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A NONFLAMMABLE GAS MIXTURE FOR PLASTIC LIMITED STREAMER TUBES*

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Abstract

The gas mixtures presently used in plastic limited streamer tubes ("Iarocci tubes" or LSTs) have a high hydrocarbon content and are very flammable when mixed with air, posing a potential safety hazard in modern large underground experiments. The SLD Warm Iron Calorimeter group has therefore made an extensive investigation of nonflammable ternary mixtures based on CO_2, Ar and various hydrocarbons. We present here brief results of this research. In particular, we describe a detailed study of a nonflammable gas mixture (2.5% Ar: 9.5% iC_4H_{10}: 88% CO_2) which indicates that this mixture has properties comparable to those of the two commonly used gases (25% Ar: 75% iC_4H_{10} and 21% Ar: 37% nC_5H_{12}: 42% CO_2) and could successfully replace these mixtures in LST-based tracking devices and hadron calorimeters.

1. Introduction

Plastic limited streamer tubes [1], mass-produced from extruded PVC tube profiles coated with resistive graphite paint, form a cost-effective solution to the problem of instrumenting the very large-volume tracking calorimeters required by many modern particle detectors. As such they are being or will be used in a wide variety of accelerator and nonaccelerator based experiments, including the SLD [Stanford Linear Accelerator Center (SLAC) Large Detector].

These tubes are conventionally operated in the limited streamer mode using a gas mixture of 25% argon and 75% isobutane by volume. The disadvantage of this "standard gas" is that it is extremely flammable and thus poses a potential safety hazard when employed in confined spaces and in conjunction with ignition sources such as HV. Because of this, several groups have conducted studies of alternative gas mixtures. Unfortunately, the only alternative gas mixture which has been widely tested in working tubes is the "Mont Blanc" mixture [2] (21% Ar: 37% nC_5H_{12}: 42% CO_2), which is still flammable in air. The same is true of the ALEPH gas (15% Ar: 25% nC_5H_{12}: 60% CO_2), a modification of the Mont Blanc mixture which has been extensively studied [3] in the context of an iron/LST hadron calorimeter much like SLD's.

This note describes the results of a search for a nonflammable alternative gas mixture for the SLD Warm Iron Calorimeter.

2. The Experimental Setup

The data presented here were acquired using two independent test setups, one at SLAC and the other at the University of Perugia. The SLAC test setup is shown in fig. 1. It consists of three planes of scintillator, used in coincidence as a cosmic-ray trigger, plus two limited streamer tube chambers, one consisting of three and the other of five LST modules laminated between copper-clad fibreglass readout electrodes. The modules are 6.7 m in length and use coverless eight-cell profiles [4]. The readout electrode facing the bottom of the profile is routed into

1-cm strips parallel to the wires, while the other electrode consists of "pads" about 30 cm × 30 cm in area. The modules were built and the chambers laminated in the course of the standard WIC-barrel chamber construction program [5]. They are functionally identical to chambers actually installed in SLD. The three-module chamber (chamber A) is filled with standard gas and is used as a reference, while the five-module chamber (chamber B) is filled with the test gas. Both gas mixtures are controlled by mass flow controllers with a nominal accuracy of 1% of the flow rate and a typical flow rate of 0.5–1 ℓ/min. The gas composition is monitored periodically with a gas chromatograph. The data acquisition software and hardware are described in detail elsewhere [6].

The Perugia test station uses specially constructed 1.5-m-long modules arranged as indicated in fig. 2. The eight wires of each module are tied together and read through a coupling circuit (also shown in fig. 2). For the data reported here, these signals were sent to scalers via a nonupdating discriminator with a 20 mV/50 Ω threshold and a dead time set to 0.09, 1.0 or 400 μs. The setup includes a scintillator cosmic-ray telescope and ADC for charge measurements, but this was not used in the data we present in this paper. The data acquisition system is based on CAMAC interfaced to a Macintosh–Plus [7,8]. The gas mixture is normally controlled by mass flow controllers similar to those used at SLAC: in addition, admixtures of heavier hydrocarbons may be introduced by bubbling a known proportion of the total gas flow through a small temperature-controlled bottle of liquid hydrocarbon. The temperature of the bottle was observed to be stable to within 0.3° C, thus providing a stable proportion of heavy hydrocarbon (with a relative error of 5%, corresponding to an absolute error of <0.5%) [7]. Both the SLAC and the Perugia test facilities also include continuous monitoring of external temperature and pressure.

3. Candidate Alternative Gas Mixtures

The aim of this study is to find a gas mixture possessed of the following properties:

1. nonflammable;
2. has operating characteristics similar to 25% Ar: 75% iC_4H_{10} (hereafter designated "standard gas"), since time and budget constraints forbid any major redesign of the SLD–WIC HV supply or readout electronics;
3. has no long-term deleterious effects on the tubes;
4. economically and technically feasible for use in a large-scale experiment like the SLD.

For simplicity and in adherence to criterion 4, we elect to concentrate on ternary mixtures of argon, isobutane and carbon dioxide [11]. (Alternative hydrocarbons and inert gases will be discussed later.) From studies conducted by the U.S. Bureau of Mines [9], we conclude that criterion 1 restricts us to <10% isobutane in CO_2 (see fig. 3). Since this figure relies upon the fire-extinguishing effect of CO_2, we are also restricted to <10% or so of other inert gas.

We have explored the resulting phase space quite thoroughly. Figure 4(a) shows the measured charge distributions obtained at SLAC as a function of high voltage and argon content. A mixture with 2–3% argon shows streamer activity with a promising similarity to the standard gas (compare reference plot at left). Such a mixture satisfies criteria 1, 2 and 4, and thus represents a *prima facie* candidate alternative gas. We have studied in detail the mixture 2.5% Ar: 10% iC_4H_{10}: 87.5% CO_2 (hereafter designated "new gas"). In later studies, the isobutane content was lowered to 9.5% to ensure that the mixture is strictly nonflammable: this change has negligible effect on the properties of the gas and we will regard the two mixtures as interchangeable.

The operating voltage for this gas mixture is some 100 V higher than for the standard gas. This can be seen from figs. 4(b) and (c), which show the efficiency as a function of high voltage for various voltage thresholds. Full streamer efficiency is attained at an operating point of about 4750–4800 V. These data were obtained using the SLAC test chambers with the SLD digital strip readout, which is for this purpose equivalent to a discriminator. They are not directly comparable to the singles plateaux in fig. 5, which were obtained by reading out the wires directly.

3.1 Singles rates.

Three distinct production mechanisms may contribute to the ungated counting rate:

(*i*) *primary streamers*, caused directly by passage of an initiating charged particle;

(*ii*) *secondary streamers*, caused by a UV photon knocking an electron out of the tube wall, which occur ~90 ns (drift time from the tube wall to the wire) after the primary streamer; and

(*iii*) *afterpulses*, caused by the impact of positive ions on the tube walls O(100 μs) after the primary streamer.

Using the Perugia test facility, we have studied singles rates for dead times of 90 ns (in which case all three types of streamer formation contribute to the total counting rate), 1 μs (for which type (ii) merges with the primary streamer, and so does not contribute) and 400 μs (counts only the primary streamers). The results for standard gas and new gas are shown in figs. 5(a) and (b) respectively. The most significant difference is the higher secondary streamer activity in the new gas, indicated by the lack of a plateau at 90 ns. However, this property seems to be characteristic of ternary mixtures—similar behavior is seen [fig. 5(c)] in the ALEPH gas—and it does not appear to degrade the performance of a hadron calorimeter [3]. The plateau at longer dead times has an acceptable length of ~400 V.

In view of these results, it is important to note that the SLAC readout electronics has an effective integration time of ~700 ns, and thus includes the secondary streamers in its charge measurement. This explains why the integrated charge seen using the new gas is about 70% more than the standard gas, although the pulses as seen on an oscilloscope [7] differ in height by only 10% or so (see fig. 6).

3.2 Dark current and aging.

The average current drawn by the SLAC test chamber is shown in fig. 7. The value for the new gas is within a factor 2 of the standard gas, consistent with the higher charge per incident particle mentioned above.

To test the long-term stability of operation of the new gas, we have conducted a 'life test' at SLAC involving 400 modules 6–7 m in length. These modules were maintained at 4750 V for 106 days (with two 10-minute "rests" in each 24-hour period). One tube failed during the test, but when examined later it proved to have a serious mechanical defect (a wire improperly located in a wire support) and cannot therefore be considered a gas-related problem. Discounting this tube, we calculate a failure rate of <2.0% per year at 90% C.L. In addition, approximately 2% of the life test modules, which had previously passed all acceptance criteria [5] with the standard gas, failed our standard first-stage acceptance criteria when re-tested with the new gas and were not included in the test. We consider this an acceptable failure rate: it is comparable to the failure rate of previously good modules in our routine pre-installation cosmic-ray test with the standard gas.

The average current drawn by a module on life test decreased from 26 nA at the start of the test (consistent with expectations from fig. 7) to 16 nA two weeks later, and remained fairly stable thereafter.

3.3 Alternative nonflammable ternary mixtures.

It is possible to envisage alternatives for both the hydrocarbon and the inert gas components of the mixture. At Perugia, we have studied the effect of replacing isobutane with a heavier alkane such as n-pentane (as used in the Mont Blanc gas) or n-hexane. In these cases the criterion of nonflammability imposes a reduction in the hydrocarbon content (to 7.5% and 6.5% respectively). The singles rates for a representative n-pentane mixture are shown in fig. 5(d). They are clearly very similar to those for the equivalent isobutane mixture. Changing the proportion of argon by a few percent changes the location of the 'knee' of the plateau but otherwise has little effect. Similar results were obtained in the case of n-hexane [7]. We conclude that there is no significant advantage to using heavier hydrocarbons, and thus elect to retain isobutane, which is simpler to handle in a bulk mixing system.

Moromisato *et al.* [10] have recently conducted a study very similar to ours, in which they have chosen to replace argon with neon. Looking at their data, we conclude that the disadvantages (primarily the much higher cost) of neon are not outweighed by the small increase in plateau length which they measure.

4. Operational Stability

In order to maintain the calibration of a calorimeter, it is important to understand the effect of varying conditions on the operation of the tubes. The variables involved include those under the control of the experimenter (*e.g.,* HV, gas mixture) and also environmental conditions such as temperature and pressure. We have used the SLAC test facility to study this question for both the standard and the new gas.

4.1 High voltage.

Figure 8 shows the average integrated charge as a function of high voltage. For the new gas, the pulse heights for proportional and streamer modes are separated where possible (the overlap between proportional and streamer peaks in standard gas is too great for reliable separation). As can be seen in fig. 4(a), the "proportional" signal is negligible above 4.6 kV — the small number of remaining counts in this region being due to noise. Above 4.8 kV, the gain of the new gas increases substantially due to the presence of multiple streamers. This is a cause of concern for the longevity of the tubes, but not for the performance of the calorimeter, since the presence of multiple streamers reduces the skewness of the charge spectrum and thus actually improves the resolution (calculated naïvely as $\sigma_q/\langle q\rangle$, q being the pad charge).

Fitting the data in fig. 8 to an exponential yields a quantitative estimate of the change of gain (*i.e.*, average pad charge) with high voltage:

$$\frac{\Delta Q}{Q} = k_V \Delta V \quad ,$$

where

$$\begin{aligned} Q &= \langle q \rangle && \text{is the average pad charge;} \\ k_V &= 3.72 \pm 0.19\ (\mathrm{kV})^{-1} && \text{for standard gas;} \\ k_V &= 3.57 \pm 0.05\ (\mathrm{kV})^{-1} && \text{for new gas.} \end{aligned}$$

The value for the new gas is based on a fit to the overall gain excluding the points below 4.6 kV, which are in the proportional/streamer transition region and do not fit well to the exponential ansatz.

4.2 Temperature and pressure.

The effect of temperature on the average pad charge is shown in fig. 9. The slope for the new gas is almost identical to that for the standard gas. However, since the new gas has a higher gain, the effect of the variation on the absolute calibration is diminished. Expressing the variation in the dimensionless form

$$\frac{\Delta Q}{Q} = k_T \frac{\Delta T}{T} \quad ,$$

where T is absolute temperature, we find at 20° C (293K) and 4750 V that

$$\begin{aligned} k_T &= 10.4 \pm 0.5 && \text{for standard gas;} \\ k_T &= 7.5 \pm 0.5 && \text{for new gas.} \end{aligned}$$

We interpret this as a gas density effect. Using natural variation in atmospheric pressure during routine cosmic-ray testing of several production chambers, we find for the standard gas

$$\frac{\Delta Q}{Q} = -(9.1 \pm 1.0) \frac{\Delta P}{P} \quad ,$$

which is quite consistent with this interpretation.

Figure 10 shows integrated pad + strip charge spectra for the new gas, based on data taken with the same chamber at two different temperatures. It may be seen that not only does the streamer gain change, but also the location of the proportional/streamer transition voltage. This property is important to note, since it is traditional to operate LST's at the lower end of the efficiency plateau, in which case a fall in the ambient temperature could result in a loss of streamer efficiency. This could in principle be compensated by adjusting the high voltage accordingly.

4.3 Gas mixture.

We have studied the sensitivity of the tube performance to small changes in the gas mixture. Varying the absolute argon content by ±0.5% (a relative change of 20%), we find for the new gas:

$$\frac{\Delta Q}{Q} \simeq 1 \times \frac{\Delta(\%\mathrm{Ar})}{\%\mathrm{Ar}} \quad .$$

A similar result is obtained for variation in the relative isobutane content. Given the accuracy of our mass flow controllers, we expect such effects to be entirely negligible in practice.

It is interesting to note that the standard gas seems to be rather more sensitive to changes in the gas mixture. For example, varying the argon:isobutane ratio to 26:74 (24:76) produces a +19% (-18%) change in the mean pad charge. Expressed in terms of argon content,

$$\frac{\Delta Q}{Q} \simeq 4.5 \times \frac{\Delta(\%\mathrm{Ar})}{\%\mathrm{Ar}} \quad .$$

5. Conclusions

We have investigated a number of possible nonflammable gas mixtures for use in plastic limited streamer tubes. We find that the nonflammable CO_2-based ternary gas mixture 2.5% Ar: 9.5% iC_4H_{10}: 88% CO_2 has properties similar to those of the flammable ternary mixtures successfully used by the Mont Blanc and ALEPH groups. The only disadvantage of the ternary mixtures appears to be the higher activity of secondary streamers.

We conclude that the ternary gas mixture 2.5% Ar: 9.5% iC_4H_{10}: 88% CO_2 may be successfully and safely used in large LST-based tracking devices and/or hadron calorimeters. We have used this gas in place of the standard binary mixture of 25% Ar: 75% iC_4H_{10} for commissioning the SLD warm iron calorimeter. Studies are continuing to search for alternative nonflammable mixtures which do not exhibit the higher activity of secondary streamers.

ACKNOWLEDGMENTS

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[10] J. H. Moromisato *et al.,* LVD Note 33 (1988) 88–11.

[11] A recent study by a group from RWTH Aachen [H. Bergstein *et al., Nucl. Inst. Meth.* **A269** (1988) 560] indicates that pure CO_2 may also be a candidate LST gas. However, in extensive tests at SLAC and at our chamber construction facility in Batavia, Illinois, we have failed to reproduce these results with production chambers. We find a streamer-mode efficiency of <50% at voltages up to our operational maximum of 5 kV, and hence conclude that pure CO_2 is not a viable candidate gas for our purposes.

FIGURE CAPTIONS

1. SLAC test setup.

2. Perugia test setup, showing readout circuit (a) and gas supply system (b).

3. Flammability of butane/CO_2 mixtures, reproduced from Ref. (9). These data are for n-butane: however, comparison of the endpoints indicates no significant difference between n-butane and isobutane in this respect. The dashed line represents the highest butane/CO_2 ratio which does not enter the flammable region when mixed with any proportion of air.

4(a) Pad + strip charge spectra as a function of high voltage and argon content in mixtures of the form $x\%$ Ar: 10% iC_4H_{10}: $(90 - x)\%$ CO_2.

   (b) Efficiency as a function of high voltage and strip readout discriminator threshold for standard gas. Geometrical inefficiencies caused by the profile walls have not been removed from this plot. The plateau value of ~90% thus represents full streamer efficiency.

   (c) As above, for 2.5%Ar: 9.5% iC_4H_{10}: 88% CO_2.

5. Singles counting rates vs. high voltage for various dead times and gas mixtures.

   (a) 25% Ar: 75% iC_4H_{10}.

   (b) 2.5% Ar: 9.5% iC_4H_{10}: 88% CO_2.

   (c) 15% Ar: 25% nC_5H_{12}: 60% CO_2.

   (d) 2.5% Ar: 7.5% nC_5H_{12}: 90% CO_2.

6. Streamer pulses on the LST anode wire, averaged on a digital oscilloscope, for standard gas (a) and new gas (b). Both pictures were taken at a high voltage of 4.7 kV, whereas the operating points for the two gases are 4.65 and 4.75 kV, respectively: the "operating" difference in pulse height is thus

somewhat larger than implied here. Note the longer tail of the pulse in (b), which indicates the presence of a larger fraction of multistreamer pulses.

7. Average current vs. high voltage for the mixtures shown in fig. 4(a).
8. Integrated pad charge for one cosmic ray muon as a function of high voltage.
9. Integrated pad charge for one cosmic ray muon as a function of temperature (at constant pressure).
10. Pad + strip charge spectra for various high voltage values at 10° C and at 19° C taken with cosmic ray muons.

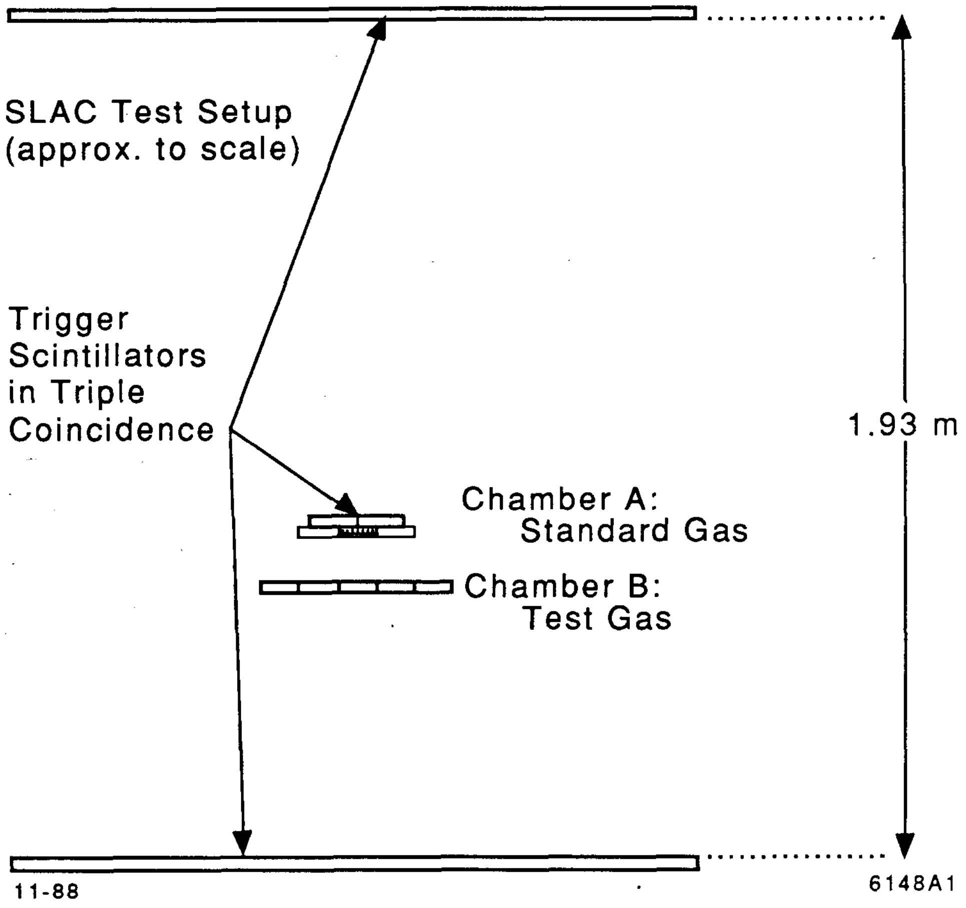

SLAC Test Setup
(approx. to scale)
Trigger
Scintillators
in Triple
Coincidence
1.93 m
Chamber A:
Standard Gas
Chamber B:
Test Gas
11-88
6148A1

Fig. 1

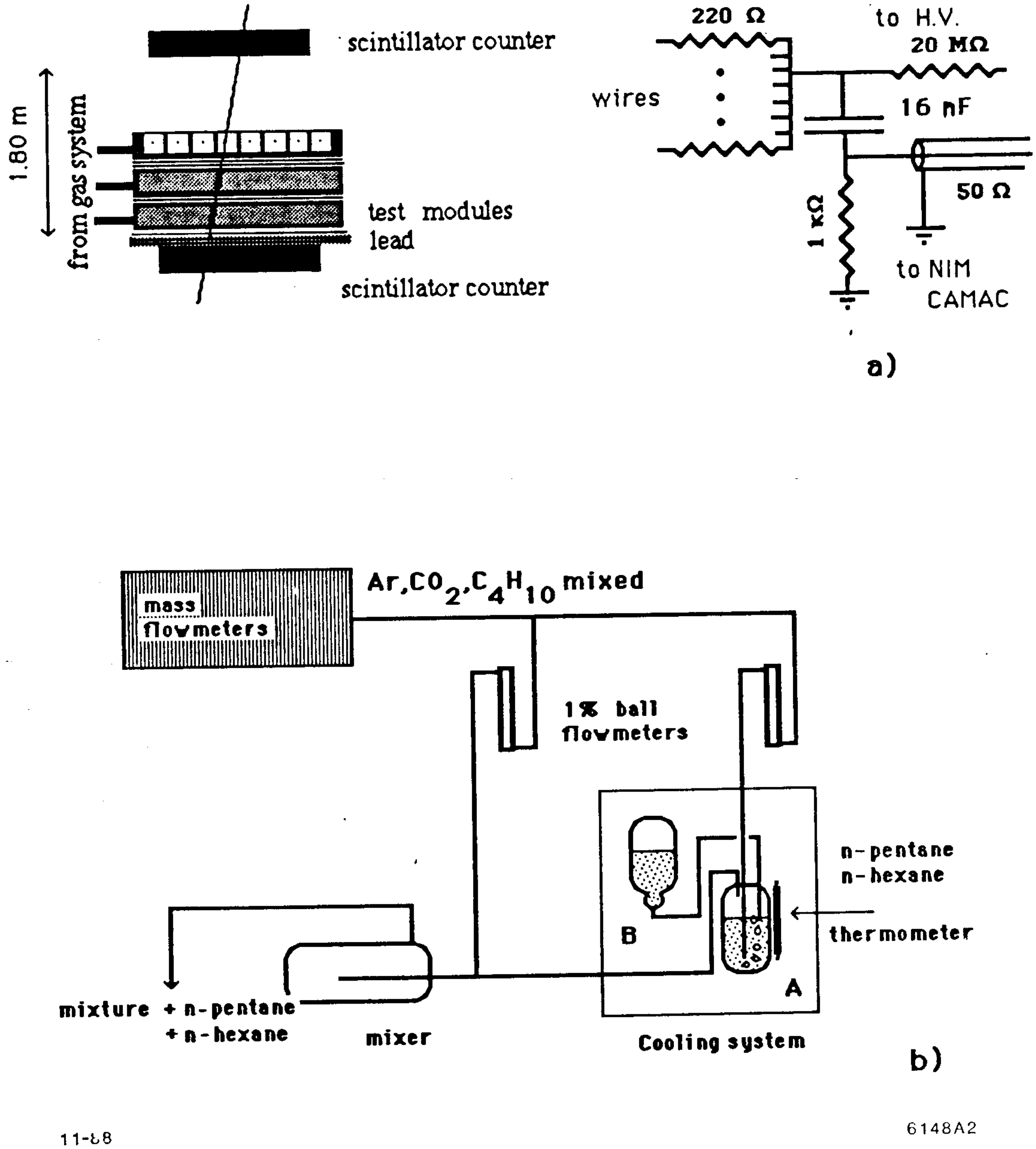

scintillator counter
1.80 m
from gas system
test modules
lead
scintillator counter
220 Ω
to H.V.
20 MΩ
wires
16 nF
50 Ω
1 kΩ
to NIM
CAMAC
a)
mass
flowmeters
Ar,CO_2,C_4H_{10} mixed
1% ball
flowmeters
n-pentane
n-hexane
B
thermometer
A
mixture + n-pentane
+ n-hexane
mixer
Cooling system
b)
11-88
6148A2

Fig. 2

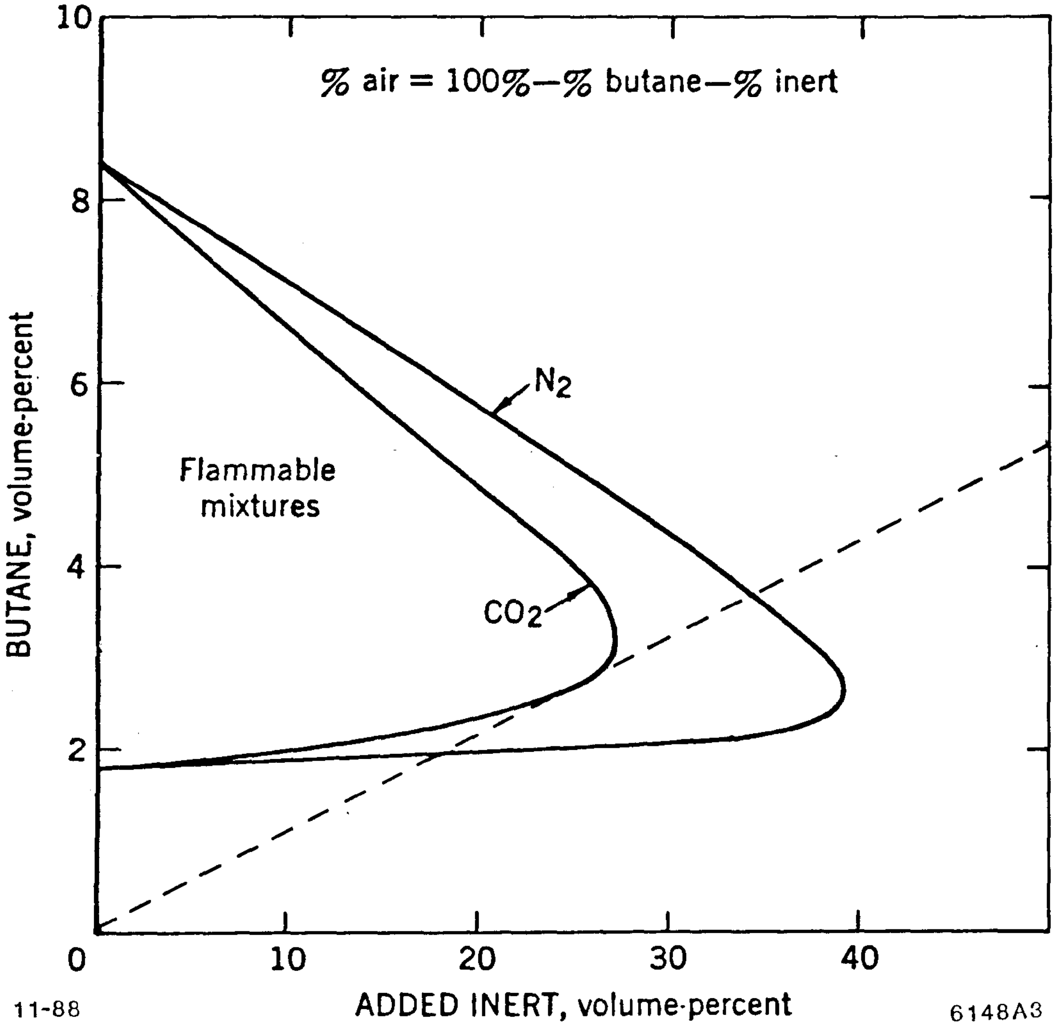
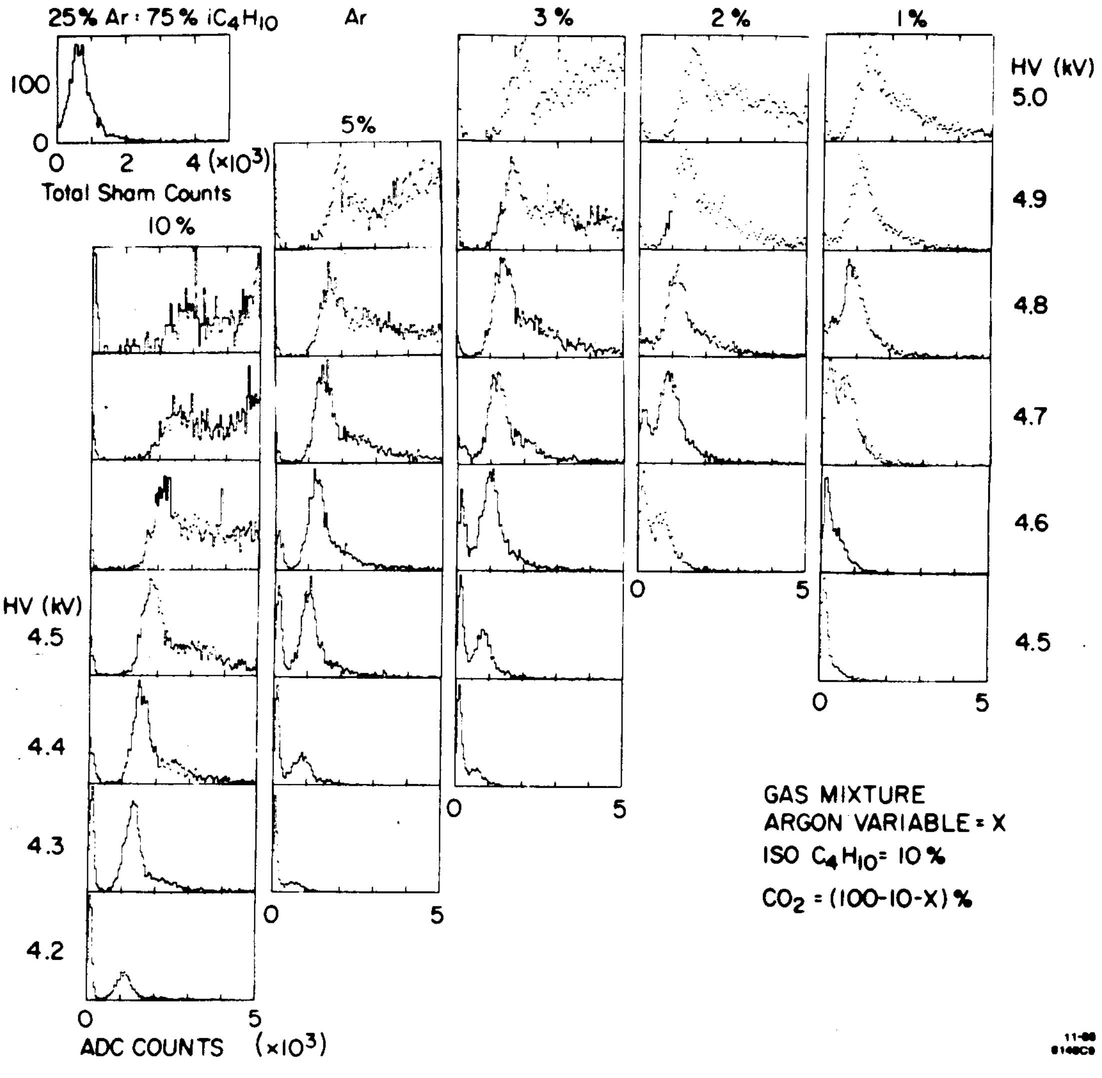

% air = 100%—% butane—% inert
BUTANE, volume-percent
ADDED INERT, volume-percent
Flammable mixtures
N_2
CO_2
0
10
20
30
40
2
4
6
8
10
11-88
6148A3

Fig. 3



25% Ar : 75% iC4H10
100
0
0 2 4 (×10³)
Total Sham Counts
Ar
10%
5%
3%
2%
1%
HV (kV)
5.0
4.9
4.8
4.7
4.6
4.5
HV (kV)
4.5
4.4
4.3
4.2
0 5
ADC COUNTS (×10³)
GAS MIXTURE
ARGON VARIABLE = X
ISO C4H10 = 10%
CO2 = (100-10-X)%
11-88
8148C8

Fig. 4a

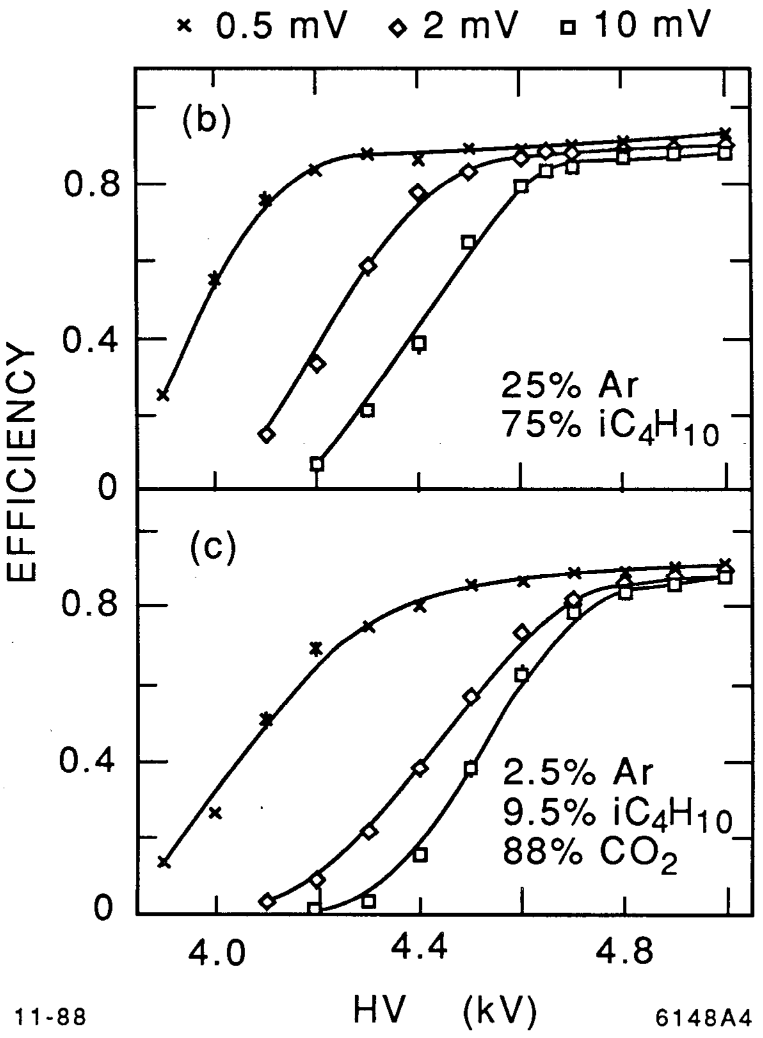
× 0.5 mV ◇ 2 mV □ 10 mV
(b)
25% Ar
75% iC_4H_{10}
(c)
2.5% Ar
9.5% iC_4H_{10}
88% CO_2
EFFICIENCY
0.8
0.4
0
4.0
4.4
4.8
HV (kV)
11-88
6148A4

Fig. 4b & c

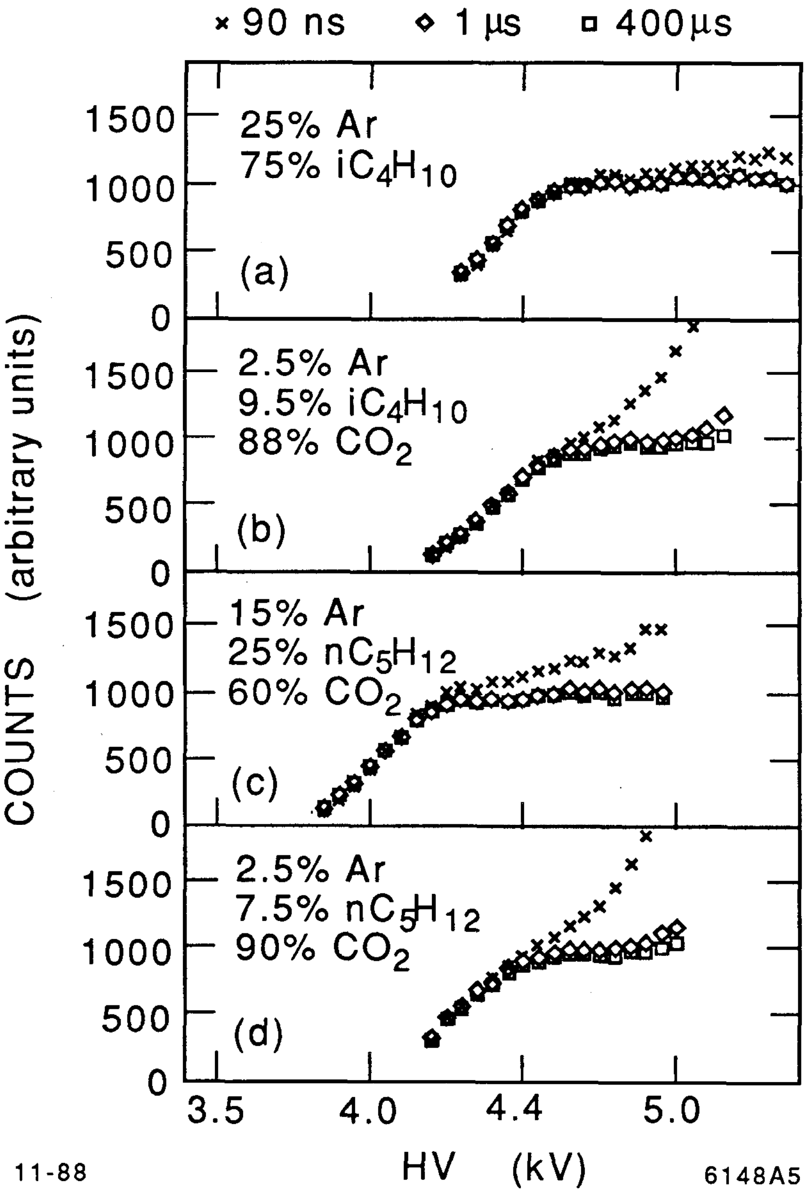
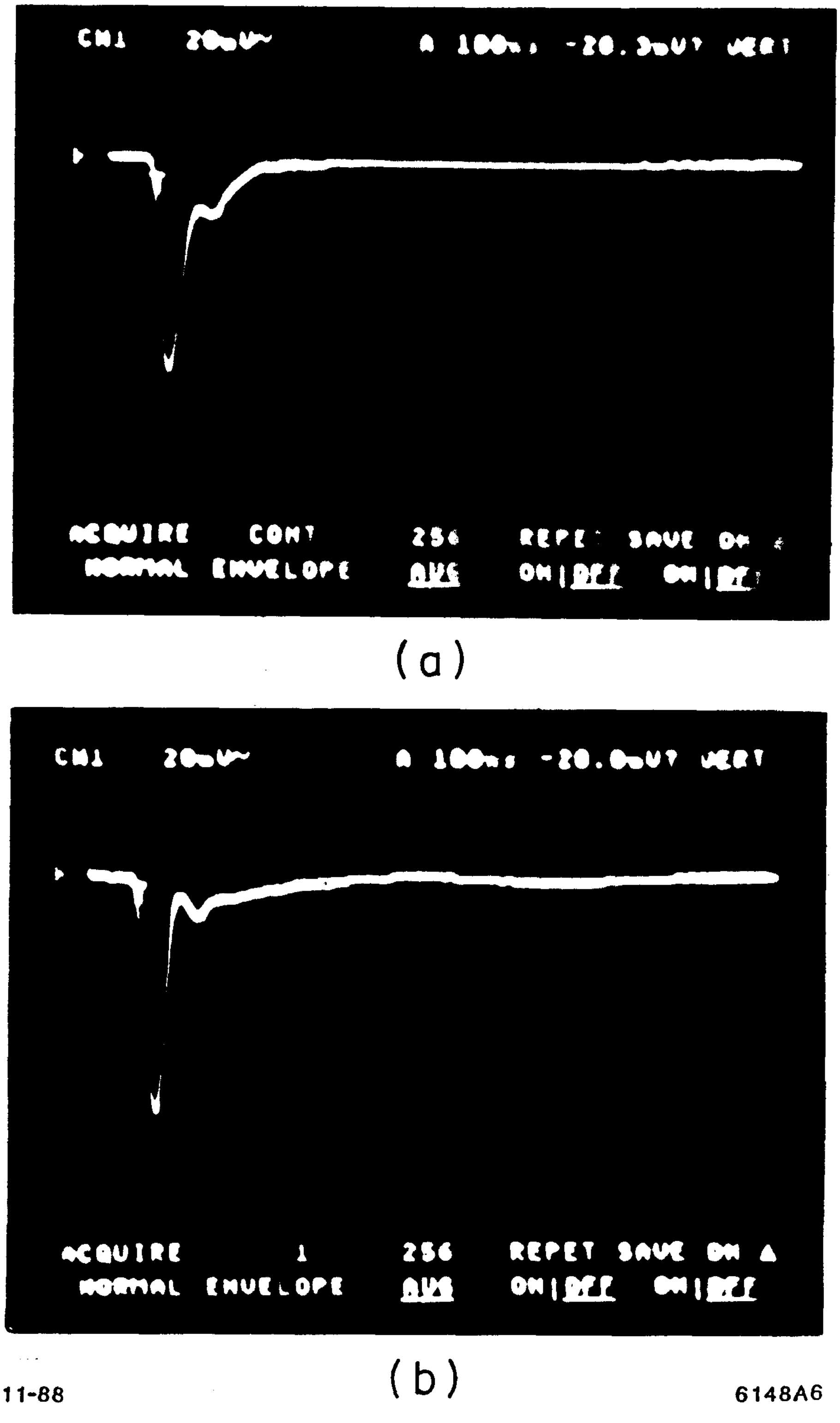

× 90 ns
◇ 1 μs
□ 400μs
25% Ar
75% iC4H10
(a)
2.5% Ar
9.5% iC4H10
88% CO2
(b)
15% Ar
25% nC5H12
60% CO2
(c)
2.5% Ar
7.5% nC5H12
90% CO2
(d)
1500
1000
500
0
COUNTS (arbitrary units)
3.5
4.0
4.4
5.0
HV (kV)
11-88
6148A5

Fig. 5



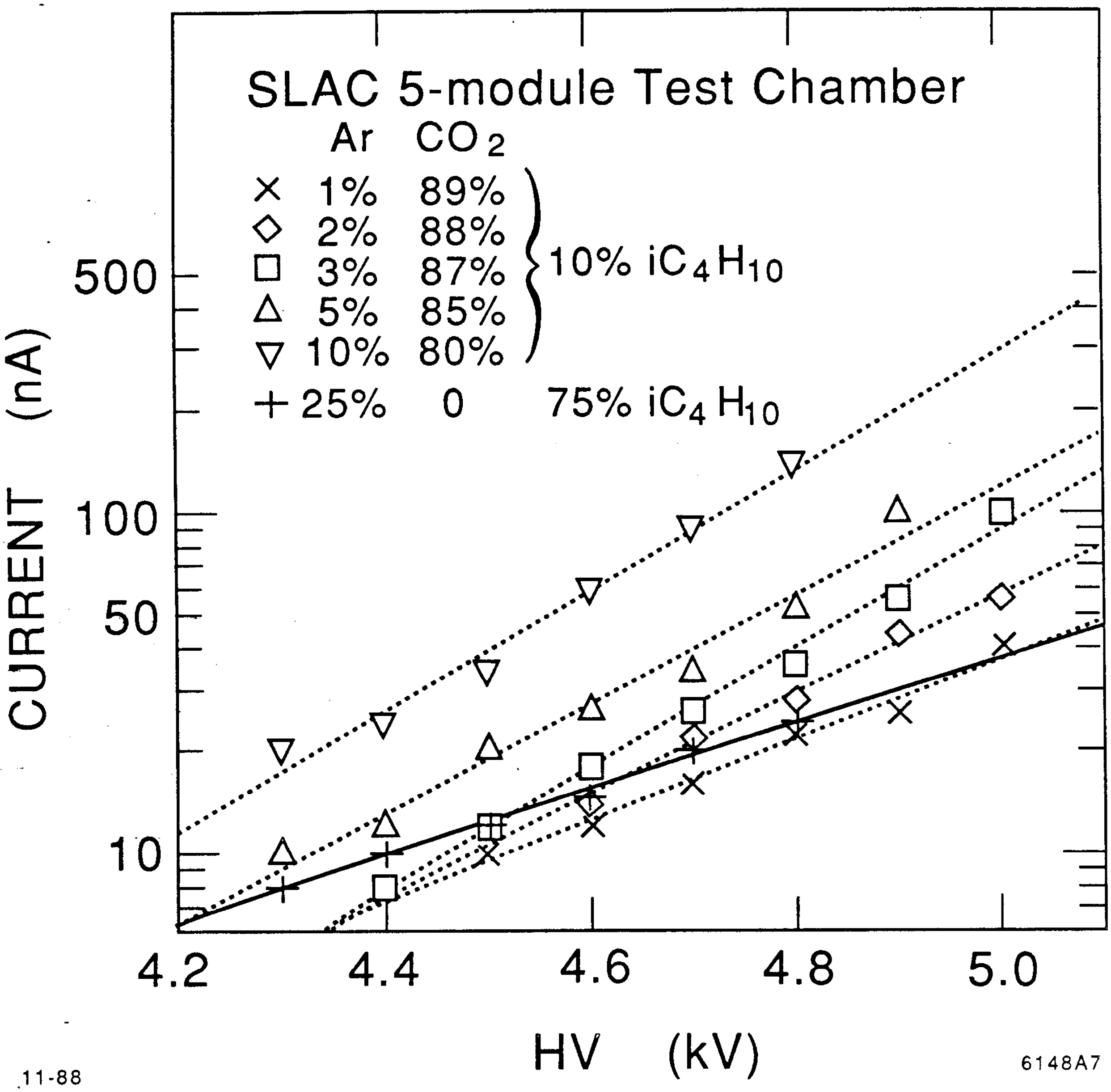
(a)

(b)

11-88

6148A6

Fig. 6



11-88

6148A7

Fig. 7

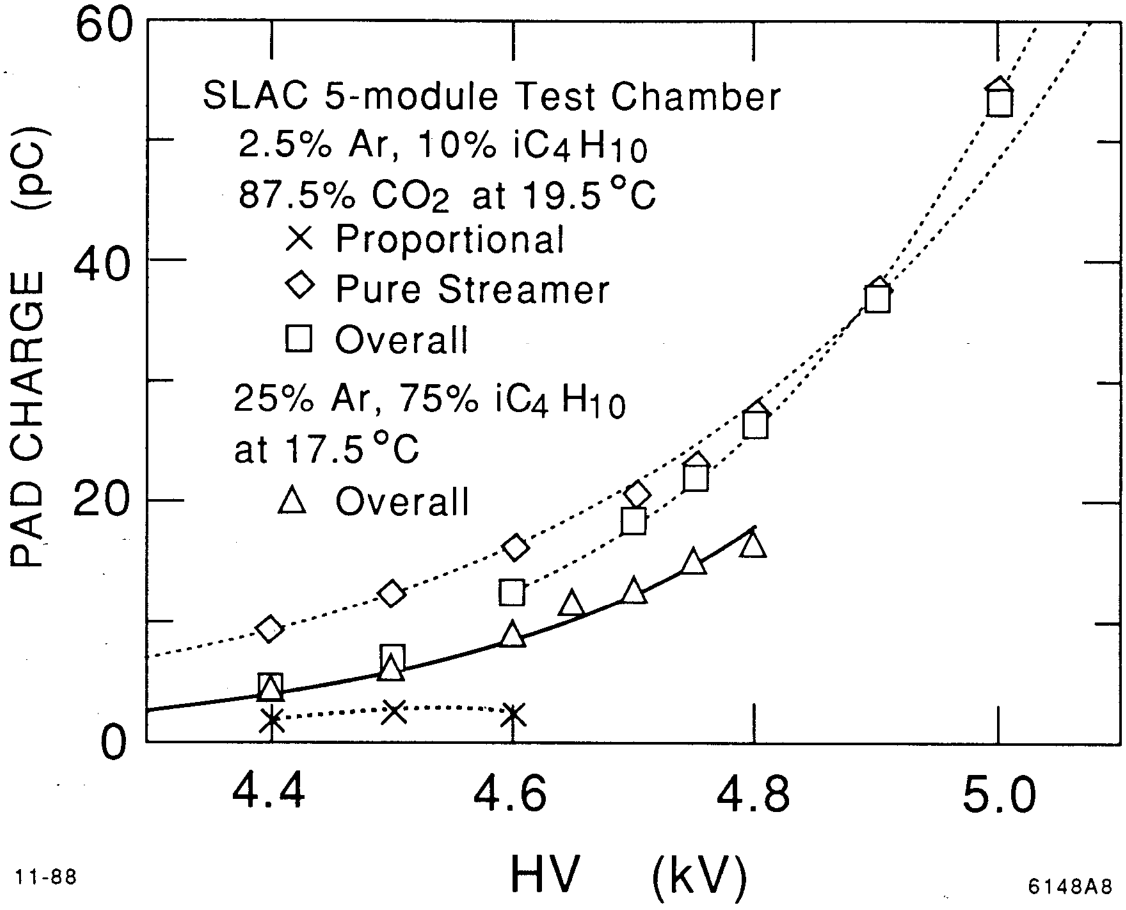

60
40
20
0
PAD CHARGE (pC)
SLAC 5-module Test Chamber
2.5% Ar, 10% iC_4H_{10}
87.5% CO_2 at 19.5 °C
× Proportional
◇ Pure Streamer
□ Overall
25% Ar, 75% iC_4H_{10}
at 17.5 °C
△ Overall
4.4
4.6
4.8
5.0
HV (kV)
11-88
6148A8

Fig. 8

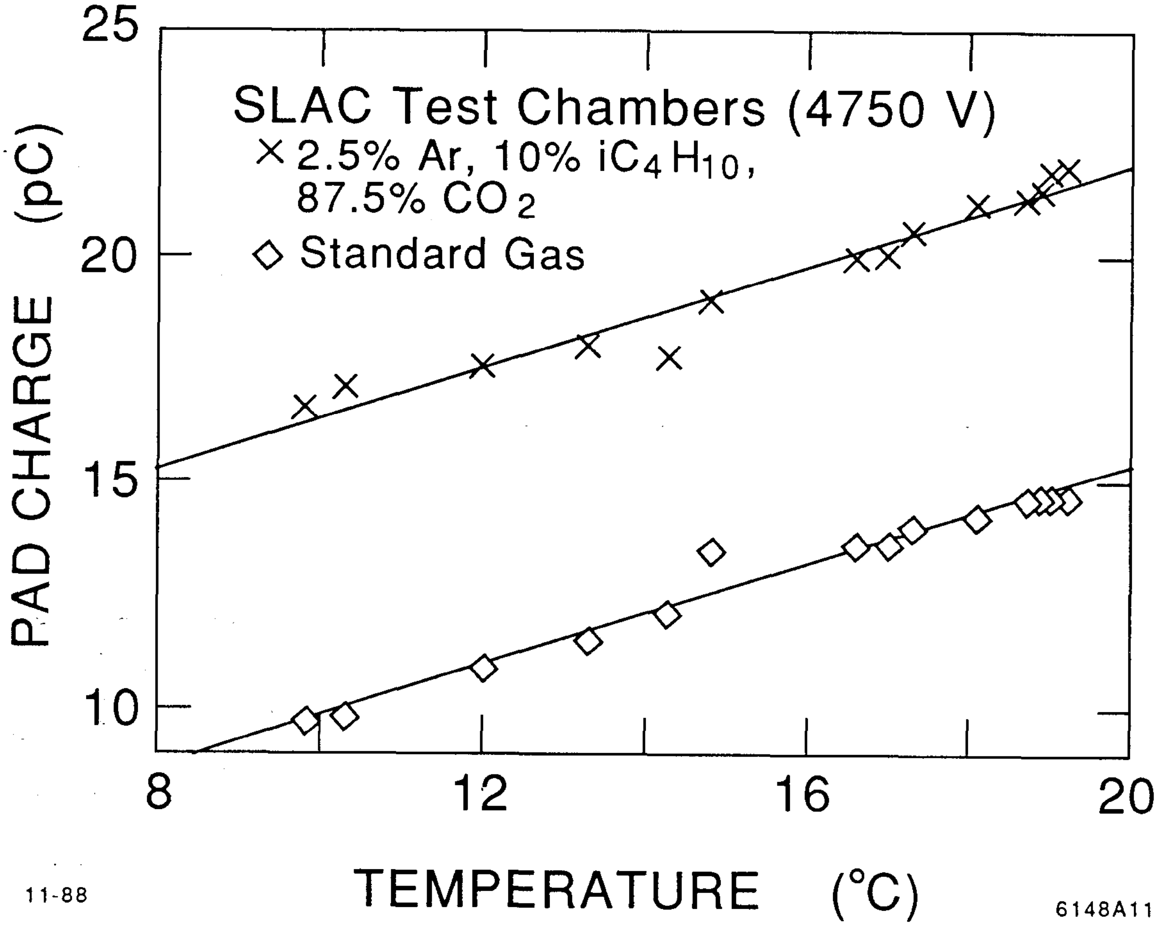
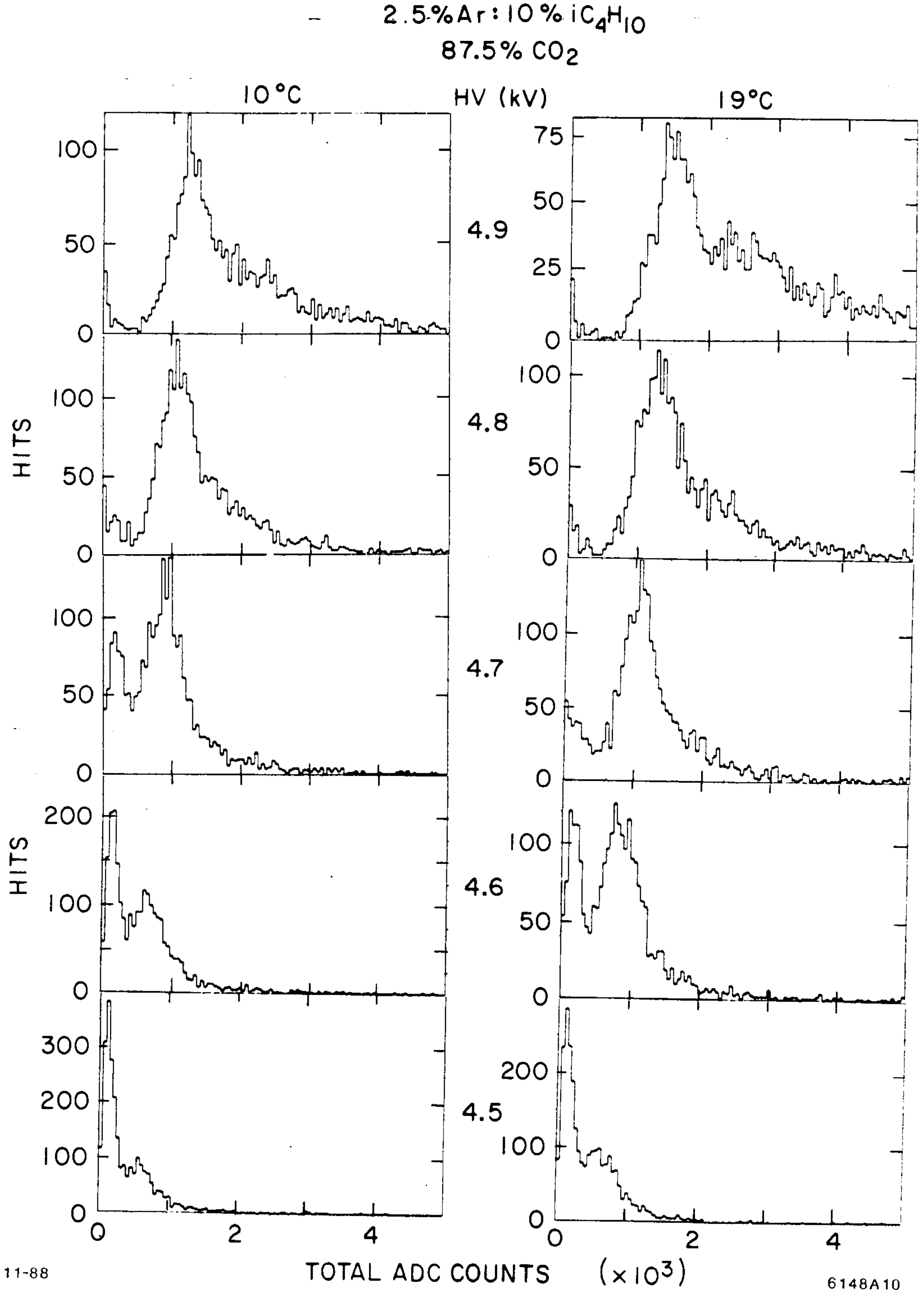

SLAC Test Chambers (4750 V)
× 2.5% Ar, 10% iC_4H_{10}, 87.5% CO_2
◇ Standard Gas
PAD CHARGE (pC)
TEMPERATURE (°C)
25
20
15
10
8
12
16
20
11-88
6148A11

Fig. 9



2.5%Ar:10% iC$_4$H$_{10}$
87.5% CO$_2$
10°C
HV (kV)
19°C
4.9
4.8
4.7
4.6
4.5
HITS
HITS
0
50
100
25
75
200
300
2
4
TOTAL ADC COUNTS
(×10^3)
11-88
6148A10

Fig. 10