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Abstract

Studies have been made of radiation-hard gases having CF_4 as a major constituent, and aging rates based upon accelerated aging testing techniques are presented. A variety of aging tests have also been performed with straw tubes of 4 mm diameter. Using a straw tube with a carbon filament anode wire, the disposition of heat generated in the avalanche process was determined to be predominantly by conduction from the anode to the cathode tube wall along the radial direction. This eliminates the need for removal of the anticipated heat load at SSC experiments through exceptionally high gas flow rates.

I. Inhibition of Wire Aging Using CF_4-Based Gases

A. Introduction

Using techniques described previously [1] to perform accelerated aging tests, we have investigated several CF_4-based gas mixtures which have properties desirable for application in wire chambers to be used in high radiation environments. Among these properties are: 1) low diffusion [2], 2) high linear ionization density [3], 3) high drift velocity [2,4], and 4) low aging rates [5,1]. The aging properties of the gas mixture CF_4/isobutane(80/20) have been studied recently, and have exhibited an exceptionally low aging rates [5,1]. These low rates may be the result of the 'etching' action of radicals produced in the breakup of the CF_4 molecule in the avalanche process [6]. We report here on additional results obtained using CF_4/isobutane(80/20) as well as using other gas mixtures containing CF_4. These results can be interpreted in terms of the model of competitive ablation and polymerization [7].

In the subsequent discussion, the aging rate is defined as the rate of current decrease (gain decrease):

$$R = (1/I_0)(dI/dQ)\ \%/C/cm,$$

where: I = current, I_0 = initial current, and Q = charge transfer. The length of the irradiated region on the wire is about 3 mm in most cases. The avalanche gains at beginning of tests are thought to be in the neighborhood of 20,000 to 50,000, but are not known with any precision.

B. Etching of Silicone-coated Wires Using CF_4/isobutane(80/20)

It has been recognized for some time now that the gas mixture CF4/isobutane(80/20) in wire chamber tests results in very low aging rates [5,1]. Additional tests have demonstrated that, in fact, previously coated wires can be restored by etching (i.e. chemical removal of deposits) using this gas mixture [8]. We have confirmed this observation by first coating anode wires using a previously developed technique [1], then restoring full gain in these wires using this gas mixture. Other types of tests were also performed to elucidate the mechanisms involved.

1. Aging Rate of CF4/isobutane(80/20)

We have done several tests of the CF_4/isobutane(80/20) mixture, and all give very low aging rates. A typical test is summarized in Table I. This confirms earlier results obtained by the TRIUMF group [5].

2. Silicone-Coating of Anode Wires

A technique for deliberately coating the anode wire with silicone polymer [1] was used to study the etching effects of CF_4/isobutane(80/20). By bubbling an argon/ethane(50/50) gas mixture through silicone diffusion pump oil (Dow 704) before the gas enters the wire chamber, a layer quickly coats the anode wire. The rate of wire aging during this process is as high as 300%/C/cm, being more rapid initially, then diminishing later as the gain decreases asymptotically toward a non-zero value. It was verified that the wire coating is not due to merely a film of oil mechanically deposited by the gas by performing a run as described above, with high voltage applied, but with no Fe^{55} source to induce avalanches. No aging was observed through either a gain decrease or a degradation in the Fe^{55} pulse height spectrum under these conditions. In contrast, a similar test, with a source applied for an equal length of time, resulted in significant gain decrease and a severely degraded pulse height spectrum. The avalanche is therefore necessary to produce the wire coating. The rate of coating seems remarkably high, since the vapor pressure of the silicone oil is only 1.4×10^{-8} Torr (at 20°C), corresponding to a concentration in the gas of only 0.018 ppb! An analysis of the surface of wires coated in this manner using

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FTIR revealed the presence of Si-O bonds, suggestive of a silicone polymer.

This technique of bubbling gas through silicone oil has been used repeatedly to create wire deposits, and is quite reproducible. Fig. 1 shows the current during a test in which a silicone coated wire was produced for the test described next.

3. Removal of Silicone Coating Using CF_4/isobutane(80/20): "Etching"

An anode wire coated in the manner described above in section IIB was subsequently irradiated while operating with a CF_4/isobutane(80/20) mixture (the Fe^{55} source location remained fixed relative to the wire between coating and etching runs). Fig. 2 shows the current (gain) during this run, and can be compared with Fig. 1. Initially, the current and gain are low, and the voltage was increased by ~5% (at "A" on Fig. 2) to accelerate the etching process. Subsequent to this point, there was a small drop in current, soon followed by an erratic increase in current up to the full-gain value, where the current becomes constant again, suggestive of complete removal of deposits in the irradiated area. Also associated with the process are frequent current surges suggestive of Malter-type breakdowns. This indicates that cathode as well as anode coatings were present. The cathode coatings also seem to be removed, by the etching action since they cease as the process of gain recovery proceeds.

4. Bubbling CF_4/isobutane(80/20) Through Silicone Oil

As an additional test of the resistance to aging, CF_4/isobutane(80/20) was bubbled through Dow 704 silicone oil before the gas entered the wire chamber, in the same manner used to coat wires using argon/ethane gas. There was a very small measured aging rate of 3%/C/cm. This test was performed with the same wire, source, and geometry used for tests described above in sections IIB and IIC.

5. Lack of Etching Using Argon/Ethane or DME

To establish that the removal of wire coating does indeed depend upon the use of the CF_4/isobutane gas mixture, two other gases, argon/ethane(50/50) and dimethyl ether (DME), were used instead, under conditions identical to those described in section IIC above, where etching was observed. In neither case is there any evidence that the current is increasing.

C. Other Results and Summary

The results of tests using several other CF_4-based gas mixtures are given in Table I. CF_4-based gases appear to be excellent candidates for many wire chamber applications, especially those involving high rates and radiation levels. The combination of low diffusion and high linear ionization density are important in obtaining good spatial resolution, and the relatively high drift velocity and very

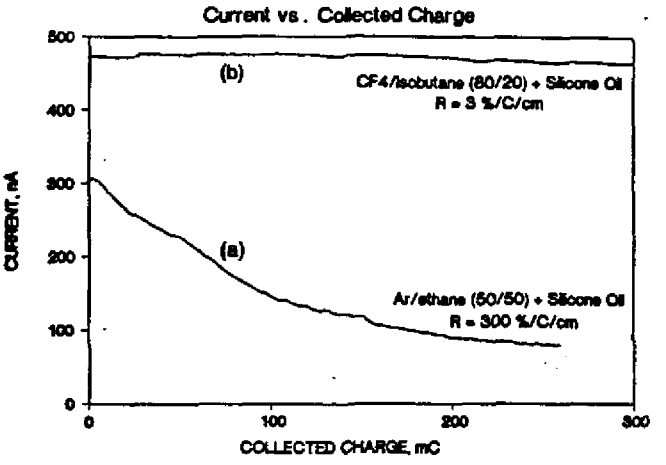

Fig. 1. (a) Aging run during which Ar/ethane(50/50) was bubbled through silicone oil (Dow 704) upstream of the wire chamber. Aging only occurs when high voltage and Fe^{55} source are both present. Note that current is asymptotic to a nonzero value. (b) Run similar to (a), except that CF_4/isobutane gas was bubbled through silicone oil.

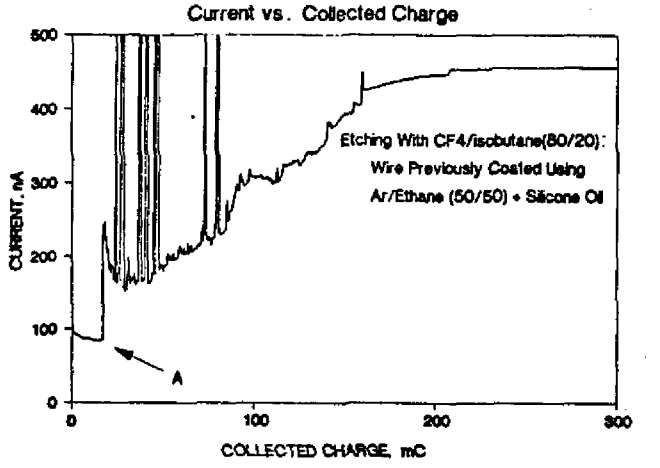

Fig. 2. Removal of Wire Deposits Using CF_4/isobutane(80/20) Gas. Avalanche-induced silicone deposits produced by bubbling Ar/ethane through silicone oil (Fig. 1) are subsequently removed by operating instead with CF_4/isobutane. All other variables were unchanged except for a 5% voltage increase to accelerate the etching process.

low aging rates are important for operation in a high radiation environment. Aging rates, using Fe^{55} sources to accelerate the aging process, have been measured for several gas mixtures containing CF_4.

The principal gas mixture investigated was CF_4/isobutane. The mixture CF_4/isobutane(80/20) was found to have a very low aging rate ($R < 2$), and to be capable of removing deposits from an existing wire coated with silicone polymer. It also exhibited a quite low aging rate ($R = 3$) when bubbled through silicone oil before entering the wire chamber, a procedure used deliberately to create the silicone wire coating using Ar/ethane(50/50) gas ($R \sim 100$). An additional proof of the distinctive etching properties of this mixture was the observation that two gases, Ar/ethane(50/50) or dimethyl ether did not result in

a removal of deposits in the manner observed for the CF_4/isobutane(80/20).

By reducing the CF_4 content, aging could be induced: although the (50/50) mixture did not age, the (20/80) mixture did (R ~ 300). The mixtures CF_4/DME(90/10) and (20/80) and CF_4/CO_2(40/60) were all observed to have very low aging rates as well. This latter gas operated stably with little aging, while, for comparison, pure CO_2 appeared to be quite unstable, although not obviously as a result of recognizable aging. There may be some advantage in using CF_4/CO_2 in applications where background signals resulting from neutron-induced proton recoil particles may be experienced, such as at future SSC experiments. Use of gases with no hydrocarbon content should avoid such background processes occurring in the gas. There may, however, be recoil protons arising from wire chamber walls (e.g. straw tube walls), unless these are also made from non-hydrogenic materials.

A model of competitive ablation and polymerization processes has been proposed [7]. A non-zero aging rate and amount of deposition, which depends upon the relative strengths of the ablation and polymerization reactions, is implied by this model. The results obtained here may be explained in terms of this model.

II. Use of Straw Tubes in High-Radiation Environments

A. Introduction

There are two parts to this investigation: (1) study of aging effects in straw tubes, including straw tubes previously damaged by discharges and (2) use of straw tubes equipped with carbon wires to study the thermal effects of avalanches. The results of aging tests are contained in Table II, and will be discussed briefly in the summary. Heating effects in straw tubes are dicussed below and summarized in Table III.

B. Heating Effects

Possible limitations to the use of straw tubes in high radiation environments are gas temperature changes and the consequent gain changes. Indeed, temperature changes as small as 6°C, corresponding to ~10% gain variations, may be unacceptable in some applications. The potential difficulty arises in removal of the power dissipated as heat in the tubes, since a temperature rise of $\sim 10^4$ °C is obtained from an estimate based upon heat transport using the heat capacity of the gas alone, assuming laminar flow of 1 mm/sec, and 2 mW/m avalanche power dissipated. Various heat transport mechanisms will surely limit the temperature rise to a much smaller amount than this. However, from this analysis we recognize the possibility that unacceptably large increases in temperature may occur.

For the purpose of investigating the heat transfer mechanisms in detail, we used a straw tube of the above-mentioned design with a 33 μm-diameter carbon anode wire through which current was passed to produce ohmic heating, and in this fashion to simulate the heat produced in a tube in a high-radiation environment. We believe this method simulates closely the gas heating near the surface of the wire and the associated heat flow through the tube.

A small dc current supplied by a battery was passed through the carbon wire, and the voltage across the wire and the current through the wire were measured simultaneously. These measurements determined directly both the resistance of the wire and the power dissipated. The resistance determination permitted an estimate of the temperature of the carbon wire, since the resistance of carbon is a

Table I

Anode wire aging rates measured for CF_4-based gases and associated tests, using wire 50 μm diameter. The gas flow rates were 10-20 cc/min through a 3/8" diameter tube. Gains were 20,000-50,000. Wire is irradiated over ~3 mm, except for the first test listed. The silicone oil used was Dow 704 diffusion pump oil with a vapor pressure at 20°C of 1.4×10^{-8} torr.

Gas mixture	Aging rate, R %/C/cm	Current density, μA/cm	Charge, C/cm	Comments
Tests using gold-plated wire:				
CF_4/iC_4H_{10} (80/20)	<2	0.3	0.8	~6 mm of wire irradiated
+silicone oil	3	1.4	1.5	Bubbled through oil upstream of chamber
Ar/C_2H_6 (50/50) +silicone oil	300→50	0.9→0.3	0.6	Aging rate decreased during test (Fig. 2)
CF_4/iC_4H_{10} (20/80)	300	0.9	0.09	
(50/50)	-2	2.0	1.6	Same wire used in (20/80) test
CF_4/DME (90/10)	1	1.2	1.8	
(20/80)	0	1.0	0.5	
CF_4/CO_2 (40/60)	7	1.2	0.8	
Tests using resistive wire:				
CF_4/iC_4H_{10} (80/20)	350	0.6	0.2	Nicotin
	110	0.6	0.2	Stablohm
	320	0.6	0.1	Stainless steel

function of temperature. To estimate the temperature, we used the coefficient for carbon resistivity as a function of temperature as measured by us, using a temperature-controlled oven (Varian model 3400 gas chromatograph).

A second method of estimating the temperature near the wire surface was measurement of the gain increase observed in the pulse-height spectrum of ^{55}Fe when the wire was heated. The dependence of gain on temperature has been well established from ambient pressure and temperature changes during many wire aging tests performed with this system.

A third method of determining the wire temperature follows from an analysis of the heat transfer. Estimates show that all except one of the potential channels for heat flow are small enough to be neglected: conduction through the gas along the radial direction between the anode and the cathode dominates the heat flow. With this simplification, an estimate of the temperature change is obtained directly from the conduction equation, using the known heat input to the wire.

Measurements of the temperature were made using all three methods, by varying the battery voltage up to about 100 V. Two specific cases, 9 V and 46 V, are summarized in Table III. The agreement between the three methods is good.

The level of agreement between these two cases gives some confidence that this procedure can be extrapolated to the still lower power levels appropriate to an SSC experiment. Although the power corresponding to the 9 V case is ~60 mW/m, perhaps 100 times the maximum expected in normal SSC operation, the temperature rise is nevertheless sufficiently small to be acceptable. Since the temperature rise is expected to scale linearly with power, the anticipated temperature rise in an SSC experiment would be very small indeed for an isolated tube.

As an additional verification of the conductive model of heat transfer, the gas flow rate was varied from 1.5 to 150 cm^3/min while monitoring the gain. No change of gain was observed for flow rates of 1.5 to 120 cm^3/min, indicating that the gas temperature in the avalanche region is largely unaffected by the gas flow rate, as expected if radial conduction is the dominant heat transfer mechanism. Some change in the gain was observed for flow rates in the 120 to 150 cm^3/min range, however. We believe that this was where the transport of heat by gas flow through the tube at higher flow rates began to compete with removal of heat by conduction radially.

Since conduction is the dominant heat transport mechanism, the gas flow rate is not dictated by heat removal, and can be as low as consistent with acceptable aging. We obtained good aging results with gas flows as low as ~1.0 cm^3/min, corresponding to an average linear gas velocity of only 1.3 mm/sec.

For isolated straw tubes, conduction alone is sufficient to remove the heat from the tube wall; some convection is expected to be necessary to remove heat from an array of tubes such as in a full-scale detector. If tubes are arranged in layers with a small number of tubes per layer, as in some current designs [9], there will still be only negligibly small temperature rises within each layer according to our estimate, with heat being carried away efficiently by the gas between layers.

Table II

Aging results in straw tubes.The aging rate, R, is defined as $R = -(1/I_0)(dI/dQ)$ where Q is the collected charge per length of wire and I is the current. All tests used gold-plated wires of 38 μm diameter except the last test listed, which used a carbon filament of 33 μm diameter. The total gain was ~$5x10^4$ for tests with gold-plated wires and ~$2x10^4$ for the test with the carbon filament. Nylon tubing was used for the gas plumbing in all tests.

gas	R %/C/cm	accumulated charge C/cm	anode voltage V	gas vel. mm/s
Ar/C_2H_6 (50/50) + 1000 ppm H_2O	15	0.4	1600	53
CF_4/iC_4H_{10} (80/20) + 1000 ppm H_2O	3	0.5	2240	53
w/out added H_2O	5	0.25	2240	53
CF_4/DME (90/10)	3	0.7	2200	26.5
Ar/C_2H_6 (50/50)	~0	0.8	1590	26.5

C. Summary

The simple prototype straw tube proportional counters described here were used for studies of aging and heating under conditions that are expected to be encountered at SSC experiments. Two major concerns investigated were the aging rates with several gases and the proportional gain fluctuations due to avalanche heating.

We have tested the aging of straw tubes having aluminum cathodes with several gases: argon/ethane (50/50) and CF_4/isobutane (80/20), with and without water added; and CF_4/dimethyl ether (90/10). With argon/ethane as the test gas, it was found that water vapor on the order of 1000 ppm was needed to prevent electrical discharges in a tube that had some previous damage from discharges. With the use of Nylon tubing, no direct water vapor addition was needed, presumably due to sufficient natural outgassing of water from or diffusion of water through the tube walls. In at least one case (CF_4/DME), however, use of stainless steel tubing resulted in immediate electrical breakdown, which we believe to have been due to the lack of water vapor. All of the gases tested were found to give satisfactory aging rates. In addition, argon/ethane gave

satisfatory aging with gas flow rates as low as 1.0 cm^3/min.

The investigation of heating effects used a 33 μm-diameter carbon anode wire to model the avalanche gas heating by ohmic heating from small electric currents. It was found that the heat transfer from the wire is essentially all by conduction through the gas along the radial direction. The recognition of this may simplify considerably the design of large straw-tube detectors.

Table III

Measurements of heating effects in straw tube with 33 μm diameter carbon filament anode: 9 V and 46 V cases. Temperature dependence of carbon resistivity: $(1/R_0)dR/dT = -2.0\times10^{-4}$/°C. The resistance of the filament was 9.22 kΩ at 21°C. The electrical length of the wire was 22.9 cm; the active length was 12.2 cm.

	9 V	46 V
Voltage across filament (V)	9.0	45.8
Current through filament (mA)	0.98	5.0
Resistance of filament (kΩ)	9.22	9.13
Power input (mW)	8.8	230
Power input to active region (mW)	4.7	123
Gas flow (cm^3/min)	20	18
^{55}Fe: Pulse-height of principal peak (channel, ped. subtr.)		
Base case* (0 V)	400	376
With voltage applied	423	769
Gain ratio G(V)/G(0):	1.06	2.04
Computation of temperature rise (°C) (estimated error)		
From filament resistance (±20%)	1.6	43
From gain change (±10%)	2.4	45
From power and conduction (±5%)	1.6	41

*The tests were made on different days, and the differences in the pulse heights of the base cases are due to barometric pressure changes.

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