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SURVEY OF THE RESPONSE OF STANDARD LIMITED STREAMER TUBES OVER THE COMPLETE RANGE OF THREE-COMPONENT GAS MIXTURES OF ISOBUTANE, CO_2, ARGON*

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Abstract

We present the results of a systematic study of three-component gas mixtures containing argon, isobutane, and carbon dioxide. The study used production-type chambers from the SLD Warm Iron Calorimeter (WIC), instrumented with standard pleastic streamert tubes, and triggered by cosmic-ray muons. Pulse height spectra are presented as a function of high voltage, over a wide range of mixtures of these three gases. Various features and similarities observed throughout this three-dimensional mixture-space are important clues to understanding the underlying physics of discharge mechanisms in wire detectors.

1. Introduction

Plastic limited streamer tubes [1], mass produced from extruded PVC profiles coated with resistive graphite paint, form a cost-effective solution to the problem of instrumenting the very large-volume tracking calorimeters required by most modern particle detectors. These tubes are used in the Warm Iron Calorimeter (WIC) of SLD [2], and a testing facility has been developed to measure the response from every individual pickup electrode on every WIC chamber prior to installation. We have already reported some results [3] from studies with this-facility, most recently-on an acceptable nonflammable gas mixture [4-5]. A review of the recent literature on this subject [6-13] finds many studies of various gas mixtures, but none that covers the combinations sufficiently to give a comprehensive description.

Using production chambers fabricated for the SLD WIC, traversed by minimum-ionizing cosmic-ray muons, we have undertaken a systematic survey of streamer tube response over the complete range of gas mixtures containing three commonly used gases: argon, isobutane, and CO_2. We have thus produced a summary of the behavioral characteristics of these popular tracking and calorimetric devices over the entire three-dimensional mixture space. Some of these characteristics (such as multiple streamer activity) may be peculiar to the specific geometry of the tubes, while others are more general. The analysis and interpretation of these data may lead to a better understanding of the underlying physical processes involved in the discharge mechanisms.

2. Data Acquisition

Our experimental set up has been described in previous publications [3-5], but all the relevant elements are shown in figs. l-3. Figure 1 shows the streamer tube module cross section and a typical chamber lamination. The cosmic ray trigger scintillators

and test chambers are shown in fig. 2. Strip and pad signals from both chambers are brought via twisted pair cables to low noise preamps with an effective integration time of roughly 600 ns. The charge integrated pulses are then sent to a sample-hold-and-multiplex circuit (SHAM) [14] and then digitized by a microprocessor-controlled ADC module (BADC)[15], as shown in the fig. 3 block diagram. It should be noted that in the following discussion, the term "SHAM counts" refers to the final digital result after pedestal subtraction. Our system has been calibrated several times and consistently gives roughly 33 SHAM-counts per picocoulomb of integrated charge.

The gas mixtures for both chambers are controlled by mass flow controllers which have shown themselves to be very reliable and reproducible to better than 1% over the 2 $\frac{1}{2}$ years this testing facility has been in operation. The top (three-module) chamber always had "standard gas" (75% isobutane: 25% argon) flowing through it, while the gas mixture under test flowed through the bottom (five-module) chamber. Only events showing a single clean track in the top chamber were used to analyze the behavior of the bottom chamber.

Figure 4(a) shows pulse height distributions from the top chamber with low and high pulse-height cuts. All values histogrammed are sums of strip or pad signals id clusters associated with a single cosmic ray muon. Thus, these spectra represent the total charge collected by strip or pad electrodes per single track crossing. Figure 4(b) shows representative distributions for the bottom (test) chamber. In the following analysis, we chose to use the total charge collected by both strips and pads for each event. Thus, our data can be compared directly to results from other experiments in which wire signals are recorded. Figure 4(c) shows the distribution of total charge for the events in fig. 4(b). Figures 4(b) and 4(c) show two clearly separated peaks, a small peak attributed to the proportional mode, and a larger one due to limited streamers.

Most of the data presented here were collected during a period when atmospheric conditions were quite stable. This is important to note, since later we will discuss the sensitivity of chamber response to changes in temperature and pressure. Throughout all data taking periods the ambient temperature and barometric pressure were recorded to ensure reliable comparisons of the data.

3. Gas Mixture—High Voltage Spectra Mosaics

To investigate systematically the three-dimensional mixture space, we chose to fix the ratio of isobutane to argon and then vary the fraction of CO_2 from 0% to near 100%. The motivation for this approach came from noticing this ratio is al-

most the same for both the standard (3: 1) mix and our new nonflammable gas (isobutane : argon : CO_2 = 9.5 : 2.5 : 88).

We found that we could cover this space adequately with five ratios (5 : 1, 3 : 1, 2 : 1, 1 : 1, and 1 : 2), along with the two boundary cases (only CO_2–argon and only CO_2–isobutane), the third two component boundary being covered by the data with 0% CO_2. For a given mixture, pulse height spectra were then recorded for several values of the high voltage. In each case, we tried to start the high voltage scan at a value low enough that nearly 100% of the pulses were in proportional mode, while the maximum voltage was determined by the limit of our HV supply (5 kV) or excessive current being drawn by our test chamber.

Figures 5-11 show the result of this study, where each figure pertains to a given isobutane/argon ratio or a boundary case. The individual distributions are arranged in rows of constant high voltage and columns of constant CO_2 fraction to form a matrix (or *"mosaic"*). The presentation of these mosaic figures is the main contribution of this report. Together, they describe the chamber operation as combinations of gas mixture and high voltage, and are varied through most of the attainable values. For some mixtures, excessive current occurred before full transition beyond proportional mode could occur (see fig. 9, isobutane : argon = 1: 2; and fig. 10, CO_2–argon only.) In other mixtures, high enough voltages were reached such that even the single streamer peak seems to evolve into all multiple streamers (see fig. 7, isobutane : argon = 2 : 1; CO_2 = 30%).

For most of the mixtures, the evolution from proportional mode to single streamer mode is clearly seen, along with the gradual appearance of higher pulse heights implying multiple streamers. We decided to use this transition as one way to characterize each gas mixture. From the estimated percentages of proportional and nonproportional events, we formed yield curves for each mix showing the transition from proportional mode to beyond. In the upper left corner of figs. 5 through 9 are the corresponding curves. In particular, fig. 12 is a blowup of the transition curves from fig. 7 for the 2: 1 ratio. We chose to interpolate the voltage for 50% nonproportional mode to characterize the transition for each mix. Figure 13 shows these characteristic transition voltages as a function of CO_2 percentages for the various argon : isobutane combinations.

As mentioned earlier, the space is covered fairly uniformly by our ratio selections. The two component boundary curves cover only a small range of CO_2 content, but their extensions can be inferred. The argon-only curve is terminated at 90% CO_2 since

smaller fractions caused excessive current and instability of the test chamber. Our interpretation is that the streamers are becoming very long and poorly quenched. The isobutane-only curve is terminated at 90% CO_2 because below that point the separation between proportional and streamer modes is not well defined. In fact the 0% CO_2 point of the 5 : 1 ratio curve also represents pure inference, as inspection of fig. 5 shows that here, too, no discernable transition is apparent. This merging of the pulse heights from the two modes will be discussed later as an advantage to be exploited.

Included on the vertical scale in, fig. 13 are values for the electric field at the wire. The calculation assumes cylindrical symmetry with a 9 mm outer wall diameter and a 100 μm diameter wire. These values may be useful for transferring our results to different geometries with different-sized wires. We are planning future studies to check this dependence by testing modules containing different sized wires.

Another quantity of interest which can be examined is the most probable pulse height of proportional and single streamer pulses. To provide a basis for comparison of various mixtures, we evaluate-the charge at the transition voltages plotted in fig. 13. That is, the most probable value of the proportional and single streamer peaks are determined for each pulse height spectrum, then plotted for each gas mixture as a function of voltage. The characteristic charge for each mode with that mixture is then determined by interpolation at the transition voltage. The resulting values are plotted in fig. 14.

Several features should be noted while examining this figure. First of all, the typical pulse heights in streamer mode are greater than in proportional mode by an order of magnitude. Also evident is the relatively small slope of most of the curves. This implies that the charge involved in these processes at the transition point is largely independent of CO_2 content, and mainly depends on the isobutane: argon ratio, except near the limits (CO2 greater than 90%, or when the argon fraction becomes too high). This observation is the result of our choice of fixing the isobutane: argon ratios as a way to explore this gas mixture space. It is also interesting to compare the pulse heights for these two modes for either high argon or high isobutane content: for high argon content the pulse heights characteristic of the the two modes are very different, while for high isobutane content they become nearly the same. For intermediate mixtures like the 2: 1 ratio, the ratio of amplitudes remains constant over the whole range. These tendencies are also evident in figs. 5-11.

Another characteristic of the different mixtures determined from examination of figs. 5-11 is the level of multiple or secondary streamer activity present when the voltage rises high enough to produce single streamers. This behavior is complex and involves changes in both the amplitude and time structure of the pulses, but some qualitative observations may be made. First, it should be noted that for many of the mixtures represented, as the high voltage is increased, the multiple streamers 'appear before the proportional mode completely disappears. The charge associated with multiple streamers seems to vary with CO_2 percentage. That is, for high CO_2 content the peaks due to multiple streamers are cleanly separated from the single streamer peak, while for low CO_2 content-and in particular near the upper left sector of fig. 13-they appear only as a slight shoulder on the single streamer peak.

To investigate multiple streamers further, we recorded the pulses on the wires of our test chamber with a digital storage oscilloscope (Textronix Model 2430A). Choosing voltages that produce sufficient multiple streamers, we looked at single events triggered by our triple scintillation counters. We found that for the high CO_2 region, the pulses tended to be separatedin time, while for the low CO;! region, they tended to be more often as narrow as single streamer pulses,- but very large in magnitude. These effects are demonstrated in fig. 15, where on the left side [fig. 15(a)] narrow pulses range from a few millivolts in the top picture to over 200 mV in the bottom picture; while on the right side [fig. 15(b)] are examples of multiple pulses separated in time.

4. Temperature and Pressure Effects

Another property that we measured for all mixtures was the effect of temperature and pressure changes. We have already reported results for the standard gas and our new three-component nonflammable gas,[l] but here we attempt to generalize these results for all the possible combinations. A shift in transition voltage with temperature is shown clearly in fig. 16, where voltage scans are shown for two different temperatures. The same effect is also seen for pressure changes. This effect is summarized for four different gas combinations in fig. 17, where the mean charge of all the histogrammed pulses is plotted as a function of voltage for various temperature and pressure conditions. What one notices is that each gas combination has a characteristic shape for the mean charge curve which only shifts in voltage for different conditions. This effective voltage shift can be measured for each gas combination. Although there are some slight variations for different gas mixtures, as an approximate rule, the shift for all gases with temperature is (for constant average charge):

$$\frac{\partial V}{\partial T} = 9 \pm 1 \text{ V/°C} ,$$

and as a function of atmospheric pressure:

$$\frac{\partial V}{\partial P} = -4 \pm 1 \text{ V/ mm Hg} .$$

These two numbers can be very useful for estimating shifts in chamber response due to changes in these two variables, and compensating with changes in high voltage.

5. Mixtures Without a Clear Transition

As mentioned above, there are two regions of the mixture space explored in this study where the transition from proportional to streamer mode is not apparent from examination of the pulse height spectra. In such cases, as the voltage is increased the shape of the distribution changes comparatively little, showing a single peak with a most probable value which grows slowly and smoothly. For chambers with. digital readout, i.e., with pulses recorded by a discriminator, this behavior could be an advantage in some cases: for a fixed threshold and assuming constant pulse shape, the efficiency for recording pulses will change relatively slowly and smoothly with changes in high voltage (or, equivalently, temperature and pressure). By contrast, this efficiency curve for a mixture which shows clearly separated peaks will tend to have a fairly rapid change or "step" where the transition occurs.

The-two regions under discussion include the low-CO2 mixtures with high isobutane : argon ratio (fig. 5) and the two-component CO_2 : isobutane mixtures with at least 10% isobutane. Of these, the former represent highly flammable mixtures, while the latter class of mixtures have much better flammability characteristics (technically nonflammable in the case of 9 : 1 CO_2 : isobutane) and are thus much safer for use in large detector systems. It is interesting to note that, of this latter class, the mixture with 20% isobutane (80% CO_2) generally yields the largest pulse height for a given high voltage, and thus also the most stable efficiency against small changes in the mixture. Similar observations have been made in studies by the DELPHI [13] and OPAL [6] groups. We have extended the study of this region and will report more detailed results later.

6. Conclusions

Data have been presented concerning the behavior of standard plastic streamer tubes over a broad range of mixtures of three commonly used gases: argon, isobutane, and CO_2. Further investigations are planned, but it is hoped that the extensive survey presented here will prove useful to others working in this field.

Acknowledgments

The work described in this paper took place within the general framework of the SLD collaboration. We would like to express our gratitude to the whole WIC staff with its many skilled people whose expertise has been essential to the design, construction, and operation of the chambers. In particular, we want to thank N. Erickson, J. Escalera, M. Mittmann, and P. Ritson, whose work created and maintained the test facility.

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Figure Captions

1. (a) Sketch of typical chamber lamination.
   (b) Cross section of streamer-tube module.
2. Cosmic ray trigger configuration.
3. Block diagram of data flow.
4. (a) Strip and pad charge spectra for the top chamber with cuts at high and low values.
   (b) Corresponding strip and pad spectra for the bottom chamber for one choice of mixture and voltage.
   (c) Total charge spectrum for (b).
5. CO_2 – voltage mosaic for isobutane/argon = 5 : 1 (matrix of charge spectra for different values of high voltage and CO_2 fraction.)
6. CO_2 – voltage mosaic for isobutane/argon = 3 : 1.
7. CO;! – voltage mosaic for isobutane/argon = 2 : 1.
8. CO_2 – voltage mosaic for isobutane/argon = 1: 1.
9. CO_2 – voltage mosaic for isobutane/argon = 1: 2.
10. CO_2 – voltage mosaic for argon only.
11. CO_2 – voltage mosaic for isobutane only.
12; Fraction of pulses not in proportional mode, as a function of high voltage for various CO_2 fractions and isobutane : argon = 2 : 1.
13. Transition voltage (proportional pulses = nonproportional pulses) for various isobutane: argon ratios as a function of CO_2 fraction.
14. (a) Most probable pulse height for streamer mode at transition voltage as a function of CO_2 fraction for various isobutane: argon ratios.
   (b) Same plot for most probable pulse height for proportional mode.
15. (a) Single wire pulses sampled for isobutane : argon = 1 : 1 and CO_2 = 30% with vertical scales of 10, 20, and 50 mV.
   (b) Single wire pulses sampled for gas mixtures with about 90% CO_2.

16. Total charge spectra for one choice of mixture at temperatures of 12.5°C and at 22°C.

17. Mean pulse height versus high voltage for four different gas mixtures under various combinations of temperature and pressure.

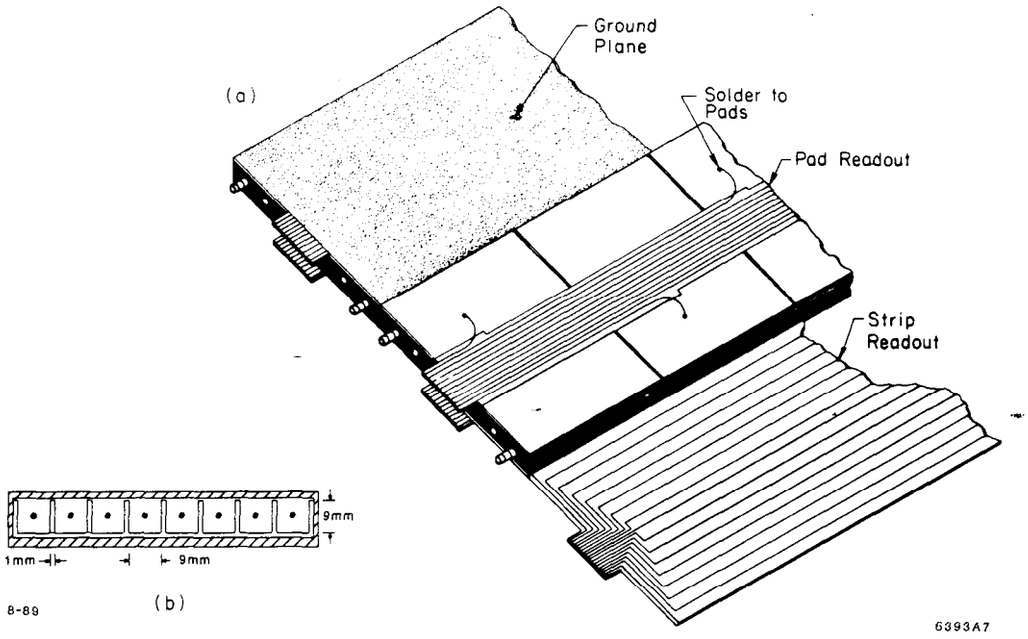

(a)
Ground Plane
Solder to Pads
Pad Readout
Strip Readout
9mm
1mm
9mm
(b)
8-89
6393A7

Fig. 1

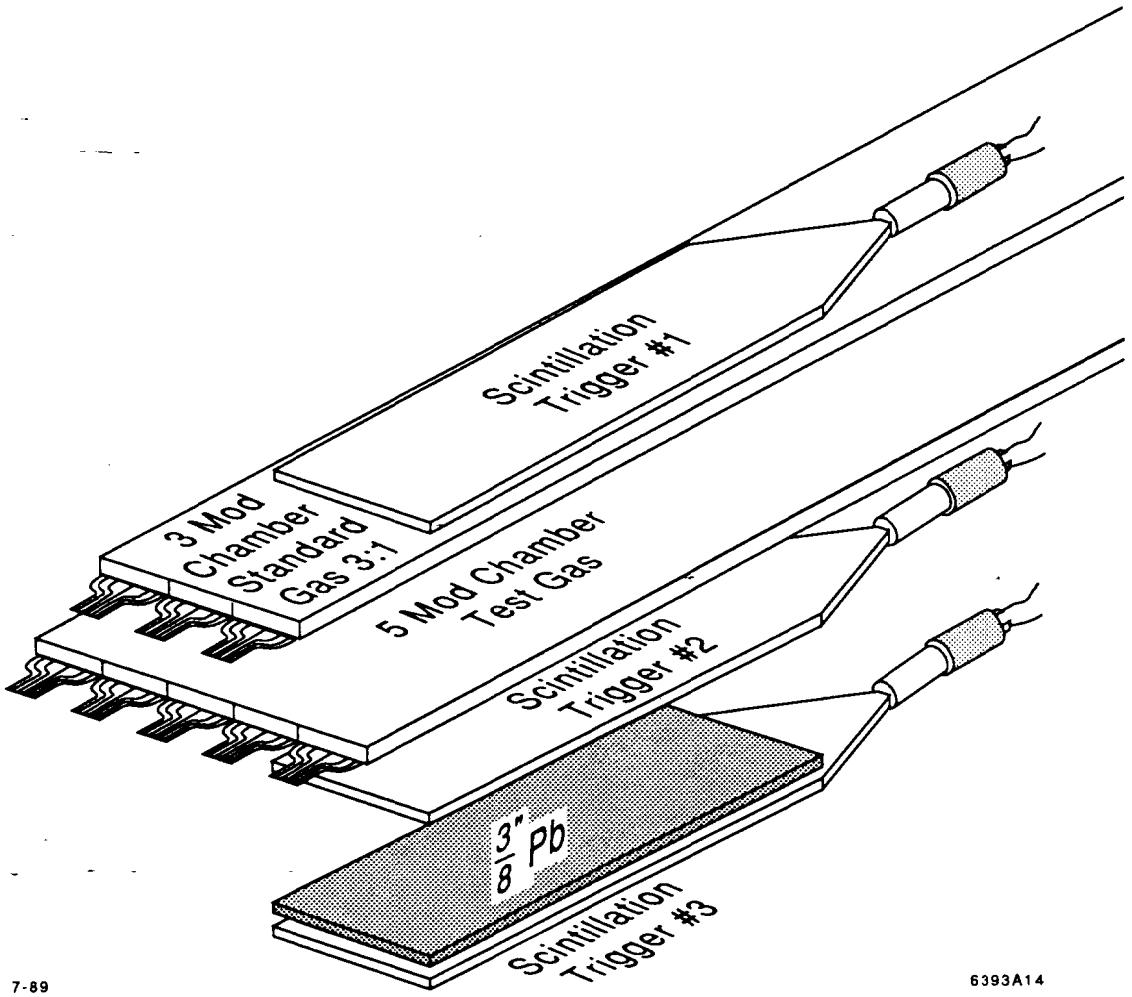

Scintillation
Trigger #1
3 Mod
Chamber
Standard
Gas 3:1
5 Mod Chamber
Test Gas
Scintillation
Trigger #2
3/8" Pb
Scintillation
Trigger #3
7-89
6393A14

Fig. 2

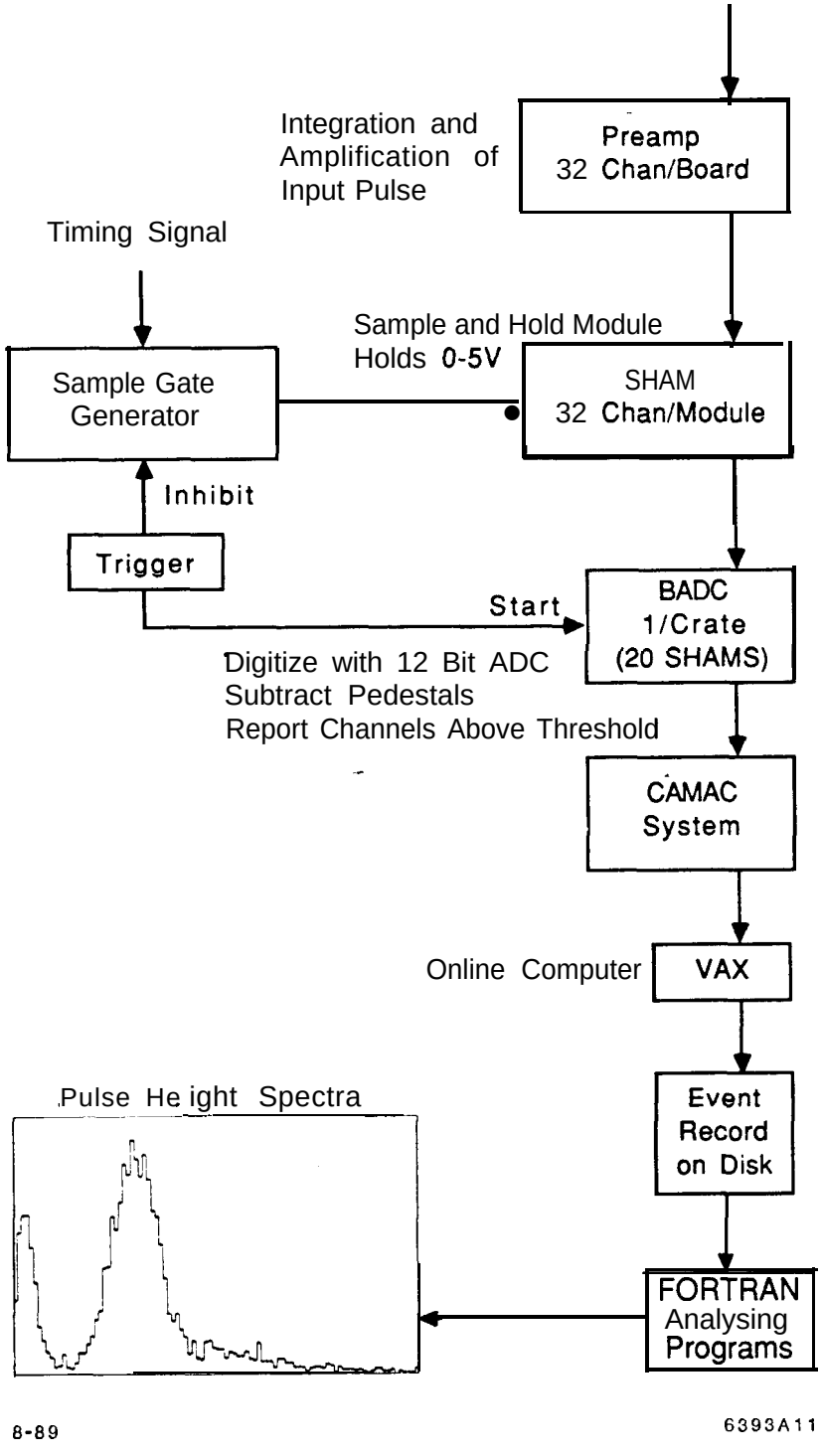

Integration and
Amplification of
Input Pulse
Preamp
32 Chan/Board
Timing Signal
Sample and Hold Module
Holds 0-5V
Sample Gate
Generator
SHAM
32 Chan/Module
Inhibit
Trigger
Start
BADC
1/Crate
(20 SHAMS)
Digitize with 12 Bit ADC
Subtract Pedestals
Report Channels Above Threshold
CAMAC
System
Online Computer
VAX
Pulse He ight Spectra
Event
Record
on Disk
FORTRAN
Analysing
Programs
8-89
6393A11

Fig. 3

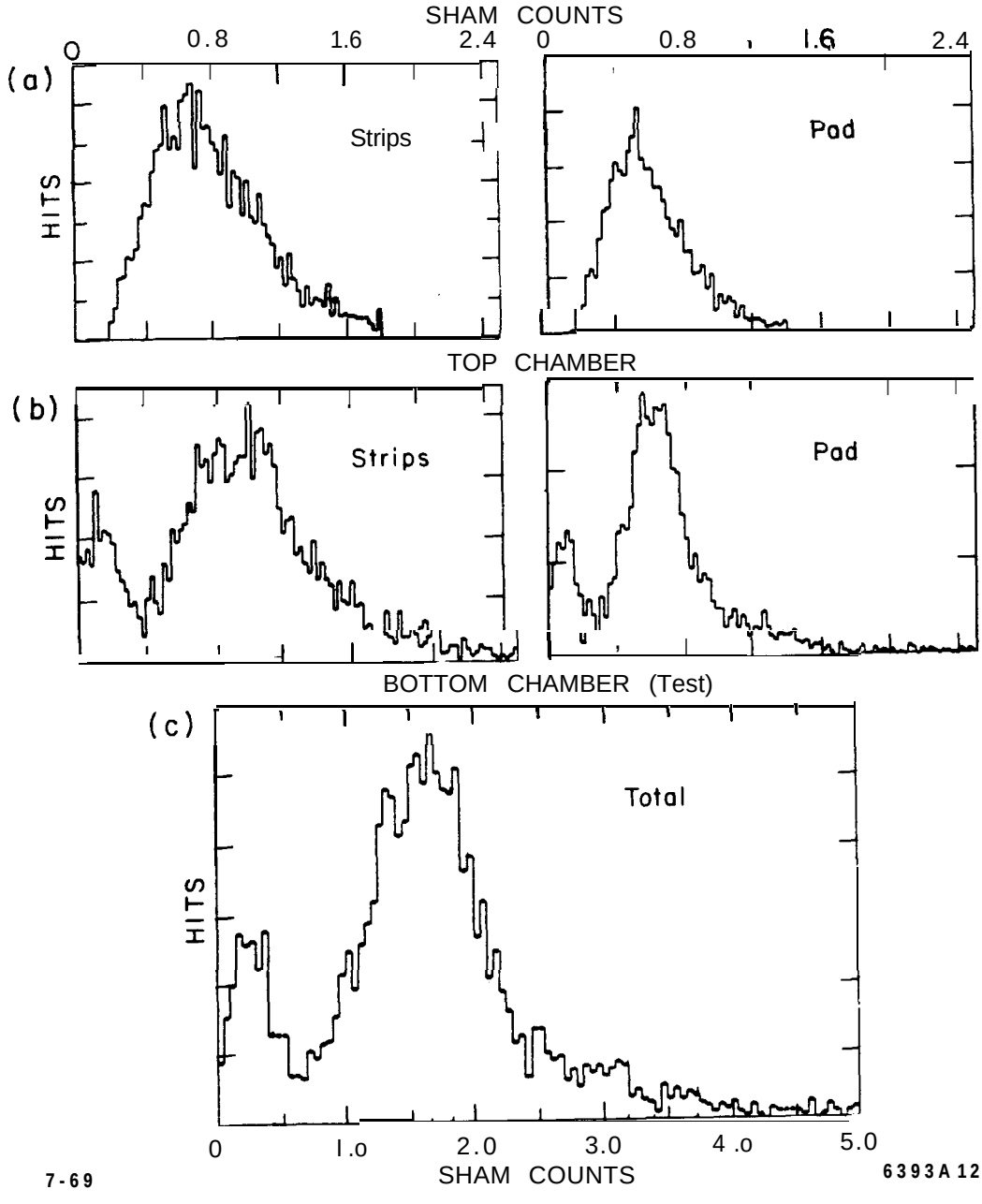

SHAM COUNTS
0
0.8
1.6
2.4
(a)
Strips
Pad
HITS
TOP CHAMBER
(b)
Strips
Pad
HITS
BOTTOM CHAMBER (Test)
(c)
Total
HITS
0
1.0
2.0
3.0
4.0
5.0
SHAM COUNTS
7-69
6393A12

Fig. 4

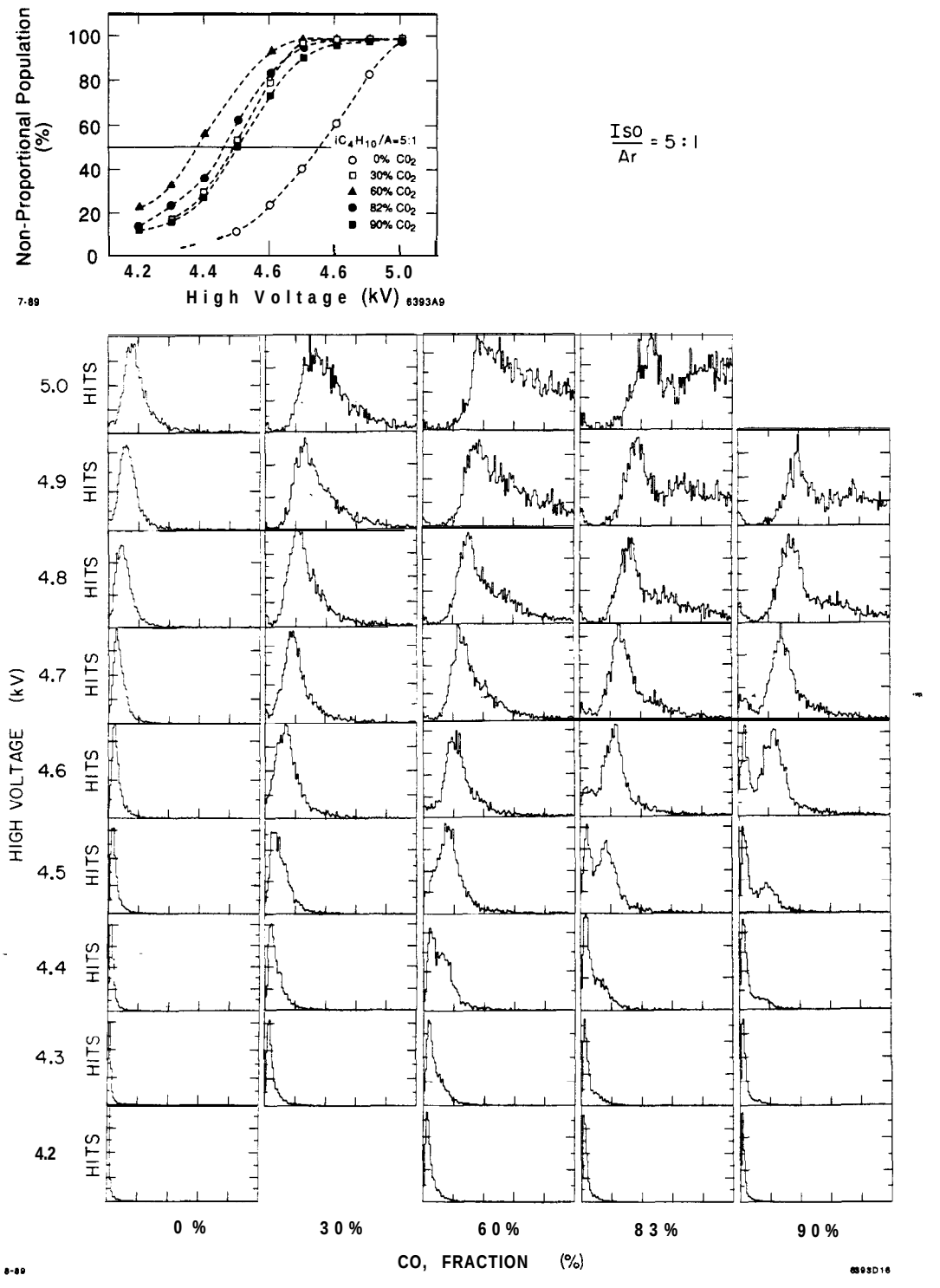
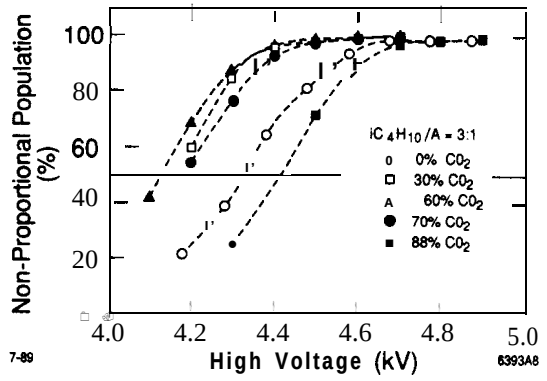

Non-Proportional Population (%)
100
80
60
40
20
0
4.2
4.4
4.6
4.6
5.0
High Voltage (kV)
iC4H10/A=5:1
0% CO2
30% CO2
60% CO2
82% CO2
90% CO2
7-89
6393A9
Iso / Ar = 5 : 1
HIGH VOLTAGE (kV)
5.0 HITS
4.9 HITS
4.8 HITS
4.7 HITS
4.6 HITS
4.5 HITS
4.4 HITS
4.3 HITS
4.2 HITS
0 %
30 %
60 %
83 %
90 %
CO, FRACTION (%)
8-89
6393D16

Fig. 5



Iso/Ar = 3:1

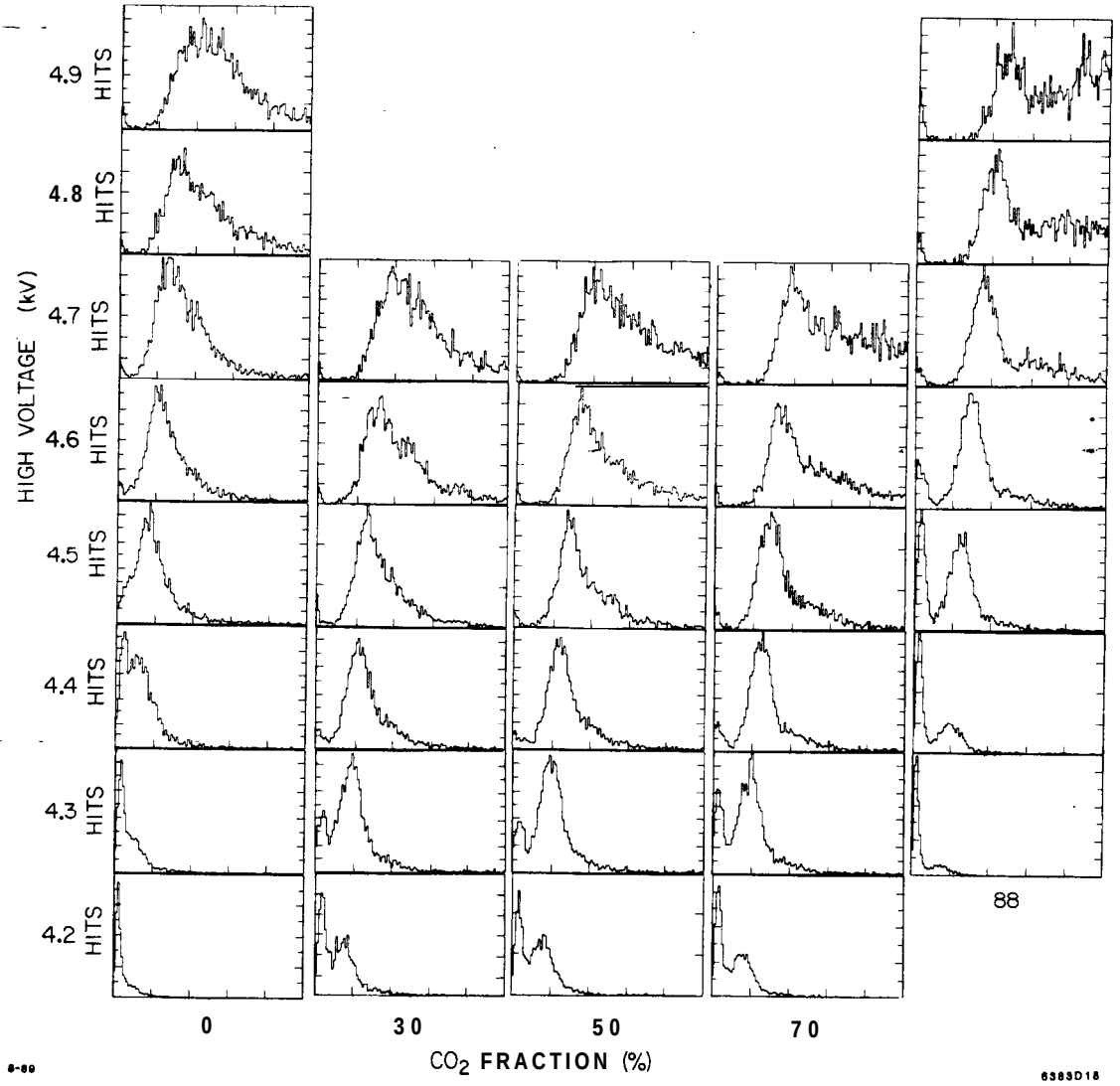


Fig. 6

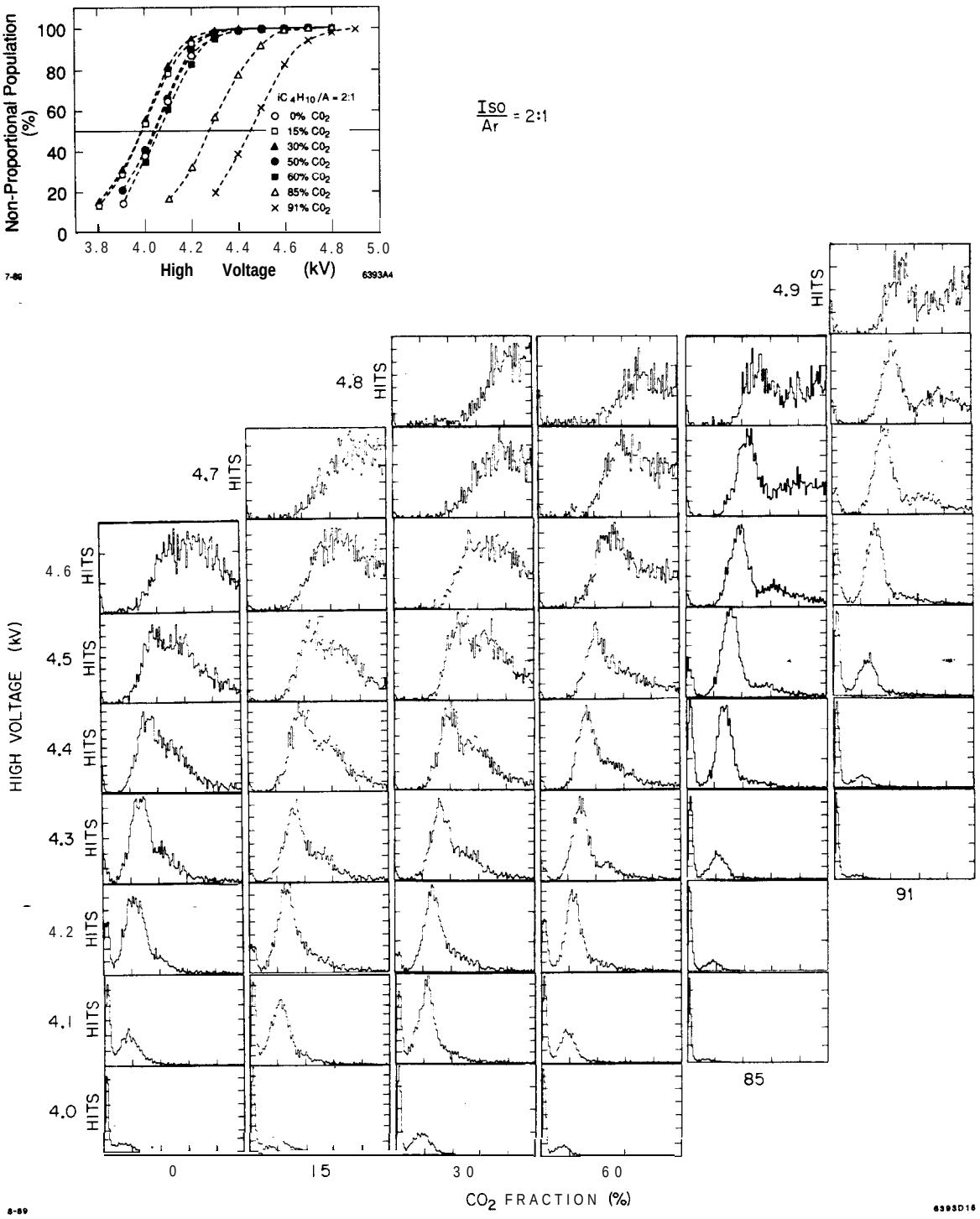

Non-Proportional Population (%)
100
80
60
40
20
0
3.8
4.0
4.2
4.4
4.6
4.8
5.0
High Voltage (kV)
iC4H10/A = 2:1
0% CO2
15% CO2
30% CO2
50% CO2
60% CO2
85% CO2
91% CO2
7-86
6393A4
Iso/Ar = 2:1
HIGH VOLTAGE (kV)
4.9 HITS
4.8 HITS
4.7 HITS
4.6 HITS
4.5 HITS
4.4 HITS
4.3 HITS
4.2 HITS
4.1 HITS
4.0 HITS
0
15
30
60
85
91
CO2 FRACTION (%)
8-89
6393D16

Fig. 7

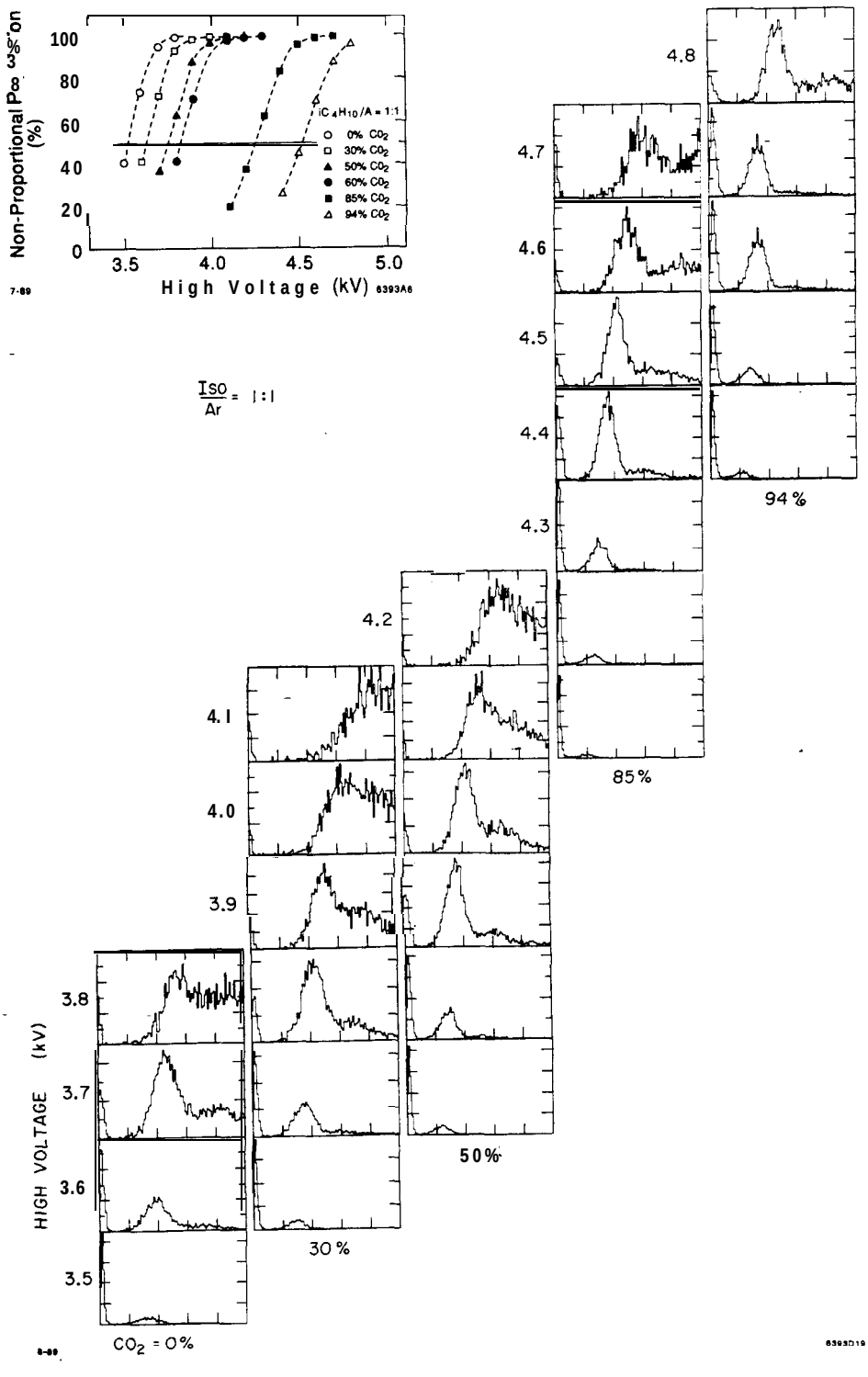

Non-Proportional Pos'on (%)
100
80
60
40
20
0
3.5
4.0
4.5
5.0
High Voltage (kV)
7-89
6393A6
$iC_4H_{10}/A = 1:1$
0% CO_2
30% CO_2
50% CO_2
60% CO_2
85% CO_2
94% CO_2
$\frac{Iso}{Ar} = 1:1$
HIGH VOLTAGE (kV)
3.5
3.6
3.7
3.8
3.9
4.0
4.1
4.2
4.3
4.4
4.5
4.6
4.7
4.8
$CO_2 = 0\%$
30 %
50%
85%
94 %
6393D19

Fig. 8

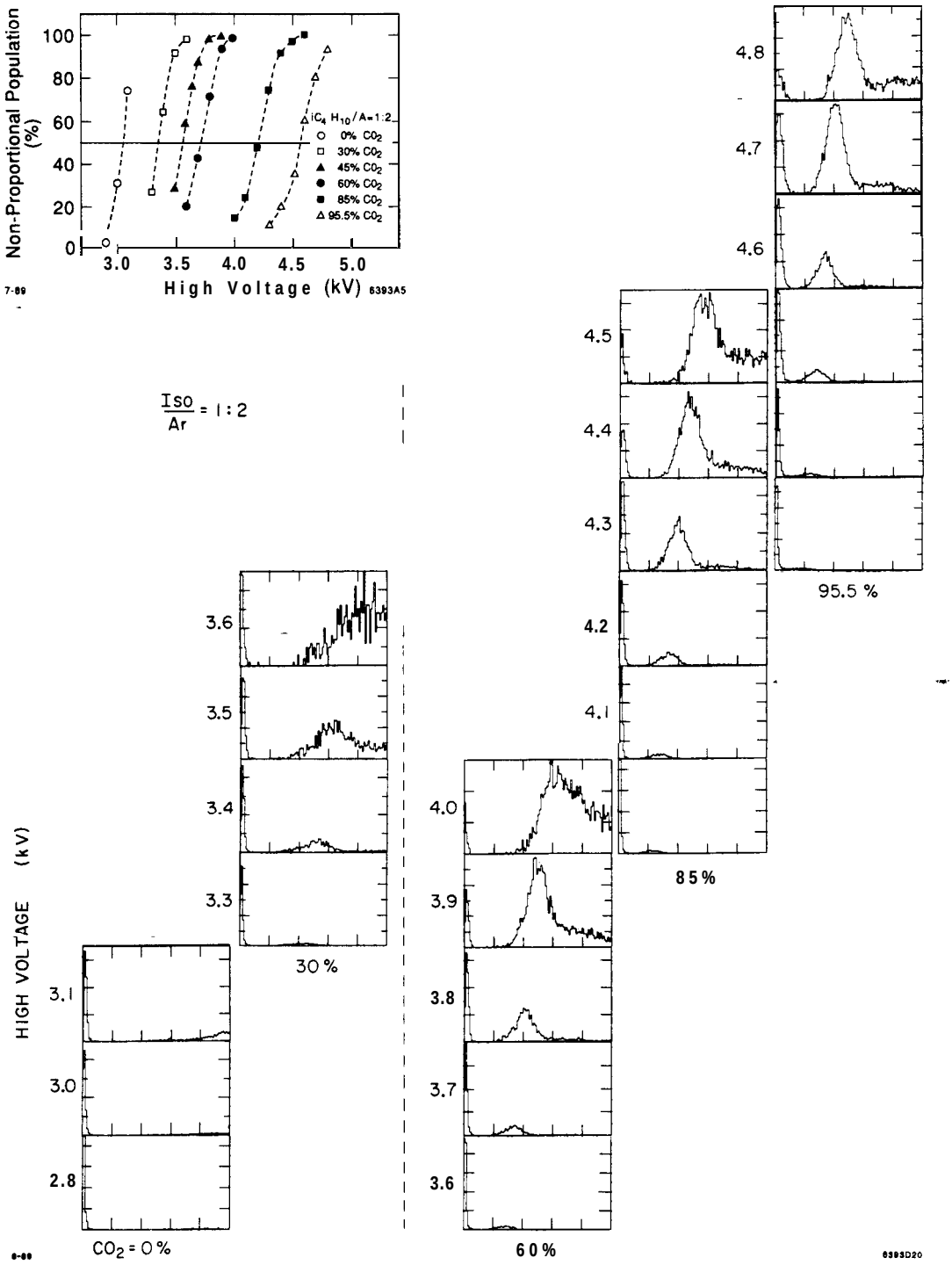

Non-Proportional Population (%)
100
80
60
40
20
0
3.0
3.5
4.0
4.5
5.0
High Voltage (kV)
6393A5
7-89
IC_4H_{10}/A=1:2
0% CO_2
30% CO_2
45% CO_2
60% CO_2
85% CO_2
95.5% CO_2
Iso/Ar = 1:2
HIGH VOLTAGE (kV)
4.8
4.7
4.6
4.5
4.4
4.3
4.2
4.1
95.5 %
3.6
3.5
3.4
3.3
30 %
4.0
3.9
3.8
3.7
3.6
85 %
3.1
3.0
2.8
CO_2 = 0 %
60 %
6393D20

Fig. 9

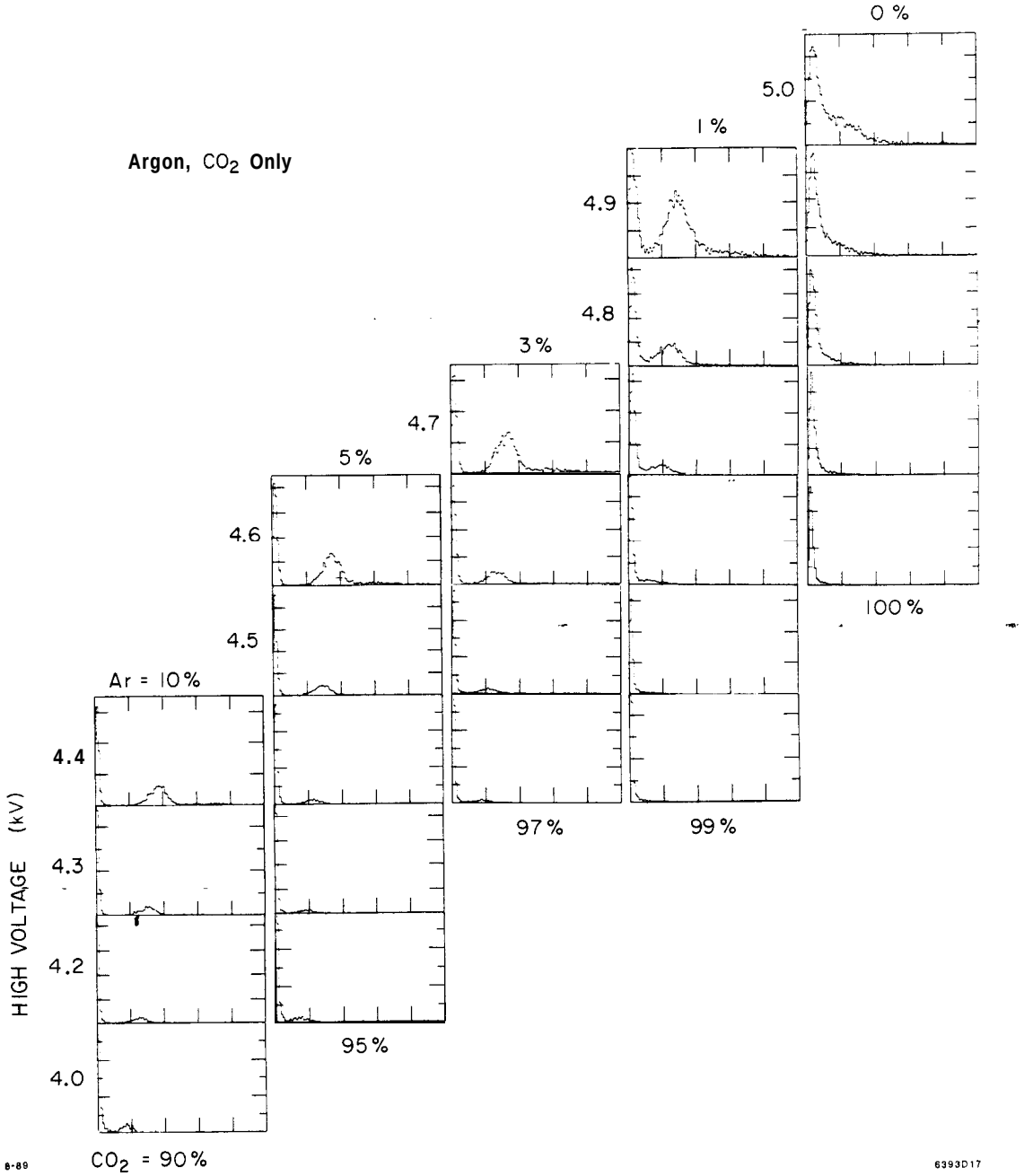

Argon, CO_2 Only
0 %
5.0
1 %
4.9
4.8
3 %
4.7
5 %
4.6
4.5
Ar = 10 %
4.4
4.3
4.2
4.0
HIGH VOLTAGE (kV)
100 %
97 %
99 %
95 %
CO_2 = 90 %
8-89
6393D17

Fig. 10

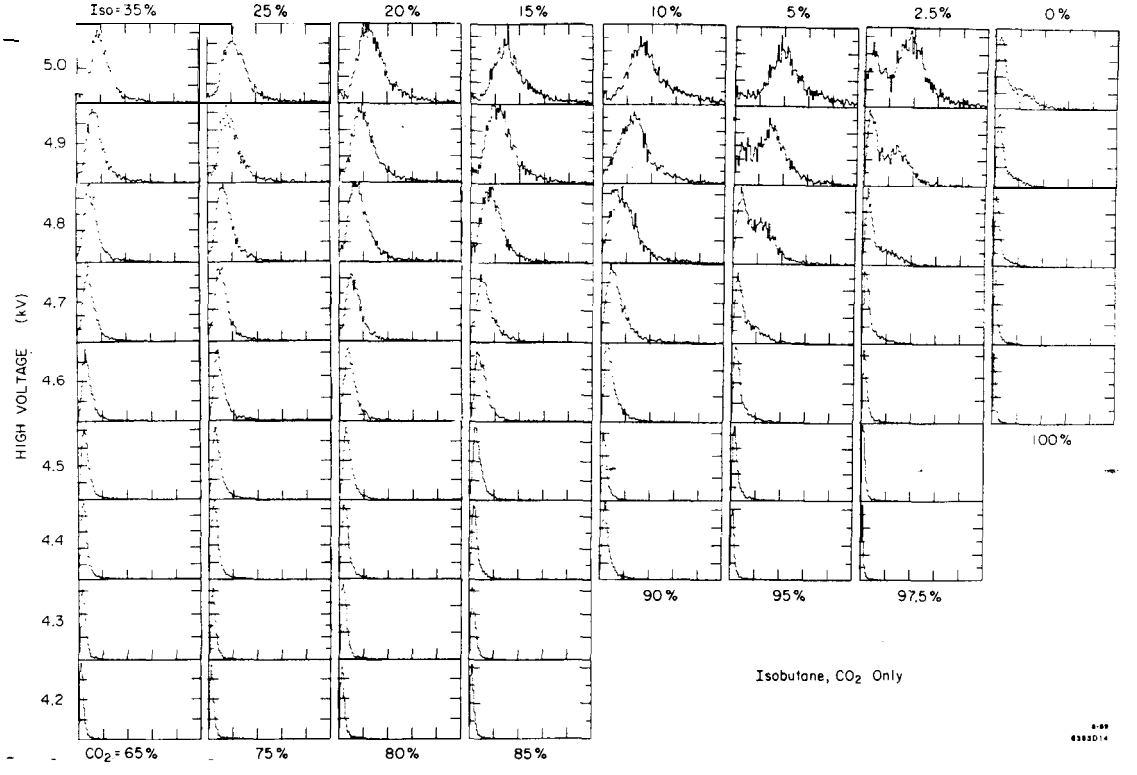

Iso=35%
25%
20%
15%
10%
5%
2.5%
0%
100%
90%
95%
97.5%
5.0
4.9
4.8
4.7
4.6
4.5
4.4
4.3
4.2
HIGH VOLTAGE (kV)
CO_2=65%
75%
80%
85%
Isobutane, CO_2 Only

Fig. 11

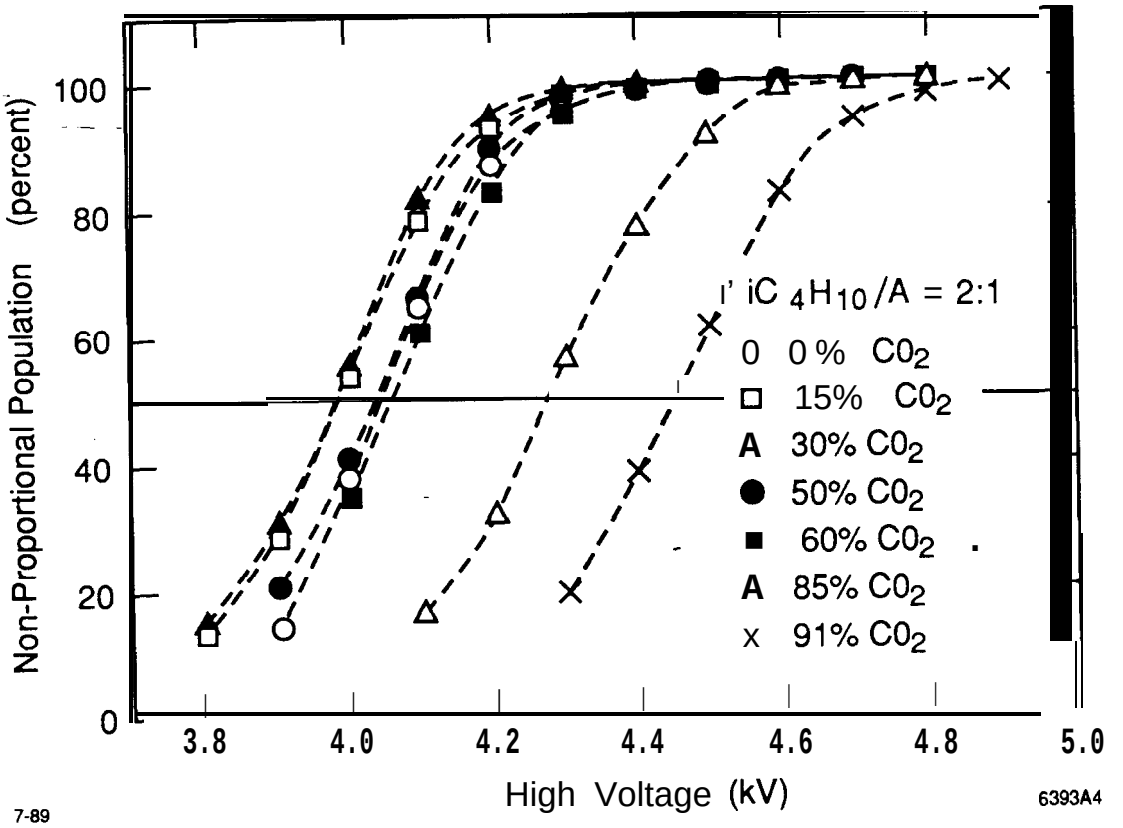

Non-Proportional Population (percent)
100
80
60
40
20
0
3.8
4.0
4.2
4.4
4.6
4.8
5.0
High Voltage (kV)
i' iC 4H10/A = 2:1
0 0% C02
15% C02
A 30% C02
50% C02
60% C02
A 85% C02
x 91% C02
7-89
6393A4

Fig. 12

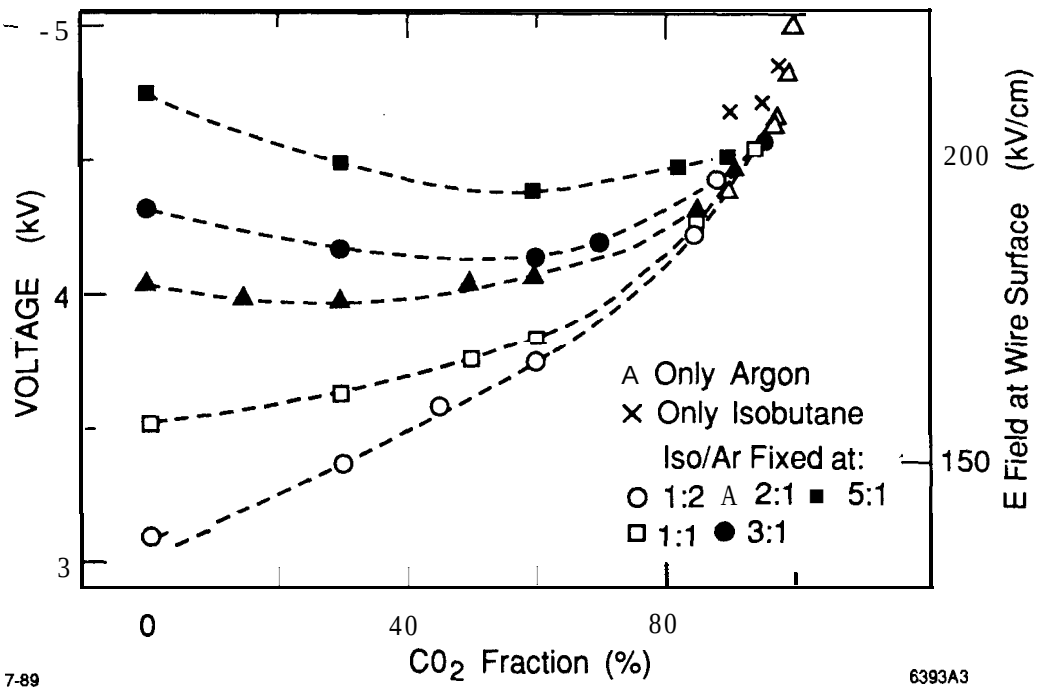

5
4
3
VOLTAGE (kV)
200
150
E Field at Wire Surface (kV/cm)
A Only Argon
× Only Isobutane
Iso/Ar Fixed at:
○ 1:2 △ 2:1 ■ 5:1
□ 1:1 ● 3:1
0
40
80
CO_2 Fraction (%)
7-89
6393A3

Fig. 13

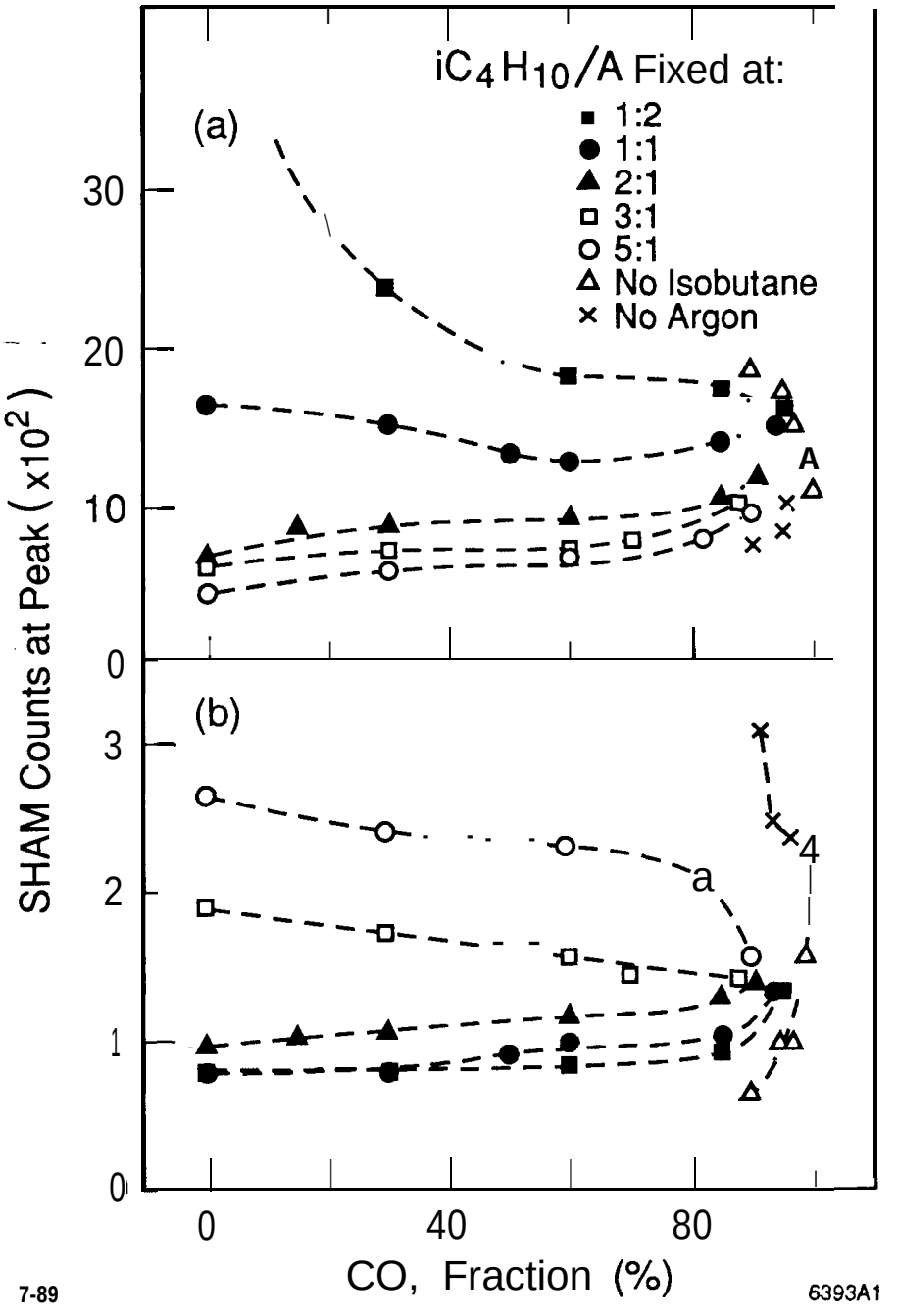
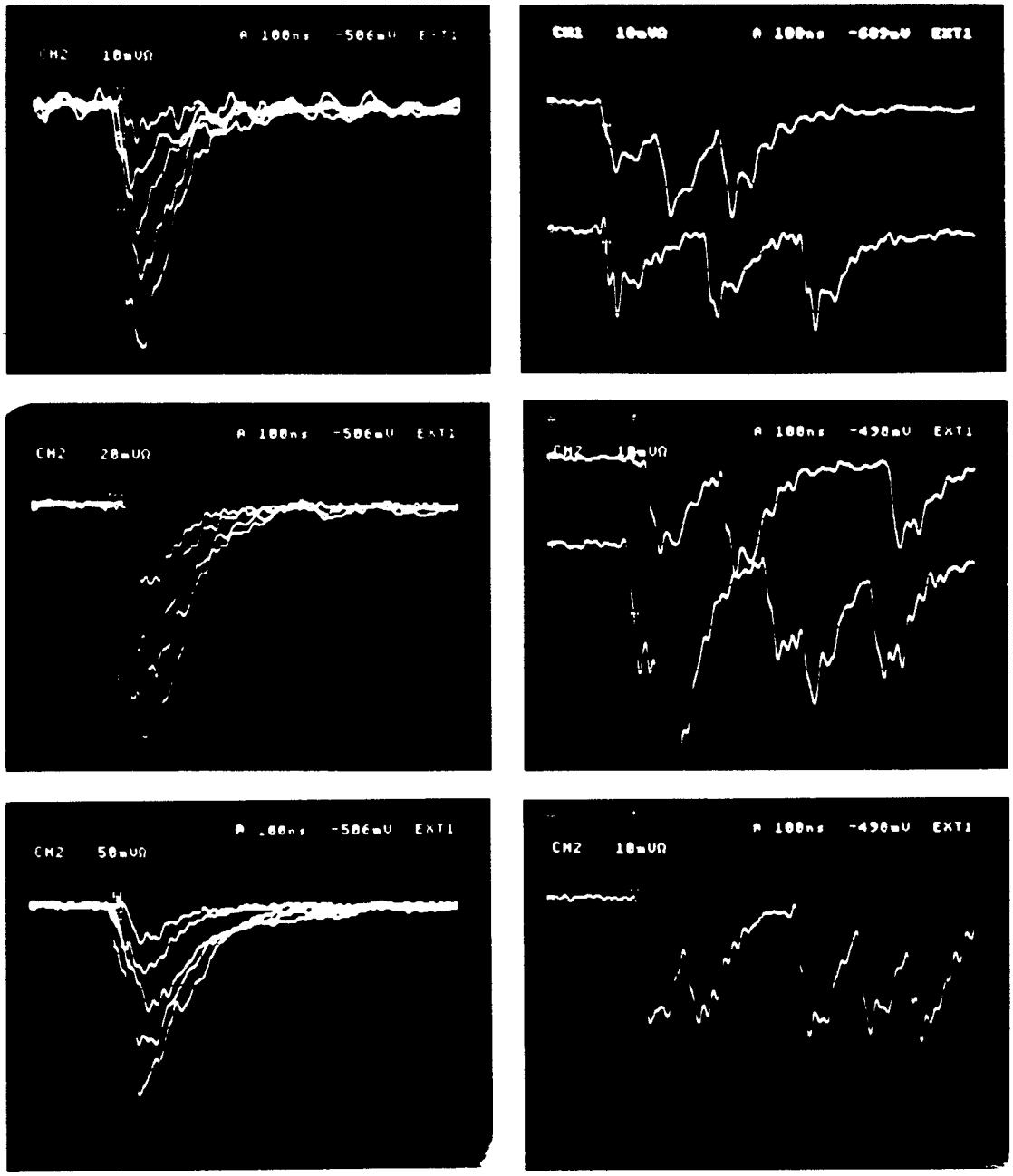

iC4H10/A Fixed at:
1:2
1:1
2:1
3:1
5:1
No Isobutane
No Argon
(a)
(b)
SHAM Counts at Peak (x10²)
CO, Fraction (%)
0
40
80
30
20
10
3
2
1
A
a
4
7-89
6393A1

Fig. 14


A 100ns -506mV EXT1
CH2 10mVΩ
CH2 10mVΩ A 100ns -609mV EXT1
A 100ns -506mV EXT1
CH2 20mVΩ
A 100ns -498mV EXT1
CH2 10mVΩ
A .00ns -506mV EXT1
CH2 50mVΩ
A 100ns -498mV EXT1
CH2 10mVΩ

(a) (b)

Fig. 15

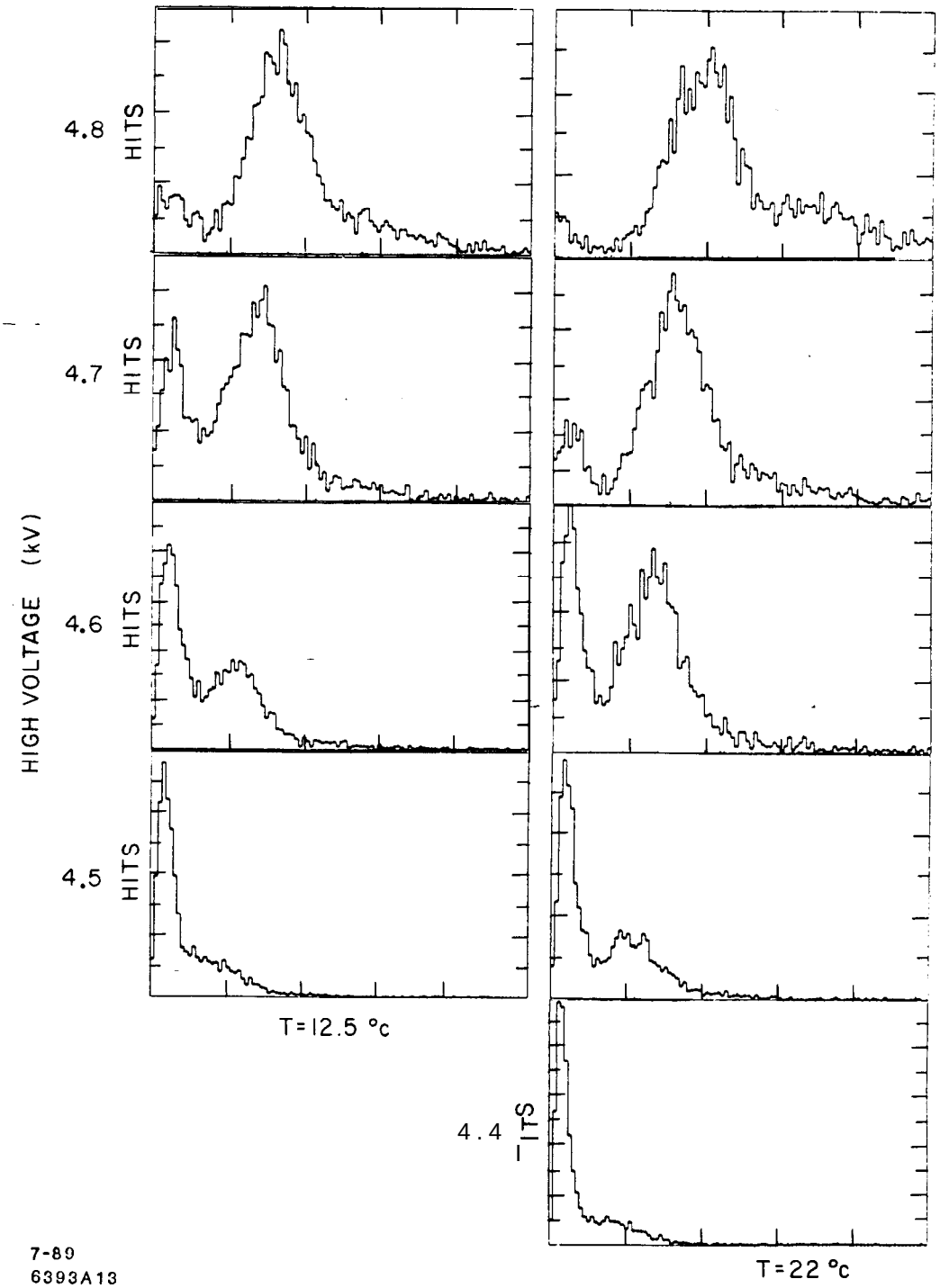


Fig. 16

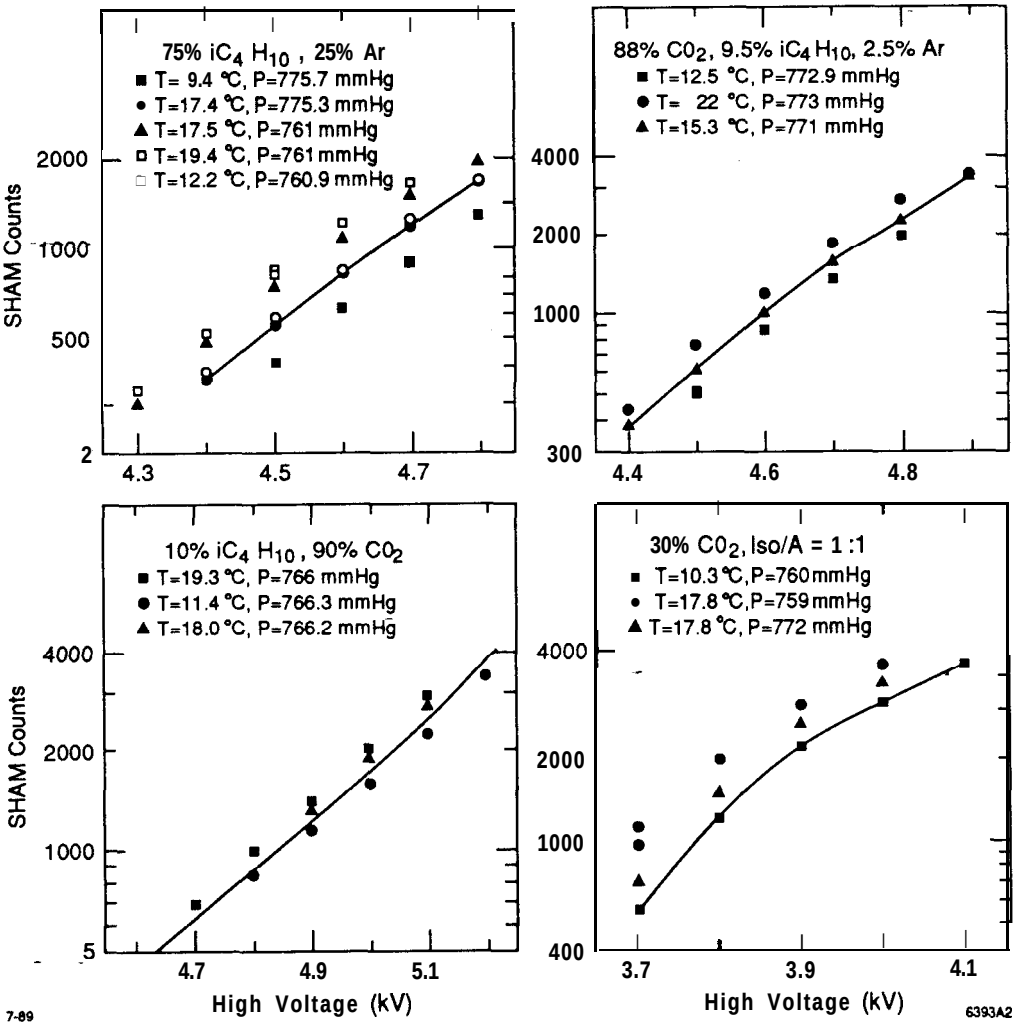

75% iC4 H10 , 25% Ar
T= 9.4 °C, P=775.7 mmHg
T=17.4 °C, P=775.3 mmHg
T=17.5 °C, P=761 mmHg
T=19.4 °C, P=761 mmHg
T=12.2 °C, P=760.9 mmHg
88% C02, 9.5% iC4 H10, 2.5% Ar
T=12.5 °C, P=772.9 mmHg
T= 22 °C, P=773 mmHg
T=15.3 °C, P=771 mmHg
10% iC4 H10 , 90% C02
T=19.3 °C, P=766 mmHg
T=11.4 °C, P=766.3 mmHg
T=18.0 °C, P=766.2 mmHg
30% C02, Iso/A = 1 :1
T=10.3 °C, P=760 mmHg
T=17.8 °C, P=759 mmHg
T=17.8 °C, P=772 mmHg
SHAM Counts
High Voltage (kV)
7-89
6393A2

Fig. 17