Fermi National Accelerator Laboratory

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A CsI-TMAE Photocathode with Low-Pressure Readout for RICH *

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Abstract

The operation of a CsI photocathode activated with an adsorbed layer of TMAE and coupled to a low-pressure wire chamber is presented. A quantum efficiency of 15% at wavelengths less than 190 nm, with single-step amplification gains of up to 10^7, and a signal width of 5 ns at the base were achieved. Ageing effects due to ion bombardment of the photocathode are discussed.

1. Introduction

The new proposed hadron colliders (SSC and LHC) put additional constraints on Ring Imaging Cherenkov detectors, RICH: they must work at high rates with one time-bucket resolution (<16 ns); due to the 4π nature of the experiments, the detectors must be insensitive to charged particles while maintaining high efficiency for single photoelectrons; the RICH detector must not suffer from ageing problems in the high rate environment. None of these requirements is adequately met by present RICH detectors. Existing detectors are operated at atmospheric pressure and have long drift regions (DELPHI, OMEGA, SLD, etc.), making them slow and sensitive to charged particles.

All operating RICH detectors use a gas photosensor, either TEA (triethylamine) or TMAE (tetrakis(dimethylamino)ethylene). The advantages of TEA are its high vapor pressure, (allowing for shallow photon conversion depth) and its insensitivity to air. The main disadvantages are that its high ionization potential (7.5 eV) requires the use of CaF_2 windows and its peak sensitivity overlaps the peak absorption of O_2. The UV windows are very expensive and the radiator is sensitive to contamination by air.

TMAE has the advantage of a low ionization potential (5.36 eV) allowing for the use of quartz windows and its greatly reduced sensitivity of the radiator to O_2 contamination. As a photosensor it has a higher quantum efficiency [1], QE, and with its large wavelength range of acceptance, it yields a higher number of photoelectrons. Its main disadvantages are that it has a long absorption length at room temperature (on the order of 2 cm) [1,2], and its reactivity with O_2 and many of the materials used in wire chamber construction. For good timing the long absorption length requires that the detector be operated at an elevated temperature (to increase the vapor pressure) and with a reduced active region (which reduces the QE).

An ideal RICH detector would have a photocathode on a surface so that all the photoelectrons would have the same transit time in the wire chamber. The first liquid photocathode was demonstrated [3] when TMAE was condensed in a thin layer on a cooled surface and read out with a low-pressure wire chamber. This photocathode was later coupled to a BaF_2 scintillator [4]. The advantage of low-pressure chambers is that they are insensitive to charged particles and the ion collection time is reduced by a factor as large as 10^3. A timing resolution of 540 ps FWHM was measured for 350 MeV α particles, while the signal when shaped with a fast amplifier was approximately 30 ns at the base [4]. (See ref.5-7 for further work on liquid photocathodes)

Another advantage of low-pressure wire chambers is that they allow stable operation with high gain in pure organic gases at reasonable operating potentials. This allows the use of gases that produce much less scintillation in the amplification process and thus allow

higher gain with reduced photon feedback. It has also been shown that the use of noble gases reduces the efficiency of a non-gaseous photocathode [4,7].

Other photocathodes, both liquid and solid, such as frozen TMAE, neopentane+ TMAE, diethyl ferrocene, and tetramethyl-p-phenylenediamine (TMPD) have been studied [5-7]. Of these, the frozen layer of neopentane+TMAE (-20°C) had the highest efficiency of about 3% at 235 nm [5]. All others were inferior to the TMAE liquid photocathode. The major disadvantage with liquid or frozen photocathodes is that they require that the chamber be operated with differentials in temperature, or both cooled and heated. This would not be practical for a low-mass, 4π detector.

It has been reported that the exposure of metal to TMAE vapor made it much more sensitive to UV light [4]. This phenomenon has been investigated and shown to increase the QE of a metal surface by as much as a factor of 10^3 [5,7]. With a QE of 10^{-4} for some metals, this yields a useful photocathode with a QE on the order of 10%. As will be seen, this is also an important phenomenon for the photocathode considered in this work.

Another interesting photocathode is pure CsI. It has the advantages that it is easy to make, can be handled for a short time in air, and has a QE of about 10% at about 170 nm [8]. This photocathode had been demonstrated to work well for the detection of the scintillation of Xe gas (peak $\lambda \approx 170$ nm) by Dangendorf et al. [9,10]. They reported a QE of 9% at that wavelength and their work is the first application of a CsI photocathode to a wire chamber. Séguinot et al. [7] have reported a higher QE of 35% at 170 nm for this photocathode.

A further development has been reported by Séguinot et al., who combined the CsI photocathode with the QE enhancing effect of adsorbed TMAE, achieving a QE of 46% at 170 nm. This is about 30% higher than for an optically thick layer of TMAE gas and much better than for photomultiplier tubes, PMT. They report two reasons for adsorbing TMAE onto the CsI: the QE of CsI increases with adsorbed TMAE, much as is seen for metal surfaces; the QE of CsI with adsorbed TMAE is less sensitive to exposure to air and can be restored with a flow of methane gas. This reduced sensitivity to air is unexpected since separately CsI reacts with the water in air [10] and TMAE reacts vigorously with oxygen [11]. Thus, the exposure to air of this photocathode should degrade the quantum efficiencies of both components.

There has been a conceptual problem of how to readout a photocathode on a surface in a high multiplicity environment with a wire chamber. For high multiplicities, it is believed by many that one must use a pad readout. If an opaque photocathode (i.e. one facing the window) is used, the amplification takes place towards the window and thus the pads must

be transparent. Charpak et al. [12] introduced the concept of depositing the photocathode on individual pads with amplification in a single step.

In this article we report the first application of a CsI-TMAE photocathode, deposited on pads in a low-pressure wire chamber. We discuss signal shape, gain characteristics and show that they fulfill the first two requirements of a RICH detector in a high-rate hadron environment. The problem of photocathode ageing is discussed in some detail.

2. Experimental Setup

The experimental detector for ultraviolet photon detection is shown schematically in Figure 1. The cathode pads are etched on a printed circuit board with copper cladding on both sides. Feedthroughs connect the photocathode pads with pads on the back. The cathode pads are sensitized by an evaporated CsI layer with adsorbed TMAE. The space between the cathode pads and the 6 mm thick quartz window can be varied but the total distance was kept at about 20 mm. In the measurements reported here, the cathode-anode spacing was varied from 3.18 mm to 0.13 mm. The anode was either a mesh (12.7 μm stainless steel wires with 254 μm pitch, 90% transparent) or a wire plane (20 μm gold plated tungsten wires with 1 mm pitch). Ground potential at the quartz window was maintained by a 90% transparent mesh which was 127 μm from the window.

The chamber was constructed with six independent photocathode pads. Using a mask on the quartz window, the photocathodes could be operated one at a time. This proved to be useful in the ageing measurements, since it provided photocathodes that had been exposed to the same environment, but not to UV light.

Several gases, transparent (or semi-transparent) down to the quartz cutoff, were tried. Before filling, the detector was first evacuated to a pressure of a few mTorr. The gas fillings typically were at pressures of 60 Torr or less, and the detector was sealed. In order to determine the absolute QE of the solid photocathode, TMAE gas was used as a reference.

An ultraviolet photon traverses the quartz window, the ground wire mesh and the anode wire mesh, releasing a single electron on the surface of the solid photo-cathode. This electron is attracted towards the anode which was held at a positive potential. The applied electric field was sufficiently high that avalanche multiplication occurs. The induced current on the pad was amplified by an external amplifier.

The ultraviolet light source was a hydrogen arc discharge lamp operating in a relaxation oscillator mode at a rate of about 120 Hz. The light source had a pickup used to form a synchronized electronic trigger. This light pulse had a width less than 3 ns and has a broad spectrum of wavelengths down to the quartz window cutoff at about 170 nm. The

desired wavelength was selected with a monochromator flushed with nitrogen to avoid the ultraviolet absorption of air.

3. Photocathode Preparation

The photocathode was fabricated as follows. The printed circuit board was cleaned in turn with an abrasive, acetone, and ethyl alcohol. A 0.2 μm layer of aluminum was evaporated onto the 28 mm^2 copper pads in vacuum at a nominal pressure of $6x10^{-5}$ Torr. (Later we determined that aluminizing the pads is not a necessary step.) The vacuum was broken and the tungsten boat used for aluminum was replaced by a molybdenum boat with CsI of scintillator purity. Layers of various thickness from 0.3 to 2.0 μm of CsI were evaporated onto the pads in vacuum at a nominal pressure of $5x10^{-5}$ Torr and at a rate between 0.01 and 0.026 μm/s. The thickness of the evaporated layers was monitored with a quartz crystal oscillator. Immediately after the evaporation of CsI, and without breaking the vacuum, the evaporation chamber was filled with TMAE gas to a pressure of about 100 mTorr in order to adsorb a layer of TMAE on the CsI film. To reduce the time from the end of the CsI evaporation to the TMAE adsorption, a tube directs the TMAE to the photocathode. The photocathode board was removed in air from the evaporation chamber and mounted into the detector chamber which was then pumped down to a nominal pressure of 1 mTorr. In this process the CsI-TMAE photocathode was exposed to the ambient air for 20 to 50 minutes. The photocathode was not exposed to TMAE gas again except for the measurement of relative QE described below.

4. Test Results

4.1. Photocathode Quantum Efficiency

To determine the QE of the CsI photocathode, its efficiency was measured relative to that of TMAE gas. For the measurement of the CsI photocathode, the counter was filled with 60 Torr of methane and was operated with single-step amplification. The cathodes pads were held at ground potential and the anode was typically at +500 V.

For the TMAE gas measurement, the detector was filled with 60 Torr of methane and 0.3 Torr of TMAE gas. The direction of electron drift was reversed from that when the CsI-TMAE photocathode was studied. The region between the quartz window and the "Anode", Fig.1, was operated as a conversion and drift region. The cathode pads were held at a higher positive potential than the mesh marked "Anode" in Fig. 1 and used as the true anode. Thus, the signal, has no component from the CsI photocathode. Typical voltages are +300 V and +800 V on the "Anode" and "Cathode" pads, respectively.

The relative efficiencies were measured with the single photon technique. First the TMAE gas was added to the counter and the detector operated as described above. The intensity of the source was reduced until the number of photons detected from TMAE was between 0.1 and 0.3 per pulse from the UV source. The TMAE was then removed, the methane replaced, and the voltages adjusted for normal operation of the photocathode. The number of photoelectrons per UV pulse was then measured for the CsI photocathode. The QE of the TMAE gas was taken to be that of the literature, corrected for transmission of the grids and corrected for the finite absorption in the space between the quartz window and the "Anode". The corrections for the grid transmission and the finite absorption of the TMAE were of order 10% and 50%, respectively.

The results of the CsI-TMAE QE efficiency measurements are given in Fig. 2. The data points are for two pads, one with a 0.3 μm thick layer of CsI and the other one a 2 μm thick layer. The solid line is the average QE from the measurements. The QE of an optically thick layer of TMAE gas [1] is shown for comparison. Séguinot et al. reported an increase in QE with increase in CsI thickness up to 0.5 μm. There was no significant difference in QE seen in this work for CsI thicknesses ≥ 0.3 μm. For wavelengths shorter than about 190 nm, the QE is ≥ 15%, adequate for a RICH detector.

The 15% QE for the CsI-TMAE photocathode is a factor of three lower than the 46% reported by Séguinot et al, who also achieved a factor of four better QE for a pure CsI photocathode than reported elsewhere [8,9]. The origin of these discrepancies may be that they are the only ones that have flushed their photocathodes with clean methane and they have shown that this is an important step in improving the QE of these photocathodes.

4.2. Gas Gain

The gases tested are listed in Table 1. The table is divided into two categories: those that gave sufficient gain ($>10^5$) and those that gave insufficient gain. Only some of these results will be reported here. Isopropyl alcohol was also tested but significant absorption of the UV light resulted in a reduction of the apparent QE of the photocathode. The data presented here were all taken with the wire-mesh anode unless otherwise stated.

A typical result for "maximum gain" as a function of gas pressure for various cathode-anode spacings is shown for methane in Fig. 3. Maximum gain is defined as just below the point where the chamber became unstable and began to spark. An interesting result, shown here for methane but seen more or less for all gases, is that there is an optimum gap thickness at around 1.59 mm. The maximum gain as a function of pressure for an anode-cathode gap of 1.59 mm is shown for a variety of gases in Fig. 4. This thickness also has

an optimum pressure. In the case of methane, this pressure is near 20 Torr. Again one can see that there appears to be an optimum pressure for each gas.

In Fig. 4, three gases (hexane, pentane, and ethane) show gains greater than 10^6. This gain gives a signal to noise ratio in excess of 10^3 for single photoelectrons when a long shaping time was used (see next section). Figure 5 shows a typical pulse-height spectrum for single photoelectrons. The spectrum is quite well resolved from the noise.

A pulse-height spectrum for the CsI taken with a small collimator and a gas filling of 49 Torr of helium plus 2 Torr of outgassing (alcohol?) from the chamber is shown in Fig. 6. The 1, 2, and 3 electron peaks are easily discernable. The noise peak has been removed. Although the conditions under which Fig. 6 was taken could not be reproduced, it does show the single-electron resolution achievable with a low pressure proportional counter.

One set of measurements was made with methane and the wire plane anode with an anode-cathode spacing of 0.794 mm. A comparison of the results for the wire-plane and wire-mesh anodes is shown in Fig. 7. A factor of almost 6 higher gain is achievable with the wire plane. Because of ease in construction with wire-meshes for large chambers, we restricted our work to the wire-mesh anode.

4.3. Signal Shape

In parallel-plate amplification, there is a fast and a slow component to the current induced on the pad. The fast component is due to the drift of the electrons. The slow component is due to the drift of the positive ions across the gap. Since the contribution of an electron or a positive ion is proportional to the fraction of the gap traversed, and since most of the electrons are liberated in the last two mean free paths for amplification, the electron component is much small than that of the positive ion. Figure 8 shows the pulse shape for a 0.794 mm gap, 7 Torr of isopropyl alcohol, and an anode voltage of -410 V. The gain in this example is 4×10^4. The signal was taken directly off the oscilloscope with a 50 Ω input impedance, and the bandwidth limited to 20 MHz. The two components are clearly visible. In this case, the area of the electron component is about 10% that of the positive ion component. If the bandwidth were not limited, the electron component would be a narrow spike 18 times higher than the positive ion signal, as can be seen in Fig. 9 which shows the detail of the "fast" component with the full 350 MHz bandwidth of the oscilloscope. The signal is only about 5 ns at the base. This example is not the pulse for single photoelectrons, but the signal for a few (<5) photoelectrons.

Figure 10 shows the ion drift times as a function of pressure for a 1.59 mm gap for several gases. The positive ion drift times were taken at the maximum gain for the gas and

defined as the total collection time for all of the ions. Note that methane and ethane are fast gases while pentane, hexane, and isopropyl alcohol are relatively slow.

4.4. Photocathode Ageing

During this investigation, measurements were made on several photocathodes over a period of approximately three weeks . The photocathodes were typically exposed to air four times for a total of approximately 160 minutes. During the three week period, there was little or no degradation of QE of unused pads. The most rapid loss of efficiency apparently occurs when measurements with TMAE gas are being made, especially if an intense mercury source was used instead of the pulsed hydrogen source. It is known that TMAE gas accelerates aging of wire chambers by forming a thick liquid on the anode. [13].

For all gases a loss in QE proportional to the collected charge was seen. There was no accompanying change in gain. A likely cause of this aging effect is that the positive ions undergo charge exchange with the CsI and the CsI dissociates. Since iodine has a substantial vapor pressure, when the CsI dissociates, the iodine leaves the photocathode:

$$X^+ + CsI \rightarrow X + CsI^+$$
$$\hookrightarrow Cs^+ + I,$$

where X^+ is the positive ion. Figure 11 shows the relative QE as a function of collected charge for three gas mixtures. Within a factor of 2, the degradation in QE is the same for the three gases and depends only on the collected charge. The QE degrades to a value of e^{-1} of its initial value when the accumulated ion charge is of the order of 4×10^{-5} C, which corresponds to about 2.5×10^{14} ions. The number of CsI molecules in a volume with an area the size of the illuminated part of the cathode (≈ 3 mm^2) and 0.3 μm thick is of the same order of magnitude.

This hypothesis is also consistent with the work by Dangendorf et al. [10] with pure CsI photocathodes. They see similar losses and also report an increase in the Cs:I ratio as the cathode ages. Another clue that this is happening in our case comes from the fact that as the photocathode ages it becomes sensitive to room light. The ionization of elemental Cs is only 3.9 eV [14] (318 nm) and thus Cs would be sensitive to room light.

It should also be noted that positive ion bombardment of the photocathode of a PMT is known to cause damage and a loss of sensitivity [15]. The rate of damage is proportional to the positive ion current.

If the positive ion charge exchange hypothesis is correct for the source of degradation of the CsI and CsI-TMAE photocathodes, this seems to be a fundamental problem. With the exception of TMAE gas, the ionization potential of all gases used in wire chamber is higher than that of the CsI photocathodes. Thus, all gases used in the wire chamber will degrade the performance of the photocathode.

5. Discussion

The CsI-TMAE photocathode, deposited on pads and coupled to a low-pressure wire chamber operated in the single step amplification mode, is a promising device for the detection of UV photons. The photocathode can be handled in air; the low-pressure wire chamber can achieve a gain as high as 10^7, has a 100% detection efficiency for the detection of single photoelectrons, and can produce a signal only a few nanoseconds at the base with excellent timing characteristics. Low-pressure, single-step amplification is also insensitive to passing charged particles since there is very little ionization and only the rare electron liberated near the cathode will have high enough amplification to be detected.

The single-step amplification also simplifies the construction problems associated with large-area, low-pressure chambers. Since the anode-mesh is less than 2 mm from the photocathode and less than 1 mm from the quartz window, small ceramic spacers can be placed every centimeter or two on both sides of the mesh to support the window and cathode planes off each other. Sparking at the spacers locations would not be a problem since low-pressure wire chambers are operated at much lower voltages than for conventional wire chambers. This would allow the window and the cathode planes to be fairly low mass and the total detector thickness to be less than 1 cm.

The real weakness of a CsI photocathode is the destruction by the positive ions. Operated with single-step amplification and a gain of 10^6, the detector would have a lifetime of about one day at the SSC and even less at the LHC. This seems to be a fundamental problem since there are no gases (other than TMAE) with a lower ionization potential than the CsI or CsI-TMAE photocathode. If the amplification is done in a multi-step chamber, it is difficult to see how high multiplicities can be handled. If the cathode is placed on the quartz window, a suitable conductive, transparent substrate must be first applied and the cathode must be semi-transparent. The construction of such a photocathode would require good uniformity and a tight tolerances on the thickness. Being a semi-transparent photocathode, the QE would be lower than than for an opaque photocathode.

One solution to the problem may be to search for a way to reconstitute the photocathode in place, possibly by flowing gas with a small concentration of iodine vapor and TMAE gas. Also, the photocathode consisting of metals activated with TMAE should

be reconsidered. The TMAE is easier to replace and the condition of the metal surface would be much more robust.

Although the solid photocathode has not been shown to be able to survive the ageing anticipated at the new hadron colliders, there are other applications where they may prove to be very useful. The instrument described above would be ideal for the detection of Cherenkov radiation from air showers. It would also be useful for the detection of the fast scintillation from BaF_2 where multi-step amplification can be used, reducing the positive ion feedback

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References

[1] R.A. Holroyd, J.M. Preses, C.L. Woody and R.A. Johnson, Nucl. Instr. and Meth. A261 (1987) 440.

[2] R. Arnold et al., Nucl. Instr. and Meth. A270 (1988) 255.

[3] D.F. Anderson, Phys. Lett. 118B (1983) 230.

[4] D.F. Anderson et al., Nucl. Instr. and Meth. 217 (1983) 217.

[5] V. Peskov et al., Nucl. Instr. and Meth. A269 (1988) 149.

[6] G. Charpak, V. Peskov, F. Sauli, and D. Scigocki, Nucl. Instr. and Meth. 277 (1989) 537.

[7] J. Séguinot et al., *Reflective UV Photocathodes with Gas-Phase Electron Extraction: Solid, Liquid, and Adsorbed Thin Films*, CERN-EP/90-88, JUNE 20, 1990, submitted to Nucl. Instr. and Meth. A.

[8] G. Charpak, V. Peskov, and D. Scigocki, *New Scintillators and Photosensitive Gaseous Detectors*, Proceedings of the Symposium on Particle Identification at High Luminosity Hadron Colliders, Fermilab, Batavia, 5-7 April 1989.

[9] V. Dangendorf, A. Breskin, R. Chechik and H. Schmidt-Bocking, Nucl. Instr. and Meth. A289 (1990) 322.

[10] V. Dangendorf, A. Breskin, R. Chechik and H. Schmidt-Böcking, presented at the SPIE 1990 Symposium on Instrumentation in Astronomy, Tucson, Arizona, 12-17 Feb. 1990.

[11] D.F. Anderson, Nucl. Instr. and Meth. 178 (1980) 125.

[12] G. Charpak, V. Peskov and D. Scigocki, *Studies of BaF_2 Calorimeters in Future Hadron Colliders*, talk given at the 8th Workshop of the INFN-ELOISATRON Project on Perspectives for New Detectors in Future Supercolliders, Erice, 17-24 Oct. 1989.

[13] J. Vavra et.al., IEEE Trans. Nucl. Sci. NS 35 (1988), p. 487; and C.L. Woody, IEEE Trans. Nucl. Sci. NS 35 (1988) 493.

[14] Handbook of Chemistry and Physics, 67th ed.,ed., C. Weast (Chemical Rubber Co.,Cleveland, Ohio, 1986)

[15] *RCA Photomultiplier Handbook*, RCA Corp., 1980.

Table 1: Gases tested either alone or in combinations.

Sufficient Gain		**Insufficient Gain**
methane	ethanol	helium
ethane	methanol	argon
pentane	acetone	nitrogen
hexane	TEA	isobutane

Figure Captions

Figure 1: Schematic of experimental detector.

Figure 2: Quantum efficiency of the CsI-adsorbed TMAE photocathode as a function of wavelength. The data points are for two measurements each of two photocathodes with different CsI thicknesses. The Quantum efficiency of an optically thick layer of TMAE gas is also shown.

Figure 3: Maximum gain as a function of methane pressure for various anode-cathode spacings.

Figure 4: Maximum gain as a function of pressure of various gases for a 1.59 mm anode-cathode spacing.

Figure 5: Single photoelectron pulse-height spectrum.

Figure 6: Best pulse-height spectrum measured. The 1, 2, and 3 electron peaks can be seen.

Figure 7: Maximum gain as a function of methane pressure for a wire-plane anode and for a wire-mesh anode.

Figure 8: Single-step amplification signal shape taken directly off the oscilloscope with a 50 Ω input impedance and a 20 MHz bandwidth.

Figure 9: Detail of the fast component with the full 350 MHz bandwidth of the oscilloscope.

Figure 10: Ion drift time, taken at maximum gain, as a function of pressure for various gases. The anode-cathode spacing is 1.59 mm.

Figure 11: Relative quantum efficiency as a function of collected charge for various gases.

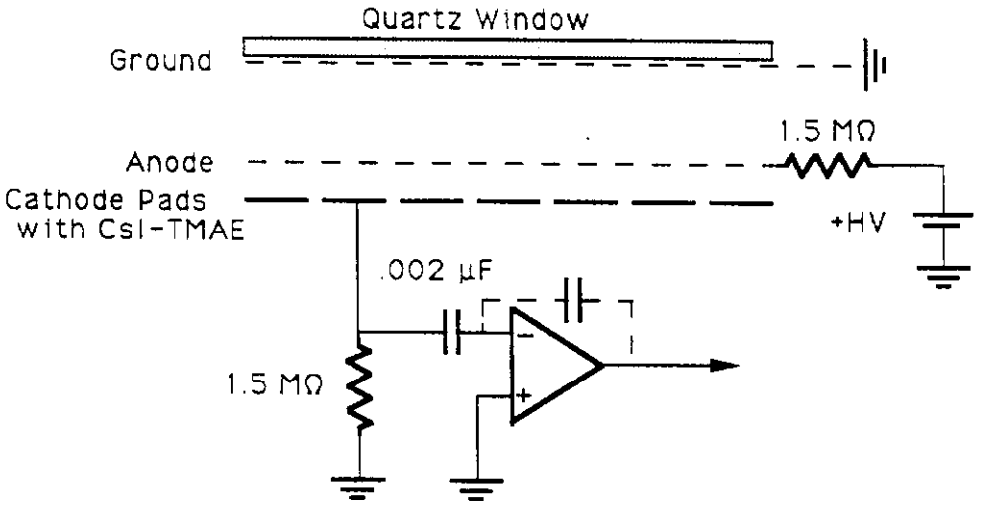

Figure 1

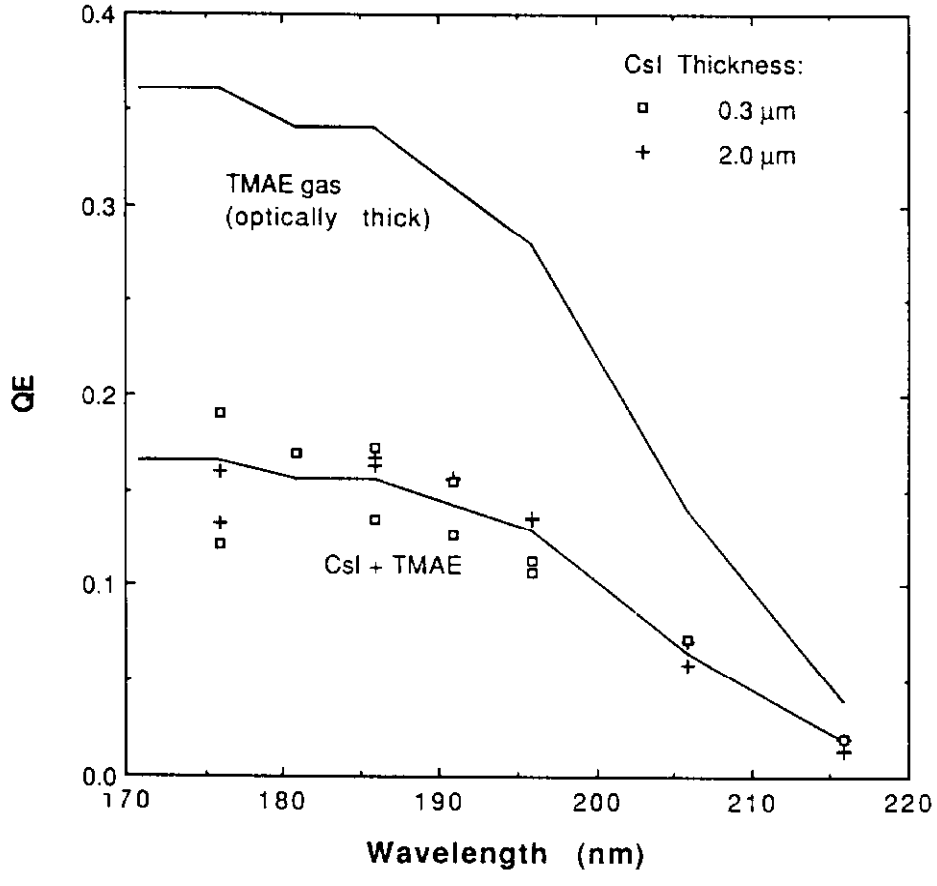

Figure 2

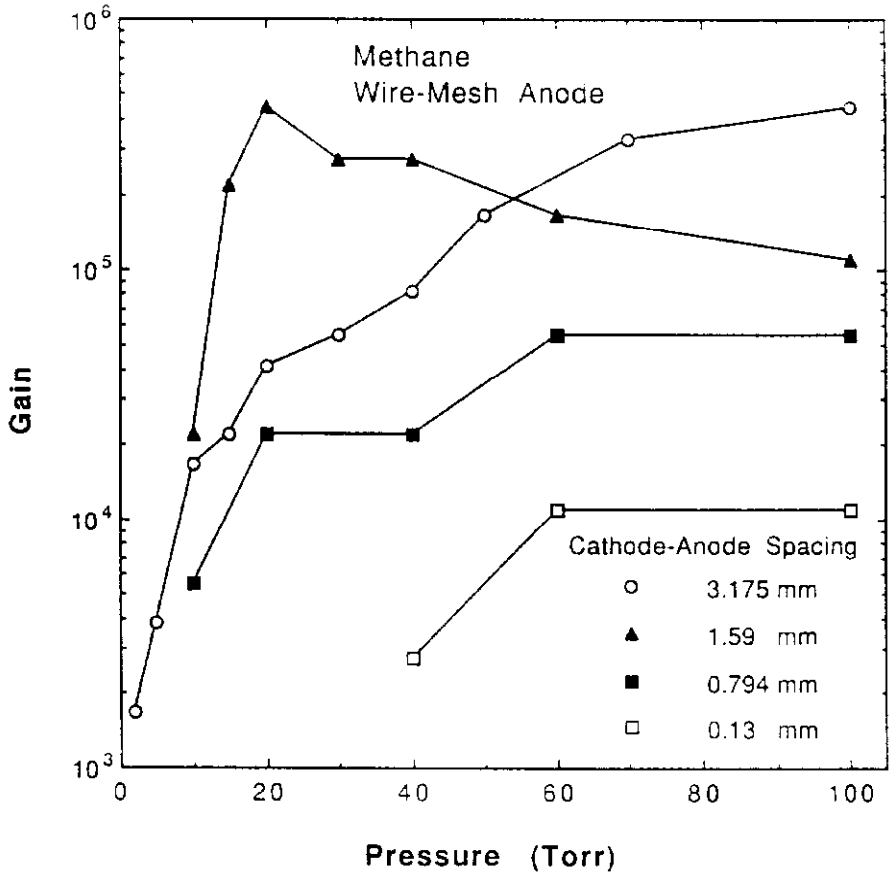

Figure 3

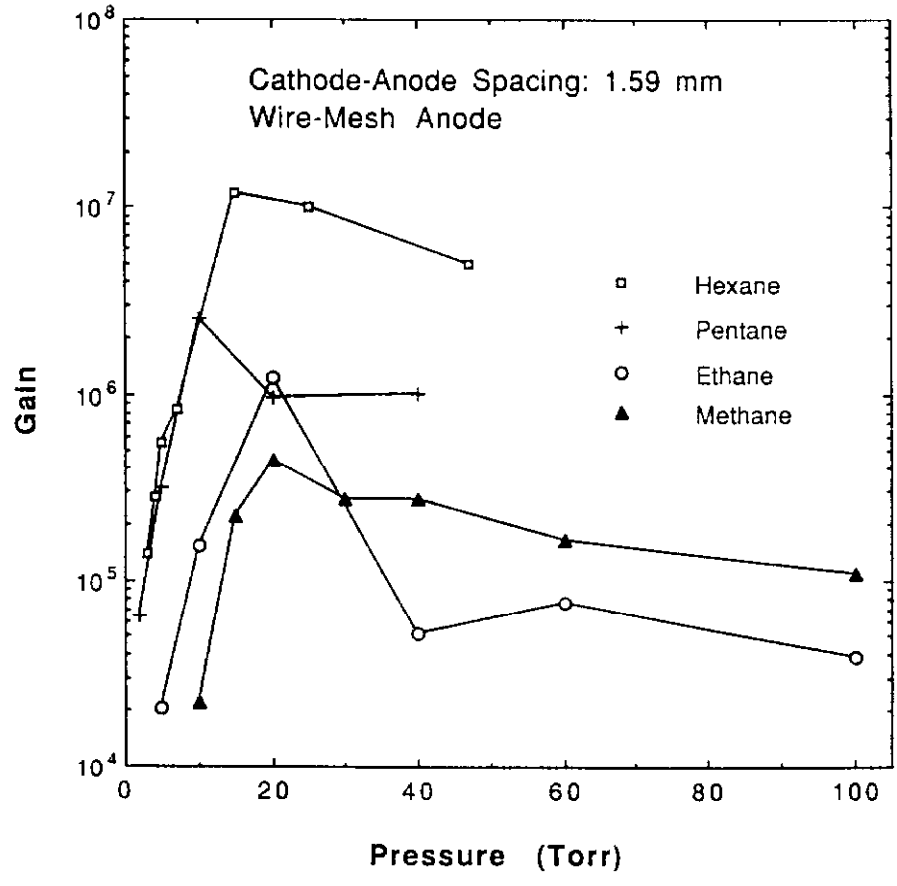

Figure 4

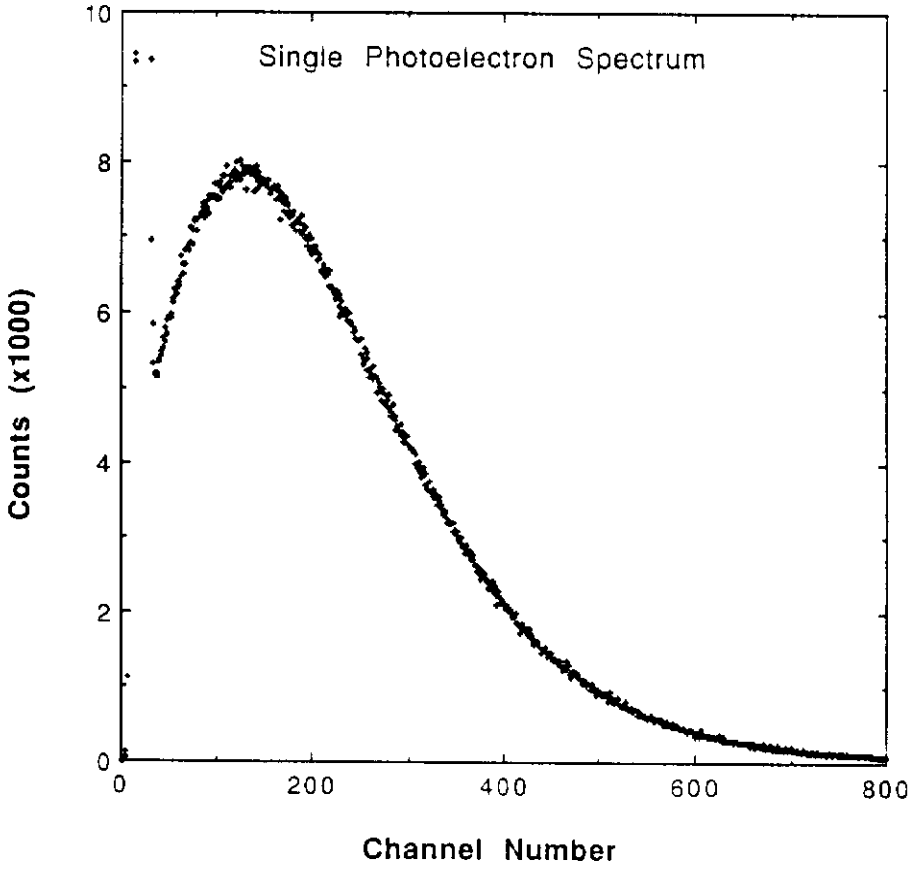

Figure 5

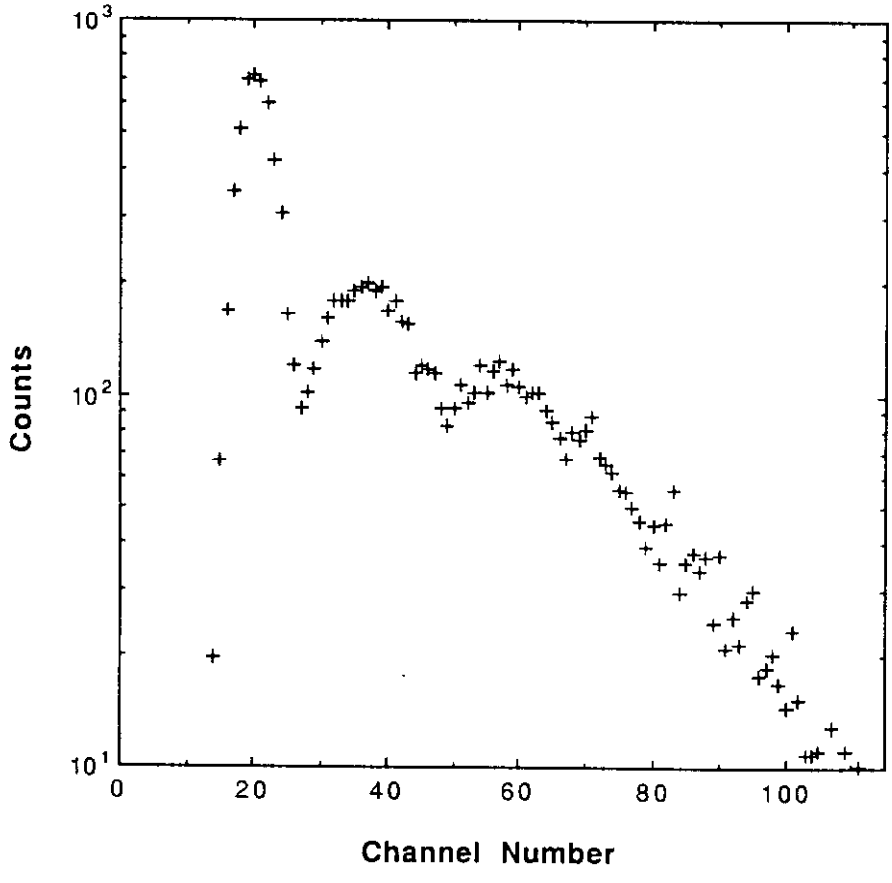

Figure 6

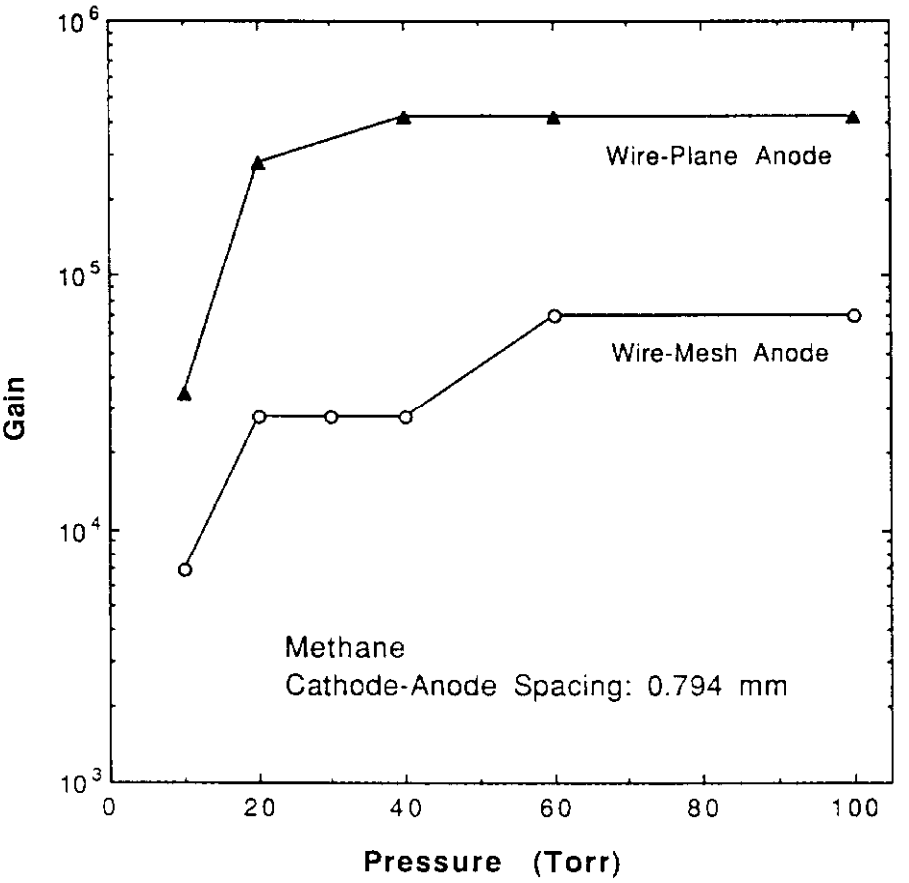

Figure 7

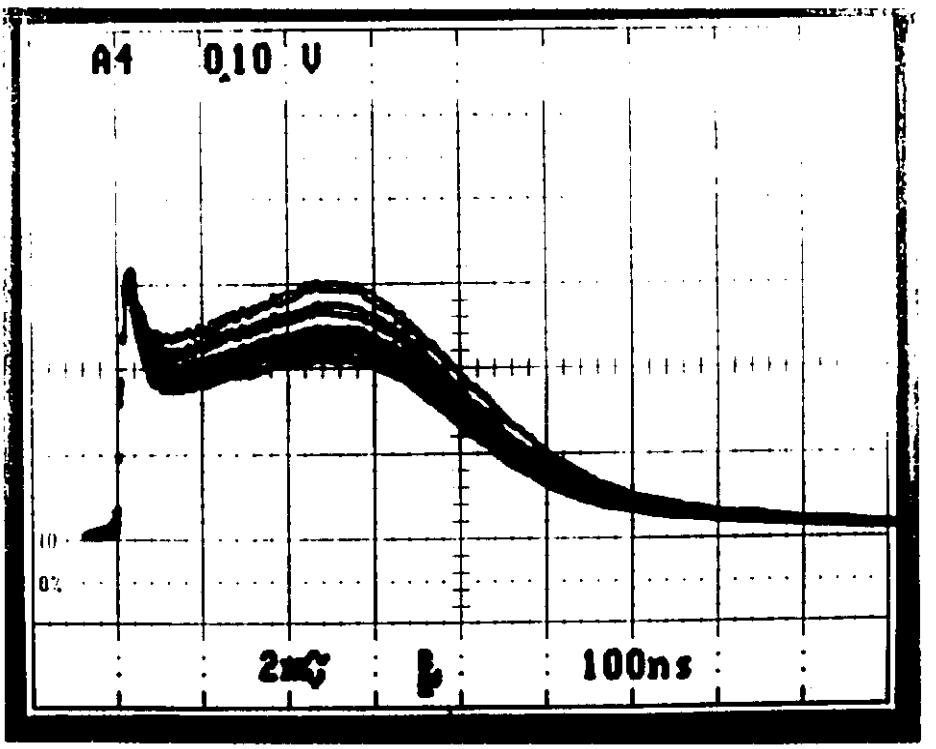

Figure 8

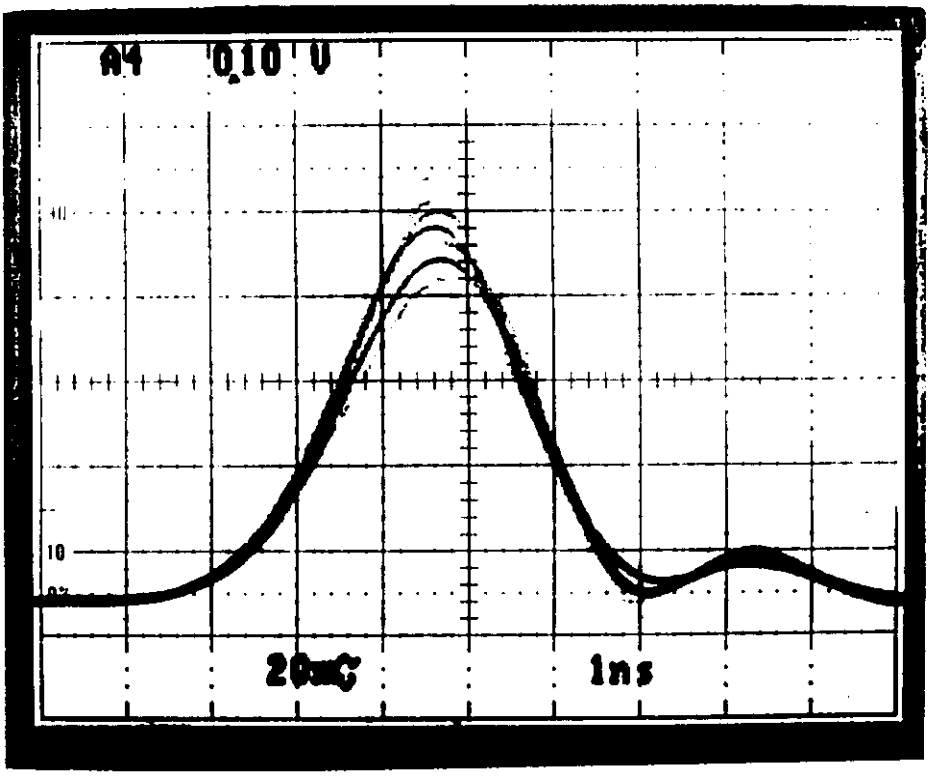

Figure 9

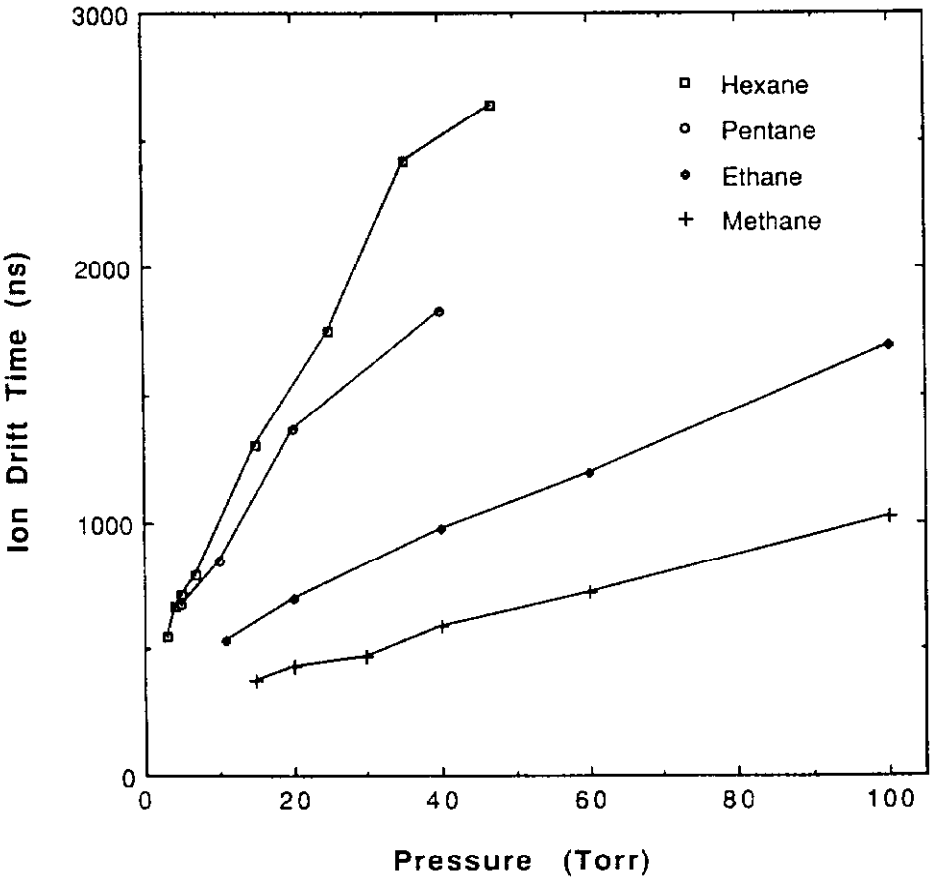

Figure 10

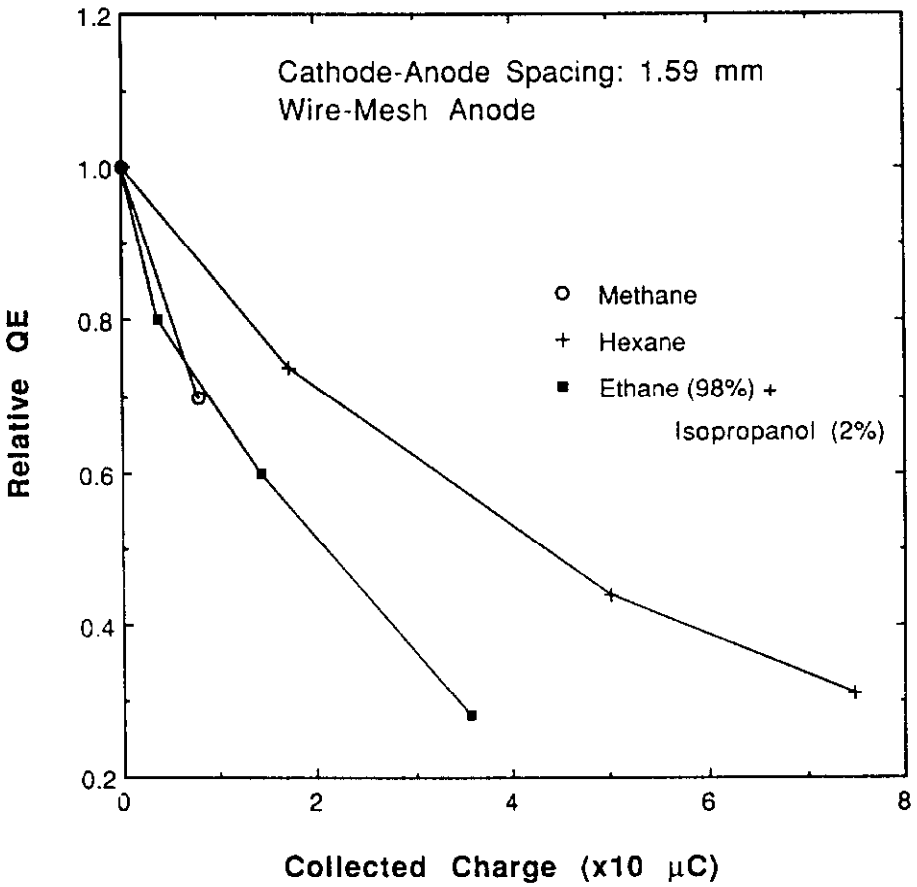
Cathode-Anode Spacing: 1.59 mm
Wire-Mesh Anode
Methane
Hexane
Ethane (98%) +
Isopropanol (2%)
Relative QE
Collected Charge (x10 μC)
1.2
1.0
0.8
0.6
0.4
0.2
0
2
4
6
8

Figure 11