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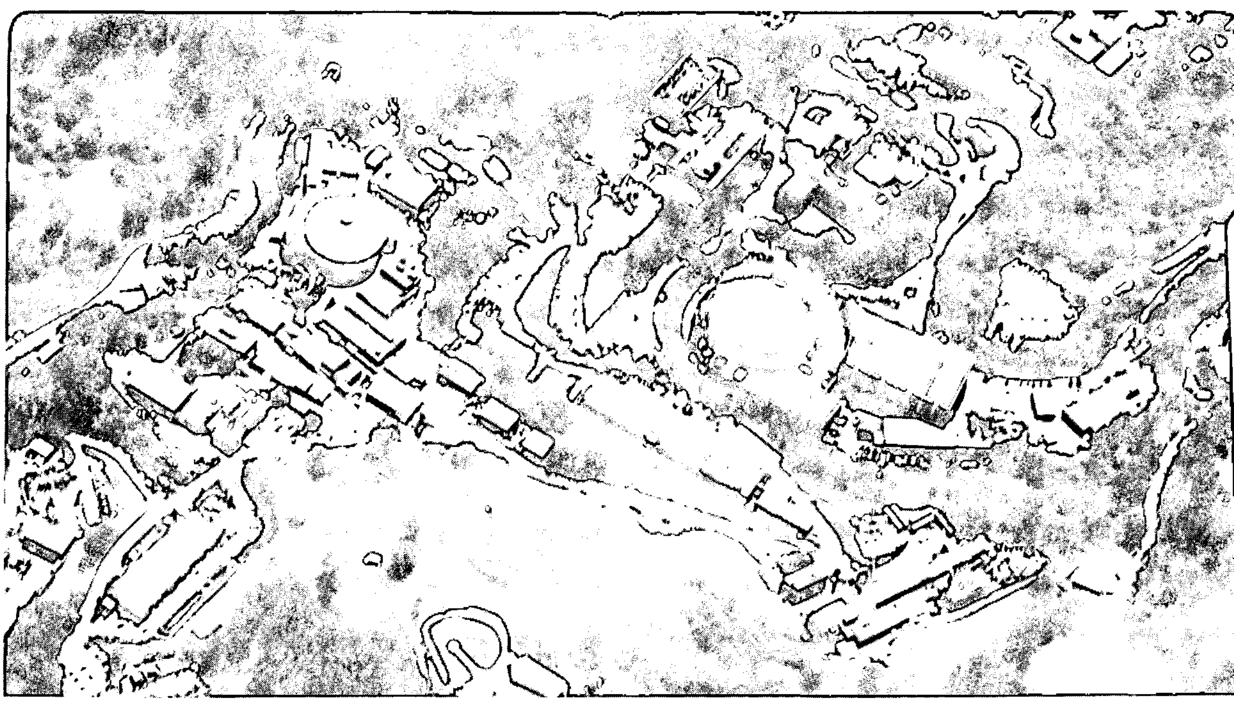

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USE OF STRAW TUBES IN HIGH-RADIATION ENVIRONMENTS*

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Abstract

We have investigated several aspects of straw tubes relating to their viability for use in SSC detectors. Gas temperature changes and the consequent gain changes resulting from the power dissipated in the tube at high rates are found to be relatively minor effects. Conduction through the gas between the wire and the wall is found to be the major mechanism by which heat is removed. Little aging is observed in straw tubes operating with any of several different gas mixtures. The dependence of aging on gas flow rate is found to be small. Water vapor at low concentrations (1000 ppm) is found to prevent breakdowns. Design and construction of straw tubes are discussed.

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1. Introduction

Straw tubes have received attention as candidates for use in detectors at the proposed Superconducting Super Collider (SSC), where they would be expected to be exposed to high-radiation environments. Before straw-tube wire chambers can be implemented, however, a number of issues, including (1) design and construction of the tubes, (2) aging behavior of the tubes, (3) possible gain fluctuations or nonuniformities due to temperature changes caused by the power dissipated in the gas, (4) signal attenuation in long tubes, and (5) optimal operating gain need to be addressed.

There are four parts to this investigation: (1) study of aging effects in straw tubes, including straw tubes previously damaged by discharges; (2) use of straw tubes equipped with carbon wires to study the thermal effects of avalanches; (3) study of the effects of various cathode materials; (4) study of tracking resolution and correlation with the rate of aging and with other aging effects. This report discusses only the first two parts.

2. Construction Techniques

A novel feature of the tubes used in these tests is that their inside diameter is only 4 mm, whereas previously-used straw tubes had 7-10 mm inside diameters [1].

Since it is known that it an efficient gas flow through the tube is necessary [2,3,4], a feedthrough was designed to ensure such a flow. Fig. 1 shows our design of a feedthrough pin made of Delrin [5]. This design assumes that the end flange has a gas manifold that allows the gas to enter the tube through four rectangular grooves, each of cross-section of about 0.5 x 1.0 mm. The grooves are machined into the pin and are located near the cathode wall.

A brass tube, shown in Fig. 1, is set into the Delrin pin and is used to support the wire. A sapphire jewel [6] with a 75 μm bore is located at the inner end of the brass tube and is used to position the wire. The wire is secured at the outer end of the brass tube by a friction fit between the wire and a tapered brass pin (the "wedge pin"). This technique worked well with 38.1 and 20 μm-diameter gold-plated tungsten wires, but not with 33 μm-diameter carbon wires [7], which were too brittle to be secured by a

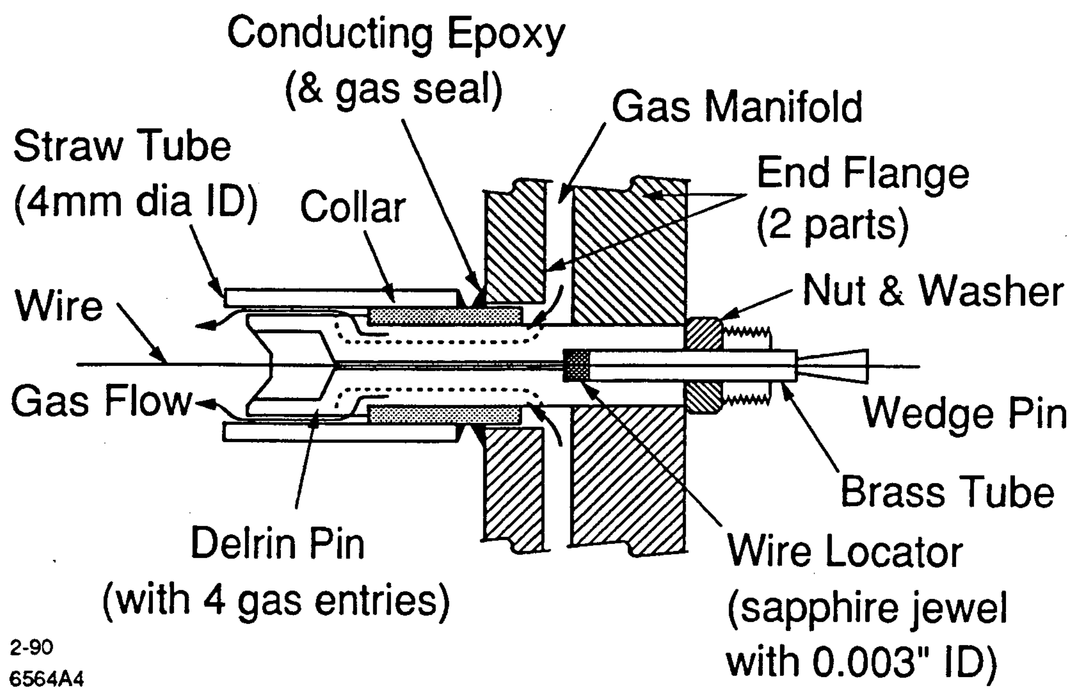
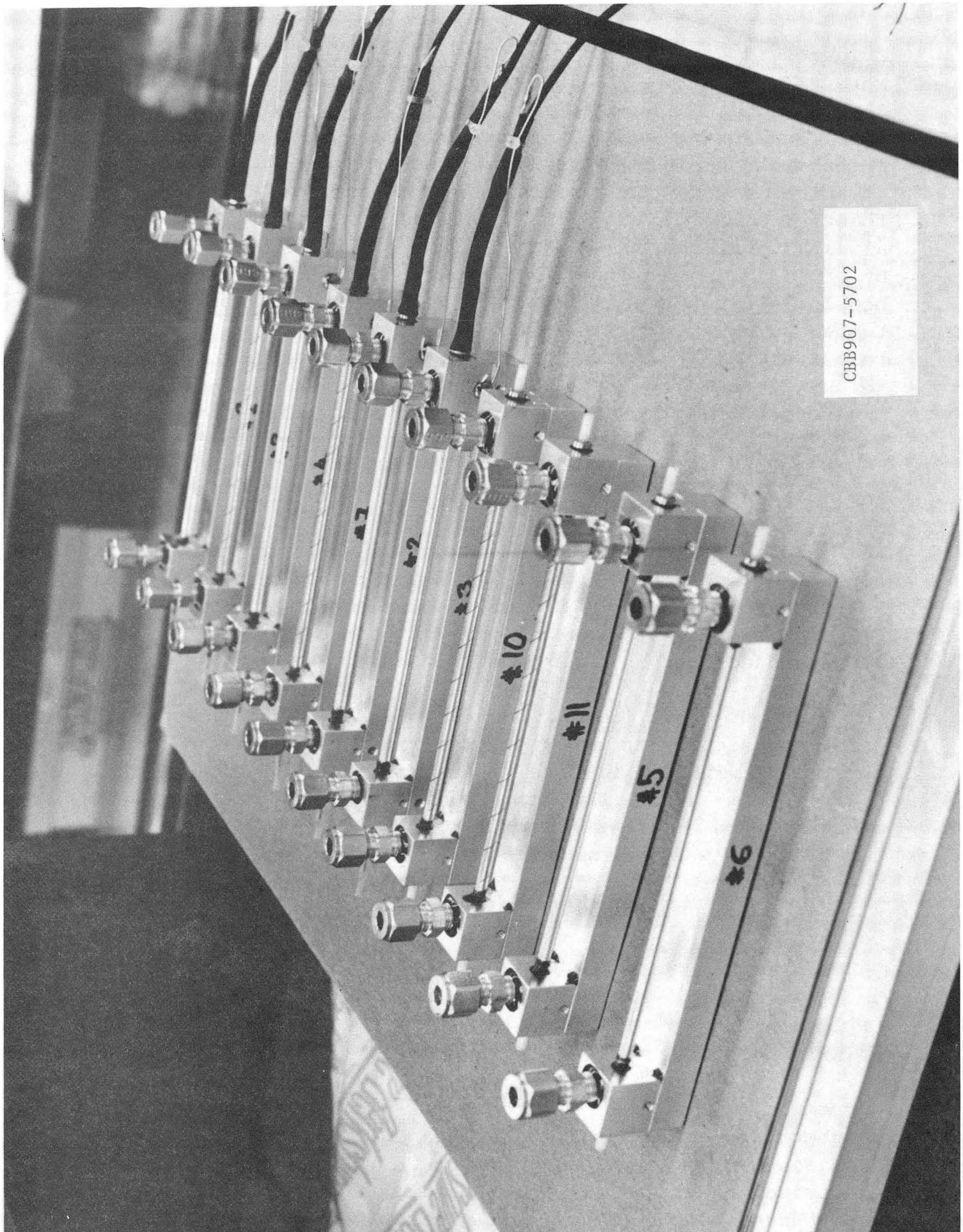


Fig. 1. Our design of the feedthrough pin.

Fig. 2. (Figure on page 3.) Photograph of the straw-tube test chambers used for these studies.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friction fit and had to be secured by gluing. Wire tensions were 140 g for the 38 μm-diameter gold-plated tungsten and 32 g for the 33 μm-diameter carbon wires. The unsupported wire length was only 17.5 cm and therefore electrostatic instability was not an issue in these tests.

The straw tube walls were constructed by bonding together four layers. The innermost layer is 9 μm-thick aluminum and the three outer layers are each 25 μm-thick Mylar [5]. Polyethylene of 7.6 μm thickness is used as the bonding medium between layers. The bonding was done at high temperature to create the straw tube body [8]. The relatively thick aluminum layer was used to prevent "etching" of the cathode surface in a high-radiation environment [9]. The thicker aluminum also helps to keep the tube straight [10]. The total thickness of the tube wall was about 107 μm in this test, although this can be reduced for applications at the SSC. (We considered the choice of wall material to be the most important variable in these tests.) The electrical contact to the cathode was made with conducting epoxy [11], which was cured at room temperature. We used DP-190 epoxy [12] for the other gluing operations. Fig. 2 shows the straw tube test chambers used for the studies described in this paper.

Prior to use, the tubes were washed in ethanol for a few minutes using an ultrasonic cleaner, and then dried under a gaseous nitrogen flow. The wires were cleaned during stretching with a lint-free tissue moistened in ethanol. All parts were handled with rubber gloves to prevent contamination of the surfaces.

The gas was in contact with the following materials in these chambers: carbon or gold-plated tungsten (anode wires), aluminum (straw tube body), brass, Delrin, Mylar, polyethylene, DP-190 epoxy, conducting epoxy, and T-6061 chemically etched aluminum (end flanges).

3. Effect of Water

It is a common experience during an experiment for high currents or discharges to occur momentarily in wire chambers, resulting in localized damage to some wires. These damaged regions are then especially vulnerable to further electrical breakdown. However, it has been found that water vapor added to the chamber gas greatly reduces this tendency towards further breakdown. This phenomenon has been studied with a straw tube that had portions of its wire damaged accidentally (by operating with excessive gain and/or current). The point at which breakdown occurs was found to depend upon both the gain and current at which the tube was operated, and upon the condition of the portion of the tube irradiated. If the gain and/or current is large, or if the tube has been previously damaged by aging, the threshold for breakdown is decreased.

When using argon (Ar)/ethane (50/50) or carbon tetrafluoride (CF_4)/dimethyl ether (DME) (90/10), the straw tube was found to operate stably when water at the 1000 ppm level was added directly to the gas with a gas bubbler. Water could also be introduced indirectly, by outgassing from the walls of the plastic tubing used for the gas plumbing and/or by diffusion through the tubing. The concentration of water added indirectly in this way is not known. Breakdown occurred within minutes after startup when using electropolished stainless steel tubing, which is impermeable to air and is known to have little outgassing [13]. No breakdown was observed up to current densities of about 400 nA/3 mm when nylon tubing was substituted for the stainless steel under otherwise identical conditions. This dependence on tubing material was quite reproducible. Based on these results, nylon tubing was used for all subsequent tests.

The exact mechanism by which water arrests or prevents Malter breakdowns is not clearly understood. We mention briefly two possible mechanisms. (1) Water may make an insulating cathode deposit slightly conducting. In this way, accumulated positive charge on the cathode, which is a precursor of the Malter breakdown, can be bled off. (2) If hard UV photons from carbon excitations [14] are responsible for photoionization at the cathode, the effect of water is can be explained by its absorption of these photons [15]. The absorption by water is plotted in Fig. 3. Although absorption of these photons by water may suppress the positive feedback necessary for the Malter breakdown, the concentration of water used in our tests appears to be insufficient: 1000 ppm of water distributed uniformly in the counter gas absorbs only ~2% of these photons in the 2 mm path between the anode and cathode. Some means of

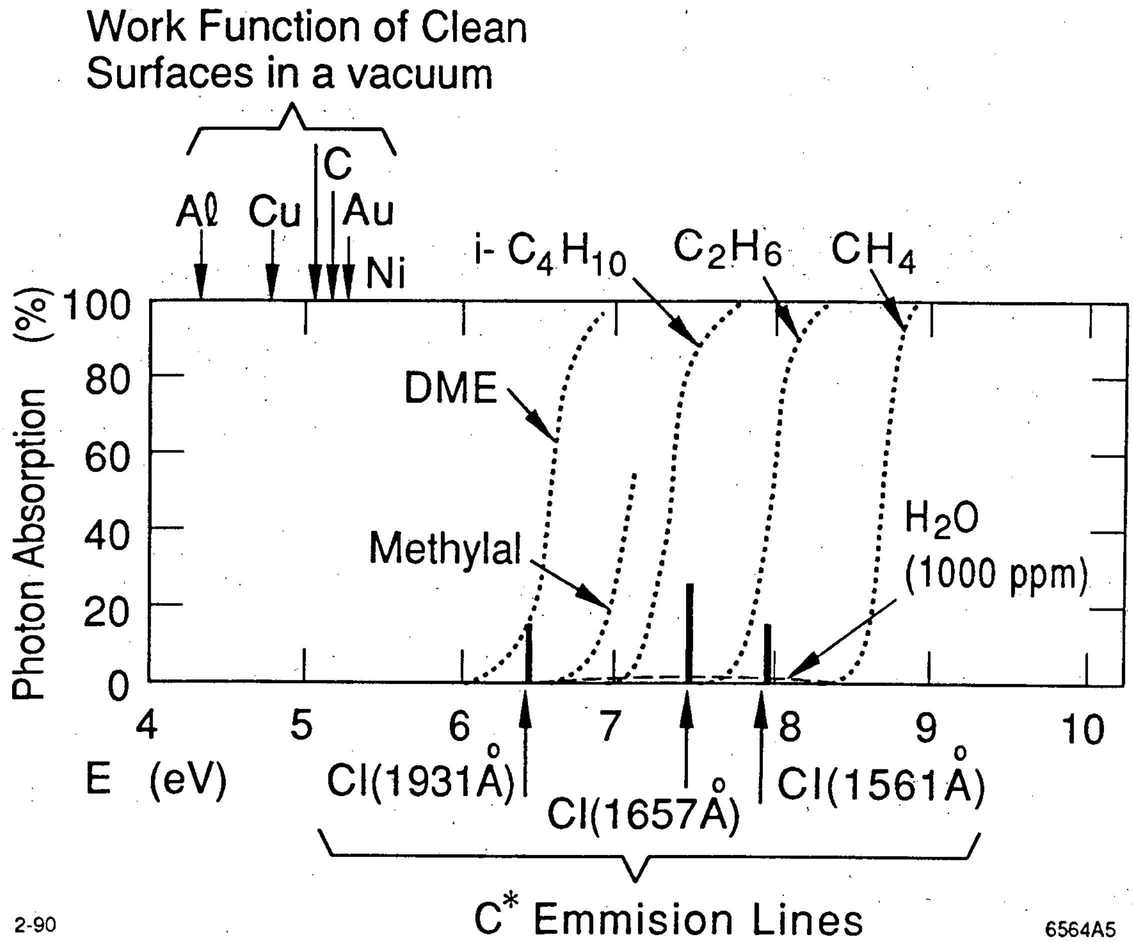

Fig. 3. Qualitative theory explaining the effect of water in arresting Malter breakdowns by hard UV photon absorption.

concentrating water molecules, e.g. on the cathode, would therefore be required for this mechanism to be effective.

It is clear that the effect of water needs to be investigated further, including its effect on drift velocities in so-called fast gases, such as those with a CF_4 component. The minimum concentration of water necessary to prevent breakdowns is not yet known.

4. Aging tests

We performed aging tests using the following gases: argon/ethane (50/50), CF_4/isobutane (80/20), and

CF_4/dimethyl ether (90/10). Argon/ethane was tested because it is a commonly used gas. The CF_4/isobutane (80/20) mixture was tested because it possesses several attractive properties: (1) it has been tested to 8 C/cm with no apparent aging [16]; (2) it has a high drift velocity (in excess of 10 cm/μsec) [17,18], a feature that may be quite important at the SSC and in other high luminosity colliders; (3) it has a relatively high ionization density for minimum ionizing tracks (180 ion pairs/cm) [19]; and (4) it has a low electron diffusion constant [18]. These properties make CF_4/isobutane (80/20) an attractive choice for use in high-resolution drift chambers in high-radiation environments. The CF_4/dimethyl ether mixture was tested in the belief that it may have similar properties.

The techniques used to collect aging data have already been described [20]. The 5.9 keV photons emitted by an ^{55}Fe source (1 or 2 mCi) were used to simulate particle radiation. The irradiated region of the wire was about 3 mm. Results of these tests are shown in Table 1.

As can be seen, the rate of gain loss, R, was determined to be small or consistent with zero in nearly every case ($R \leq 10$ %/C/cm). As little as 1000 ppm of water vapor, added to the argon/ethane by means of a gas bubbler, was found to be sufficient to avoid the electrical breakdown, and tests were not made with smaller amounts of water added in this way.

Measurements of R vs. gas flow rate were made with argon/ethane at relatively low flow rates to find the minimum acceptable flow rate. As shown in Table 2, negligible aging rates were observed for gas flow rates as low as 1.0 cm^3/min, corresponding to an average linear gas velocity of ~1.3 mm/sec. Indeed, no gain change was observed until the gas flow was completely interrupted.

Although the above results indicate that straw tubes are or can be made resistant to wire aging, it is important to realize that under less-well-controlled conditions, aging may still occur.

Table 1
Summary of aging results in straw tubes. Gold-plated wires were 38 μm diameter; carbon wires were 33 μm diameter. The aging rate, R, is defined as $R = -(1/G_o)(dG/dQ)$, where Q is the collected charge per length of wire and G is the gas gain. The total gain was ~5x10^4 for tests with gold-plated wires and ~2x10^4 for tests with carbon wires. Nylon tubing was used for the gas plumbing in all tests.

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

Table 2
Summary of aging results in straw tube with a 33 μm diameter carbon wire as a function of the gas flow rate. Argon/ethane (50/50) was used for all tests. The anode wire voltage was 1590 V. All measured values of R are consistent with zero within our estimated systematic uncertainties.

gas flow rate cm^3/min	average gas velocity mm/sec	R %/C/cm	accumulated charge C/cm
20	26.5	−2	1.0
2.7	3.6	0	0.4
1.0	1.3	−3	0.3
1.0	1.3	0	0.2

5. 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.

To illustrate the potential difficulty caused by heating effects on gain, we consider the following hypothetical case in which heat removal from the straw tube occurs solely by the gas flow. In this case, the temperature rise is determined by the gas heat capacity, gas flow rate, and power input. For the latter, we will assume 2 mW of power generated over a 1 m length of wire (2000 V * 1 μA/m). The heat is deposited mainly by drifting positive ions produced in the avalanche, and not by the electrons, since the former charges traverse a much larger potential difference (nearly the full anode-cathode voltage). However, the heating is concentrated near the anode wire because the potential difference, and hence the power deposited, is logarithmic with the radius. For a 4 mm-diameter tube with a 33 μm-diameter wire, one-half of the power is produced within a radius of about 260 μm. Since the gas velocity is relatively small (low Reynolds number), we expect laminar flow, and the power deposited within this radius will heat the gas in a corresponding volume. For a 1 m-long tube, we calculate that the heated volume of 0.053 cm^3 contains 2.4×10^{-6} moles of gas. At an assumed flow velocity of 1 mm/sec, there would be a volume change every 1000 sec. For the case of argon/ethane (50/50), which has a heat capacity of about 40 J/mol-K, this volume will experience a temperature rise of:

$$(1 \text{ mW})(1000 \text{ sec})/(40 \text{ J/mol-K})(2.4\text{x}10^{-6} \text{ mol}) = 10^4 \text{ °K}.$$

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.

If the heat is removed entirely by a uniform heating of the gas, the gas flow necessary to maintain an acceptable temperature rise is inconveniently large: average linear gas velocities of several centimeters per second are needed to achieve the assumed 6°C maximum allowable temperature rise. We note, however, that even at these velocites, the Reynolds number is on the order of ten, far below the values corresponding to turbulent flow [21], suggesting that uniform heat distribution would not be achieved.

There are, however, other mechanisms by which heat can be removed, namely radiation and conduction. At the small temperature increase allowable for acceptable operation, radiant heat transfer is negligible. This is not the case, however, for conduction.

The heat, Q, transferred by conduction between concentric cylinders is given by

$$Q = 2\pi Lk\Delta T/[\ln(r_2/r_1)], \tag{1}$$

where L is the length of the cylinders, k is the thermal conductivity of the medium between the cylinders, ΔT is the temperature difference between the cylinders, and r_2 and r_1 are the radii of the outer and inner cylinders, respectively. For the above-mentioned example of the 4 mm-diameter straw tube with the 33 μm-diameter wire, a temperature difference of only about 0.1°C is needed to conduct all of the heat from the wire to the wall through an argon/ethane (50/50) gas mixture. A smaller temperature difference is needed to conduct the heat from the wall into a surrounding gas environment.

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 function of temperature. To estimate the temperature, we used the coefficient for carbon resistance as a function of temperature [22]. Fig. 4 shows the estimate of the anode wire temperature as a function of voltage across the wire. A similar method was previously used to estimate the surface temperature of 7-μm-diameter carbon wires [23].

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 (eqn. 1), 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 3. The agreement between the three methods for the 46 V case is good. In the 9 V case, there is considerable uncertainty in the measurement of resistivity at low voltage, due to the apparent non-linearity of the curve in this region (Fig. 4). Therefore, Table 3 does not include a value determined by this method for the 9 V case. Estimates, however, give a temperature value close to that found by the other two methods.

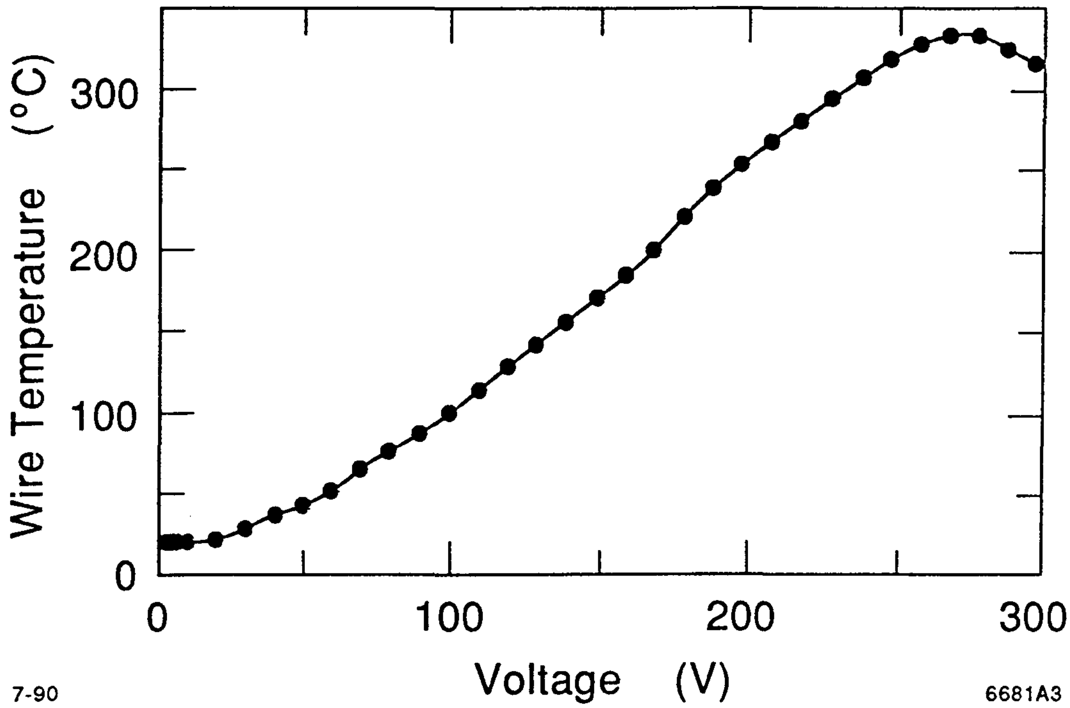

Fig. 4. Estimate of the carbon-wire anode temperature as a function of the applied voltage. The temperature dependence of carbon resistivity was taken to be -5×10^{-4}/°C [22]. The resistance of the wire was 9.24 kΩ at 21°C. The wire fails near 300°C in air.

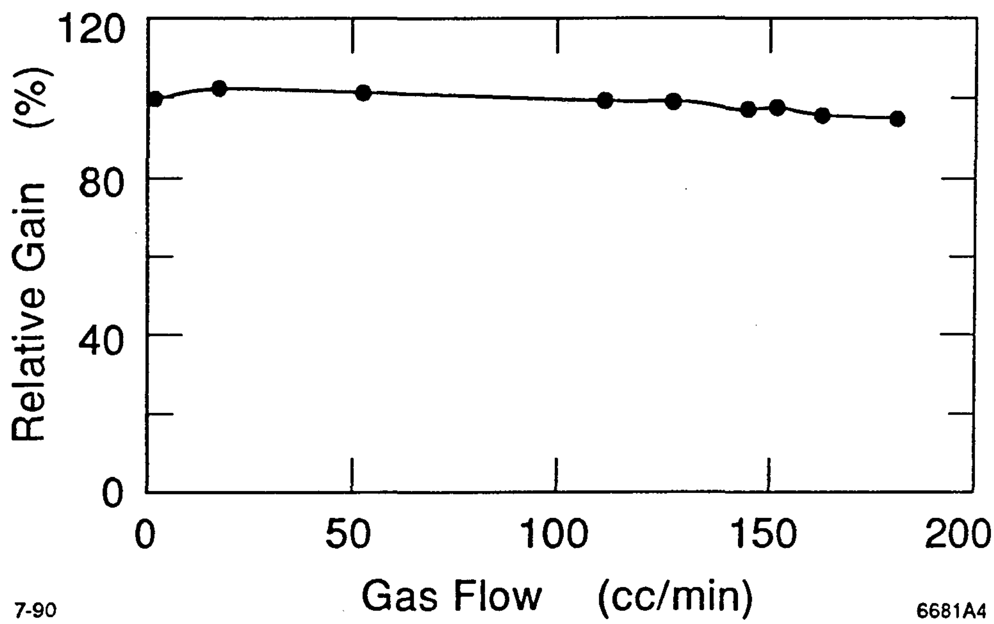

Fig. 5. Observed gain in a straw tube as a function of the gas flow rate through the tube.

Table 3
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: $(1/R_0)dR/dT = -5\times10^{-4}/°C$. The resistance of the filament was 9.24 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)	9.23	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, pedestal subtracted (channel)		
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 (±10%)	—	43
From fractional gain change (±5%)	2.4	45
From power and radial conduction Eq. (±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.

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. In any event, even though 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 (Fig. 5). 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 (Table 2).

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 [24], 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.

6. Conclusions

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.

The construction details of the straw tube prototype and the associated feedthroughs are also described.

Acknowledgements

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References

[1] HRS: D. Rust, SLAC-PUB-3311 (1984).
MAC: W.W. Ash *et al.*, SLAC-PUB-4047 (1986), and *Nucl. Instr. and Meth.*, **A261** (1987) 399.
MARK II: W.T. Ford, *et al.*, *Nucl. Instr. and Meth.*, **A255** (1987) 486.
MARK III: J. Adler *et al.*, *Nucl. Instr. and Meth.*, **A276** (1989) 42.
TPC: (a) Proc. AIP Conference on Heavy Quark Physics, No. 196, Cornell Univ., Ithaca, NY (1989), p. 130, (b) M.T. Ronan *et al.*, *IEEE Trans. Nucl. Sci.*, **NS-35** (1988) 329.
KEDR: V.M. Aulchenko *et al.*, *Nucl. Instr. and Meth.*, **A283** (1989) 528.
CLEO: H. Kagan, to be published in Proc. Fifth International Conference on Instrumentation for Colliding Beam Physics, Novosibirsk, USSR, March 15-21, 1990.

[2] J. Kadyk, ed., Proc. Workshop on Radiation Damage to Wire Chambers, Berkeley, CA, LBL-21170 (1986).

[3] J. Va'vra, *Nucl. Instr. and Meth.*, **A252** (1986) 547, and review article in Reference 2, p. 263.

[4] J. Adler *et al.*, *Nucl. Instr. and Meth.*, **A283** (1989) 679.

[5] Registered trademark of E.I. DuPont de Nemours & Co., Inc.

[6] Bird Precision Jewels, Waltham, MA 02154, USA; p/n 24319.

[7] Avco Specialty Materials - Textron, Lowell, MA 01851, USA. This particular carbon wire is made of pure homogeneous glassy-phase carbon, and not from an acrylic fiber, which is more typical in the industry.

[8] Euclid Spiral Paper Tube, Applecreek, OH 44606, USA.

[9] H. Nelson, Reference 2, p. 131.

[10] G. Godfrey, private communication.

[11] Chomerics, Woburn, MA 01801, USA; p/n 50-02-0584-0029.

[12] 3M, St. Paul, MN 55144-1000, USA.

[13] J. Wise, J.A. Kadyk, D.W. Hess, and M.C. Williams, *IEEE Trans. Nucl. Sci.*, **NS-37** (1990) 470.

[14] H.D. Morgan and J.E. Mentall, *J. Chem. Phys.*, **60** (1974) 4734.

[15] J. Va'vra, SLAC-PUB-5207 (1990).

[16] R. Openshaw *et al.*, *IEEE Trans. Nucl. Sci.*, **NS-36** (1989) 567.

[17] (a) T. Yamashita *et al.*, *Nucl. Instr. and Meth.*, **A283** (1989) 709, (b) L.G. Christophorou *et al.*, *Nucl. Instr. and Meth.*, **163** (1979) 141.

[18] B. Schmidt, HD-PY/86/06, Univ. of Heidelberg.

[19] J. Fehlmann and G. Viertel, Compliation of Data for Drift Chamber Operation, ETH Zurich (August 1983).

[20] J. Kadyk, J. Wise, D. Hess, and M. Williams, *IEEE Trans. Nucl. Sci.*, **NS-37** (1990) 478.

[21] R.B. Bird, W.E. Stewart, and E.N. Lightfoot, Transport Phenomena (Wiley, New York, 1960), p. 54.

[22] R.I. Sarbacher, Encyclopedic Dictionary of Electronics & Nuclear Engineering (Prentice-Hall, Englewood Cliffs, NJ, 1959), p. 1121.

[23] J. Va'vra, SLAC-PUB-4432 (1987), and *IEEE Trans. Nucl. Sci.*, **NS-34** (1987) 486.

[24] H. Ogren, Tracking Review for the SCD Collaboration, 1990 Snowmass DPF Meeting.

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