittently observed with other detectors that incorporated CsI-coated MCPs. Further, it can be noted that differentially brightened noise images have been observed with half-coated MCPs operated in VTF 2 [60], in which the available light paths to the detector were extremely tortuous. These observations are possibly indicative of a second effect, namely the greater sensitivity to positive ions of the CsI coating.

5.4 Effects of storage on CsI photocathodes

5.4.1 Effects of storage in poor vacuum

After initial testing, the MCPs of Detector 1 were removed from the detector body and placed in an aluminium pressure vessel. This vessel was rough-pumped to a pressure of $10^{-2}$ mbar (7.5 x $10^{-3}$ torr) and sealed. After 30 days storage, the MCP was removed and the X-ray detector was reassembled in its original configuration. A limited set of measurements with Al K X-rays show that the detection efficiency at large angles of X-ray incidence had fallen significantly (see Figure 5-6(a)). These measurements were curtailed because of problems with the vacuum test chamber and the readout electronics of the detector. We decided, therefore, to return the coated MCP to storage.

A full set of efficiency measurements was taken after this second period of storage under rough vacuum, which lasted 10 days. As shown in Figures 5-6(a,b), the open area efficiencies at large angles of X-ray incidence, measured with both C K and Al K X-rays, had then fallen to about one half of their original values. The convergence of the efficiency curves at small values of $\theta_X$ ($\theta_X < \theta_0'$, the central coating angle) clearly shows that a degradation in the CsI coating was responsible for the observed fall in efficiency. For values of $\theta_X$ very much less than $\theta_0'$, the response of the lead glass largely determined the detector sensitivity.

Monitoring of the pressure of the empty aluminium vessel showed an increase in pressure to approximately 1 mbar
Figure 5-6 (a) Effects of storage under rough vacuum on the open area QDE, \( Q_C(\theta, 8.38 \text{ Å}) \) of Detector 1. Open circles - efficiencies before storage. Squares - efficiencies after the first, thirty-day, period of storage. Filled circles - efficiencies after a second, 10-day, period (accumulated storage time 40 days). The broken vertical line indicates the coating angle, \( \phi_0 = 15^\circ \).

(b) As for Figure 5-6(a) except that the measurements were made with C K (44.7 Å) X-rays.
(0.75 torr) one week after sealing. It appears that outgassing from the (unbaked) walls of the storage vessel provided a more severe test of the CsI photocathode than had originally been intended. Water vapour was almost certainly a major component of the storage atmosphere.

5.4.2 The effects of storage in a dry atmosphere

After completion of the air exposure tests, the largely unaffected front MCP of Detector 8 was used to study the longterm effects of storage in a dry atmosphere, namely dry nitrogen / desiccated air, at normal temperature and pressure.

After we had completed the air exposure tests, the half-coated front MCP, together with the corresponding rear MCP, was placed in a dry \( N_2 \)-filled polythene bag and stored in a desiccator jar charged with silica gel capsules, where the inferred relative humidity was approximately 10 percent. At intervals of a few weeks, the MCPs were retrieved, re-assembled into their detector body, and retested. Later in the measurement sequence, the method of storage was changed somewhat. The complete MCP assembly, including electrodes, MCP mountings, etc., was placed intact in a sealed container (similar to that referred to in Section 5.4.1) filled with dry \( N_2 \) at slightly greater than atmospheric pressure. Initial efficiency and gain measurements were made on 29 June 1982. The complete measurement sequence for MCP F8 extended from that date for 450 days.

Figure 5-7(a) shows the variation in the C K X-ray detection efficiency with time, for three angles of X-ray incidence. The air exposure measurements of Section 5.3 occupied the first ten days of the MCP history. By the end of the tests, with final efficiencies, within error, identical to initial efficiencies, the coated MCP had been in some sort of dry storage for 402 days. Efficiency measurements that were made with Al K X-rays reveal a similar degree of explicit stability. We may also infer an added immunity to MCP handling from this data. Detector assembly and disassembly took place more than a dozen times during the measurement sequence; with each such MCP
Figure 5-7  (a) The variation of open area QDE, $Q_C(\theta_x, 44.7 \text{ Å})$, of Detector 8 as a function of time. The air exposure tests occupy days 1-10. Thereafter, the detector was stored in a dry atmosphere at normal pressure between tests.

(b) The variation of the peak gain, $G_C$ (filled circles - left hand scale), and FWHM, $\Delta G_C / G_C$ (open circles - right hand scale), versus time for Detector 8.
manipulation, the opportunity arose both for exposure to humid air and mechanical damage to the photocathode surface. Our safe storage time of 400 days for CsI-coated MCPs even exceeds the nine months dry $N_2$ lifetime reported by Saloman et al [101] for planar CsI photocathodes.

Figure 5-7(b) shows the variation in detector peak gain and FWHM with time over the same test period. The peak gain increased initially. After the first long (67 day) period of dry storage, $G_C$ increased two-fold. This increase is attributed to gaseous absorption onto the MCP channel walls [104]. Apart from the peculiar reversion to low gain exhibited on Day 155, high gains in the 3.5-5.0 pC range were the norm for the remainder of the test period. The large scatter in $G_C$ values in the period from Day 214 to Day 450 may, in part, be due to small variations in the MCP output count rate from observation to observation. The resistance of the rear MCP of the detector was so high (1690 MΩ) that relatively small changes in count rate (60-200 counts per second) were later observed to cause significant changes in peak gain (6.8-4.0 pC respectively) as shown in Figure 5-8.

We conclude that coated MCP storage in a normal pressure dry atmosphere is acceptable on long timescales, provided

![Figure 5-8](image-url)  
**Figure 5-8** The variation of peak gain, $G_C$ (filled circles - left-hand scale), and FWHM (open circles - right-hand scale) for Detector 8 as a function of output count rate.
that a recalibration of the detector gain is permissible afterwards. At the end of the measurement sequence, the CsI coated half of MCP F8 was observed to have a definite "cloudy" appearance, similar to that of the films which had been deposited onto glass blanks and stored for long periods by J.F. Pearson [60]. A change in the opacity of a CsI photocathode does not, therefore, automatically indicate a change in X-ray sensitivity.

5.5 Effects on CsI photocathodes of prolonged X-ray bombardment in vacuum

MCP F4, half-coated with 14000 Å of CsI, was used in a series of experiments, culminating in an investigation of MCP energy resolution by Fraser and Pearson [105]. After completion of these measurements, the detector incorporating MCP F8 was stored intact in the test vacuum chamber of VTF 2 in a normal pressure atmosphere of dry N₂ for a period of two months. The detector was then re-activated for use in an X-ray lifetest; this involved its prolonged bombardment at high count rates under vacuum. The aims of this test were

1) to discover the effects of both X-ray bombardment and time spent under vacuum on the QDE of a CsI-coated MCP and

2) to investigate changes in gain (see Chapter 6) and noise count rate arising from the same causes.

Three test positions were identified on the front surface of MCP F4. Position A, which was on the CsI-coated half, was illuminated continuously by C K X-rays. Position B, also on the CsI-coated half, served as a reference spot. Any change in the efficiency of the CsI layer at this position could be attributed to time spent under vacuum, as position B was illuminated only for brief (30 second) periods at intervals of several hours. A third X-ray beam position, position C, served as a reference spot on the uncoated half of the MCP. The chosen areas of the MCP had not been heavily bombarded prior to the commencement of the lifetest. Each test spot was 6 mm in diameter.

Initially, absolute efficiency measurements were made at all three test positions. These measurements, made at an
X-ray angle of incidence of 15°, are reported in Table 5-2. After completing these, the PC was flushed with dry N₂. This was done to reduce the total pressure in the detector chamber, which was primarily due to leakage of PC gas through the PC window, and, more importantly, to eliminate carbon contamination (in the form of methane) from the MCP operating environment. The X-ray lifetest of the MCPs was conducted at pressures within the vacuum chamber of 1-2 x 10⁻⁶ mbar (7.5 x 10⁻⁷ torr).

The test was conducted with an output count rate from test spot A of 2100±400 counts per second and continued until approximately 4 x 10⁹ counts cm⁻² had been abstracted. Such a dose corresponds to an average rate of approximately 100 counts cm⁻² per second for a period of one year, a flux and duration typical of satellite borne X-ray astronomy experiments. Bombardment of the test spot was not continuous. The source anode had to be periodically recoated in order to maintain the X-ray count rate. The design of VTF 2 enabled the source to be recoated without breaking the detector chamber vacuum; this allowed measurements to be made over a period of 23 days with the MCP high voltages continuously applied in high vacuum.

The relative efficiencies of test spots A, B and C were measured throughout by traversing the X-ray beam appropriately and recording the MCP output count rate. The open area efficiency ratios

\[ R_1 = \frac{\text{Count rate at test position B}}{\text{Count rate at test position A}} \]

\[ R_2 = \frac{\text{Count rate at test position C}}{\text{Count rate at test position A}} \]

are plotted as functions of accumulated count at position A in Figures 5-9(a,b). Both ratios change very little over the period of the lifetest. That this constancy can be interpreted in terms of the stability of the CsI coating under X-ray bombardment was confirmed by the post-lifetest measurements of the absolute efficiencies at positions A and C (see Table 5-2). Inspection of the "before" and "after" efficiencies measured at position B also indicate stability of the CsI photocathode under high vacuum. Such stability, on timescales of up to 60 days, has also been demonstrated.
Figure 5-9 (a) The open area efficiency ratio, $R_1$, as a function of accumulated output counts from test spot A of Detector A.  
(b) The open area efficiency ratio, $R_2$, as a function of accumulated output counts from test spot A of Detector A.
for planar CsI photocathodes by Premaratne et al [100].

The metallization of CsI photocathodes under prolonged electron bombardment, involving the liberation of iodine and the production of an easily visible caesium rich layer, has been reported by several authors [97,102]. Visual inspection of MCP F4 after completion of our lifetest revealed no changes in appearance that could be associated with the X-ray bombardment spot.

5.6 Conclusions

The results presented in this chapter indicate that CsI photocathodes can stably, and reproducibly, increase the soft X-ray QDE of MCPs. Of the processes to which our coated MCPs have been subjected, only storage under rough vacuum produced a serious degradation in sensitivity. Most of the storage and air exposure tests were performed on the front MCP of Detector 1 which was half-coated with 6000 Å of CsI. It may be inferred, however, from the work with glass blanks performed by J.F. Pearson [60] that thicker coatings will prove equally robust in terms of handling and storage.

<table>
<thead>
<tr>
<th>Position</th>
<th>Efficiency before (%)</th>
<th>Efficiency after (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (CsI)</td>
<td>28.0 ± 1.4</td>
<td>29.8 ± 1.5</td>
</tr>
<tr>
<td>B (CsI)</td>
<td>26.7 ± 1.3</td>
<td>28.8 ± 1.4</td>
</tr>
<tr>
<td>C (bare MCP)</td>
<td>8.1 ± 0.4</td>
<td>8.6 ± 0.4</td>
</tr>
</tbody>
</table>

Table 5-2 MCP open area quantum detection efficiencies $Q_C(15^\circ, 44.7 \text{ Å})$ at three test positions before and after X-ray bombardment of MCP F4.
CHAPTER 6
MICROCHANNEL PLATE DETECTOR LIFETESTS

6.1 Introduction

The variation of the gain of both CEMs and MCPs as a function of the total number of detected events has been investigated by a number of researchers. Several CEMs have been subjected to prolonged electron \([105-110]\), proton \([111, 112]\) and photon \([113]\) excitation. All the results, with the exception of those of Sharber et al \([112]\), show that, everything else remaining constant, gain degrades as the accumulated number of detected events increases. Sharber et al reported a gain increase after an initial gain decrease. The behaviour of their CEM is almost certainly explained because the input count rate to their detector decreased throughout the duration of the test.

It seems probable that gain degradation is determined not by the total number of detected events but by the total amount of charge abstracted from the multiplier. Table 6-1 lists a number of MCP configurations that have had their gain investigated as a function of total abstracted charge. Only the tests of Henry et al. \([35]\) and Malina and Coburn \([64]\) were carried out with tandem-pair detectors operated in the pulse saturated mode.

The variation of gain with abstracted charge, and its causes, is of interest to MCP manufacturers who would like to produce image tubes that have a greater gain stability (see Section 6.8). Also, because there are several planned satellite experiments that will require the longterm operation of a photon counting MCP detector, it is important to investigate the manner in which the output PHD of an MCP detector changes as charge is abstracted. The imaging MCP detector for the ROSAT WFC, for example, should be operational for two or more years. The anticipated output count rate is of the order of 100 counts sec\(^{-1}\) cm\(^{-2}\). The initial WFC detector peak output charge level will be set at approximately 2.5 pC (equivalent to a gain of approximately \(1.5 \times 10^7\)). If this gain is to be maintained, a 1 year
<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Ref.</th>
<th>D (µm)</th>
<th>Operational mode</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oba K. et al.</td>
<td>[30]</td>
<td>15.0</td>
<td>Pulse Unsaturated</td>
<td>Single Hamamatsu</td>
</tr>
<tr>
<td>Henry J. et al.</td>
<td>[35]</td>
<td>11.8-12.5</td>
<td>Pulse Saturated</td>
<td>Tandem-pair</td>
</tr>
<tr>
<td>Ruggieri D.</td>
<td>[51]</td>
<td>14.6</td>
<td>Current Unsaturated</td>
<td>Single Varian</td>
</tr>
<tr>
<td>Malina R. and Coburn K.</td>
<td>[64]</td>
<td>12.0-25.0</td>
<td>Pulse Saturated</td>
<td>Tandem-pair various</td>
</tr>
<tr>
<td>Timothy J. Mount G. and Bybee R.</td>
<td>[69]</td>
<td>25.0</td>
<td>Pulse Saturated</td>
<td>Single Curved-Channel Galileo</td>
</tr>
<tr>
<td>Parkes W. Gott R. and Pounds K.</td>
<td>[71]</td>
<td>40.0</td>
<td>Pulse Unsaturated</td>
<td>Single Mullard</td>
</tr>
<tr>
<td>Timothy J. and Bybee R.</td>
<td>[114]</td>
<td>25.0</td>
<td>Pulse Unsaturated</td>
<td>Single Curved Channel Mullard</td>
</tr>
</tbody>
</table>

Table 6-1 MCP detector configurations that have been lifetested.
mission would result in a total abstracted charge of $8 \times 10^7 \text{ pC mm}^{-2}$. As MCP detector gain degradation has been observed at levels of total abstracted charge much lower than this (for example see ref. (64) where gain degradation was observed on some detectors after only $6 \times 10^6 \text{ pC mm}^{-2}$ had been abstracted), it is probable that the peak gain of the WFC will degrade. It can be noted that the effects of gain degradation can be compensated for by increasing the detector voltages.

When photon counting electronics with a fixed lower level discriminator are employed, any degradation of gain manifests itself as a decrease in QDE because a greater fraction of real events fall below the discriminator level and, therefore, are not counted. Also, because the average charge abstracted per event decreases, the signal-to-noise ratio at the readout terminals decreases and, hence, the position resolution of the detector is degraded (see Section 2.2).

As a part of the WFC detector development programme, we performed a number of "lifetime" tests on several MCP tandem-pair detectors in order to investigate the effects of the abstraction of quite large amounts of charge (upto a total of over $10^8 \text{ pC mm}^2$) on detector gain. The results of these tests, which are presented in this chapter, indicate that the "natural" MCP gain (defined as the gain of an uncontaminated MCP when operated in a perfect vacuum) decreases almost continuously with increased abstracted charge. Concurrently with the natural gain degradation, which we believe to be an intrinsic property of the MCP glass, there can also be additional gain degradation due to ambient conditions. For example, vacuum system oil is one possible source of contamination which may induce gain degradation.

Having investigated the lifetime characteristics of detectors containing MCPs as received from the manufacturer, one MCP was treated in the manner described in a recent patent application [116] in an attempt to introduce caesium into the surface layers of its channel walls. This MCP was assembled into a detector and tested. We hoped that the treatment would reduce the rate of gain degradation of this
detector. The nature of this treatment, and its effects, are presented.

6.2 The lifetests of Detector 3

6.2.1 The first lifetest of Detector 3

The first lifetest was conducted on Detector 3 in VTF 1. The original aim of this test was to simulate the effects of charge abstraction on a WFC-type detector. Thus, the front MCP was coated with 6000 Å of CsI at a central coating angle of 15°. Initially, the operating characteristics of the detector were investigated. The following bias voltages were chosen:

\[ V_F = 1600 \text{ volts}; \quad V_R = 1600 \text{ volts}; \quad V_G = 50 \text{ volts}. \]

These particular values resulted in a peak gain of 6.2 pC and a FWHM of 24 percent when the detector was illuminated by C K X-rays at an incidence angle of 15°.

The vacuum chamber was let up to atmospheric pressure with dry N₂. The carbon-coated polypropylene window of the MCP detector was removed and replaced with a circular Cu-Be mask that had a 5 mm diameter aperture positioned 12 mm from the mask centre. The mask was orientated so that the aperture was not over a previously illuminated area of the detector. Dry N₂ was flowed over the detector during this procedure in order to protect the photocathode. The X-ray source was removed from the vacuum chamber and replaced with the mirror and collimating system necessary for the use of the mercury discharge lamp, as described in Section 3.4.1.3. We decided to use the mercury discharge lamp, which is an intense source of UV radiation, instead of the much less intense VTF 1 X-ray source in order to get as high an input count rate to the MCP detector as possible. As the input count rate increased above a threshold level, the average charge per output count decreased, but the charge abstracted per unit time increased. It was this last parameter, rather than the output count rate, that we attempted to maximize in all of the lifetests that used the UV source. Prior measurements of \( G_C \) versus output count rate were made and a sensible count rate (in terms of output PHD shape) was
chosen.

6.2.1.1 Determination of the lifetest output count rate

The UV flux from a Hg discharge lamp primarily consists of 4.89 and 6.70 eV photons [88]. The probability of these photons being detected by an MCP detector is lower than the corresponding probability for soft X-rays. The CsI photocathode, however, greatly increased the UV sensitivity of the detector. Initially, we found that the flux from the Hg lamp was much too great. Thus, we placed a 1 mm diameter pinhole in the lamp collimator.

Initially, we investigated the variation of peak gain with output count rate. We varied the UV flux by inserting pieces of wire mesh into the collimator. The test radiation was incident at an angle of 30° with respect to the channels. The peak gain of the output PHD decreased as the output count rate increased, being 3.96 pC at an output count rate of 200 sec\(^{-1}\), 3.70 pC at an output rate of 3100 sec\(^{-1}\) and only 1.69 pC at an output rate of 12000 sec\(^{-1}\). We decided to run the lifetest at an output count rate of 3000 counts sec\(^{-1}\), corresponding to an initial peak gain of approximately 3.7 pC. As the illuminated area was 17 mm\(^2\) (the projection of the 5 mm diameter mask aperture, angled at 30°, onto the detector front face), the charge abstraction rate was 680 pC mm\(^{-2}\) sec\(^{-1}\). Thus, on the assumption that the detector gain would remain constant, we calculated that a total test duration of 20 days would have been necessary for the total abstracted charge per unit area to have equalled the anticipated total abstracted charge per unit area for the ROSAT WFC detector.

6.2.1.2 Lifetest L3.1

The lifetest (henceforth referred to as L3.1) was started. Initially, both a detector noise distribution and a distribution with the test area illuminated were accumulated over separate 100 second periods and then plotted out. Afterwards, at various intervals, further PHDs were accumulated and recorded. The resistance of both of the MCPs
was also recorded. The noise PHDs were obtained by shuttering the UV source (for the accumulation period of the noise PHD only). Thus, a region of the detector (region L3.1) was illuminated continuously except for 100 second periods every four hours or so. This procedure was carried out 14 times until a detector failure occurred. It appears that the rear MCP had been shorted out; we believe that this was due to insufficient spacers being placed into the detector body during assembly. The short caused burn marks to appear on the edge of the rear MCP but no damage was observed on the active area of either MCP.

6.2.1.3 The analysis of the output PHDs

We decided to plot the logarithm of the peak gain of the output PHDs against the calculated total charge that had been abstracted from the rear MCP. We estimated the total charge abstracted from analysis of the accumulated PHDs. Since an output PHD is a histogram of number density, \( N_i \), as a function of charge level, \( Q_i \), the total charge, \( Q_T \), abstracted during the aquisition of a distribution is

\[
Q_T = Q_i \cdot N_i
\]

and, therefore, if all of the \( N_i \) and \( Q_i \) values are known, it is a simple task to calculate the total abstracted charge.

Unfortunately, at the time of the investigation, it was not practicable to read out and record the number of counts in each of the 512 channels of the pulse height analyser. Thus, the plotted distributions were analysed as indicated in Figure 6-1. The area under each distribution was divided into strips of equal charge range (e.g. 0-1 pC, 1-2 pC, etc). The mean charge level of each strip, \( Q_i \), was calculated using the calibration markers added to each distribution. Also, the area of each strip was calculated as a fraction of the total distribution area. As the total number of counts, \( N_T \), in each distribution was known, the number of counts, \( N_i \), in each strip could be calculated. The total charge abstracted in each strip was found from the product of \( Q_i \) and \( N_i \). The total charge abstracted from the detector during the acquisition of each distribution was calculated by summing all the sub-total charges \( (N_i \cdot Q_i) \).
Figure 6-1 Conversion of an output PHD into the corresponding histogram in the analysis.  
(a) The output PHD, $N_I(Q_1)$.  
(b) Obtain the envelope, $N(Q)$, around the distribution.  
(c) The smooth envelope is quantized giving (d) the data, $N_i(Q_i)$, to be analysed.  
The vertical arrow in (a) indicates a typical setting of the lower level discriminator.
Hence, the average charge abstracted per event, $\bar{Q}$, was calculated from

$$\bar{Q} = \frac{Q_T}{N_T}$$

If the output PHDs had been truly Gaussian, the average gain per event and the peak gain would have been equal.

For a number of the PHDs, especially those with a low peak gain, the lower level discriminator of the electronics cut off a significant fraction of real events. Even though these events were not counted, they did result in the abstraction of charge from the test zone.

In order to estimate this "invisible" abstracted charge, the distribution curves were extrapolated below the discriminator level, as indicated in Figure 6-2. The calculations were suitably modified to take into account the fact that the events in the extrapolated area did not contribute to the total count, $N_T$.

Figure 6-2  a) A typical output PHD that has a fraction of its events falling below the lower level discriminator (arrowed).
   b) Reconstruction of the "invisible" section of the distribution by extrapolation.
The noise events, typically, were primarily of low charge level, but they still caused charge to be abstracted from the detector. The noise counts, however, were usually fairly uniformly distributed over the whole detector area and, therefore, contributed little to the amount of charge abstracted from the illuminated zone.

Having calculated the average charge abstracted per event, the total charge abstracted in the period between the acquisition of each pair of consecutive distributions had to be calculated. If the average charge abstracted per event for each of a pair of distributions was $Q_1$ and $Q_2$ respectively, the total charge abstracted in the period between the two measurements was calculated from

$$[\frac{Q_1 + Q_2}{2}], N_S$$

where $N_S$ is the total number of events that had been detected between the acquisition of the two distributions.

By analysing the data in this way, it was possible to plot the variation of the peak gain of each distribution as a function of total abstracted charge.

6.2.1.4 The results of lifetest L3.1

Figure 6-3 shows the variation of the logarithm of the peak gain as a function of the total charge abstracted from the illuminated region. As can be seen, the gain decreased throughout almost the whole extent of the test. The peak gain of the first measurement was 3.09 pC. This value was lower than the equivalent peak gain measured in Section 6.2.1.1. We attribute the difference to gain degradation caused by the abstraction of charge during the detector characterization process.

After a total of $1.2 \times 10^9$ pC had been abstracted, the peak gain had fallen to 1.12 pC. It can be seen that, up to a total abstracted charge of $8 \times 10^8$ pC, the data points fall on a straight line that has a gradient of $-1.09 \times 10^{-9}$ pC$^{-1}$. Between total abstracted charge levels of approximately $8.0 - 9.3 \times 10^8$ pC, the peak gain appeared to be stable at about 1.3 pC. Such a period of stable gain has been reported from lifetests carried out on both CEMs (for example see
Figure 6-3 Variation of the logarithm of the peak gain, $G_C$, as a function of the accumulated charge abstracted from test region L3.1 of Detector 3. The gradient of the initial data is $-1.09 \times 10^{-9}$ pC$^{-1}$ and that of the later data is $-7.33 \times 10^{-10}$ pC$^{-1}$.

$V_F = 1600$ volts;

$V_G = 50$ volts;

$V_R = 1600$ volts.
ref. [108]) and MCPs [51, 64]. After the period of approximately constant gain, the gain degraded again, but at a lower rate than previously, the gradient being $-7.33 \times 10^{-10} \text{ pC}^{-1}$.

Figure 6-4 shows the variation of the PHD FWHM, and Figure 6-5 the variation of detector noise count, as a function of the total abstracted charge per unit area. The FWHM varied between 140 and 190 percent. These are high values for a detector operated with an accelerating interplate gap voltage but are probably due to the increased probability of photon reflection at larger angles of incidence. The critical angle of reflection for UV photons from MCP glass is probably of the order of 25 degrees or more. For X-rays, the reflection coefficient $R(\alpha)$ exhibits a "top-hat" profile, being unity for angles greater than the critical angle and rapidly falling to zero for smaller angles, whereas, for UV photons, the transition from no reflection to total reflection is much smoother.

After an initial rise, the detector noise count rate decreased as the lifetest proceeded, the final noise count rate being approximately the same as the noise rate at the start of the lifetest. This time-dependent source of noise was probably due to the outgassing of the MCPs (the surface area of an MCP can be several hundreds of cm$^2$).

The variation of the resistance of the front and rear MCPs is plotted in Figure 6-6(a). If the abstraction of charge from a channel affects its resistance, then the resistance of that area of the rear MCP under illumination should change more than the resistance of both the front MCP and the remaining area of the rear MCP. (If the illuminated area is only a small fraction of the total detection area, as was the case for most of our lifetests, any change might not be observed.) Figure 6-6(a) indicates that resistance of both the front and rear MCPs varied in a cyclic manner and by a similar degree. If the initial resistance values were $R_{F0}$ and $R_{R0}$ for the front and rear MCPs respectively, then, for a subsequent pair of measurements, $R_F$ and $R_R$, we can define a coefficient of resistance, $f_R$, as follows:

$$f_R = \frac{R_F}{R_R} \times \frac{R_{R0}}{R_{F0}}$$
Figure 6-4 Variation of the FWHM, $\Delta G_C / G_C$, as a function of the charge abstracted from region L3.1 of Detector 3. $V_F = 1600$ volts; $V_G = 50$ volts; $V_R = 1600$ volts.
Figure 6-5 Variation of the noise count rate, \( N_n \), as a function of the charge abstracted from region L3.1 of Detector 3.

\( V_p = 1600 \) volts; \( V_g = 50 \) volts; \( V_r = 1600 \) volts.
Figure 6-6 (a) Variation of the front and rear MCP resistances, $R_F$ and $R_R$, as a function of the charge abstracted from Region L3.1 of Detector 3.

(b) Variation of the normalized, corrected rear MCP resistance, $f_R$, as a function of the abstracted charge from Region L3.1 of Detector 3.

$V_F = 1600$ volts, $V_G = 50$ volts, $V_R = 1600$ volts.
In Figure 6-6(b), $f_R$ is plotted as a function of total abstracted charge per unit area. It can be seen that $f_R$ remained almost constant.

In Figure 6-7, the resistance data of Figure 6-6(a) is replotted as a function of time. There is some indication that the variation of the MCP resistances seems to repeat every 24 hours or so. Such behaviour might have been due to temporal temperature variations in the detector itself.

6.3 The effects of temperature on MCP resistance

The resistance of an MCP is a function of its temperature which, itself, is a function of both the ambient temperature and the heat dissipated in the MCP by Joule heating (the latter being a function of the applied voltage and the MCP resistance).

![Graph showing variation of MCP resistances](image)

**Figure 6-7** Variation of the front (open circles) and rear (filled circles) MCP resistances, $R_F$ and $R_R$, of Detector 3 as a function of time elapsed during LifeTest L3.1. The vertical dashed lines divide the total period into twenty four hour intervals. The crosses and squares in the first interval represent the data in the second and third intervals respectively overlayed onto the data in the first interval.
During another lifetest on Detector 3 (L3.2), which will be described later (see Section 6.4), the resistances of both MCPs were recorded together with the temperature of the outside of the VTF 1 chamber. The variation of these resistances as a function of chamber temperature is plotted in Figure 6-8. The data was obtained over an eleven day period. It is clear that the MCP resistances decreased as the chamber temperature increased. The relationship seems to be linear. The gradient of the lower line is $-9.3 \text{ M} \Omega/\text{per } ^\circ\text{C}$.
and that of the upper line is \(-18.0\) M\(\Omega\) per \(\degree\)C. A negative temperature coefficient of resistance has been measured previously \([44]\) for a high-conductivity curved channel MCP. Our values can be taken as lower limits to the actual temperature coefficients of resistance of the MCPs because any variation of the ambient temperature could only have been partially transmitted to the MCPs (after a time lag of unknown, but estimatable, period).

Referring back to Figure 6-7, the lowest resistance was measured at about seven o'clock in the evening. Figure 6-8 implies that this should have corresponded to the greatest MCP temperature. As the hottest part of the day occurred in the mid-afternoon, this may indicate that the time lag between a temperature change at the chamber and a corresponding temperature change at the detector was of the order of two to four hours.

6.4 Lifetest L3.2

Detector 3 was removed from VTF 1 and the problem that had prematurely ended lifetest L3.1 was investigated. The detector was stored in a dry \(N_2\) atmosphere during this time. When the problem had been corrected, the detector was re-assembled but with both MCPs rotated through \(180^\circ\) about the detector z-axis. The rotation of the MCPs ensured that a previously un-illuminated area of the detector (region L3.2) was tested. The lifetesting of the detector was recommenced. This second lifetest, L3.2, was carried out in the same manner as lifetest L3.1 and with the same voltages, namely

\[
V_F = 1600 \text{ volts; } V_G = 50 \text{ volts; } V_R = 1600 \text{ volts.}
\]

After a total of \(3.46 \times 10^9\) events had been recorded from region L3.2, the detector bias voltages were increased; the noise count rate was recorded after the increase. The new chosen voltages were

\[
V_F = 1690 \text{ volts; } V_G = 56 \text{ volts; } V_R = 1690 \text{ volts.}
\]

The voltages were increased in steps appropriate for the ROSAT WFC. The WFC detector voltages will be supplied from a single power supply via a resistor chain. It will be possible to vary the voltage from this supply in 10 volt steps and, therefore, the detector voltages will be variable.
in well defined steps.

The lifetest of region L3.2 was restarted. At the conclusion of this phase, we made a series of measurements to see if the detector gain recovered when the detector was masked from the UV source. The detector was masked (except for the length of time needed to acquire the distributions, which were recorded at intervals) for a total of about 24 hours.

Finally, the detector voltages were increased again in order to check that the gain could still be increased. The final bias voltages were

\[ V_F = 1740 \text{ volts}; \quad V_G = 58 \text{ volts}; \quad V_R = 1740 \text{ volts}. \]

6.4.1 Initial results from lifetest L3.2

Initially, the output PHDs had the usual quasi-Gaussian form (see Figure 6-9(a) for an example). As the lifetest progressed, the detector gain decreased, apparently in the same manner as had been observed during Lifetest L3.1. After several days of testing, however, the form of the output distributions was observed to change. The single peak, observed at the outset of the lifetest, began to split into two peaks. The two peaks diverged further as the test proceeded. Figure 6-9(b) shows a typical double-peaked PHD.

As it appears that there were only two peaks, the simplest interpretation is that the illuminated region consisted of two distinct areas. In the following discussion, we will assume that the output distributions were the superposition of two independent quasi-Gaussian sub-distributions, each one associated with one of the two areas.

We attempted to split each output distribution into two Gaussian components. We estimated that about 65 percent of the total counts were associated with the region of high degradation rate (which we will call zone 1) whilst the remaining counts were associated with the other zone (zone 2).

In Figure 6-10, the logarithm of the peak gain of the zone 1 components is plotted against the total charge abstracted from that zone. The data points fall on quite a
Figure 6-9 Two representative output PHDs obtained from test region L3.2 of Detector 3.

V_G = 1600 volts; V_O = 50; V_R = 1600 volts.

a) The initial distribution.
b) The distribution after 1.0 x 10^9 counts had been recorded from region L3.2.

It can be seen that distribution (b) appears to be splitting into two sub-distributions.
Figure 6-10 Variation of the logarithm of the peak gain, $G_C$, as a function of the accumulated charge abstracted from test region L3.2 (zone 1) of Detector 3.

The gradient of the initial data (open circles) is $-7.87 \times 10^{-10}$ pC$^{-1}$.

- $V_F = 1600$ volts; $V_G = 50$ volts; $V_R = 1600$ volts

The gradient of the latter data (filled circles) is $-3.56 \times 10^{-10}$ pC$^{-1}$.

- $V_F = 1690$ volts; $V_G = 56$ volts; $V_R = 1690$ volts.
good straight line. The gradient of the line is $-7.87 \times 10^{-10} \text{ pc}^{-1}$, or, expressed differently, the peak gain of zone 1 fell by 50 percent for every $8.8 \times 10^8 \text{ pC}$ of abstracted charge. The corresponding data for zone 2 is plotted in Figure 6-11, the gradient being $1.68 \times 10^{-10} \text{ pc}^{-1}$ in this case.

Figure 6-12 is a plot of the noise count rate for the detector as a function of the total charge abstracted. The detector noise count initially increased from 90 counts sec$^{-1}$ to 270 counts sec$^{-1}$ and then decreased steadily to finish at 20 counts sec$^{-1}$.

The variation of the resistance of the two MCPs F3 and R3 is plotted in Figure 6-13(a) and the coefficient, $f_R$, is plotted in Figure 6-13(b). As with the data of lifetest L3.1, both of the resistances varied in a cyclic manner. This time, however, $f_R$ decreased steadily as a function of abstracted charge. If it is assumed that the variation of the resistance of the front MCP was independent of the minute amount of charge abstracted from it, the conclusion is that the rear MCP resistance decreased as charge was abstracted. If the illuminated area was 17 mm$^2$, the resistance of those channels from which charge was abstracted would have been quite large. If, however, the illuminated area was much larger than expected, the decrease in $f_R$ is easier to explain. As the decrease in $f_R$ is fairly smooth, and does not appear to show any cyclic variation unlike the actual resistances, it also appears that the decrease in the resistance of the rear MCP was not a function of the absolute magnitude of $R_R$.

### 6.4.2 The results with increased voltage:

At the end of the first stage of lifetest L3.2, the peak gain of the zone 1 component had decreased from 3.81 pC to approximately 0.5 pC. When the detector voltages were raised, the peak gain of zone 1 increased to 2.2 pC. The noise count rate increased by a factor of two approximately.

The variation of the logarithm of the peak gain of the zone 1 sub-distributions at the increased detector voltages is also plotted in Figure 6-10. These data points also fall
Fleure 6-11 Variation of the logarithm of the peak gain, $G_C$, as a function of the accumulated charge abstracted from test region L3.2(zone 2) of Detector 3. The gradient of the data is $-1.68 \times 10^{-10}$ pC$^{-1}$.

$V_F = 1690$ volts; $V_G = 56$ volts; $V_R = 1690$ volts.
Figure 6-12 Variation of the noise count rate, N, as a function of the charge abstracted from region 13.2 (zone 1) of Detector 3.

\[ (l_{-\text{zone}}) N \]
Figure 6-13 (a) Variation of the front and rear MCP resistances, $R_F$ and $R_R$, as a function of the charge abstracted from Region L3.2 (zone 1) of Detector 3.
(b) Variation of the normalized, corrected rear MCP resistance, $f_R$, as a function of the abstracted charge from Region L3.1 (zone 1) of Detector 3.

$V_P = 1600$ volts, $V_q = 50$ volts, $V_R = 1600$ volts.
on a straight line, but in this case the gradient is \(-3.56 \times 10^{-10}\) pC\(^{-1}\). Thus, when the voltages were raised, the peak gain decreased by 50 percent for every \(1.95 \times 10^9\) pC of abstracted charge.

After a total accumulated count of \(6.078 \times 10^9\) counts, the UV source was shuttered off. The variation of the peak gain of zone 1 as a function of the time after the source was shuttered, \(t_{\text{off}}\), is shown in Figure 6-14 (the filled circles). 15 hours after excitation of the detector ceased, the detector gain had increased by 48 percent. The detector voltages were applied at all times.

When test area L3.2 was once again illuminated, the peak gain of zone 1 quickly degraded to its previous low value and continued to decrease as more charge was abstracted. Previously, it had required a total of \(1.3 \times 10^9\) events to be detected for the peak gain of zone 1 to fall from 1.30 to 0.85 pC whereas after re-illumination, it only required a total of \(1.6 \times 10^8\) events.

After a total of \(7.25 \times 10^9\) events had been detected from area L3.2, the source was again shuttered off. The variation of the peak charge level of zone 1 with time is also plotted in Figure 6-14 (the open circles). It can be seen that the gain of the detector recovered steadily. It also appears that both this and the previous set of data fall on the same curve.

6.5 The lifetests on Detector 4

A lifetest of a region of Detector 4 was performed concurrently with the investigations (described in Chapter 5) into the effects of prolonged X-ray bombardment on the CsI photocathode. Position A on the CsI-coated half of the detector was lifetested. The test was performed in VTF 2.

Lifetest L4.1 was conducted with an output count rate from position A of \(2100 \pm 400\) counts sec\(^{-1}\). C K X-rays were used as the test radiation. The test continued until some \(1.5 \times 10^9\) counts had been detected. The bombardment of the test spot was not continuous. The source anode had to be periodically recoated with SiC in order to maintain the X-ray count rate. These recoatings could be done without
In Figure 6-15, In \(G_C\) is plotted as a function of total abstracted charge for L4.1. Once again, the initial data fell on a straight line (the gradient of the line being \(-7.95 \times 10^{-3} \text{pc}^{-1}\)). There was a narrow range of stable gain extending between abstracted charges of \(0.9 - 1.5 \times 10^8 \text{pc}\). The peak gain could be reached by increasing the MCP gain by 10 percent (see Figure 6-15). The FWHM of the output peak was 119 and 150 percent. The large values of detector illuminated by C-K (1700 A) are attributed to a lack of an accelerating interstage voltage in the detector configuration.

Figure 6-16 shows the variation in the MCP detector count rate over the period of the lifetime test. The detector was decreased by more than a factor of two from high to low activity. Since the bombarded spot, which is a small fraction of the detector active area (0.25 cm\(^2\) in a 7 cm area), such changes cannot be attributed to the counting efficiency, \(e\). The values of \(n_P\) and \(n_P\) since the start were cyclical. \(e\), however, varied from unity to less than 2 percent. We conclude that the resistance of the detector was unaffected by the abstraction of upto \(2 \times 10^8 \text{pc}\).

![Graph showing normalized peak gain as a function of the time elapsed after the UV source was masked from the detector.](image-url)

Figure 6-14 Variation of the normalized peak gain of region L3-2(zone 1) as a function of the time elapsed after the UV source was masked from the detector.
breaking the detector chamber vacuum because of the construction of VTF 2. Measurements were made over a period of 23 days with the MCP high voltages continuously applied in high vacuum. At the conclusion of the test, the detector voltages were increased and the effect of these increases on the detector peak gain was noted.

6.5.1 The results of lifetest L4.1

In Figure 6-15, ln (G_C) is plotted as a function of total abstracted charge for L4.1. Once again, the initial data fell on a good straight line (the gradient of this line being \(-7.86 \times 10^{-10} \text{ pC}^{-1}\)). There was a narrow plateau of stable gain extending between abstracted charge levels of \(0.9 - 1.5 \times 10^8 \text{ pC}\). The peak gain could be restored to its original levels by modest increases in the MCP bias voltages (see Figure 6-15). The FWHM of the output PHD varied between 110 and 150 percent. These large values (large for a detector illuminated by C K X-rays) are attributable to the lack of an accelerating inter-plate voltage in the test detector configuration.

Figure 6-16 shows the variation in the MCP dark noise count rate over the period of the lifetest. The dark noise decreased by more than a factor of two from beginning to end. Since the bombarded spot constituted such a small fraction of the detector active area (\(0.28 \text{ cm}^2\) in a total area of \(7 \text{ cm}^2\)), such changes cannot be attributed to "burning in" of the detector but must rather be attributable to the time spent by the detector under vacuum.

Figure 6-17 is a plot of the MCP resistances as a function of total abstracted charge. Also plotted is the coefficient, \(f_R\). The values of \(R_F\) and \(R_R\) once again varied in a cyclic manner. \(f_R\), however, varied from unity by less than 2 percent. We conclude that the resistance of MCP R4 was unaffected by the abstraction of upto \(2.1 \times 10^9 \text{ pC}\).

As mentioned previously, the X-ray source had to be recoated periodically. While this was being done the detector was un-illuminated. At no time during the lifetest was any gain recovery at all observed. Since 24 or more hours typically elapsed before the source was restarted,
Figure 6-15 Variation of the logarithm of the peak gain, $G_C$, of Detector 4 as a function of the accumulated charge abstracted from region LA.1. The gradient of the initial data is $-7.86 \times 10^{-10} \text{ pC}^{-1}$.

* $V_F = 1500$ volts; $V_G = 0$ volts; $V_R = 1700$ volts.
* The voltage increases at the termination of the test resulted in
  1) $V_F = 1500$ volts; $V_R = 1800$ volts.
  2) $V_F = 1550$ volts; $V_R = 1800$ volts.
  3) $V_F = 1600$ volts; $V_R = 1800$ volts.
  4) $V_F = 1650$ volts; $V_R = 1800$ volts.
Figure 6-17 (a) Variation of the front and rear MCP resistances, $R_F$ and $R_R$, of Detector 4 as a function of the charge abstracted from Region L4.1.

(b) Variation of the normalized, corrected rear MCP resistance, $f_R$ of Detector 4 as a function of the charge abstracted from Region L4.1.

$V_F = 1500$ volts, $V_G = 0$ volts, $V_R = 1700$ volts.
this behaviour is in contrast to that recorded from Detector 3 in VTF 1 when it was masked from the UV source.

6.6 Conclusions from the lifetests on Detectors 3 and 4

In this section, we will attempt to summarise the results from the lifetests on Detectors 3 and 4.

The detector noise count rate increased initially and then decreased as all of the lifetests proceeded (compare Figures 6-5, 6-12 and 6-16). As the noise count rate was integrated over the whole active area of the detectors, and not just over the illuminated areas, we believe that this behaviour must be due to the time spent under vacuum by the detectors.

Much of the data plotted in Figures 6-3, 6-10 and 6-15, can be represented by the equation

\[ \ln (G_C) = k \cdot Q + \ln (G_{C0}) \]

where \( k \) and \( G_{C0} \) are constants. This equation can be rewritten either as

\[ G_C = G_{C0} \cdot \exp (kQ) \]

or

\[ \frac{1}{G_C} \frac{dG_C}{dQ} = k \]

\( k \) is a measure of the gain degradation rate of the detector but is dependent on the illuminated area because, for a given MCP, the greater the illuminated area, the greater the total charge abstracted and hence the smaller the value of \( k \). In order to compare the gain degradation behaviour of different detectors that have MCPs of the same channel diameter and the same open area fraction but different illuminated areas, we define an MCP property, namely the gain degradation rate, \( D_m \) by

\[ D_m = \frac{A}{G_C} \frac{dG_C}{dQ} = kA \]

where \( A \) is the illuminated area.

In lifetest L3.1, the gain decreased exponentially, stabilized and finally decreased exponentially again. The various gain degradation rates are tabulated in Table 6-2. The gain of the detector tested in L4.1 behaved similarly. Also, in both of these lifetests, the resistance of the rear
<table>
<thead>
<tr>
<th>Lifetest #</th>
<th>Abstracted Charge Range ($10^8$ pC)</th>
<th>Illuminated Area (mm$^2$)</th>
<th>k ($10^{-10}$ C$^{-1}$)</th>
<th>Dm ($10^{-10}$ mm$^2$ C$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>0 - 10</td>
<td>27.3</td>
<td>-7.86</td>
<td>-2.15</td>
</tr>
<tr>
<td>3.1</td>
<td>0 - 8 10 - 12</td>
<td>17.0</td>
<td>-10.9  -7.33</td>
<td>-1.85  -1.25</td>
</tr>
<tr>
<td>3.2 (i)</td>
<td>0 - 25</td>
<td>not known</td>
<td>-7.87  -3.56</td>
<td>-1.68</td>
</tr>
<tr>
<td>3.2 (ii)</td>
<td>25 - 55 0 - 30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>0 - 5</td>
<td>17.0</td>
<td>-10.4</td>
<td>-1.77</td>
</tr>
<tr>
<td>2.2</td>
<td>0 - 6 14 - 22</td>
<td>18.5</td>
<td>-1.46  -6.93</td>
<td>-2.70  -1.28</td>
</tr>
</tbody>
</table>

Table 6-2: The gain degradation rates, k and D_m, for all of our lifetests.
* Zones 1 and 2 of Lifetest L3.2.
MCP was unaffected by the abstraction of charge indicating both that the conductive layer had not been affected to any great degree and that no conductive deposits had been laid down on the channels.

In contrast, lifetest L3.2 behaved in a completely different manner. The most noticeable difference was that, as the lifetest proceeded, the output PHD became more and more double-peaked. Both of the peak gains decreased as charge was abstracted. The resistance of the rear MCP decreased by ten percent relative to the resistance of the front MCP.

We assumed that the region illuminated in L3.2 consisted of two distinct areas, one associated with each peak of the output PHDs. If this was the case, one explanation of the peak splitting is that the rate of gain degradation, $D_m$, was different in the two areas. The exact gain degradation mechanism would have to be quite complex as it would have to explain just two components rather than a continuous range. An MCP with varying gain degradation rates has been previously reported; Sandel et al [115] illuminated three areas of a single MCP with electrons and observed different degradation rates from those areas. The initial gain of the three regions was the same, however, indicating that the gain degradation mechanism was not dependent on the gain mechanism. For example, if the different degradation rates were due to an initial non-uniform electron source population concentration, it might be expected that the initial gains would have been different. Sandel et al proposed that the electron source population was being reduced by reaction with a resident poisoning species.

A second explanation of our results from L3.2 is that the two areas had the same gain degradation rate but were illuminated at different intensities. There was some evidence supporting this. It appeared from looking at the readout storage 'scope that there was some scattered UV radiation but the imaging was not good enough to be certain. This could have led to a central area illuminated at the expected intensity surrounded by an annulus illuminated at reduced intensity.

If $D_m$ was constant over the whole detection area of Detector 3, the area of zone 2 would have had to be $4.7$
times greater than that of zone 1 in order to explain the
difference in the values of k. Further, as the area of
region L3.1 was 17 mm$^2$, the area of zone 1 would have had to
be 23.6 mm$^2$ and that of zone 2 would have had to be 110 mm$^2$
or approximately 10 percent of the total detection area.

When the detector voltages were increased, the gain
degradation rate of zone 1 decreased. This is a very
interesting result because it implies that raising the
detector voltages decreased the gain degradation rate at a
particular gain. This could be because the increased applied
voltage increased the strip current through the MCP and,
therefore, caused the abstracted charge to be replenished at a
faster rate. If gain degradation is at least partly due to
the displacement of mobile ions (see Section 6.7), then, if
the abstracted charge is replaced faster after the passage
of a charge cloud, the electric forces displacing the mobile
ions would be neutralized faster.

The gain of the detector investigated in lifetest L3.2
was observed to recover when that detector was masked from
the source. In contrast, no gain recovery was observed
during lifetest L4.1 when illumination of Detector 4 ceased.
Lifetest L3.1 ended prematurely before a similar test could
be performed.

In conclusion, we have shown that the gain of a
tandem-pair MCP detector incorporating MCPs procured from
Mullard Ltd. degrades as charge is abstracted. In one of our
tests, namely L3.2, some of this degradation could be
partially reversed temporarily.

In an attempt to explain all of these results we will
now recall previous research in this area.

6.7 Causes of gain degradation

With a constant voltage applied, a reduction of the
gain of an MCP implies a reduction in the effective SEEC of
the electron emitting region. There are a number of theories
which attempt to explain this reduction. They divide between
two mechanisms, namely those that result in an actual
decrease in the SEEC of the emitting region and those that
lead to an apparent decrease in the SEEC of the active layer,
Examples of the first type of mechanism are the removal or diffusion from the emission region of an electron source population. An example of the second type is the coating of the channel walls with a layer of material that perturbs the applied electric field. Of course, a combination of mechanisms could occur together.

6.7.1 Gain degradation due to species removal

There have been several investigations into the nature of the physical processes that cause both reversible and irreversible changes in the characteristics of continuous dynode devices. Hill [46] and Authinarayanan and Dudding [47] bombarded reduced lead glass samples with electrons and observed a reduction in the SEEC of the samples. Surface analysis of the pre- and post-bombardment samples suggested that the SEEC decrease had been caused both by the desorption of hydrogen from the surface of the samples and by the migration of potassium away from the electron emitting region (and hence towards the bulk) of the samples. Both hydrogen and potassium are electropositive elements.

Hill [46] showed that increases in the surface layer concentration of potassium produced increases in the secondary electron yield. He also showed that exposure of a lead glass sample to a hydrogen atmosphere caused a yield increase.

In conclusion, we believe that, under electron bombardment, any surface layers of hydrogen, which may have been present after the glass reduction process, were desorbed. Being electropositive, hydrogen is a species that tends to enhance the probability of electron escape from the surface of the sample and, therefore, its desorption reduces the electron escape probability and, hence, the SEEC of the sample material. It can be noted that our gain degradation could have been due to the desorption of hydrogen even though our MCPs had been baked because the translational kinetic energy of a particle associated with a temperature of 300°C is only 0.04 eV compared to the average electron collisional energy of 25 eV.

The migration of potassium can be explained by the
following mechanism. As a charge cloud is propagated along a channel, the electron emission region charges positively. The abstracted charge is not replenished immediately and, therefore, any ions that are present in the surface regions experience a force. The more mobile ions, such as potassium $K^+$, might be repelled into the bulk of the material. Such a process might be aided by diffusion because of the non-homogeneity of the concentration of potassium near the surface of the channels. The migration of mobile ions would result in an actual SEEC reduction if they are a major component of the electron source population. (Potassium is probably present in the surface layers in the form of bound $K_2O$ molecules. Under electron bombardment, $K_2O$ molecules are dissociated and it is the $K^+$ ions that are mobile. Diffusion of potassium should not occur when there is no electron bombardment.)

6.7.2 Gain degradation due to contamination or poisoning

The type of gain degradation described above is an intrinsic property of MCP glass. We refer to this as "natural" gain degradation. Concurrently with any natural gain degradation, there can also be additional degradation caused by, for example, contamination of the channel surfaces or poisoning of the electron emitting region. We suspect that this occurred in lifetest L3.2 and explains the behaviour when that detector was masked from the source.

Rager and Renaud [104] attributed the 20 percent drop in the gain of one of their CEMs after 1000 hours of operation to pump oil contamination. When the device was cleaned in $CCl_3F$, the original performance was partially restored.

Similarly, the gain of CEMs operated by Gibson and Reid [117] decreased over a period of several years of operation. Some recovery occurred if the devices were rested but upon resumption of operation the gain rapidly deteriorated. This is similar to the behaviour observed in L3.2. The original shiny appearance of the CEMs had been replaced by a dull lustre. One CEM was washed in propan-2-ol (see Mullard's Technical Information [118]) in an attempt to restore its gain. No improvement was observed. The CEM was then washed
in hot NaOH. Finally, it was rinsed in distilled water. This treatment restored the original appearance of the CEM. The gain of the CEM was also partially restored although it is not reported by how much.

From the work reported above, it seems that either the NaOH reacted chemically with the CEM or that it removed a deposit that was responsible for the gain degradation. NaOH attacks both oily and carbonaceous deposits and, therefore, vacuum system pump oil may have been the source of the contamination.

A study of gain fatigue of another type of CEM, in which a thin film of MgF$_2$ acted as the high yield secondary electron emitter, was reported by Sakai and Mogami [119]. They observed that, compared to a fresh CEM, a fatigued CEM was characterized by an increased thickness of carbon on its surface and a decrease in the surface concentrations of magnesium and fluorine. By investigating a number of regions along the length of a fatigued CEM, they showed that the above-mentioned effects increased towards the output aperture of the channel. The carbon layer was twice as thick at the output end than it was at the input. The decrease in the surface concentrations of magnesium and fluorine may be correlated with the migration of potassium reported by Hill and others.

Carbon contamination of reduced lead glass samples situated in a "clean" vacuum system pumped by sorption and getter ion pumps has also been reported [120]. This carbon was either inherent in the original glass mixture and diffused to the surface or else arose from some part of the manufacturing process.

We think that all of our MCPs experienced a degree of irreversible, natural, gain degradation as charge was abstracted. That such degradation is a function of the amount of abstracted charge and, hence, is greatest at the channel outputs, is supported by the work of Frank et al [107]. They restored the gain of depleted CEMs by replacing the last section of channel with an equivalent length of an identical, but unused CEM. In the analogous case of a tandem-pair detector, it is the gain of the rear MCP that degrades the most.
The resistance decrease observed in L3.2 could have been caused either by a chemical reaction, resulting in the modification of the conductive layer, or by a physical process, such as the steady deposition of conductive material onto the channel walls, resulting in another conduction pathway in parallel with the conductive glass layer. In any case, because the illuminated region was only a small fraction of the total detection area, and because the measured resistance was the resistance of thousands of channels in parallel, any change to the total resistance was due to a proportionately larger change to the resistance of the channels in the illuminated region.

The differences between the lifetests on Detector 3 and that on Detector 4 are that Detector 3 was tested in VTF 1 with UV radiation whilst Detector 4 was tested in VTF 2 with C K radiation. The pump fluid in the diffusion pump of VTF 1 was Edwards type 704/F4 silicone fluid, a synthetic organo-silicon oxide polymer. Due to backstreaming, some of this oil invariably found its way into the test chamber and thence onto the detector MCPs. Under electron bombardment, this type of pumping fluid breaks down, giving products that tend to be insulating [121]. The decomposition of the fluids is catalysed by traces of the alkali metals [121].

If a particular channel was to be stimulated many times, while in an atmosphere consisting largely of silicone fluid, an insulating layer might be deposited onto the channel wall. This layer would be thickest at the output end of the channel. Such a mechanism is supported by a previous inspection of the surface of the anode of the VTF 1 X-ray source by means of an electron microscope. Silicon was found to be a major component of the surface constituents [98]. A compound containing silicon had not been coated onto the anode prior to this investigation. The VTF 1 X-ray source experiences the same atmosphere as any detector under test in VTF 1.

If an insulating layer was to be deposited onto the channel walls, then, under the electron and, perhaps, ion bombardment encountered during the passage of a pulse, this layer would charge up. Such a charged layer would perturb the applied electric field that is set up in the channels,
reducing the gain. As more insulating material was deposited, the applied field would be further perturbed, further reducing the gain.

If a detector was to be continuously excited, it would exhibit a degree of natural gain degradation together with some gain reduction due to a deposited layer. The two effects would be indistinguishable. If the source was then masked, the (charged) insulating layer would slowly discharge. The result would be an apparent recovery of the gain of the detector. The gain could not recover to its original level, however, because of the natural (and, we believe, irreversible) gain degradation. Upon unmasking the source, the insulating layer already present would charge up quickly, resulting in a fast reduction of gain to the previous low level.

Both lifetests L3.1 and L3.2 were carried out in VTF 1 with the proportional counter in place. At the conclusion of lifetest L3.2, the pressure in the vacuum chamber was $5 \times 10^{-5}$ torr. This high pressure was due to a leaky proportional counter window. The ambient atmosphere in the chamber, therefore, consisted primarily of P10 (which is 10 percent methane) gas. Under electron bombardment, the methane in the channels might have been polymerized, causing carbonaceous deposits to be formed on the channel walls. A suitable mechanism is given by Love et al [122]. If such deposits were conductive, and continuous (the latter being likely), the resistance of the channels would have been reduced.

It appears that the two mechanisms mentioned above are mutually exclusive, because one is required to deposit an insulating layer whereas the other is required to deposit a conductive layer.

6.8 Extending the lifetime of devices incorporating MCPs

It appears that the gain of an MCP degrades as charge is abstracted. In the next section, we will describe a treatment that has been suggested as a way of reducing the rate of gain degradation of an MCP. It is possible, however, to improve the useful lifetime of a specific device by
cleverly exploiting the natural gain degradation characteristics of an MCP. A good example of this concerns the lifetimes of military image intensifiers. The typical lifetime of such a device is 1000 to 2000 hours [123]. The factor that limits lifetime is gain degradation of the MCP. It is possible to obtain commercial, so-called "long-life" (L²) MCPs for image intensification applications [123]. Using these MCPs, the lifetime of an intensifier can be extended by a factor of five whilst still maintaining the device specifications, as indicated in Figure 6-18.

Figure 6-18  a) Relative performance data, reproduced from ref. (123), illustrating the general gain degradation characteristics, under similar desorption levels, of an L²MCP and a "standard" MCP.

b) Relative tube life performance data, also reproduced from ref. (123), illustrating the effectiveness of the L²MCP in an imaging tube.
Unfortunately, this type of lifetime extension is achieved by utilizing a MCP fabricated from a non-standard, high-gain glass and not by reducing the gain degradation rate of an MCP, which is our aim. The special type of glass gives the L^2 MCP a gain that is higher than that of an MCP fabricated from standard glass when operated at the same bias voltage. If the operating characteristics of an image intensifier device are unchanged, the L^2 MCP can maintain a device gain above the threshold gain level for a much longer time than a standard MCP, thus extending the useful lifetime of the device.

6.9. Treatment of MCP glass with CsOH

On the assumption that at least some of the natural gain degradation of MCPs is due to the migration of the highly mobile K^+ ions away from the surface layers of the channels, it might be possible to reduce the rate of gain degradation if a similarly electropositive, but less mobile, ion species, such as Cs^+, could be introduced in place of the K^+ ions. This was the idea behind a patent application on behalf of Tektronix Inc. [116].

The method given in the patent for the substitution of potassium by caesium is as follows. A standard MCP is dipped in a solution of CsOH/propan-2-ol/water. The MCP is allowed to dry, leaving a layer of CsOH on the channel walls. It is then baked in order to convert the surface film to a stable form, caesium oxide.

If this treatment does result in a greater degree of gain stability, the patent does not indicate if it produces any unwanted "side effects" in the MCPs, such as a variation in gain as a function of detection event position. Also, the patent refers to the current gain, measured in a sealed CRT enclosure, rather than the pulse gain, of the test MCPs. There is no mention of changes, if any, to MCP noise, quantum detection efficiency, or resistance as a result of the treatment.

It is also uncertain as to whether the patent description gives a correct account of the glass chemistry involved. The patent says that if the caesium compound
(CsOH) deposited onto the wall surfaces is one that is not stable under operating conditions, it can be converted to a stable form (caesium oxide, probably Cs₂O) by, for example, subjecting the MCP to a high temperature vacuum bake. All caesium oxides (Cs₂O, CsO, and CsO₂), however, are highly reactive. Cs₂O, for example, reacts with H₂O, CO, CO₂ and the halogens amongst other chemicals [124]. If Cs₂O was indeed the form of the deposited film after the bake, it would be expected that storage and handling of a CsOH treated MCP would pose problems of a much greater magnitude than those encountered with the storage and handling of CsI photocathodes. Nevertheless, we decided to treat a single MCP with a CsOH solution as described in the patent and then to incorporate this MCP into a tandem-pair detector so that the effects of the treatment could be ascertained. If we found that the treatment had not adversely affected the detector characteristics, a lifetest was to be performed on the detector.

Detector 2 was chosen to be the test detector; the front MCP was treated. The exact history of MCP F2 prior to these tests was unknown, but it had not been extensively used. The rear MCP had been used as the rear MCP of Detector 1. It had, therefore, been vacuum baked.

6.9.1. Detector characteristics prior to treatment

The detector was tested in VTF 1 prior to the treatment of MCP F2. Measurements with both C K and Al K X-rays were made as a function of the front MCP bias voltage. With 1400 volts across it, the front MCP had a resistance of approximately 360 MΩ. At all times, the voltage across the rear MCP was 1400 volts and the interplate gap voltage was 50 volts. The detector noise count rate was investigated as Vₚ was varied. Detector efficiency measurements were also carried out.

6.9.2. Treatment of the front MCP

The Tektronix patent specifies a 0.01 to 0.05 M solution of CsOH in an 80:20 mixture of propan-2-ol and water. We
dipped MCP F2 in a 0.033 M solution of CsOH in an 80:20 mixture. CsOH is very hygroscopic in its solid phase and turns from a powder to a paste in a matter of minutes.

MCP F2 was mounted on a stainless steel holder which allowed the CsOH solution access to both of its faces. Initially, bubbles were evolved from the channels. After the bubbling had stopped, which, we assumed, indicated that all of the channels were full of liquid, the MCP was left in the solution for a further 10-15 minutes. The submersion time was arbitrary; there is no mention in the patent of the immersion time needed for the "caesiation" process to proceed to completion. The length of this period could be crucial. As CsOH is the strongest known base [124], we decided to leave our MCP in the solution for only a quite short time in case the solution started to attack or react with the channel wall surfaces in a disadvantageous manner.

Recently, it has been shown at Leicester [125] that an MCP does not need to be submerged in a liquid in order to produce a film of that liquid over the walls of the channels. If an MCP is positioned such that it just touches the liquid surface, capillary action will draw the solution up into the channels. This method probably produces a more uniform wall coating than our method of totally submerging the MCP.

After submersion, we allowed MCP F2 to dry overnight in a dust-free laminar flow cabinet. In the morning, the MCP had a fairly uniform appearance, marked only by faint lines caused by the uneven evaporation of the propan-2-ol solution.

The MCP was baked for 48 hours at 275°C, a temperature and time compatible with our previous bakes, rather than the 8 hour, 320-350°C "tube-processing" bakeout implied in the patent. After the bakeout, the MCP was always manipulated and assembled in a dry N2 environment.

6.9.3. Results from Detector 2 with the treated front MCP

In order to be able to attribute any changes in the characteristics of the detector to the treatment alone, the effects of a 48 hour vacuum bake have to be recalled. A
vacuum bake tends to increase the resistance of an MCP by 10-30 percent but does not affect its gain or efficiency (see Chapter 4).

Detector 2 was retested in VTF 1. Again, the rear MCP voltage was set at 1400 volts, with the interplate gap voltage at 50 volts. With 1200, 1300 and 1400 volts applied across the treated front MCP, its resistance was 632 MΩ. Thus, the CsOH treatment and subsequent bake resulted in a 70 percent increase in the resistance of the MCP. This is a larger increase than we would have anticipated due to the bakeout alone and, therefore, it appears that the treatment itself brought about a 20 percent increase in the MCP resistance. The CsOH may have reacted with the metallic lead in the conduction layer of the channel walls. It is also possible, though, that the CsOH removed some deposit from the walls of the channels, in the same way as the NaOH is suspected of having done in the research of Gibson and Reid [117]. If this was the case, the deposit would have had to have been conductive with a resistance equal to approximately four times that of the conductive (lead) layer (in order to produce the 20 percent increase in resistance when removed from the MCP) which suggests that the deposited layer was carbonaceous.

Figure 6-19 compares the peak gain data obtained before and after the treatment. The measurements were all made at "large" angles of X-ray incidence. The C K gains obtained prior to caesiumation are very similar to those values obtained from the uncoated half of Detector 1. Detector 1 had an identical configuration to Detector 2 (see Table 3-1).

It can be seen that the treatment led to an increase in the detector peak gains at all voltages, but especially at front MCP voltages in excess of 1400 volts, the voltage at which the front MCP was entering fully saturated operation. The gain-voltage curve for the caesiated MCP is similar for both Al K and C K illumination.

A comparison of the gain with C K X-rays at two positions on Detector 2 is shown in Figure 6-20. The gains at position 2 are lower than those measured at position 1. All relevant parameters remained constant between the two
Figure 6-19 Variation of the peak gain, $G_C$, of Detector 2, both before and after the treatment, as a function of the front MCP potential difference, $V_F$.

$V_G = 50$ volts; $V_R = 1400$ volts.

Data obtained from Detector 1 is also presented.
sets of measurements. Unfortunately, we made no measurements at position 2 prior to the treatment and, therefore, this non-uniformity of gain cannot be attributed to the CsOH treatment alone. (See, however, the noise measurements presented below).

The gain measurements indicate a real increase in the gain of the front MCP, manifest as an increase of the detector gain. The peak gain, $G_C$, and the single electron peak gains, $G_F$ and $G_R$, which are attributed to each of the constituent MCPs of the detector, are related by

$$G_C = G_F (1-\beta) G_R \nu_C$$

as defined in Section 2.4.1.4. For MCPs with channels of 12.5 μm diameter, $\beta$ is equal to 0.6. The actual enhancement of the front MCP gain, $E_F$, can be calculated from

$$E_F = \left( \frac{\text{Gain of tandem-pair after caesion}}{\text{Gain of tandem-pair before caesion}} \right)^{2.5}$$

The computed value of $E_F$ for C K X-rays incident at

![Figure 6-20](image)

**Figure 6-20** Variation of the peak gain, $G_C$, of Detector 2, both before (filled circles) and after (open circles and squares) the treatment and at two positions (circles - position 1, squares - position 2), as a function of $V_F$. $V_G = 50$ volts; $V_R = 1400$ volts.
position 1, averaged over all values of $V_p$, is 1.78. This compares reasonably well with the gain increases of 50-60 percent after caesiation reported in the patent [116], albeit in a different mode of operation.

Figure 6-21 compares the FWHM values, measured at position 1, before and after the treatment. There was no significant change in the FWHM values. It can also be noted that, even after treatment, the limiting value of the FWHM was approximately 30 percent. This seems to imply that it is the magnitude of the channel diameter rather than the nature of the secondary electron emission surfaces, that, due to the electrostatics of pulse saturation, alone determines the limiting FWHM [54]. The asymptotic FWHM value was reached at a front MCP voltage in the region of the transitional voltage, $(V_0)_s$, which is calculated to be 1522 volts for a 120:1 L/D MCP (shown as the dashed vertical line in Figure 6-21). This indicates that there had been no really dramatic change in the secondary electron yield and electron emission energies of the channel surfaces.

The quantum detection efficiencies of the detector before and after treatment are shown in Figures 6-22(a) (C K) and 6-22(b) (Al K). At large angles of X-ray incidence (greater than approximately $7^\circ$), the efficiencies are unchanged. The differences at small angles of incidence are thought to be due to the incorrect orientation of the $4^\circ$ bias front MCP during the pre-treatment tests.

Figure 6-23 shows the variation of detector background noise rate, $N_n$, as a function of the front MCP voltage. With a lower level discriminator setting of 0.3 pC, we found that the caesiation treatment had increased the noise count considerably at the higher bias voltages. The adoption of a typical "flight configuration" lower level discriminator setting of 3 pC (a value chosen so that, with a front MCP bias voltage of 1500 volts, almost all the X-ray events are detected whilst most of the noise counts are rejected) reduced these high levels by a factor of approximately three. At the higher voltage settings, the noise was non-uniform as shown in Figure 6-24. Small, central hotspots had appeared. When the front MCP voltage was reduced from 1650 volts, a period of 3-4 minutes was required for the
Figure 6-21 Variation of the FWHM, $\Delta G_C / G_C$, as a function of $V_F$ at position 1 of Detector 2 both before and after the treatment of MCP F2. $V_G = 50$ volts; $V_R = 1400$ volts.

Filled circles - untreated front MCP, C K X-rays, $\theta_X = 17^\circ$.
Filled squares - treated front MCP, C K X-rays, $\theta_X = 17^\circ$.
Open squares - treated front MCP, Al K X-rays, $\theta_X = 11^\circ$. 
Figure 6-22  Variation of the quantum detection efficiency, $Q(\theta_x, \lambda)$, as a function of the X-ray incidence angle at position 1 of Detector 2 both before and after the treatment of MCP F2.

$V_F = 1400$ volts; $V_G = 50$ volts; $V_R = 1400$ volts.

Open circles - untreated front MCP.
Filled circles - treated front MCP.
(a) C K X-rays.
(b) Al K X-rays.
Figure 6-23  Variation of the dark noise count rate, N_n, as a function of V_F for Detector 2 both before and after the treatment of MCP F2.

V_G = 50 volts; V_R = 1400 volts.

Filled circles - untreated front MCP, LLD = 0.5 pC.
Open circles - treated front MCP, LLD = 0.5 pC.
Open squares - treated front MCP, LLD = 3 pC.
noise level to decay from its initial value of approximately 30 counts sec$^{-1}$. On one occasion, when the detector was operated with the following voltages

\[ V_F = 1600 \text{ volts}; \quad V_G = 50 \text{ volts}; \quad V_R = 1400 \text{ volts}. \]

noise levels of the order of 30 counts sec$^{-1}$ were recorded, localised in the same way as those associated with higher values of $V_F$. These levels decayed over a period of minutes. Initially, the pulse height distribution of the noise events was peaked but this transformed into an exponential distribution as $N_n$ decreased. The apparent change of the form of the distribution may have been illusionary; it could have been due to the gradual shift of the (peaked) noise distribution below the discriminator level.

These phenomena suggest that small areas of the front surface of the treated MCP were acting as noise sources, possibly through some "charge and discharge" mechanism.

In conclusion, it appears that the caesiation of an MCP by means of our submersion and baking method could be accompanied by increased gain, increased noise and possibly non-uniformity of gain.

Figure 6-24 Noise image obtained from Detector 2 after the treatment of MCP F2. The integrated noise count, $N_n$, was 14 counts sec$^{-1}$. $V_F = 1600 \text{ volts}; \quad V_G = 50 \text{ volts}; \quad V_R = 1400 \text{ volts.}$
6.10 Life test of Detector 2

Before the life test on the treated MCP commenced, the detector was disassembled and the front and rear MCPs were interchanged. Thus, the treated MCP was positioned at the rear of the detector; thus, it would be the MCP from which the largest amount of charge was abstracted. It was difficult to correctly orientate the (new) front MCP, which had a 13° channel bias angle, because this had to be done in a dry \( \text{N}_2 \) tent.

The detector was re-characterized with \( \text{C K} \) X-rays. We decided to life test the detector with the following bias voltages:

\[
V_F = 1300 \text{ volts}; \quad V_G = 50 \text{ volts}; \quad V_R = 1400 \text{ volts}.
\]

Initially, the detector was very noisy, a typical count rate being hundreds of counts per second. The noise appeared to be concentrated in a region that was near to the edge of the active area of the detector. We replaced the rear electrode with another electrode that had a smaller inside diameter (28 mm instead of 30 mm). This reduced the noise rate to approximately four counts sec\(^{-1}\).

The variation of detector peak gain and FWHM with operating voltages is shown in Figure 6-25.

The X-ray source and collimator were removed from the vacuum chamber and replaced with the mirror and collimator that were required for the UV source. The proportional counter was blocked off in an effort to reduce the amount of hydrocarbons present in the test chamber. The carbon-coated polypropylene window of the test detector was removed and replaced with the Cu-Be mask that had been used for the life tests on Detector 3.

6.10.1 The variation of detector gain with output count rate

The effect of the output count rate on the peak gain of Detector 2 is shown in Figure 6-26. The gain started to decrease at a count rate of approximately 600 counts sec\(^{-1}\). When un-illuminated, the strip current through the rear MCP was 2.30 ± 0.01 \( \mu \text{A} \) \( (V_R = 1400 \text{ volts}) \). When the output count rate was increased to 6000 counts sec\(^{-1}\), the rear MCP
Figure 6-25 a) Variation of the peak gain, $G_C$, of Detector 2 as a function of $V_R$ after the treatment of MCP F2.

b) Variation of the FWHM, $\Delta G_C / G_C$, of Detector 2 as a function of $V_R$ after the treatment of MCP F2.

C K X-rays; $\theta_X = 17.5^\circ$; $V_G = 50$ volts.
strip current increased to $2.34 \pm 0.01 \mu A$. At an average charge level of 4.5 pC (a value chosen from inspection of Figure 6-26), an output count rate of 6000 counts sec$^{-1}$ is equivalent to an output current of approximately 0.03 pA. This is equal, within error, to the increase in the rear MCP strip current.

While making these measurements, an interesting observation was made. After exposure to an input flux that produced 25000 output counts sec$^{-1}$, an after-image of the illuminated area was observed. Figure 6-27(a) shows the position of the UV spot as seen on the storage 'scope. This photograph was taken when the output count rate was 6000 counts sec$^{-1}$. A typical noise image from the detector is shown in Figure 6-27(b), a typical noise count rate being

![Graph](image)

**Figure 6-26** The variation of the peak gain, $G_C$, as a function of the output count rate from Detector 2.

$\theta_x = 30^\circ$.

$V_F = 1300$ volts; $V_G = 50$ volts; $V_R = 1400$ volts.
Figure 6-27  a) The image obtained from Detector 2 when illuminated by the UV source at an output count rate of 6000 counts sec$^{-1}$. The position of the beam is clearly seen.
b) A typical noise image obtained from Detector 2. The noise rate was typically $3-4$ counts sec$^{-1}$.
c) The noise image obtained from Detector 2 immediately after illumination by the UV source at an output count rate of 25000 counts sec$^{-1}$. 
3-4 counts sec$^{-1}$. Immediately after an output count rate of 25000 counts sec$^{-1}$, however, the noise image was as shown in Figure 6-27(c). This photograph clearly shows a hotspot coincident with the previously illuminated zone. The noise count rate was variable from a few to several tens of counts sec$^{-1}$. Similar behaviour was observed later (see Section 6.10.4).

This after-imaging behaviour may have been caused by the phenomenon of exo-electron emission [126-128]. As we have stated previously, the surfaces of the channels charge positively when an electron cloud is propagated. Those bombarding electrons that penetrate to the greatest depth then have so little kinetic energy that they can be captured by electron traps. A negative space-charge region can be built up. The (internal) electric field that is set up between the negative space charge region and the positive surface layer causes a dynamic equilibrium to be established such that the rate of electron capture by the traps and the rate of electron release from the traps are equal. Once the electron cloud has passed, any electrons held in traps can be thermally released into the conduction band. This can happen for several minutes after the passage of the cloud [128]. They are accelerated towards the channel surface by the internal field, gaining energy as they go. With this energy, the electrons can overcome the electron affinity of the surface, escape from the surface, and initiate further electron avalanches.

The greatest number of trapped electrons occurs where the bombarding electron flux is the greatest, namely at the output end of the channels. It is at the output, however, where an avalanche initiator (an exo-electron for example) has the least effect because the resultant charge cloud is of minimal size. It is those trapped electrons that escape nearer to the channel input that can produce the largest charge clouds. The density of trapped electrons there, though, is much lower than the density further down the channels. We propose, therefore, that after-images will only be observed when the input flux is so great that current saturation of the MCPs takes place. In this situation, there may be a significantly large number of trapped electrons.
well away from the channel output. Upon removal of the source of excitation, some of these electrons might trigger avalanches with sufficient gain to be detected.

6.10.2 Lifetest L2.1

The detector was lifetested with UV radiation at an output count rate of \(5400 \pm 400\) counts sec\(^{-1}\). The radiation was incident at \(30^\circ\). At this output count rate, some gain reduction occurred as would be expected from Figure 6-26. The peak gain was reduced from 5.8 pC (at almost zero output count rate) to approximately 4.5 pC at the count rate quoted above. Throughout the lifetest, this count rate varied little and, therefore, any gain reduction observed throughout the test was attributed to gain degradation. Such a low count rate was chosen for this lifetest to be comparable with the previous ones.

The variation of detector gain as a function of the total abstracted charge is shown in Figure 6-28. The gain initially decreased exponentially, the value of \(k\) being \(-1.04 \times 10^{-9}\). During a gap in the measurement sequence, however, the detector gain fell from 2.32 pC, after \(2 \times 10^8\) accumulated counts, to 0.44 pC after \(3.7 \times 10^8\) counts when the output PHD appeared to have a negative exponential form. The source was shuttered off to see if the form of the PHD changed. Four hours later, after no apparent change, we reduced the lower level discriminator of the processing electronics from 0.54 pC to 0.13 pC. It was then apparent that the output PHD really had a quasi-Gaussian form but had appeared to be a negative exponential because the peak gain had (unexpectedly) fallen below the lower level discriminator.

When the UV source was initially shuttered, the peak gain was unknown (but it was less than 0.54 pC). When the discriminator level was lowered, which was nearly four hours after the source was shuttered off, the peak gain was \(0.41 \pm 0.01\) pC (the error on all of the following gain values is 0.01 pC). Twelve hours later, the gain had recovered to 0.46 pC. After a further 36 hours, the detector was re-illuminated. The gain decayed slowly from 0.46 pC to
Figure 6-28  The variation of the peak gain, $d_C$, as a function of the charge abstracted from area L2.1 of Detector 2. The gradient of the initial data is $-1.04 \times 10^{-9}$ pC$^{-1}$.

$V_F = 1300$ volts; $V_G = 50$ volts; $V_R = 1400$ volts.
0.32 pC after a total of $1.99 \times 10^9$ counts had been recorded. The source was once again shuttered.

The variation of the peak gain of the detector when the source was switched off for the second time is shown in Figure 6-29 (open circles). After being un-illuminated for a period of 5.5 hours, the gain of the detector had increased from 0.32 pC to 0.39 pC, an increase of 22 percent.

At the end of this series of measurements, the pressure in the vacuum chamber of VTF 1 was $3 \times 10^5$ torr. This low pressure was achievable in the chamber of VTF 1 because the proportional counter was blocked off.

6.10.3 Lifetest L2.2

We decided to lifetest another area of Detector 2, with the same detector voltages, in order to see if the gain degradation behaviour observed in lifetest L2.1 was representative of the behaviour of the whole active detection area. The Cu-Be mask was repositioned so as to define a new region to be tested. The proportional counter was not blocked off for this test. Initially, the variation of gain with output count rate was investigated. Once again, the detector gain was reduced at modest (less than 1000 counts sec$^{-1}$) output count rates. It appears that the treatment of the rear MCP (MCP F2) may have affected the gain capabilities at low count rates although this is by no means certain because we did not investigate the variation of detector gain as a function of output count rate prior to the treatment. The photon incidence angle had to be reduced to 20° in order to illuminate the whole of the aperture because the detector body obscured part of the aperture from the source with the incidence angle set at 30°. Another "after-image" was observed after an output count rate of 36000 counts sec$^{-1}$ had been recorded by the detector (see Section 6.10.1).

The second lifetest was conducted with an output count rate of $6000 \pm 400$ counts sec$^{-1}$. The lifetest was terminated after $3.98 \times 10^9$ events had been detected. The source was switched off for a period after which the detector voltages were increased. The lifetest was restarted and was finally
Figure 6-29  The variation of the peak gain, $G_C$, of Detector 2 as a function of the time elapsed after the UV source was masked from the detector for lifetests L2.1 (open circles) and L2.2 (filled circles). $V_P = 1300$ volts; $V_G = 50$ volts; $V_R = 1400$ volts.
terminated when a total of $6.52 \times 10^9$ events had been accumulated.

6.10.4 The results from lifetest L2.2

The variation of peak gain with abstracted charge is plotted in Figure 6-30. The form of this plot is similar to that obtained from lifetest L4.1. Initially, the gain decreased exponentially, $k$ being $-1.46 \times 10^{-9}$. This was followed by a period of varying gain degradation rate which itself was followed by another period of exponential gain decrease. The final gain was $0.24 \mu C$. There was no sign of any sudden gain degradation as had been seen in lifetest L2.1. When the source was shuttered off, the gain recovered.

![Figure 6-30](image)

Figure 6-30 The variation of the peak gain, $G_C$, as a function of the charge abstracted from area L2.2 of Detector 2. The gradient of the initial data is $-1.46 \times 10^{-9} \mu C^{-1}$ and that of the latter data is $-6.93 \times 10^{-10} \mu C^{-1}$. $V_F = 1300$ volts; $V_G = 50$ volts; $V_R = 1400$ volts.
to about \(0.27 \pm 0.01\) pC after 28 hours, as shown in Figure 6-29 (filled circles).

The variations of peak gain as a function of abstracted charge for lifetests L2.1 and L2.2 are compared in Figure 6-31. It is interesting to note that after the discontinuity, the data of L2.1 closely followed the data of L2.2. This may be indicative that the data of L2.2 and the data from the latter part of L2.1 were representative of the real behaviour of Detector 2, with the gain data of the early part of L2.1 being anomalous.

We have already shown that the caesium treatment had some effect on the characteristics of MCP F2, increasing its gain, resistance and noise count rate. We have also shown that the gain and noise characteristics were non-uniform. It is possible that the gain increase was primarily due to the coating of the channel walls with a "cocktail" of caesium compounds, rather than to a chemical reaction. Such a coating would almost certainly be non-uniform. Hence, any gain enhancement correlated with such a coating would also tend to be non-uniform. If a cocktail had been deposited, particles containing caesium compounds might also have been deposited onto the channel walls. This could explain our erratic noise count rates.

If Lifetest L2.1 had been performed on a region of the detector having a higher than usual gain because of the deposition of compounds containing caesium, the bombardment of that region may have led to the desorption of the deposit. Eventually, when the majority of the deposit had been desorped, the real behaviour of the detector would have become apparent.

6.10.5 Conclusions arising from the CsOH treatment of an MCP

The reason for treating an MCP with a CsOH solution was to reduce the rate of gain degradation as a function of the abstraction of charge. This aim was not achieved as is apparent from inspection of Table 6-2. The treatment did, however, affect the characteristics of the plate. Its gain was increased by a factor of approximately 1.7 on average. Unfortunately, the dark noise count rate also increased,
Figure 6-31 Superimposition of the variation of the peak gain, $G_C$, as a function of abstracted charge for both Lifetest L2.1 (filled circles) and L2.2 (open circles).

$V_F = 1300$ volts, $V_G = 50$ volts, $V_R = 1400$ volts.
together with the MCP resistance.

The gain of the MCP varied with position; this suggests that the treatment was non-uniform. We propose that the treatment resulted in both the coating of the channel walls with a layer of caesium compounds and the removal of an existing deposit, which was possibly carbonaceous in nature. We also propose that the layer of caesium compounds caused an initial gain enhancement but was easily desorbed. Thus, as a lifetest was performed, the detector gain decreased rapidly until the deposited layer was removed, at which point the rate of gain degradation followed the standard curve.

6.11 Conclusions

We have shown that the gain of our tandem-pair MCP detectors degraded as a function of the accumulated charge abstracted per unit detection area. Some of this gain degradation is attributed to a "natural" degradation of the channel plate material. Such degradation would always occur regardless of any other mechanism inducing detector gain reduction. The remaining degradation is thought to have been caused by contamination.

We propose that natural gain degradation is caused by the removal of an electron source population. According to some authors [46, 47], this population consists of K⁺ ions. Gain degradation can be explained by assuming that these ions are displaced from the electron emitting region under the effect of the electric field set up when an electron cloud passes. The decreased gain degradation rate that we recorded with Detector 3 at the increased detector voltages also supports this gain degradation mechanism because, at a constant gain, the faster that abstracted charge is replenished the less that the K⁺ ions would be displaced.

We also propose that if a MCP detector is operated in a "dirty" vacuum system, i.e. in a vacuum system contaminated by either hydrocarbons or certain diffusion pump fluids, various changes can occur to the MCPs. First, if a detector is operated in a relatively high pressure, hydrocarbon-dominated atmosphere, (a pressure in excess of approximately
5 \times 10^{-5} \text{ torr}), layers of carbonaceous material are deposited onto the channels. The channels are made more conductive and, hence, the MCP resistance decreases. It is unknown if these layers would greatly affect the gain capabilities of the MCP.

Secondly, if a detector is operated in a vacuum chamber that is pumped by a diffusion pump that utilizes a pump fluid that breaks down under electron bombardment to produce an insulating product, insulating layers are laid down on the channel walls. Under electron bombardment, these layers charge up, disturbing the applied electric field and reducing the gain of the channels. When excitation of the channels ceases, these layers discharge and the detector gain recovers, but only partially because there is inevitably some natural gain degradation.

An MCP was treated in an attempt to reduce the rate of gain degradation of the detector containing it. This method relied on the assumption that at least some of the natural gain degradation was due to the movement of mobile K^+ ions. The treatment was supposed to replace the potassium ions with similarly electro-positive, but less mobile, caesium ions. When the detector with the treated MCP underwent lifetesting, its gain degraded in much the same way as the gain of detectors incorporating untreated MCPs as is indicated in Table 6-2.

In Figure 6-32, the gain recovery curves of the various detectors are plotted with the initial gains after switch off, \( G_{0} \), being normalized. The data from L2.2 appears to show a flattening off of the recovery curve; we attribute this to the fact that the gain had recovered to the level determined by the natural gain degradation.

Because the gain of the plateau was only 1.2 times greater than the initial gain after the source was shuttered off but was much lower than the original gain, it appears that almost all of the gain degradation was due to natural degradation. Indeed, the CsOH treatment process may have "cleaned up" the channels of any decomposed vacuum fluid, resulting in a rear MCP that was less prone to charging up under the influence of electron bombardment.

This idea is supported by the gain recovery data of
Figure 6-32 The variation of the normalized peak gain of Detector 2 and Detector 3 as a function of the elapsed time since illumination, $t_{off}$, for Life-tests L2.1 (filled circles), L2.2 (crosses) and L3.2 (open squares and open circles).
L3.2. First, the two sets of data from L3.2 fall on the same gain recovery curve. This implies that the form of the recovery does not depend too strongly on the magnitude of $G_{C0}$ (the two values being 0.89 and 0.79 pC). Secondly, there is no obvious plateau. As the gain had increased by a factor of at least 1.6, we believe that a large proportion of the gain degradation observed throughout Lifetest L3.2 must have been due to reversible gain degradation.

Overall, it appears as if the caesiation treatment process had no substantial effect on the rate of gain degradation of Detector 2. This lack of any effect might have been due to our treatment method. It is also possible that the reason why our method failed was that the original premise, namely that gain reduction is primarily due to the displacement of the $K^+$ ions, was incorrect. A further possibility is that the MCP treated in the patent behaved differently from our MCP.

Figure 6-33 is a composite plot of all of the lifetest results. All of the detectors exhibited a fairly continuous decrease of gain. Plateaus of stable gain, if they were observed at all, were not long lived. Our data is thus in qualitative agreement with the data of Sandel et al [115], Henry et al [35] and Malina and Coburn [64].

The noise count rate tended to decrease throughout the duration of the various lifetests. As these tests were performed on small areas of detector, this decrease cannot be attributed to any "burning in" of the test zone. It has to be due to the length of time spent by the detector under vacuum and is probably due to outgassing of the MCP channels. This is indicated by the work of Fraser et al [58].
Figure 6-33 Composite diagram showing the variation of the peak gain, $G_C$, as a function of the charge abstracted for all of the lifetests reported in this thesis.
7.1 Introduction

In previous chapters, we have shown how the soft X-ray quantum detection efficiency of an MCP detector can be enhanced by the use of one or more CsI deposition photocathodes. In this chapter, we investigate the one property that MCP detectors have lacked until recently, namely the capability of X-ray energy resolution.

In order for the output pulse height distribution of a tandem-pair MCP detector to be dependent on the energy of the incident photons, it is required that

1) the initial photon-to-photoelectron conversion process is proportional; i.e. \( N_p \), the most probable number of photoelectrons released into a channel, has to vary with the energy of the incident photon

and

2) the initial electron batch has to be proportionally propagated, leading to an energy dependent detector gain, \( G_e \) electrons photon\(^{-1}\).

The low QDEs that had been measured with both bare MCPs and MgF\(_2\)-coated ones suggested that \( N_p \) was equal to unity, and this discouraged any further speculation about condition (1). Condition (2) had always appeared to be impossible to satisfy for a tandem-pair detector. A narrow peaked output distribution, which is ideal for photon counting, is only achieved when a detector is operated in the high gain régime. Under such conditions, output pulse saturation occurs, and this tends to annul any dependence of event gain on \( E_X \). Alternatively, the output distribution obtained from an MCP detector operated in the low gain, or linear, régime is exponential, and any energy information is difficult to extract from the output PHDs.
With the use of CsI photocathodes, and the resulting increases in efficiency, it became apparent that condition (1) might be achievable. It was demonstrated in ref. (105) that, as long as the detector bias voltages are carefully chosen, some soft X-ray energy discrimination could be obtained from an MCP detector that had the input face of its front MCP coated with CsI. In this chapter, we present further work that was carried out to examine the soft X-ray energy discrimination capabilities of MCP detectors. This work included some measurements that were made on a number of "non-standard" detector configurations. For example, we report the first operation in the photon counting mode of MCPs that have 8 micron diameter channels. We also describe the operation of a detector with a "thin" front MCP (namely one that had a 40:1 L/D ratio).

Models of MCP pulse gain [54, 105] indicate that, in the limit of hard gain saturation, the FWHM of an output distribution should decrease if the channel diameter is reduced. Smaller diameter channels would also give improved position resolution, which is relevant for the AXAF mission, but this feature was not investigated in the present work. Also, as we will show later (see Section 7.7), the QDE at photon energies of several keV is enhanced by the use of MCPs that have a smaller inter-channel septal thickness (which implies a smaller channel diameter assuming a constant open-area fraction). First, however, a model of MCP detector energy resolution is presented [105].

7.2 A model of MCP tandem-pair detector energy resolution

7.2.1 The statistics of secondary electron photoemission

The model outlined in this section, which is based on the account to be found in ref. (105), deals with the initiation of the electron avalanche from both MCP lead glass and CsI. Only the dominant secondary electron yield [80, 83] is considered.

Consider a planar photocathode, such as lead glass or CsI, of thickness T. If P(n) is the probability that n secondary electrons are released from the photocathode by an
X-ray of energy $E_X$ incident at a grazing angle $\alpha$, then

$$P(0) = R(\alpha) + (1 - R(\alpha)).p(0)$$
$$P(n; n \geq 1) = (1 - R(\alpha)).p(n)$$

where $p(n)$, the probability per absorbed photon that $n$ electrons will be emitted into the channel, is given by

$$p(n) = \mu \cdot \csc^2 \int_0^L \left[ \frac{p_g(0) \exp(-x/L_g)}{[1-p_g(0) \exp(-x/L_g)]^{n+1}} \right] dx$$

**EQN 7-1**

where $N$, the total number of internal secondaries excited by the energy loss of the primary electron(s) in the photocathode, is given by [80]

$$N = \frac{E_X}{\varepsilon}$$

and $C_N^n$ is the binomial coefficient. $P'(n)$, the relative probability of $n$ electrons being emitted, is defined by

$$P'(n) = \frac{P(n)}{\sum_{n=1}^{\infty} P(n)} = \frac{p(n)}{[1-p(0)]^{-1}}$$

As shown in ref. (105), Equation 7-1 allows the electron number distributions for X-ray interaction geometries that are appropriate for both bare and coated MCPs to be calculated with some certainty. Such calculations allow the investigation of the possibility of meeting the requirements of condition (1) above, namely that the electron avalanche be initiated proportionally.

The calculated relative probabilities of $n$-electron emission for both C K and Si K X-rays incident on a plane sample of MCP glass are shown in Figures 7-1(a,b) [105]. It can be seen that the most probable number of emitted electrons is 1 for both energies. This is likely to be the case even if the primary yield of the glass was also taken into account [28]. The mean number of emitted electrons is, however, greater for Si K X-rays than for C K X-rays.

Figures 7-2(a,b,c,d) show the variation of the calculated probability distribution $p(n)$ as a function of both the X-ray grazing incidence angle and the thickness of
Figure 7-1 (a) Calculated relative probability distribution $P'(n)$. C K X-rays (0.28 keV) incident at grazing angle $\alpha = 5^\circ$ onto a silica-like surface layer of MCP lead glass, Phillips Type 3502 [28]. $p(0) = 0.394$.

(b) As Figure 7-1 (a), for Si K X-rays (1.74 keV). $p(0) = 0.965$. 
Figure 7-2 (a) Calculated probability distribution \( p(n) \). C K X-rays (0.28 keV) incident at grazing angle \( \alpha = 5^\circ \) to a 300 \( \text{Å} \) thick CsI layer.

\( p(0) = 0.026 \).

(b) As Figure 7-2(a) except that \( \alpha = 15^\circ \).

\( p(0) = 0.684 \).

(c) As Figure 7-2(a) except that \( \alpha = 45^\circ \).

\( p(0) = 0.877 \).

(d) Calculated probability distribution \( p(n) \). Si K X-rays (1.74 keV) incident at grazing angle \( \alpha = 5^\circ \) to a plane CsI photocathode of thickness

(i) \( T = 300 \text{ Å} \)

(ii) \( T = 450 \text{ Å} \).

Probabilities, per absorbed photon, that no secondary emission occurs are

(1) \( p(0) = 0.63 \) (\( T = 300 \text{ Å} \))

and

(11) \( p(0) = 0.50 \) (\( T = 450 \text{ Å} \)).
the CsI photocathode. Figures 7-2(a,d) are the counterparts of Figures 7-1(a,b) for a 300 Å thick layer of CsI. As we reported in Chapter 4, 300 Å is a typical value for the thickness of a coating deposited onto the wall of a channel.

It is seen that, unlike those for bare MCP glass, the CsI number distributions are peaked. Also, the most probable number of emitted secondary electrons increases with an increase in the magnitude of $E_x$. Figure 7-3 shows the calculated relation between $n_p$ and $E_x$ for photon energies in the range 0.1 to 3 keV. These electron number distributions have a similar form to those reported by Bardas et al [7] for negative electron affinity GaAsP photocathodes. The values of $n_p$ for CsI, however, are calculated to be some three to five times lower because of the shorter secondary electron escape length of CsI.

![Figure 7-3](image)

**Figure 7-3** Calculated variation of $n_p$, the most probable number of photoemitted secondary electrons, with X-ray energy $E_x$. $n_p$ values evaluated for a series of named characteristic X-ray energies. Plane CsI photocathode. $T = 300$ Å; $\alpha = 50^\circ$. The M edges of Cs and I lie between the vertical lines shown.
Figures 7-2(a,b,c) also highlight the fact that the peaked nature of the distribution becomes less marked as the X-ray grazing incidence angle, \( \alpha \), is increased.

Finally, as the photocathode thickness \( T \) is increased, with \( \alpha \) held constant, the distribution \( p(n) \) broadens towards low values of \( n \), as indicated in Figure 7-2(d).

These calculations predict that the electron avalanches that are output by an MCP detector whose input MCP has a CsI-coated front face should be initiated proportionally.

The calculated number distributions that have the lowest FWHMs are those for which the X-rays are incident at small angles onto a relatively thin photocathode. As we reported in Chapter 4, however, a thin photocathode results in reduced QDE enhancement. Thus, it appears that there is a balance to be found between detector efficiency and any energy resolution.

### 7.2.2 The peak gain of a tandem-pair MCP detector

If the front MCP of a tandem-pair detector is operated with a sufficiently low bias voltage so that any initial photoelectron distribution is multiplied linearly, then \( G_F \), the peak gain of its output charge distribution, is given by

\[
G_F = k n_p(E_X)
\]

where \( k \) is a constant. From Equation 2-1, this leads to the following X-ray energy dependent peak tandem-pair gain

\[
G_C = k (1 - \beta) \cdot G_F^\beta \cdot n_p(E_X)^{(1 - \beta)}
\]

The parameter \( \beta \) appears to depend on the channel diameter, \( D \), as follows \([54]\):

\[
\beta = 0.6 : D = 12.5 \mu m \\
\beta = 0.8 : D = 25 \mu m
\]

Using values of \( n_p \) plotted in Figure 7-3, and assuming a microchannel diameter of 12.5 microns (and, therefore, that \( \beta = 0.6 \)), the ratio of the gain at 2.7 keV to that at
0.18 keV is given by [105]

\[
\frac{G_c(0.18 \text{ keV})}{G_c(2.7 \text{ keV})} = \left[ \frac{22}{3} \right]^{0.4} = 22
\]

7.3 The initial work of Fraser and Pearson

Measurements were made at Leicester by J.F. Pearson and G.W. Fraser to see if the model outlined above described the actual behaviour of a CsI-coated MCP detector. This initial work is reported in refs. (60) and (105). Almost all of the measurements were carried out using either Si K or C K illumination. It was shown that some energy resolution could be attained.

In order for \( G_c \) to be proportional to \( n_p \), a detector has to be operated in the linear mode, whereas, in order to minimize the FWHM of the output PHD, a detector has to be operated in the saturated mode. There is, therefore, a conflict as to how to set the voltages of a MCP detector for optimum energy resolution.

In the work reported in ref. (105), a compromise was reached by operating the front MCP with a bias voltage less than \( (V_0)^S \), the transitional voltage between linear and saturated operation, and by operating the rear MCP with a bias voltage greater than \( (V_0)^S \). This transitional voltage is given by Equation 2-2. (From the work reported in refs. (54) and (129), it is clear that \( G_c \) will vary as a function of \( V_F \) even when the rear MCP is operated with a bias voltage sufficiently high to induce saturation.)

7.3.1 Energy resolution parameters

One measure of energy resolution is the ratio of the peak gain at photon energy \( E_{X1} \) to that at photon energy \( E_{X2} \). We denote such a ratio by \( R(\frac{E_{X1}}{E_{X2}}) \) where

\[
R\left(\frac{E_{X1}}{E_{X2}}\right) = \frac{G_c(E_{X1})}{G_c(E_{X2})}
\]

The ratio of the peak gains of two distributions, however, does not explicitly quantify the energy resolution.
of a detector because energy resolution is also dependent on the FWHMs of the individual output distributions.

It has also been shown, both theoretically (see Figure 7-3) and in practice, that the gain of a tandem-pair MCP detector does not vary linearly with X-ray energy. Thus, a knowledge of the FWHMs of the two distributions to be compared is also insufficient as a measure of energy resolution. For this reason, a figure of merit, \( S(E_{x1}, E_{x2}) \) was introduced in ref. (105). This figure is obtained by calculating the fractional area of overlap of two Gaussian distributions, each of unit area, whose peak and FWHM values are the same as those of the experimentally obtained distributions. Although some of the experimental distributions that we recorded were appreciably non-Gaussian (especially the C K ones), the figure of merit is a useful indicator of energy resolution because its value lies in the range from zero, for two quite distinct distributions, to unity, for two distributions having the same peak and FWHM values.

### 7.4 MCPs with 8 micron diameter channels

Inspection of Equation 7-2 suggests that a decrease in \( \beta \) should lead to an improvement in energy resolution. As \( \beta \) appears to decrease as the channel diameter of the MCPs decreases, we decided to perform measurements with a detector that incorporated MCPs with 8 micron diameter channels. Four of these MCPs were procured from Mullard - two had a 13°, and two a 0°, channel bias angle. Unfortunately, these MCPs had an L/D ratio of approximately 175:1, rather than 120:1 (as had most of the MCPs that we had previously used), because they were cut to the same thickness, namely 1.5 mm, as a 12.5 micron MCP with a 120:1 L/D ratio. They should have had a thickness of 0.96 mm.

We could not obtain any 8 micron MCPs with the desired L/D ratio within a sufficiently short time, and, therefore, we used the 175:1 L/D ratio MCPs.
7.4.1 Initial measurements

Two of the 8 micron MCPs were assembled into Body 2 as Detector 6. This was installed into VTF 2. After a period of pumping, the MCP bias voltages were increased very slowly at first. The in vacuo resistance of the MCPs was approximately 900 MΩ. This resistance decreased slowly as the bias voltage was increased.

Figures 7-4(a,b,c) show the variation of the detector peak gain and FWHM as a function of \( V_F, V_G \) and \( V_R \). The detector was illuminated with C K X-rays at an angle of incidence of 5°. The dashed vertical lines, drawn on Figures 7-4(a,b), indicate the transitional voltage \((V_0)_S\), calculated from Equation 2-2, that should coincide with the onset of hard saturation. These results were promising because of the low FWHM values that were obtained at the higher rear MCP bias voltages. When we illuminated the detector with Si K photons, the distribution shown in Figure 7-5 was obtained. The detector bias voltages were

\[
V_F = 2050 \text{ volts}; \quad V_G = 200 \text{ volts}; \quad V_R = 2000 \text{ volts}.
\]

The FWHM (19 percent) is possibly the lowest ever reported for any multi-stage MCP detector, and is narrower than for any single curved-channel MCP [44].

We recorded both a C K and a Si K output PHD at the same detector bias voltages. As, at that time, we had not deposited a photocathode onto either of the MCPs, both of the output distributions should have been essentially the same. In practice, however, the peak gains of the corresponding C K and Si K distributions were well separated. \( R \) (1.74 keV, 0.28 keV) was approximately 1.2.

This gain difference was also reported in ref. (105) where it was attributed to the small angle of X-ray incidence, which was 5° for both of our measurements. At such a small incidence angle, the probability that C K photons are reflected is higher than for Si K photons. By interacting further down the channels of the front MCP, reflected photons give rise to output pulses of lower gain. Thus, the peak of the C K distribution should have, and did,
Figure 7-4 (a) Variation of the tandem-pair peak gain (circles, left-hand scale) and FWHM (squares, right-hand scale) of uncoated Detector 6 as a function of $V_F$.

C K X-rays (0.28 keV), $\theta_X = 5^\circ$.

$V_G = 200$ volts, $V_R = 1900$ volts.

The dashed vertical line indicates the transitional voltage ($V_0$)$_S$.

(b) Variation of the tandem-pair peak gain (circles, left-hand scale) and FWHM (squares, right-hand scale) of uncoated Detector 6 as a function of $V_R$.

C K X-rays, $\theta_X = 5^\circ$.

$V_F = 1900$ volts (open symbols), 2050 volts (filled symbols), $V_G = 200$ volts.

The dashed vertical line indicates the transitional voltage ($V_0$)$_S$. 
Figure 7-4 (c) Variation of the tandem-pair peak gain (circles, left-hand scale) and FWHM (squares, right-hand scale) of uncoated Detector 6 as a function of $V_G$.

C K X-rays (0.28 keV), $\theta_X = 5^\circ$.

$V_P = 1900$ volts, $V_R = 1900$ volts.
Figure 7-5 Output pulse height distribution from uncoated Detector 6.
Si K X-rays (1.74 keV), $\theta_X = 5^\circ$.
$V_F = 2050$ volts, $V_G = 200$ volts, $V_R = 2000$ volts.
The FWHM (19 percent) is possibly the lowest ever reported for a multi-stage MCP detector.
become skewed towards the lower gains. If \( g_x \) had been increased, the ratio of the Si K peak gain to the C K peak gain should have fallen towards unity [105].

Comparison of these bare MCP peak gains with the theoretical model [54] indicated that the value of \( \beta \) for the 8 micron MCPs was between 0.55 and 0.6, a value not much lower than that established for 12.5 micron MCPs. Despite this somewhat disappointing indication that the energy resolution obtained from Detector 6 would not be a great improvement on that obtained with the previous detector, we decided to deposit a CsI photocathode onto MCP F6.

7.4.2 Coating of MCP F6 with CsI

Detector 6 was removed from VTF 2 and disassembled. Both of the MCPs were baked at 275°C for 48 hours in the manner described in Chapter 4. The front MCP, which had a 0° channel bias angle, was coated with a 14000 Å layer of CsI at a central coating angle of 4°. The detector was reassembled and replaced in VTF 2. It is shown schematically in Figure 7-6.

![Diagram of Detector 6 after the first coating of MCP F6.](image)

**Figure 7-6** Schematic diagram of Detector 6 after the first coating of MCP F6. Coating 1 - CsI, \( t_F = 14000 \text{ Å}, \ \phi_0 = 4°. \)**

Test position A is at the \( x = 25.5 \text{ mm} \) detector position.
7.4.3 Initial energy resolution results from Detector 6

Figures 7-7(a,b,c,d) show the variation of peak gain and FWHM as a function of $V_F$ on the CsI-coated Detector 6. At each setting of $V_F$, Detector 6 was illuminated alternately with C K and Si K X-rays. The peak gains for these two X-ray lines were separated at all values of $V_F$. The peak gain ratio decreased towards unity as $V_F$ was increased. The maximum setting of $V_F$ was only 1900 volts, and, because this was lower than $(V_0)_S$ (namely 2015 volts), the FWHM values did not reach a plateau. The optimum value of $V_F$, determined by the maximum peak gain ratio and the minimum value of $S$, was in the region of 1750 volts. We set $V_F$ to 1750 volts, and varied the rear MCP voltage. The peak gain separations were greater than those obtained by Fraser and Pearson [105] with a detector incorporating 12.5 micron MCPs. The Si K and C K distributions that we recorded with the optimum bias voltages ($V_F = 1750$ volts, $V_G = 200$ volts, $V_R = 2000$ volts) are shown overlayed in Figure 7-8.

Unlike previous measurement sequences, we were unable to obtain reproducible results. Either the detector gain varied on a short timescale or the detector gain varied with beam position and the beam position was unreproducible. The second explanation seemed the most likely. It will be recalled from Chapter 3 that a filter had to be positioned in the path of the beam in order to produce a "clean" X-ray line. When the X-ray line was changed, the filter also had to be changed. Unfortunately, a set of beam collimation holes was also mounted on the filter wheel. At each filter setting, one of these holes combined with a fixed collimating hole to collimate the beam. The result of this was that the position of the X-ray beam at the detector could move slightly when a filter was changed. It was impossible to ensure that exactly the same area of detector was illuminated before and after a change of X-ray line - the imaging system could not be utilized because it did not have sufficient accuracy.

Any slight misalignment of the C K and Si K beams would not have been a problem if we had been testing a detector that had a negligible variation of its gain with test
Figure 7-7 Tandem-pair energy resolution as a function of front MCP voltage $V_F$ for Detector 6 in the configuration shown in Figure 7-6. Test position A.

X-ray energies Si K (1.74 keV) and C K (0.28 keV). $\theta_X = 5^\circ$.

$V_G = 200$ volts, $V_R = 2000$ volts.

(a) Peak gains, $G_C$.
(b) FWHMs, $\Delta G_C / G_C$.
(c) Separation $S$ (0.28 keV, 1.74 keV).
(d) Ratio $R$, $G_C (1.74 \text{ keV}) / G_C (0.28 \text{ keV})$. 
Figure 7-8 Superimposed tandem-pair output pulse height distributions from Detector 6 in the configuration shown in Figure 7-6. Test position A.

X-ray energies Si K (1.74 keV) and C K (0.28 keV) \( \theta_X = 5^\circ \).

\( V_F = 1750 \) volts, \( V_G = 200 \) volts, \( V_R = 2000 \) volts.
position. If the gain did vary with position, however, the alignment of the test beam at the two energies would have had to be exact in order for the quantity $S$ to have any real meaning.

The detector used in ref. (105) (Detector 4) was shown to have a constant gain as a function of position so that it was not necessary for the regions that were illuminated by the C K and Si K beams to be perfectly aligned. We investigated the variation, if any, with position of the gain of Detector 6 by traversing the X-ray beam across its input face. Figure (7-9) shows the variation of gain across a diameter of the detector. The 25.5 mm detector position marked the centre of the detector. It is possible to interpret a pattern of radially-increasing gain caused by the increasing penetration of CsI down the channels as a function of radial distance from the MCP centre. The fall-off in peak gain, which was observed towards the edge of the active area (indicated by the broken vertical lines in Figure 7-9), appears to be intrinsic to the front MCP.

Nothing could be done about this apparent non-uniformity. Neither of the MCPs used in Detector 6 had been tested by the manufacturer. One of the manufacturer's usual acceptance tests consists of illuminating the MCPs with a flood of electrons and observing the output electron flux with a phosphor screen [130].

The second pair of (uncoated) 8 micron MCPs were incorporated into Body 2. This detector (Detector 7) also showed a variation of gain with test position. It is possible that variation of gain with position is inherent to 8 micron MCPs. Why this may be is unknown at present. Because they are non-standard, 8 micron MCPs have only been made in small numbers and, therefore, they have not been extensively studied.

As the problem could not be resolved, we decided to continue the investigation. To get around the problem of beam misalignment (which has now been eradicated by a modification to VTF 2), we tried to change the X-ray line as seldom as possible. Thus, when a particular detector parameter was being varied, all of the C K measurements were performed first followed by all of the Si K measurements, or
Figure 7-9 (a) Variation of the detector peak gain $G_C$ as a function of the X-ray beam position on Detector 6 in the configuration shown in Figure 7-6. Test position A.

(b) Variation of the detector FWHM $\Delta G_C / G_C$ as a function of the X-ray beam position on Detector 6 in the configuration shown in Figure 7-6. Test position A.

X-ray energies Si K (1.74 keV) and C K (0.28 keV). $\theta_X = 5^\circ$.

$V_F = 1750$ volts, $V_G = 50$ volts, $V_R = 2000$ volts.
vice versa. This did mean that a period of several hours could have elapsed between a C K measurement and the corresponding Si K one.

7.4.4 Variation of the energy resolution parameters with $V_G$

We set the front and rear MCP bias voltages of Detector 6 at the experimentally obtained optimum values of 1750 and 2000 volts respectively, and varied the interplate gap voltage. A tandem-pair MCP detector is usually operated with an electron accelerating interplate electric field; this field constrains the lateral spread of the electron cloud in the gap between the plates.

Initially, we varied $V_G$ from +600 volts down to 0 volts. While making these measurements, the work of Ainbund and Maslenkov [131] became known to us. They investigated the operation of a tandem-pair MCP detector with an electron-retarding interplate electric field. They reported that this mode of operation was superior to the usual operating mode because it resulted in narrower output distributions, lower peak gains and reduced dark noise count rates. As we had previously obtained no measurements with a retarding interplate electric field, we decided to include some in the present series of measurements to see if the advantages claimed in ref. (131) were real.

Figure 7-10 shows the variation of $G_C$ and $\Delta G_C / G_C$ with $V_G$. Both the FWHMs and the value of the figure of merit $S$ were as low or lower at large negative values of $V_G$ as they were at large positive values. These initial negative $V_G$ results were encouraging from the viewpoint of energy resolution. At small negative values of $V_G$, $S$ was relatively large, even though the C K and Si K distributions appeared to be quite well separated, as can be seen in Figure 7-11 where the two distributions that were recorded with $V_G$ set at -3 volts are overlayed. This discrepancy between the observed energy resolution and the calculated figure of merit $S$ was primarily due to the non-Gaussian nature of the distributions. Indeed, the comparison of distributions by eye sometimes gave a better indication of energy resolution than $S$. For this reason, in Section 7.4.5 and the following
Figure 7-10 Tandem-pair energy resolution as a function of the interplate gap voltage $V_G$ for Detector 6 in the configuration shown in Figure 7-6. Test position A.

X-ray energies Si K (1.74 keV) and C K (0.28 keV). $\theta_X = 5^\circ$.

V$_p$ = 1750 volts, V$_R$ = 2000 volts.

(a) Peak gains G$_C$.

(b) FWHMs $\Delta G_C / G_C$.

(c) Separation S (0.28 keV, 1.74 keV).

(d) Ratio R, $G_C (1.74 \text{ keV}) / G_C (0.28 \text{ keV})$. 
Figure 7-11 Superimposed tandem-pair pulse height distribution from Detector 6 in the configuration shown in Figure 7-6. Test position A.

X-ray energies Si K (1.74 keV) and C K (0.28 keV), $\theta_X = 5^\circ$.

$V_F = 1750$ volts, $V_G = -3$ volts, $V_R = 2000$ volts.
sections, we operated Detector 6 with an interplate gap voltage of zero volts because this resulted in the best peak gain separation, and not necessarily the optimum value of $S$.

7.4.4.1 The output energy distribution of the electrons emitted from the channels of the front MCP

The energy that an electron gains after it is emitted from a channel wall is determined by the change in potential that it experiences which, in turn, is a measure of the distance that it moves along the channel. For an electron that leaves the channel, this distance controls $\theta_e$, the angle between the electron trajectory and the channel axis. An electron that is emitted deep inside a channel can gain an appreciable amount of energy, but, assuming that it does not collide with the channel wall, it can only leave the channel at a small angle with respect to the channel axis. Alternatively, an electron emitted near the channel exit can gain only a little energy, but it can leave the channel at upto $45^0$ to the channel axis - the limit of $45^0$ is determined by electrode and spoiling down to a depth of one channel diameter. Thus, the cone of electrons leaving a single channel does not have a uniform distribution of electron energies, but is made up of a central core of electrons with a high emission energy $E_e$ (characterized by $\theta_e < 10^0$, $E_e < 200$ eV) together with a surrounding cone of low energy electrons (characterized by $\theta_e < 45^0$, $E_e < 50$ eV) as indicated in Figure 7-12. (The emission energies quoted above will change if the front MCP is operated in the saturated mode.) Bronshtein et al [132] have made measurements that support the idea of this coupling between electron emission angle and electron energy.

The experimental results reported in Section 7.4.4 can be explained in terms of the level of saturation of the channels of the rear MCP. The average time taken by an electron to cross the interplate gap decreases as the interplate gap voltage is increased from zero volts. As this time is reduced, the radial spread of the electron cloud is reduced, and, therefore, the area illuminated on the rear MCP is also reduced. As the same number of electrons
Figure 7-12 The relationship between electron energy $E_e$ and emission angle $\theta_e$ for electrons emitted from a microchannel operating in the linear mode. Those electrons that have a large emission angle are predominantly of low energy. The higher energy electrons are only emitted at small angles. For example, those electrons emitted from a depth $d$ have an energy which is characteristic of that depth, but they are only found in the crossed region. Those electrons emitted from close to the maximum extent of the nichrome electrode have a lower energy, but they are found in both the crossed and dotted regions.
illuminates fewer and fewer channels of the rear MCP, those channels are driven further into saturation. This causes the FWHM of the output PHD to decrease. The peak gain also decreases slightly.

With a large negative interplate gap voltage, many electrons are repelled back to the front MCP. Only those electrons with a high enough energy \( E > e.V_C \) can reach the rear MCP; the impact area on the rear MCP is increased, but the number of electrons reaching the rear MCP is reduced. This results in a decreased level of saturation of the channels of the rear MCP. Consequently, the FWHM increases and the peak gain decreases.

With a small negative gap voltage, the low energy electrons are repelled back to the front MCP, but the higher energy electrons reach the rear MCP. These electrons illuminate a smaller area of the rear MCP than in the case of a large negative interplate gap voltage. Nevertheless, sufficient electrons enter the rear MCP's channels to drive them into saturation. The combination of a few channels being driven hard into saturation results in low peak gains together with very low FWHM values. In Section 7.5, we present further negative interplate gap voltage measurements.

7.4.5 Variation of the energy resolution parameters with \( V_F \).

In an attempt to minimize the problem of X-ray beam misalignment, we replaced the 2 mm diameter collimating holes that were mounted on the filter wheel with 0.85 mm diameter holes. This action reduced the photon flux at the detector, but it meant that the beam could be more accurately positioned.

As we had previously obtained the best peak gain separations from detectors operated with an interplate gap voltage of zero volts (see Section 7.4.4), and, because this mode of operation had not been investigated by Pearson, we decided to vary \( V_F \) and \( V_R \) with \( V_C \) set at zero volts. Initially, \( V_R \) was set at 2000 volts and \( V_F \) was varied. Figure 7-13 shows the variation of \( G_C \) and \( \Delta G_C / G_C \) with \( V_F \). The peak gain ratio \( R \) decreased and the figure of merit \( S \)
Figure 7-13 Tandem-pair energy resolution as a function of the front MCP voltage $V_F$ for Detector 6 in the configuration shown in Figure 7-6. Test position A.

X-ray energies Si K (1.74 keV) and C K (0.28 keV). $\theta_X = 5^\circ$.

$V_G = 0$ volts, $V_R = 2000$ volts.

(a) Peak gains $G_C$.

(b) FWHMs $\Delta G_C / G_C$.

(c) Separation $S$ (0.28 keV, 1.74 keV).

(d) Ratio $R$, $G_C (1.74 \text{ keV}) / G_C (0.28 \text{ keV})$. 
increased as $V_F$ was increased. $S$ was a minimum of approximately 0.3 for values of $V_F$ less than approximately 1750 volts.

We increased $V_R$ to 2150 volts and made a further set of measurements. Figure 7-14 shows the variation of $G_C$ and $\Delta G_C / G_C$ as a function of $V_F$ at the higher rear MCP bias voltage. The results of Figure 7-14 were similar to those results obtained with $V_F$ set at 2000 volts. Once again, the greatest peak gain ratio and the lowest value of $S$ were obtained at the lowest values of $V_F$. Viewing Figures 7-13 and 7-14 together, it can be seen that the greatest peak gain ratio was measured with a rear MCP bias voltage of 2000 volts and a front MCP bias voltage of 1750 volts.

From these results, it seems that peak gain separation is increased by operating the front MCP with as low a bias voltage as possible (and, therefore, running it as linearly as possible) whilst operating the rear MCP at a voltage just sufficient to induce some saturation in the output pulses. The energy resolution results, however, showed that no advantage accrued in terms of low values of $S$: we conclude that it is better to operate detectors with $V_G$ set at that value, be it positive or negative, that minimizes the value of $S$ because, although the peak gain ratio $R$ might not be a maximum, the FWHMs of the output distributions are also much reduced.

This concludes the main investigation of 8 micron MCPs, although some noise count rate measurements are presented in Section 7.5.1.

7.5 Further energy resolution measurements on Detector 4

We decided to make further measurements on Detector 4 because we had not previously investigated the variation of its energy resolution as a function of $V_G$. This detector, which incorporated 12.5 micron MCPs, was the one on which the original energy resolution measurements were made [60]. Half of the input face of both the front and rear MCPs had been coated with CsI. The gain of Detector 4 was stable as a function of the test position. We investigated both the (CsI/bare) and (CsI/CsI) MCP configurations. (By the
Figure 7-14 As for Figure 7-13 except $V_R = 2150$ volts.

(a) Peak gains $G_C$.
(b) FWHMs $\Delta G_C / G_C$.
(c) Separation $S$ (0.28 keV, 1.74 keV).
(d) Ratio $R$, $G_C$ (1.74 keV) / $G_C$ (0.28 keV).
(CsI/CsI) configuration, we mean the configuration with the half-coated input face of the front MCP in alignment with the half-coated input face of the rear MCP.)

7.5.1 Variation of the noise count rate with $V_g$

Detector 4 was assembled in the CsI/bare configuration (shown schematically in Figure 7-15), and installed in VTF 2. The original 2 mm diameter beam collimating holes were replaced on the filter wheel of VTF 2.

We varied $V_g$ with $V_p$ set at 1400 volts and $V_R$ set at 1700 volts. The area of the CsI photocathode that was illuminated was the one that was used as the reference area during lifetests L4.1 and L4.2. The angle of X-ray incidence was 5°. The variation of $G_C$ and $\Delta G_C / G_C$ with $V_g$ are shown in Figure 7-16. The greatest peak gain ratio ($R = 2.8$) was measured with $V_g$ set at zero volts.

![Figure 7-15 Schematic diagram of Detector 4.](image)

Coating 1 - CsI, $t_p = 14000 \AA$, $\phi_0 = 4^\circ$.
Coating 2 - CsI, $t_p = 12500 \AA$, $\phi_0 = 0^\circ$.
Test position A is at the $x = 32$ detector position and is 6.5 mm from the coating boundary.
Figure 7-16 Tandem-pair energy resolution as a function of the interplate gap voltage $V_G$ for Detector 4 in the configuration shown in Figure 7-15. Test position A.
X-ray energies Si K (1.74 keV) and C K (0.28 keV). $\theta_X = 5^\circ$.
$V_F = 1400$ volts, $V_R = 1700$ volts.
(a) Peak gains $G_C$.
(b) FWHMs $\Delta G_C / G_C$.
(c) Separation $S$ (0.28 keV, 1.74 keV).
(d) Ratio $R$, $G_C$ (1.74 keV) / $G_C$ (0.28 keV).
Figure 7-17 shows the variation of the Detector 4 noise count rate as a function of the interplate gap voltage. The noise count rate at large negative values of $V_G$ was 33 percent lower than at positive values of $V_G$. This reduction can be compared with the 80-95 percent reduction in dark current reported by Ainbund and Maslenkov [131]. This disagreement may have been due to the high noise count rates (upto 80 counts cm$^{-2}$ sec$^{-1}$) reported by these authors at positive $V_G$ values. These values, which are much larger than the accepted noise count rates for "quiet" detectors (0.1-0.2 counts cm$^{-2}$ sec$^{-1}$), could be indicative of ion feedback induced events. Indeed, the large reduction of the dark noise count rate reported in ref. (131) as $V_G$ was made negative can be explained in terms of a decrease in the number of ion induced events. Positive ions, created in
either the interplate gap or the channels of the rear MCP, should be inhibited from reaching channels in the front MCP (where they can initiate an avalanche that can be detected as a noise event) by an electron-retarding interplate electric field. Thus, if ion feedback induced events represent a large fraction of the total noise events at positive values of \( V_G \), the noise rate should decrease at zero or negative values of \( V_G \).

Returning to our results, the small decrease in noise count rate observed was probably due to our use of a fixed electronic lower level discriminator (LLD). As \( V_G \) was made more negative, the detector gain decreased, a greater percentage of noise pulses fell below the discriminator level, and the measured noise count rate was reduced. Our LLD setting of 0.1 pC corresponded to 4 percent of the Si K peak gain with \( V_G \) set at a value in excess of 50 volts, whereas, with \( V_G \) set at -50 volts, the same LLD setting corresponded to 18 percent of the Si K peak gain.

Also plotted in Figure 7-17 are the equivalent data obtained from Detector 6. It can be seen that the noise count rates per unit area are essentially the same for both the 12.5 micron and the 8 micron detectors. It is concluded [58] that our 8 micron MCPs were intrinsically no noisier than our 12.5 micron MCPs. Referring back to Section 2.5, we can infer that field-emission from channel defects is not the dominant source of dark noise.

7.5.2 Energy resolution as a function of \( V_F \) and \( V_R \)

We investigated the energy resolution of Detector 4 as a function of both \( V_F \) and \( V_R \) with a zero volts interplate gap voltage. There was no improvement to the energy resolution. We obtained the best peak gain ratio with \( V_F \) set at 1300 volts and \( V_R \) set at 1800 volts; the peak gain ratio \( R \) was 2.9. The corresponding output distributions are shown overlayed in Figure 7-18. Each distribution contains approximately 85000 counts.
Figure 7-18 Superimposed tandem-pair output pulse height distributions from Detector 4 in the configuration shown in Figure 7-15. Test position A. 
X-ray energies Si K (1.74 keV) and C K (0.28 keV). $\theta_X = 5^\circ$. 
$V_F = 1300$ volts, $V_G = 0$ volts, $V_R = 1800$ volts.
As we stated in Section 7.3, for the purpose of energy discrimination, a trade-off has to be made between linear operation of a tandem-pair detector (resulting in high values of both FWHM and peak gain ratio R) and saturated operation (resulting in low values of FWHM and R). Our previous measurements, together with those of refs. (105) and (133), indicate that the deposition of CsI onto the front surface and channel entrances of an MCP changes the initial, or "first-strike", SEEC $\delta_1$ insufficiently to promote MCP gain characteristics that are ideal for energy discrimination, namely a peaked PHD without the dynamic range limitation caused by wall charge saturation at the channel exits. It has been shown theoretically [133, 134] that an increase in $\delta_1$ should cause the output PHD to become peaked in the absence of any saturation mechanism. Thus, we attempted to modify the SEEC of the channels of the front MCP of Detector 4, not only at the first-strike position, but over a substantial fraction of their entire length.

The detector was disassembled, and we deposited 14000 Å of CsI onto the already coated half of MCP F4. The nominal coating angle was 0°, although there undoubtedly was a considerable spread in the actual coating angle due to the finite extent of the source (as mentioned in Chapter 4). We did not rebake the MCP prior to recoating. It can be noted that there appeared to be no difficulty in depositing CsI onto CsI. At the $x = 36$ mm position (which was the position of the X-ray measurements), $\hat{\gamma}$ varies from 0° to 4.6° (assuming $h = 330$ mm). At the entrance of the channels, the CsI coating should have increased in thickness by 155 Å (assuming $\hat{\gamma} = 2^\circ$).

Theoretically, the second coating should have penetrated further down the channels than the first coating, and, at the $x = 36$ mm position, the penetration should have been 29 D (approximately 25 percent of the channel length). With $V_d$ set at zero volts, which, as we have previously shown, results in the most linear operation of the detector, any change to the output distribution of the first MCP should have been maximized.
7.5.3.1 Further energy resolution results

Detector 4 then had the configuration shown in Figure 7-19. With $V_R$ set at 1700 volts, Detector 4 was very noisy when $V_F$ was increased above 1300 volts. Figures 7-20(a,b) show the variation of $G_C$ and $\Delta G_C/G_C$ as a function of $V_F$ and $V_R$ respectively. The second front face coating did indeed induce an approximately 20 percent reduction of the FWHMs; most of this reduction was due to removal of counts from the low charge end of the distributions. The peak gains were increased by up to 20 percent, and this indicates that, at least for part of the channels, the SEECE had been increased. The gain could have been increased by a similar amount by increasing $V_F$ by 25 volts. Such a voltage on its own would not, however, have resulted in the observed reduction of the FWHM values. Thus, it appears that the SEECE increase improved the statistics of the avalanche process. The FWHM reduction resulted in modest improvements to the energy resolution of the detector.

![Figure 7-19 Schematic diagram of Detector 4 after the recoating of MCP F4. Coating 1 - CsI, $t_F = 14000 \, \text{Å}, \alpha = 40^\circ$. Coating 2 - CsI, $t_F = 12500 \, \text{Å}, \alpha = 0^\circ$. Coating 3 - CsI, $t_F = 14000 \, \text{Å}, \alpha = 0^\circ$.
Test position A is at the x = 32 detector position and is 6.5 mm from the coating boundary.](image)
Figure 7-20 (a) Tandem-pair energy resolution as a function of the front MCP voltage $V_F$ for Detector 4 in the configuration shown in Figure 7-19. Test position A.
X-ray energies Si K (1.74 keV) and C K (0.28 keV). $8_X = 5^\circ$.
$V_G = 0$ volts, $V_R = 1800$ volts.
(a) Peak gains $G_C$.
(b) FWHMs $\Delta G_C / G_C$.
(c) Separation $S (0.28$ keV, 1.74 keV).
(d) Ratio $R$, $G_C (1.74$ keV) / $G_C (0.28$ keV).
Figure 7-20 (b) As Figure 7-20 (a) except $V_R = 1700$ volts.
(a) Peak gains $G_C$
(b) FWHMs $\Delta G_C / G_C$
(c) Separation $S (0.28 \text{ keV}, 1.74 \text{ keV})$.
(d) Ratio $R, G_C (1.74 \text{ keV}) / G_C (0.28 \text{ keV})$. 
7.5.3.2 Efficiency measurements on the recoated half of Detector U

We measured the Si K and C K efficiencies of Detector U at the $x = 32$ mm position as a function of the angle of X-ray incidence. The results are shown in Figure 7-21 where they are compared with pre-second coating data, which was obtained at the same position by J.F. Pearson. The second coating resulted in increased Si K efficiencies even at the small incidence angles that are pertinent for the proposed AXAF mission ($1.8^\circ - 3.5^\circ$). The C K efficiencies were almost unchanged. These results inspired hope that there would be significant efficiency enhancements at the higher (e.g. 6 keV) X-ray energies (see Section 7.7).

![Figure 7-21](image)

**Figure 7-21** MCP quantum detection efficiency as a function of the angle of X-ray incidence $\theta_x$ before (filled symbols) and after (open symbols) the second coating of MCP F4. X-ray energies - Si K (1.74 keV (squares)) and C K (0.28 keV (circles)). $V_F = 1400$ volts; $V_G = 200$ volts; $V_R = 1700$ volts.
7.5.4 Coating of the exit face of MCP F4

Having observed the benefits that were brought about by increasing the length of channel coated with CsI, we coated half of the rear face of the front MCP with 13000 Å of CsI at a coating angle of 0°. This coating should have caused CsI to penetrate approximately 29 D up the channels from the exit face (at the x = 36 mm test position), and the channel coating thickness should have been 150 Å.

7.5.4.1 Results

We re-assembled Detector 4 in the configuration shown in Figure 7-22. Figure 7-23 shows the variation of $G_C$ and $\Delta G_C / G_C$ as a function of $V_F$. The additional coating

![Figure 7-22 Schematic diagram of Detector 4 after the coating of the exit face of MCP F4. Coating 1 - CsI, $t_F = 14000$ Å, $\alpha = 0°$. Coating 2 - CsI, $t_F = 12500$ Å, $\alpha = 0°$. Coating 3 - CsI, $t_F = 14000$ Å, $\alpha = 0°$. Coating 4 - CsI, $t_F = 13500$ Å, $\alpha = 0°$. Test position A is at the x = 32 mm detector position and is 6.5 mm from the coating boundary.](image-url)
Figure 7-23 Tandem-pair energy resolution as a function of the front MCP voltage $V_F$ for Detector 4 in the configuration shown in Figure 7-22. Test position A.

X-ray energies Si K (1.74 keV) and C K (0.28 keV). $\theta_x = 5^\circ$.

$V_g = 0$ volts, $V_R = 1700$ volts.

(a) Peak gains $G_C$.
(b) FWHMs $\Delta G_C / G_C$.
(c) Separation $S$ (0.28 keV, 1.74 keV).
(d) Ratio $R, G_C (1.74 \text{ keV}) / G_C (0.28 \text{ keV})$. 
increased the peak gain of the detector. Figure 7-24 shows the variation of $G_C$ and $\Delta G_C / G_C$ as a function of $V_G$ with $V_R$ set at 1400 volts. The form of the $G_C$ versus $V_G$ curve was similar to that of the data set plotted in Figure 7-16. The FWHM values, however, were lower, particularly at negative values of $V_G$, being typically 60 percent (both C K and Si K) compared to the previous values of 70 percent (Si K) and 80 percent (C K). The data plotted in Figure 7-24 suggested the use of an interplate voltage of between -25 or -50 volts. Thus, we varied $V_F$ with $V_G$ first set at -25 volts (see Figure 7-25) and then at -50 volts (see Figure 7-26). The former setting of $V_G$ resulted in the best results.

The C K and Si K output PHDs recorded with the following voltages - $V_F = 1200$ volts; $V_G = -25$ volts; $V_R = 1700$ volts - are shown overlaid in Figure 7-27. This figure shows the best peak gain separation that we ever obtained; only 35 percent of the Si K distribution was overlapped by the C K distribution.

Having optimized $V_G$ and $V_F$, we measured $G_C$ and $\Delta G_C / G_C$ as a function of $V_R$. The results are shown in Figure 7-28. The lowest value of $S$ was obtained with $V_R$ set at 1600 volts; thus, we performed another iteration, varying $V_F$ with $V_G$ set at -25 volts and $V_R$ set at 1600 volts. Figure 7-29 shows the variation of the energy resolution parameters.

Figure 7-30 shows the variation of $G_C$ and $\Delta G_C / G_C$, and Figure 7-31 the change in the form of the Si K distributions, as a function of the angle of X-ray incidence. At large incidence angles, the Si K distributions were broadened towards low charge levels. This result is consistent with the energy resolution model, which suggests that broad distributions are associated with large X-ray incidence angles and thick photocathodes, as indicated by Figure 7-2. As the incidence angle was reduced, the distributions became skewed towards the higher charge levels until, at the onset of reflection ($\theta_C$, the critical angle of reflection, is 1.5° for Si K photons), a low charge bump appeared in the output PHDs.
Figure 7-24 Tandem-pair energy resolution as a function of the interplate gap voltage $V_G$ for Detector 4 in the configuration shown in Figure 7-22. Test position A.
X-ray energies Si K (1.74 keV) and C K (0.28 keV). $\theta_X = 5^\circ$.
$V_F = 1400$ volts, $V_R = 1700$ volts.
(a) Peak gains $G_C$.
(b) FWHMs $\Delta G_C / G_C$.
(c) Separation $S$ (0.28 keV, 1.74 keV).
(d) Ratio $R$, $G_C (1.74$ keV) / $G_C (0.28$ keV).
Figure 7-25 Tandem-pair energy resolution as a function of the front MCP voltage $V_F$ for Detector 4 in the configuration shown in Figure 7-22. Test position A.

X-ray energies Si K (1.74 keV) and C K (0.28 keV). $\theta_X = 5^\circ$.

$V_G = -25$ volts, $V_R = 1700$ volts.

(a) Peak gains $G_C$.
(b) FWHMs $\Delta G_C / G_C$.
(c) Separation $S$ (0.28 keV, 1.74 keV).
(d) Ratio $R$, $G_C (1.74 \text{ keV}) / G_C (0.28 \text{ keV})$. 
Figure 7-26 As Figure 7-25 except $V_G = -50$ volts.
(a) Peak gains $G_C$.
(b) FWHMs $\Delta G_C / G_C$.
(c) Separation $S$ (0.28 keV, 1.74 keV).
(d) Ratio $R$, $G_C(1.74$ keV) / $G_C (0.28$ keV).
Figure 7-27 Superimposed tandem-pair output pulse height distributions from Detector A in the configuration shown in Figure 7-22. Test position A.

X-ray energies Si K (1.74 keV) and C K (0.28 keV). \( \theta_X = 5^\circ \).

\( V_F = 1200 \) volts, \( V_G = -25 \) volts, \( V_R = 1700 \) volts.
Figure 7-28 Tandem-pair energy resolution as a function of the rear MCP voltage $V_R$ for Detector A in the configuration shown in Figure 7-22. Test position A.
X-ray energies Si K (1.74 keV) and C K (0.28 keV). $\theta_X = 5^\circ$.
$V_F = 1400$ volts, $V_G = -25$ volts.
(a) Peak gains $G_C$.
(b) FWHMs $\Delta G_C / G_C$.
(c) Separation $S$ (0.28 keV, 1.74 keV).
(d) Ratio $R$, $G_C (1.74 \text{ keV}) / G_C (0.28 \text{ keV})$. 
Figure 7-29 Tandem-pair energy resolution as a function of the front MCP voltage $V_F$ for Detector 4 in the configuration shown in Figure 7-22. Test position A.

- X-ray energies Si K (1.74 keV) and C K (0.28 keV), $\theta_X = 5^\circ$.
- $V_G = -25$ volts, $V_R = 1600$ volts.
- (a) Peak gains $G_C$.
- (b) FWHMs $\Delta G_C / G_C$.
- (c) Separation $S (0.28$ keV, 1.74 keV).
- (d) Ratio $R$, $G_C (1.74$ keV) / $G_C (0.28$ keV).
Figure 7-30 Tandem-pair energy resolution as a function of the X-ray angle of incidence $\theta_X$ for Detector 4 in the configuration shown in Figure 7-22. Test position A.

X-ray energies Si K (1.74 keV) and C K (0.28 keV).

$V_F = 1400$ volts, $V_G = -25$ volts, $V_R = 1600$ volts

(a) Peak gains $G_C$.

(b) FWHMs $\Delta G_C / G_C$.

(c) Separation $S (0.28 \text{ keV}, 1.74 \text{ keV})$.

(d) Ratio $R, G_C (1.74 \text{ keV}) / G_C (0.28 \text{ keV})$. 
Figure 7-31 Tandem-pair output pulse height distributions from Detector 4 in the configuration shown in Figure 7-22. Test position A. Si K (1.74 keV) X-rays incident at five named angles of incidence. 

$V_F = 1400$ volts, $V_G = -25$ volts, $V_R = 1700$ volts.
7.5.5 **Rotation of the rear MCP through 180°**

We rotated the rear MCP of Detector 4 through 180° about the detector z-axis to give a detector with four co-aligned coatings, as shown schematically in Figure 7-32.

We investigated the characteristics of the coated half of the detector. Figure 7-33 shows the variation of $G_C$ and $\Delta G_C / G_C$ as a function of $V_G$. The changes that can be attributed to the additional coating can be seen by comparing Figure 7-33 with Figure 7-24. The peak gain ratio $R$ was reduced and the peak gains greatly increased at all settings of $V_G$, but it was only at positive $V_G$ values that the FWHMs were reduced. The energy resolution of this detector configuration was no better than that of previous configurations and, therefore, we did not investigate it further.

![Schematic Diagram](image)

**Figure 7-32** Schematic diagram showing the relationship between the four coatings of Detector 4 in the "four coatings aligned" configuration.

- Coating 1 - CsI, $t_F = 14000 \text{ Å}, \alpha_0 = 45°$.
- Coating 2 - CsI, $t_F = 12500 \text{ Å}, \alpha_0 = 0°$.
- Coating 3 - CsI, $t_F = 14000 \text{ Å}, \alpha_0 = 0°$.
- Coating 4 - CsI, $t_F = 13500 \text{ Å}, \alpha_0 = 0°$.

Test position A is at the $x = 32$ mm detector position and is 6.5 mm from the coating boundary.
Figure 7-33 Tandem-pair energy resolution as a function of the interplate gap voltage for Detector 4 in the configuration shown in Figure 7-32. Test position A.

X-ray energies Si K (1.74 keV) and C K (0.28 keV). \( \theta_x = 5^\circ \).

- \( V_p = 1400 \) volts, \( V_R = 1700 \) volts.
- (a) Peak gains \( G_C \).
- (b) FWHMs \( \Delta G_C / G_C \).
- (c) Separation \( S (0.28 \text{ keV}, 1.74 \text{ keV}) \).
- (d) Ratio \( R = G_C (1.74 \text{ keV}) / G_C (0.28 \text{ keV}) \).
The previous results indicated one way to proceed. With each additional coating, and the consequent charge density increases at the entrance to the channels of the rear MCP, the peak gain ratio, $R$, had tended to decrease. Thus, we thought that if the charge densities at the input to the rear MCP could be decreased, that MCP might operate more linearly, resulting in an increase of the peak gain ratio. In an attempt to achieve such a charge density reduction, the size of the interplate gap of Detector 4 was increased, allowing the interplate charge clouds to expand radially to a further extent.

7.5.6 Operation of Detector 4 with a 400 micron interplate gap

Ainbund and Maslenkov [131] investigated the dependence of peak gain and FWHM of a number of tandem-pair MCP detectors as a function of both positive and negative values of $V_g$. The lowest FWHMs that they reported were obtained from detectors that had a 400 micron interplate gap. (Detectors that had a 1 mm gap and a 100 micron gap were also investigated in ref. (131).) Our desire to reduce the charge densities at the input of the channels of the rear MCP coupled with our knowledge of the results of ref. (131) lead us to introduce spacers between the two interplate electrodes of Detector 4, increasing the interplate distance from 160 to 400 microns. The rear MCP was again rotated by $180^\circ$ to give the detector configuration in which the three front MCP coatings were directly positioned over the uncoated half of the rear MCP (see Figure 7-22).

Figure 7-34 shows the variation of $G_c$ and $\Delta G_c / G_c$ with $V_g$. The increased size of the interplate gap induced a large increase in the peak gains at all values of $V_g$. We attribute this result to the increased radial extent of the interplate electron clouds which illuminated a greater number of channels in the rear MCP. At large positive values of $V_g$, both the FWHM values and the peak gain ratio, $R$, were higher than previously. These results were also due to the larger number of channels in the rear MCP that were excited and the consequent reduction in the level of saturation. At negative
Figure 7-34 Tandem-pair energy resolution as a function of the interplate gap voltage $V_G$ for Detector 4 in the configuration shown in Figure 7-32 and with a 400 micron interplate gap. Test position A. X-rays energies Si K (1.74 keV) and C K (0.28 keV). $\theta_X = 5^\circ$.

- Peak gains $G_C$.
- FWHMs $\Delta G_C / G_C$.
- Separation $S (0.28 \text{ keV}, 1.74 \text{ keV})$.
- Ratio $R$, $G_C (1.74 \text{ keV}) / G_C (0.28 \text{ keV})$. 

$b$ peak gains $G_C$. $\Delta G_C / G_C$. $c$ separation $S (0.28 \text{ keV}, 1.74 \text{ keV})$. $d$ ratio $R$, $G_C (1.74 \text{ keV}) / G_C (0.28 \text{ keV})$. 

$V_F = 1400$ volts, $V_R = 1700$ volts.
$V_g$ values, however, the lowest FWHM value was unchanged and $R$ decreased from 1.7 to 1.6. It appeared, therefore, that the operation of the detector had become more linear at positive values of $V_g$ but not at negative values.

It appears that, no matter what coatings had been deposited on, or geometrical modifications or voltage adjustments made to, the detector, we could not reduce the value of the figure of merit, $S$, below about 0.3.

7.5.7 The use of a thinner photocathode

The uncoated half of the input face of the front MCP was coated with 7100 $\AA$ of CsI at a nominal coating angle of $40^\circ$. This geometry should have resulted in the deposition of a "thin" (approximately 150 $\AA$) CsI layer on the channel walls. The detector was re-assembled so that no other coatings were aligned with the 7100 $\AA$ front MCP coating (see Figure 7-35). The "standard" double-sided interplate electrode was put back into the detector - the size of the interplate gap was, therefore, 160 microns.

According to the model outlined at the beginning of this chapter, a thinner channel-wall coating should have caused both the most probable number and the average number of electrons in the initial batch to increase, and the Si K distributions should have been affected more than the C K ones (as indicated in Figure 7-2(d)).

After installation in VTF 2, the detector had to be pumped for a longer than usual period before the dark noise count rate dropped to an acceptable level. When the noise rate had stabilized, we scanned the X-ray beam across the detector in order to find the most suitable test position. The $x = 22$ mm position was chosen. There was no sign of gain degradation. (The $x = 19$ mm position was illuminated as the uncoated reference area in Lifetest L4.1.)

The Si K distribution recorded in this position had a prominent low charge "bump" (see Figure 7-36). It is possible that some of the test beam did fall onto the previously illuminated region. The bump could also have been due to a higher than usual noise count rate, although the actual noise rate, which was measured both before and after
Figure 7-35 Schematic diagram of Detector 4 after the deposition of the 7100 Å coating.

Coating 1 - CsI, $t_F = 14000 \text{ Å}, \alpha_0 = 4^\circ$.
Coating 2 - CsI, $t_F = 12500 \text{ Å}, \alpha_0 = 0^\circ$.
Coating 3 - CsI, $t_F = 14000 \text{ Å}, \alpha_0 = 0^\circ$.
Coating 4 - CsI, $t_F = 13500 \text{ Å}, \alpha_0 = 0^\circ$.
Coating 5 - CsI, $t_F = 7100 \text{ Å}, \alpha_0 = 4^\circ$.

Test position A is at the $x = 32 \text{ mm}$ detector position and is 6.5 mm from the coating boundary.
Test position B is at the $x = 22 \text{ mm}$ detector position and is 3.5 mm from the coating boundary.
Figure 7-36 Tandem-pair output pulse height distribution from Detector 4 in the configuration shown in Figure 7-35. Test position B.
Si K (1.74 keV) X-rays. $\theta_X = 5^\circ$.
$V_F = 1400$ volts, $V_G = 200$ volts, $V_R = 1700$ volts.
the accumulation of the distribution, was so low that it could not have lead to the observed effect. A third possibility is that the CsI coating was so thin that a significant fraction of the incident photons penetrated it and interacted with the underlying lead glass, and that it was the 1-electron distribution of the lead glass that produced the low charge bump.

To investigate the last of these possibilities, we varied the angle of X-ray incidence and recorded the Si K distributions. The distributions are shown in Figure 7-37. Comparing this figure with Figure 7-31 (in which the distributions were obtained with the detector configured as shown in Figure 7-22), it can be seen that the asymmetry of the distributions at large values of $\theta_X$ is less pronounced in Figure 7-37. This was undoubtedly due to the thin nature of the coating. As $\theta_X$ was reduced below approximately $10^\circ$, the low charge bump appeared. At an incidence angle of $1.5^\circ$, the Si K distribution had two distinct peaks which we associate with the 1 (lead glass) and many (CsI) electron distributions. The gain of the lower charge peak should have, and indeed did, vary with incidence angle (being greater at the larger incidence angles) because, as $\theta_X$ was decreased, the mean X-ray interaction depth down the channel increased.

In conclusion, at large incidence angles the initial electron emission distribution was indeed modified by the deposition of a thinner coating, but at small incidence angles any useful modification was negated because the thin coating became transparent.

7.5.8 Conclusions

The work with Detector 4 has shown that the electron emission statistics can be modified by manipulating the photocathode thickness and extent. Nevertheless, we were still limited by the way the avalanche propagated inside the MCP. We have shown some advantages of the use of negative interplate gap voltages. We have also shown that detector gains can be greatly increased by depositing multiple coatings. The peak gain and FWHM of the distributions
Figure 7-37 Tandem-pair output pulse height distribution from Detector A in the configuration shown in Figure 7-35. Test position B. Si K (1.74 keV) X-rays incident at four named incidence angles. 

$V_p = 1400$ volts, $V_G = 200$ volts, $V_R = 1700$ volts.
obtained under C K illumination from a number of the detector configurations are compared in Table 7-1. It can be seen that the peak gain of the "4-coatings" distribution is 3.6 times greater than the "uncoated" distribution peak gain.

7.6 A detector with a 40:1 L/D ratio front MCP

There only appeared to be one more way to proceed with "standard" MCPs - this was to use a thin MCP (i.e. one with a small L/D ratio) as the front MCP of a detector and to completely coat the walls of its channels with CsI. We hoped to improve the statistics of the avalanche process by reducing the number of channel wall collisions. Both Adams and Manley [48] and Fraser et al [54] model a channel that is operated in the low gain mode as a multiplier with discrete, evenly-spaced dynodes. For a voltage, $V_0$, applied along the length of a channel, the number of dynodes is given by

$$4.\frac{V_0}{L/D}^2$$

where $eV$ is the initial emission energy of a secondary electron. For a 120:1 L/D ratio MCP, the number of dynodes is $57600 / V_0$ whereas it is only $6400 / V_0$ for a 40:1 MCP.

The only 40:1 MCP that we had available had a 13° channel bias angle. In order to deposit CsI down as much of the length of the channels as possible, we had to coat the MCP at a nominal coating angle of 0° with respect to the channels. Because of the channel bias angle, the MCP had to be positioned in a 13° "wedge" which maintained the channels vertically during the deposition.

We deposited 13000 Å of CsI onto one half of the front face of the 40:1 MCP and incorporated it, together with the much used rear MCP R4, into Detector 5 in the configuration shown in Figure 7-38.

7.6.1 Results

The use of a front MCP with a 13° bias angle dictated
Table 7-1 Comparison of the peak gain $G_C$ and FWHM $\Delta G_C / G_C$ of a number of configurations of Detector 4.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$G_C$(pC)</th>
<th>$\Delta G_C / G_C$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 1 F4 4 2 R4</td>
<td>5.76</td>
<td>68</td>
</tr>
<tr>
<td>3 1 F4 2 R4</td>
<td>3.68</td>
<td>91</td>
</tr>
<tr>
<td>3 1 F4 2 R4</td>
<td>2.76</td>
<td>101</td>
</tr>
<tr>
<td>1 2 F4 2 R4</td>
<td>2.39</td>
<td>120</td>
</tr>
<tr>
<td>4 2 R4</td>
<td>1.60</td>
<td>176</td>
</tr>
</tbody>
</table>

C K (0.28 keV) X-rays, $\theta_X = 5^\circ$.

$V_P = 1400$ volts, $V_G = 200$ volts, $V_R = 1700$ volts

Coating 1 - CsI, $t_P = 14000 \, \AA$, $\delta_P = 4^\circ$.
Coating 2 - CsI, $t_P = 12500 \, \AA$, $\delta_P = 0^\circ$.
Coating 3 - CsI, $t_P = 14000 \, \AA$, $\delta_P = 0^\circ$.
Coating 4 - CsI, $t_P = 13500 \, \AA$, $\delta_P = 0^\circ$. 
that we illuminated the detector at normal incidence. Indeed, it may be advantageous to use such an MCP as the front MCP in the proposed AXAF HRC. The cone angle of the AXAF mirrors will be so small that, if an MCP with a zero degree channel bias angle is used, the incident photons will illuminate a large fraction of the length of the channels (32 D at an incidence angle of 1.8°) and this would result in a large dispersion of the detector gain.

When we operated Detector 5, noise counts were first detected with a front MCP bias voltage of approximately 200 volts. For a theoretical channel composed wholly of CsI with a 40:1 L/D ratio, the voltage at which it behaves as a multiplier of unity gain is 190 volts. (This compares with 360 volts for a channel composed wholly of lead glass.) Thus, we concluded that the CsI coating extended almost the whole way down the channels. With a front MCP bias voltage of 500 volts, peaked output distributions were obtained under both C K and Si K illumination. We traversed the test beam across the coated half of the detector. There was almost no variation of the gain across the detector. It is probable, therefore, that a relatively uniform coating of

![Diagram](image)

**Figure 7-38** Schematic diagram of Detector 5 after the first coating of MCP F5.

- **Coating 1** - CsI, \( t_F = 12500 \ \text{Å}, \ \varphi_0 = 0^\circ \).
- **Coating 2** - CsI, \( t_F = 13000 \ \text{Å}, \ \varphi_0 = 0^\circ \).

Test position A is at the \( x = 32 \text{ mm} \) detector position and is 6.5 mm from the coating boundary.
Csl had been deposited over the whole detection area. This result was unexpected. Upon consideration, though, it was apparent that the combination of the coating geometry and the use of a linear source that had an extent similar to the diameter of the MCP caused every point on the face of the MCP being coated to subtend an angle of $0^\circ$ to some point on the source.

The output PHDs that we obtained from Detector 5 once again had a low charge excess (see Figure 7-39). It is possible that the Csl coating was too thin, and that the low charge excess was due to the underlying lead glass. To test this hypothesis, we measured the C K efficiency at an X-ray incidence angle of $13^\circ$ on both the coated and uncoated halves of the detector. The efficiency of the coated side was 18.8 percent, which was lower than the expected value of approximately 30 percent. The efficiency of the uncoated half was also lower than predicted. As both the uncoated and coated efficiencies were low, the anomalous coated efficiency could not be attributed to the thin photocathode. Other causes, such as ageing of the front MCP, or the geometry of the nichrome electrode, must have been the reason for the low efficiencies.

7.6.2 A second coating of MCP F5

We coated the input face of the 40:1 front MCP with a further 16000 Å of Csl at a coating angle of $0^\circ$ giving the detector configuration shown in Figure 7-40. Once again, the efficiency of the coated side was lower than expected. The low charge bump was still present on both the C K and Si K distributions, as indicated by the Si K distribution shown in Figure 7-41. This observation further indicated that photocathode transparency was not responsible for the low charge bump. As the ratio of the coated efficiency to the uncoated efficiency was 4:1 for both the one- and two-coatings configuration, it appeared that both halves of the detector had an anomalously low QDE. Assuming that the initial photon-to-photoelectron conversion process was unchanged, some, if not the majority, of the initial photoelectrons were not initiating avalanches.
Figure 7-39 Tandem-pair output pulse height distribution from Detector 5 in the configuration shown in Figure 7-38. Test position A. Si K (1.74 keV) X-rays. $\theta_X = 13^\circ$. $V_F = 500$ volts, $V_G = 200$ volts, $V_R = 1700$ volts.
Figure 7-40 Schematic diagram of Detector 5 after the second coating of MCP F5.

Coating 1 - CsI, \( t_F = 12500 \, \text{Å}, \theta_0 = 4^\circ \).
Coating 2 - CsI, \( t_F = 13000 \, \text{Å}, \theta_0 = 0^\circ \).
Coating 3 - CsI, \( t_F = 16000 \, \text{Å}, \theta_0 = 0^\circ \).

Test position A is at the \( x = 32 \, \text{mm} \) detector position and is 6.5 mm from the coating boundary.
Figure 7-41 Tandem-pair output pulse height distribution from Detector 5 in the configuration shown in Figure 7-40. Test position A. Si K (1.74 keV) X-rays. $\theta_x = 13^\circ$.

$V_F = 500$ volts, $V_G = 200$ volts, $V_R = 1700$ volts.
Detector 5 was the first one to incorporate a front MCP with a 13° channel bias angle. For a given channel, we knew [79] that the depth to which the nichrome electrode extended varied around the circumference, as indicated in Figure 7-42. Computer simulations [79] show that the application of a bias voltage to an MCP with a 13° channel bias angle results in electrical potential contours at the inputs of the channels which are skewed towards the side of deepest electrode penetration. This produces a transverse component of the electric field which reduces the collision energy of some of the primary electrons and returns others to their plane of emission. We hypothesized that transverse electric fields were indeed set up in the channels of the front MCP of Detector 5. Those electrons that actually initiated avalanches then corresponded to an initial number distribution with \( n_p = 1 \) for all photon energies.

Figure 7-42 Each nichrome electrode of an MCP is deposited at a central coating angle of 45° from a fixed source. The MCP is rotated about the source during coating. For any particular channel, at one position of the MCP, material is deposited along AA'. Half a revolution of the MCP later, material is deposited along BB'. It is clear that for any non-zero channel bias angle \( \theta_B \), the depth of penetration of the nichrome coating varies around the channel.
7.7 Efficiency measurements with Fe$^{55}$

The various coatings applied to Detector 4 enabled us to investigate the influence of coating thickness on X-ray detection efficiency. In particular, we investigated the Fe$^{55}$ (5.9 keV) quantum detection efficiencies. The efficiency of a detector at 5.9 keV is of interest for the AXAF satellite. In order to make such measurements, we removed the "standard" VTF 2 X-ray source and replaced it with an Fe$^{55}$ source. This source had a strength of 20 millicuries (equivalent to 7.4 x 10$^8$ disintegrations per second). We removed the VTF 2 collimating holes in order to increase the count rate at the detector, but this resulted in the source illuminating the whole front face of the detector. The variation of the Fe$^{55}$ quantum detection efficiency is shown in Figure 7-43 as a function of the angle of X-ray incidence for a number of the coating configurations of Detector 4. At the AXAF largest incidence angle (3.5°), the highest efficiency that we measured was 18 percent.

The variation with X-ray energy of the peak gain and FWHM of both the "four-coatings" configuration (test position A) and the "7100 Å coating" configuration (test position B) of Figure 7-35 is tabulated in Table 7-2. The results from the four coatings configuration show the Fe$^{55}$ peak gain to be some 7-8 percent greater than that of the corresponding Si K measurement, but, unfortunately, the fraction of Fe$^{55}$ counts that had a gain higher than the upper limit of the Si K distribution was minimal.

The distributions obtained from the 7100 Å coating configuration under Fe$^{55}$ illumination were doubly peaked, even at an incidence angle as high as 5° (see Figure 7-44). Under Si K illumination, the corresponding distributions became doubly peaked only at incidence angles less than 1.5°. The higher photon energy accentuated the transparency of the photocathode.

7.7.1 Multiple channel crossings

We performed some Fe$^{55}$ efficiency measurements on
Figure 7-43 Variation of MCP quantum detection efficiency as a function of X-ray angle of incidence $\theta_x$ for four coating configurations of MCP F4. Fe$^{55}$ (5.9 keV) X-rays.

- $V_F = 1400$ volts, $V_G = 200$ or 600 volts, $V_R = 1700$ volts.
- (1) - uncoated MCP F4.
- (2) - $t_F = 7100$ Å of CsI.
- (3) - $t_F = 14000$ Å of CsI.
- (4) - $t_F = 27500$ Å of CsI.
<table>
<thead>
<tr>
<th>Configuration</th>
<th>Figure 7-35</th>
<th>Figure 7-35</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Position A</td>
<td>Position B</td>
</tr>
<tr>
<td>X-ray line</td>
<td>$V_g = -25$ volts</td>
<td>$V_g = 200$ volts</td>
</tr>
<tr>
<td></td>
<td>$G_C$</td>
<td>$\Delta G_C$ / $G_C$</td>
</tr>
<tr>
<td>C K</td>
<td>1.32</td>
<td>70</td>
</tr>
<tr>
<td>Si K</td>
<td>2.14</td>
<td>65</td>
</tr>
<tr>
<td>Fe$^{55}$</td>
<td>1.81</td>
<td>99</td>
</tr>
</tbody>
</table>

Table 7-2 Comparison of the peak gain $G_C$ and FWHM $\Delta G_C / G_C$ of two coating configurations of Detector 4, each at two values of $V_g$. X-ray energies C K (0.28 keV), Si K (1.74 keV) and Fe$^{55}$ (5.9 keV). $\theta X = 50$. $V_F = 1400$ volts, $V_R = 1700$ volts.
Figure 7-44 Tandem-pair output pulse height distribution from Detector 4 in the configuration shown in Figure 7-35. Test position B.

Fe$^{55}$ (5.9 keV) X-rays. $\theta_x = 5^\circ$.

$V_F = 1400$ volts, $V_G = 200$ volts, $V_R = 1700$ volts. The double peak indicates the transparency of the photocathode at this photon energy.
Detector 6. This detector, it will be recalled, incorporated 8 micron MCPs. The measured efficiencies are plotted in Figure 7-45, together with six calculated curves. Curves (1) and (2) are the "single-channel" efficiencies [28] associated with the minimum and maximum channel wall coating thicknesses (310 Å and 550 Å respectively for a 14000 Å coating of CsI deposited at 4°). By "single-channel", we mean that no significant fraction of the beam penetrates a septum and illuminates a second channel.

Figure 7-45 Quantum detection efficiency of Detector 6 as a function of X-ray angle of incidence $\theta_X$. Fe$^{55}$ (5.9 keV) X-rays. The six curves are:
(1) Single-channel efficiency, $t_C = 310$ Å.
(2) Single-channel efficiency, $t_C = 550$ Å.
(3) Multiple-channel efficiency, $t_C = 310$ Å, $S_M = S_{av} = 4.51$ microns.
(4) Multiple-channel efficiency, $t_C = 550$ Å, $S_M = S_{av} = 4.51$ microns.
(5) Multiple-channel efficiency, $t_C = 310$ Å, $S_M = S_{min} = 1.6$ microns.
(6) Multiple-channel efficiency, $t_C = 550$ Å, $S_M = S_{min} = 1.6$ microns.
Considering an MCP as an array of parallel multipliers, and referring the X-ray flux at each channel back to the input, the following weighting factor [28] can be arrived at:

$$F(\theta, \lambda) = \frac{(1 + a - 2.a(M + 1))}{(1 - a)}$$

where:

- $$a = \exp(-\mu.S_M.\csc \theta_X)$$
- $$M = \frac{\text{L}_{\text{eff}} \tan(\theta)}{\theta}$$ is the number of channels traversed by the beam
- $$S_M$$ is the characteristic separation of the channels
- $$\text{L}_{\text{eff}}$$ is the effective MCP thickness, which is equal to the length of channel coated with CsI (because the efficiency of the glass is negligible compared to that of the CsI)
- $$\mu$$ is the linear absorption coefficient for channel plate glass.

Because $$S_M$$ is not a well defined quantity (the channel "separation" varies from a minimum value of $$p - D = S_{\text{min}}$$ upwards), this expression is approximate. For Detector 6, $$\text{L}_{\text{eff}}$$ was 14.3 D, or 0.11 mm.

Curves (3-6) plotted in Figure 7-45 were calculated by taking into account the weighting factor $$F(\theta, \lambda)$$ appropriate for multiple channel crossings. Curves (3) and (5) were calculated assuming a 310 Å thickness and curves (4) and (6) were calculated assuming a 550 Å thickness of CsI. Curves (3) and (4) were calculated with $$S_M$$ set equal to $$S_{\text{av}}$$, the average septal thickness, where

$$S_{\text{av}} = p - \left[\frac{4}{\pi}\right].\left[\frac{D}{2}\right]$$

($$S_{\text{av}}$$ is 4.51 microns for an 8 micron MCP) and curves (5) and (6) were calculated with $$S_M$$ set equal to $$S_{\text{min}}$$, the minimum septal thickness ($$S_{\text{min}}$$ = 1.6 microns for an 8 micron MCP). Both curves (4) and (5) fit the experimental data rather well for incidence angles greater than 10 percent.

Figure 7-46 corresponds to Figure 7-45 except that the data is for Detector 4, which incorporated 12.5 micron MCPs.
Figure 7-46 Quantum detection efficiency of Detector 4 as a function of the X-ray angle of incidence, $\theta_X$. Fe$^{55}$ (5.9 keV) X-rays.

The six curves are:

1. Single-channel efficiency, $t_C = 310 \, \mu$m.
2. Single-channel efficiency, $t_C = 550 \, \mu$m.
3. Multiple-channel efficiency, $t_C = 310 \, \mu$m,
   $S_M = S_{av} = 7.04$ microns.
4. Multiple-channel efficiency, $t_C = 550 \, \mu$m,
   $S_M = S_{av} = 7.04$ microns.
5. Multiple-channel efficiency, $t_C = 310 \, \mu$m,
   $S_M = S_{min} = 2.5$ microns.
6. Multiple-channel efficiency, $t_C = 550 \, \mu$m,
   $S_M = S_{min} = 2.5$ microns.
Once again, curve (5) fits the data surprisingly well. There was not much difference between the efficiencies of the 8 micron detector and the 12.5 micron detector despite differences in p - D because the fraction of channel coated with CsI was small in both cases.

7.8 Conclusions

In this chapter, we have summarized the energy resolution results obtained from a number of detectors. The first detector that we tested incorporated MCPs which had 8 micron diameter channels. With no CsI coating, corresponding C K and Si K distributions had different forms. We attributed this "apparent" energy resolution to photon reflections rather than to any real difference in the initiating electron number distributions. When a 14000 Å coating of CsI was deposited on to the detector (at a central coating angle of 45°), actual energy resolution was observed. The results were not much improved on those reported by Fraser and Pearson [105]. We did observe that there was a considerable variation of the peak gain with position on the detector. We investigated the variation of \( G_C \) and \( \Delta G_C / G_C \), together with the calculated figures \( R \) and \( S \), as a function of \( V_G \). This work includes results obtained from detectors that were operated with an electron-retarding interplate electric field. Fraser and Pearson [105] had showed that energy resolution was degraded as \( V_G \) was reduced from +600 volts to 0 volts. We observed that, as \( V_G \) was made negative, the peak gain ratio of the Si K and C K distributions increased. We postulate that such behaviour was due to an electron energy selection effect. The best energy resolution was obtained with \( V_F \) set at as low a voltage as possible. The negative \( V_G \) mode of operation has several advantages. It enables tandem-pair detectors to be operated in a way that is comparable to that of curved-channel detectors, namely with a peak gain of the order of \( 10^6 \) and a low FWHM, and, consequently, an increased count lifetime if, as indicated in Chapter 6, gain degrades as a function of total abstracted charge.

Having noted the effect of negative interplate gap
voltages, we re-tested the detector that had been originally tested by Fraser and Pearson (Detector 4). We investigated the variation of the noise count rate initially. The measured rate decreased at negative values of $V_G$, but this was an artificial effect caused by our use of a fixed electronic lower level discriminator. There was no real change to the number of noise events. The peak gain ratio $R$ and the figure of merit $S$ were calculated, but at both small positive and negative $V_G$ values, the results were not much improved.

In an attempt to decrease the FWHMs of the output distributions, we recoated the already coated half of the input face of the front MCP at a coating angle of $0^\circ$ with 14000 Å of CsI. This caused the FWHM of the output distributions to be decreased by approximately 20 percent, the peak gains being increased by a similar amount, and this implied that the SEEC of the channels had been increased. The figure of merit $S$ decreased, and the efficiency of the detector increased, even at low angles of incidence.

In a further attempt to coat as much of the length of the channels of the front MCP as possible, we coated the rear face of the front MCP with 14000 Å of CsI at a coating angle of $0^\circ$. This coating induced no appreciable improvement of the energy resolution, although the peak gains were increased and the FWHMs were decreased. $S$ was independent of $V_F$ for $V_F$ values greater than 1200 volts. $S$ had a value of 0.31. When $V_R$ was reduced, $S$ decreased slightly.

The next detector configuration that we tested had an increased interplate gap. Under none of our test conditions did the energy resolution parameter $S$ decrease below approximately 0.3. We suspected that this limit was due either to the initiating photoelectron number distributions or to the statistics of the propagation of the avalanche. We deposited a 7100 Å layer of CsI onto the uncoated half of the front MCP. In theory, this should have resulted in a decrease of the low charge component of the distributions. At large incidence angles, the electron distributions were changed. At small incidence angles, though, the Si K distributions developed a distinct low charge bump. We believe that this contradiction with the theory was due to
the emergence of the 1-electron distribution of the underlying lead glass.

Finally, we tested a detector that incorporated a front MCP that had a 40:1 L/D ratio. We hoped that a single deposition of CsI would cause the whole length of the channels to be coated and it appears that we succeeded in this. Unfortunately, the MCP had a 13° channel bias angle. This almost certainly was the cause of the disappointing results that we obtained. We think that the nichrome electrode on the input face caused transverse electric fields to be set up at the input of the channels, inducing reduced detection efficiencies and producing output distributions that were characteristic of 1-electron initiating distributions.

It can be concluded from all of these results that a degree of energy resolution can be obtained, under certain operating voltages, from a detector that has been coated with CsI. The best results can be obtained by applying a voltage of approximately -25 volts across the 160 micron wide interplate gap and by operating the front MCP with a bias voltage close to the transition voltage \( V_{0} \).

Several of our attempts to improve the energy resolution figures were hampered by non-ideal MCPs. This was unfortunate, of course, but it does give some hope for further improvements. The 8 micron MCPs that we used had a larger than desired L/D ratio and they had gain non-uniformity problems. The 40:1 L/D ratio MCP had a nichrome electrode that negated any possible improvements.

Overall, we have shown what the limits to X-ray energy resolution are when using commercial MCPs whose SEEC is rather low. Theory suggests that increasing the SEEC of the channels from the present low glass values of just greater than unity up to three or four should allow a peaked output PHD to emerge from the present exponential distribution even for single electron initiation and no saturation. Rather than change the SEEC by CsI coatings, the way to proceed could be the production of special MCPs, having high SEEC, by modifying the manufacturing process. A collaborative program is being set up with Mullard Ltd. with this aim.
MCP glass with high SEEC would allow

1. peaked PHDs without saturation
2. lower voltages to give the same gain

Giving

3. lower intrinsic noise (if field-strength is the important factor in determining noise).
CHAPTER 8

CONCLUSIONS

Although much of the work reported in this thesis has general applications, many of the measurements were made with either the ROSAT WFC or the AXAF HRC directly in mind. When we began our work, position-sensitive detectors incorporating MCPs had been quite widely used in X-ray astronomy. The intrinsic quantum detection efficiency of these detectors was typically in the 1 - 10 percent range. Even with a deposition photocathode of MgF2, the resultant efficiencies were only enhanced by a factor of 1.1 to 1.6. Also, intrinsic energy resolution had never been reported from an MCP detector.

We will now review the main results reported in this thesis and finally will present some of the observations that it is hoped will be made by the WFC and the HRC.

8.1 Soft X-ray efficiency enhancements

Our initial aim was to investigate the use of CsI as a deposition photocathode material; CsI had been predicted to be far superior to MgF2 in terms of efficiency enhancement. Our preliminary measurements showed that the deposition of a CsI photocathode greatly increased the soft X-ray detection efficiency at all angles of incidence. By coating MCPs at coating angles and thicknesses pertinent for the ROSAT WFC detector, we have shown that the efficiency enhancements conferred by a CsI coating should be a factor of 4 greater than the equivalent enhancements due to an MgF2 coating. Indeed, the open area detection efficiency of the WFC at an incidence angle of 30° has been measured to be greater than 50 percent.

By coating a number of MCPs, we have shown that CsI can reproducibly enhance the soft X-ray sensitivity. We have also shown that, of the processes to which we subjected coated MCPs, namely long-term storage in poor vacuum, high vacuum, dry air and dry N2, deliberate exposure to laboratory air and prolonged X-ray bombardment, only storage
8.2 Energy resolution enhancements

We attempted to improve the limited energy resolution conferred on MCP detectors by CsI photocathodes that was first reported by Fraser and Pearson [105]. We investigated the effects of multiple CsI coatings on energy resolution; this work is relevant for the AXAF HRC. Each additional coating resulted in slight energy resolution improvements, but overall, there was no substantial energy resolution improvement. We believe that the low SEEC of standard commercial MCPs is the prime reason why we were not more successful. If an MCP could be manufactured with a higher SEEC, the soft X-ray energy resolution might be drastically increased.

During the course of the energy resolution investigation, we made quantum efficiency measurements after each additional coating. Over the AXAF range of X-ray incidence angles, the thickest CsI layer enhanced the corresponding bare MCP 5.9 keV efficiencies by a factor of approximately 3. The enhancement of Si K efficiencies over the same incidence angles ranged from 2 to 3.

8.3 Eight micron MCPs

We have tested tandem-pair detectors incorporating 8 micron MCPs. The L/D ratio of the MCPs was 175:1. With \( V_F \) and \( V_R \) set in excess of \( (V_0)_{g} \), the FWHMs were very low. We obtained one Si K output PHD with a FWHM of only 19 percent. With 14000 Å of CsI deposited onto the front MCP, the separation of C K and Si K distributions was better than previously obtained from detectors incorporating 12.5 micron MCPs. The resolution results were not reproducible, though. The gain of the detectors varied markedly with position. This appeared to be an intrinsic property of the MCPs.

The C K and Si K QDEs of an 8 micron detector were similar to the corresponding efficiencies of our 12.5 micron detectors. The Fe\(^{55}\) efficiencies were also similar.
8.4 Negative interplate gap voltages

We have evaluated a new mode of tandem-pair operation. By applying an electron-retarding electric field across the interplate gap, the peak gains were reduced but so were the FWHMs; with between -25 and -50 volts applied across the gap, we achieved the best energy resolution to date.

With a fixed electronic lower level discriminator, operation of a detector with an electron-retarding interplate field results in a reduced dark noise count rate. This apparent decrease is due to the gain decrease. There is no real advantage, in terms of the actual number of noise events, in operating a detector with an electron-retarding interplate field.

8.5 Gain degradation

The gain of our MCP detectors degraded as a function of the accumulated abstracted charge per unit area. This degradation was irreversible; we attribute this to the displacement or removal of an electron source population, possibly K⁺ ions. In addition, operating a detector in a "dirty" vacuum system (i.e. in a vacuum system contaminated by either hydrocarbons or certain diffusion pump fluids) can induce a further degradation of gain.

If natural gain degradation is caused by the displacement of K⁺ ions, it might be possible to reduce the rate of gain degradation by replacing the K⁺ ions with similarly electro-positive but less mobile ions. We treated one MCP with the aim of replacing the K⁺ ions with Cs⁺ ions, and incorporated it as the rear MCP of a detector. The gain degradation rate of this detector was no different from that of detectors that incorporated untreated MCPs.

The use of an electron-retarding interplate potential difference should increase the lifetime of tandem-pair detectors by reducing the charge abstraction rate. Also, by increasing the MCP bias voltages, the gain can be maintained at a high level.
8.6 Proposed observations

The work reported in this thesis will be directly applicable to the ROSAT WFC detectors and the AXAF HRC detectors. In this section, we will describe the observations that should be possible with the ROSAT WFC and the AXAF HRC.

An all-sky survey in the 0.04 - 0.2 keV energy band will be performed by the WFC. Such a survey has only recently appeared to be worthwhile because of the discovery that the density of the interstellar medium in the vicinity (upto 100 parsecs) of the Sun is much lower than the average density (1 hydrogen atom cm$^{-3}$) implied from 21 cm observations. The distance at which the attenuation of EUV radiation is 90 percent should range from tens to hundreds of parsecs. Thus, it may be possible to observe extra-galactic objects at high galactic latitudes.

Only a small fraction of the sky has been observed in the EUV spectral region. Several types of objects have been identified as being strong EUV emitters. These include hot white dwarves ($T = 100000$ K), such as HZ 43, Feige 24 and G191 B2B. The survey will enable the space density of these white dwarves to be estimated.

Stellar coronae and chromospheres are another type of EUV emitter. Proxima Centauri has already been observed. There may be many such observable objects.

Several other types of object may be strong sources of EUV radiation. SS Cygni, a cataclysmic variable, has been detected in the EUV and other cataclysmic variables are known to be soft X-ray sources. Theoretical models of cataclysmic variables disagree as to the presence of an EUV component and, therefore, EUV observations of such objects will be important. Accreting neutron stars, hot sub-dwarves, and the nuclei of planetary nebulae may also be EUV emitters.

The AXAF HRC is designed to make observations in the 0.2 - 8 keV energy range that have a greater sensitivity and spatial resolution than previous observations. It is proposed that the HRC will make observations of objects ranging from X-ray binaries, X-ray pulsars and stellar
coronae, through globular clusters and active galaxies, to clusters of galaxies and quasars at large redshifts. The X-ray background will also be observed.

The observations made by the WFC and HRC over the 0.04 - 8 keV energy range will undoubtedly improve our knowledge of many high energy astrophysical processes and may result in new phenomena being discovered.
## REFERENCES

### Abbreviations

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<tr>
<td>Acta Elec.</td>
<td>Acta Electronica</td>
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<td>Instr. Exp. Tech.</td>
<td>Instruments and Experimental Techniques</td>
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<td>J. Vac. Sci. Tech.</td>
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<td>Nuc. Instr. Meth.</td>
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Reference List

1. Introductory Astronomy and Astrophysics,
   W.B. Saunders Company, Philadelphia, 1973

2. Petersen L.E.

3. Wolter H.
   Ann. Phys. 10 (1952) 94

4. Bleeker J.A.M., Huizinga H., den Boggende A.J.F. and
   Brinkman A.C.

5. Davelaar J., Mango G., Peacock A., Taylor B.G. and
   Bleeker J.A.M.

6. Peckerer M.C., Baker W.D. and Nagel D.J.
   J. Appl. Phys. 48 (1977) 2565

7. Bardas D., Kellogg E., Murray S. and Enck R.

8. Wiza J.L.
   Nuc. Instr. Meth. 162 (1979) 587

9. Manley B.W., Guest A.J. and Holmshaw R.J.

10. Dmitriev V.D., Luk'yanov S.M., Penionzhkevich Yu.E. and
    Sattarov D.K.

11. Lecomte P. and Perez-Mendez V.

12. Fraser G.W.
13. Graf J. and Polaert R.
   Acta Elec. 16 (1973) 11


15. Bateman J.E., Apsimon R.J. and Arndt U.W.
   Rutherford Appleton Laboratory report RL-81-008 (1981)

   Acta Elec. 16 (1973) 43

17. Turner P.J., Cartwright P., Southon M.J.,
    Van Oostrom A. and Manley B.W.

18. Van Oostrom A.
   Acta Elec. 16 (1973) 59

19. Chalmeton V.
   Acta Elec. 16 (1973) 73

20. Clement G. and Loty C.
   Acta Elec. 16 (1973) 101

21. Giacconi R. and thirty co-authors:

22. Van Speybroeck L.P.
    Proc. SPIE 106 (1977) 136

23. Kubierschky K., Austin G.K., Harrison D.C. and
    Roy A.G.


25. de Korte P.A.J. and eight co-authors

27. Barstow M.A., Willingale R., Kent B.J. and Wells A.

28. Proposal to National Aeronautics and Space Administration for High Resolution Camera (HRC) on the Advanced X-ray Astrophysics Facility (AXAF), P1392-2-84

29. Fraser G.W.

30. Oba K., Sugiyama M., Suzuki Y. and Yoshimura Y.

31. Parkes W., Evans K.D. and Mathieson E.

32. Fraser G.W. and Mathieson E.

33. Fraser G.W. and Mathieson E.

34. Gott R., Parkes W. and Pounds K.A.

   Proc. SPIE 106 (1977) 196


37. Smith G.C., Pearson J.P. and Mathieson E.
38. Mathieson E., Smith G.C. and Gilvin P.J.

39. Martin C., Jelinsky P., Lampton M., Malina R.F. and
   Anger H.O.

40. Mackenzie J.D.
   "MCP glass analysis studies" final technical report,
   Materials Department, UCLA (1977)

41. Siddiqui S.H.

42. Washington D., Duchenois V., Polaert R. and
   Beasley R.M.
   Acta Elec. **14** (1971) 201

43. Dhawan S. and Majka R.

44. Timothy J.G.

45. Asam A. R.

46. Hill G.E.

47. Authinarayanan A. and Dudding R.W.

48. Adams J. and Manley B.W.

49. Eberhardt E.E.
50. Evans D.S.

51. Ruggieri D.J.

52. Schmidt K.C. and Hendee C.F.

53. Loty C.

54. Fraser G.W., Pearson J.F., Smith G.C., Lewis M. and Barstow M.A.

55. Fraser G.W., Whiteley M.J. and Pearson J.F.
   Proc. SPIE **597** (1985) 343

56. Timothy J.G. and Bybee R.L.

57. Bateman J.E.
   Nuc. Instr. Meth **142** (1977) 371

58. Fraser G.W., Pearson J.F. and Lees J.E.

59. Siddiqui S.H.
   J. Appl. Phys. **48** (1977) 3053

60. Pearson J.F.

61. Barstow M.A.

62. Firmani C., Ruiz E., Carlson C.W., Lampton M. and Paresce F.
63. Parkes W. and Gott R.
   Nuc. Instr. Meth. 25 (1971) 487

64. Malina R.F. and Coburn K.R.

65. Weston G.F.
   Vacuum 28 (1978) 209

66. Maurice L., Duval P. and Gorinas G.
   J. Vac. Sci. Tech. 16 (1979) 741

67. Smith D.G. and Pounds K.A.

68. Weiser H., Vitz R.C., Moos H.W. and Weinstein A.

69. Timothy J.G., Mount G. and Bybee R.L.
   Proc. SPIE 183 (1979) 169

70. Bjorkholm P.J., Van Speybroeck L.P. and Hecht M.
    Proc. SPIE 106 (1977) 189

71. Parkes W., Gott R. and Pounds K.A.

72. Taylor R.C., Hettrick M.C. and Malina R.F.

73. Fraser G.W., Barstow M.A., Pearson J.F., Whiteley M.J.
   and Lewis M.

74. Polaert R. and Rodiere J.
    Philips Tech. Rev. 34 (1974) 270

75. Carruthers G.R.
76. Henke B.L., Liesegang J. and Smith S.D.  

77. Fraser G.W.  
Nuc. Instr. Meth. 228 (1985) 532

78. Bateman J.E.  
Private Communication

79. Fraser G.W.  
Private Communication

80. Fraser G.W.  

81. Eng W. and Landecker P.B.  

82. Lapson L.B. and Timothy J.G.  
Appl. Opt. 12 (1973) 388

83. Fraser G.W.  

84. Edgcumbe J. and Garwin E.L.  
J. Appl. Phys. 37 (1966) 3321

85. Llacer J. and Garwin E.L.  

86. Gomoyunova M.V. and Garwin E.L.  
Sov. Phys. Solid State 71 (1965) 316

87. Verma R.L.  
J. Phys. D 6 (1973) 2137

88. Handbook of Chemistry and Physics, 55th edition  
CRC Press, Cleveland, Ohio (1974)
89. Heroux L., McMahon W.J. and Hinteregger H.E.  

90. Polehn H., Bratton J. and Feingold R.  

91. Smith D.G.  
   Ph.D. Thesis, University of Leicester (1968)

92. Boutot J.P.  
   Acta Elec. 14 (1971) 245

93. Morgan R.  

94. Rager J.P., Renaud J.F. and Tezenas du Montcel V.  

95. Bates C.W.  

96. Van der Ven H.W.  
   Nuc. Instr. Meth. 75 (1969) 347

97. Antoniv I.P., Vaschenyuk N.N., Levitskaya Ya. A.,  
    Matyukhin V.A. and Tsai* N.A.  

98. Lewis M.  
   Private Communication

99. Scott J.P.  
   J. Appl. Phys. 46 (1975) 661

100. Premaratne K., Dietz E.R. and Henke B.L.  

101. Saloman E.B., Pearlman J.S. and Henke J.L.  
102. Verma R.L.

103. Martin C. and Bowyer S.

104. Rager J.P. and Renaud J.F.

105. Fraser G.W. and Pearson J.F.

106. Lind D.L. and McIlwraith N.


109. Egidi A., Marconero R., Pizella G. and Sperli F.

110. Smith D.G.
    J. Sci. Instr. 44 (1967) 1053

111. Tatry B., Bousqued J.M. and Reine H.
    Nucl. Instr. Meth. 69 (1969) 254

112. Sharber J.R., Winningham J.D. and Sheldon W.R.

113. Bedo D.E.
    Rev. Sci. Instr. 43 (1972) 130

114. Timothy J.G. and Bybee R.L.
    Proc. SPIE 116 (1977) 24
115. Sandel B.R., Broadfoot A.L. and Shemansky D.E.
   Appl. Opt. 16 (1977) 1435

116. U.K. Patent Application, GB 2020481 A, on behalf of
   Tektronix Inc.

117. Gibson D.K. and Reid I.D.

118. Mullard Technical Information 16 (1975)

119. Sakai Y. and Mogami A.
   Surface Science 86 (1979) 359

120. Prince R.H. and Cross J.A.

121. Edwards high-vacuum data

122. Love G., Scott V.D., Dennis N.M.T. and Laurenson L.
   Scanning 4 (1981) 32

123. Cortez J. and Laprade B.
   Galileo Electro-Optics Corporation, Report 427-46

124. Handbook of Reactive Chemical Hazards
   Butterworths, London (1979)

125. Pearson J.F.
   Private Communication

126. Drenkhan J., Gross H. and Glaefeke H.

127. Muller F. and Rickes W.

128. Muller F.
   Exp. Tech. Phys. 20 (1972) 455
129. Audier M., Delmotte J.C. and Boutot J.P.

130. Field R.
Private Communication

131. Ainbund M.R. and Maslenkov I.P.


133. Oba K., Rehak P. and Smith S.D.

134. Bell R.L.

135. Barstow M.A., Fraser G.W. and Milward S.R.
Proc. SPIE **597** (1985) 352
ABSTRACT

The initial aim of the work presented in this thesis was to increase the soft X-ray quantum detection efficiency of a tandem-pair microchannel plate detector by the use of a CsI deposition photocathode. This aim was achieved. The coating technique and initial measurements are presented herein. After showing the use of such photocathodes, we investigated their stability and reproducibility. The effects of storage in poor vacuum, high vacuum and desiccated air are presented as is the stability of CsI photocathodes under prolonged X-ray bombardment.

One consequence of the use of CsI is that a degree of energy resolution can be conferred upon a microchannel plate detector. We present further research in this field, including measurements performed on detectors with eight micron diameter channels.

A feature of microchannel plate operation that is undesirable is the phenomenon of gain degradation. We performed a series of lifetests on a number of microchannel plate detectors.