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LIMITED STREAMER TUBES FOR THE OPAL HADRON CALORIMETER

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ABSTRACT

This paper describes the manufacture of multi-cell plastic limited streamer chambers for use in the hadron calorimeter of the OPAL detector at LEP. The chambers are of the PVC coverless type with highly resistive cathodes. We discuss the assembly procedure with particular emphasis on the crucial cathode preparation process. A summary of test results is also presented.

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1. INTRODUCTION

The OPAL detector is one of the large detectors approved for experimentation at the LEP electron-positron collider at CERN [1]. The OPAL hadron calorimeter is a sampling calorimeter with 8 layers of iron absorber each 100 mm thick, and 9 layers of limited streamer tubes as active elements. The calorimeter has a cylindrical structure with a barrel and two end-caps^{*}.

The barrel contains 3482 chambers, each consisting of 8 cells $9 \times 9 \text{ mm}^2$ in cross-section, and 900 chambers of 7 cells, again $9 \times 9 \text{ mm}^2$ in cross-section. The length of the barrel chambers ranges from 3.0 m to 7.3 m.

The endcap contains 2304 chambers of 8 cells ranging in length from 0.5 m to 2.2 m.

Signals from the chamber layers will be read out capacitively by pads on one side and longitudinal strips (one per $9 \text{ mm} \times 9 \text{ mm}$ cell) on the other. Analog sums of the total charge induced in towers of pads pointing towards the interaction region will measure the hadronic energy deposited in 976 separate intervals of solid angle. Logical signals from the individual 4 mm wide strips will allow the tracks of particles traversing gaps in the detector to be reconstructed.

The chambers used were made of PVC and are analogous to those used in the Mont Blanc proton decay detector and further developed by the Frascati group [2,3]. They are coverless, i.e. with only three coated walls in each cell. The 8-cell chambers were constructed at the Frascati National Laboratories, where a facility with semiautomatic machines was developed and set up by INFN for that specific purpose [4,5]. The 7-cell chambers were constructed at the University of Maryland following essentially the same criteria adopted for the 8-cell chambers.

^{*} The magnet pole-tip iron is also instrumented as a hadron calorimeter. A general description of the design is given in ref. [1].

Section 2 describes the basic streamer chamber design. The critical process of preparing the resistive cathodes is discussed in Section 3, while the chamber assembly is presented in Section 4. Testing procedures and results are briefly summarised in Section 5.

2. PLASTIC LIMITED STREAMER CHAMBERS USED IN THE OPAL HADRON CALORIMETER

Many existing and forthcoming particle physics experiments incorporate multi-cell plastic chambers with one wire per cell. The popularity of these chambers has come about because of the cheapness of the plastic (usually PVC) components, which can be extruded and injection moulded, and the suitability of PVC for coating or impregnating with graphite to produce resistive cathode cell-walls. When strung with thick anode wires and operated in the limited streamer mode, the streamer pulses can be read out without amplification by capacitive coupling through the chamber walls to external electrodes of any chosen size or shape.

The basic structure of the chamber used in the OPAL hadron calorimeter is shown in Fig. 1. A comb-like PVC extruded profile defines the cell structure and is coated with graphite to form the resistive cathode. The anode wires are strung between solder-pad boards mounted in board holders which clip into the notched ends of the extrusion. The entire assembly of wired cells is contained within an extruded PVC gas-envelope, whose ends are heat-sealed onto injection moulded PVC plugs, containing electrical and gas connections.

Layers of these chambers are used to instrument the iron of the OPAL magnet return yoke, resulting in a cylindrical sampling calorimeter 10.4 m long. As shown in Fig. 2, the calorimeter can be divided longitudinally into 2 halves for maintenance. Starting from an inner radius of 3.3 m, 9 layers of chambers alternate with 100 mm thick iron slabs to form a barrel shaped detector about one meter thick. The barrel is composed of 24 wedge-shaped modules. Just inside each barrel end there is an endcap section consisting of 7 doughnut-shaped slabs of 100 mm thick iron, alternating with 8 layers of streamer chambers. Signals from each cell are induced through the coated bottom wall onto large area pads (typically 500 mm x 500 mm) and through the open top onto a 4 mm wide strip which runs full chamber length. The

pads are arranged in 9 or 8-layer deep towers, which divide the solid angle into 976 approximately equal elements radiating from the interaction point. The analog sum of the charges induced on the separate layers of such a tower measures the hadronic energy deposited in that interval of solid angle. Logical signals from the strips will be used to count the numbers of particles reaching each layer and to follow individual particle tracks through the calorimeter.

Typical barrel and endcap assemblies are depicted in Fig. 3.

The width at the ends of the barrel layers is reduced due to the presence of the magnetic-flux return iron. The width of each barrel layer has been adjusted to conform to the wedge-like shape of the module by using an appropriate mix of 7 and 8 cell chambers. Layers 2 to 7 are each made up of half length chambers with the junction at the detector equator staggered from layer to layer. The innermost and outermost layers use full length chambers. These detailed differences between layers and between modules result in a requirement of 76 different chamber lengths for both 7 and 8 cell variants.

3. PREPARATION OF THE RESISTIVE CATHODE

3.1 Carbon Coating

The chamber cathodes consist of an extruded PVC profile with 7-cell or 8-cell (Fig. 1) whose surface is coated with graphite. The "thickness" of the graphite layer determines the cathode resistivity which is usually defined as the resistance between two appropriately spaced metallic electrodes. This quantity does not depend on the size of the electrodes and depends only weakly on their shape. Resistivity is measured in Ohm/square (Ω /square).

Before starting the coating operation, the quality of the extruded PVC profiles was controlled, discarding those with surface irregularities or visible damage. The critical dimensions of each profile were checked over the whole length using a brass die. The resistivity at the bottom of the profile of at least 80 k Ω /square was required to give good transparency of the cathode to fast signals.

The machines used for carbon coating at Frascati and at Maryland consist of three parts :

- a) a transport and cleaning system for the profiles;
- b) a station where the graphite is deposited on the profiles;
- c) a hot air fan to dry the coated profiles.

The transport system moved the profiles at an adjustable speed of about 10 cm/sec, first through a vacuum cleaning head, and then through a coating head, made of three or four layers of compressed sponges cut so as to fit the shape of the profile. The coating head (hereafter called the pen) was connected to a reservoir bottle suspended above it, containing a suspension of 1 part colloidal graphite (DAG 305) and 8 parts Methyl Isobutyl Ketone (MIBK). The suspension fed into the pen at a rate of about $0.2 \text{ cm}^3/\text{sec}$. Fine tuning of this rate and the transport speed adjusted the cathode resistivity.

Immediately after the coating operation, ventilated hot air accelerates solvent evaporation and the profiles left the coating machine essentially dry. The routine measurement of resistivity immediately after drying ensured that values in the desired range were obtained. The resistivity value measured immediately after coating does not correspond to the final one. There was a rapid decrease in resistivity during the first few days with higher values of resistivity showing a higher absolute decrease. After the first few weeks the rate of decrease became slower, and after several months the final values did not change appreciably. This temporal behaviour of resistivity is not the same as that observed for Breox coated profiles and reported in Section 3.

Measurement of the adhesion of the carbon coating to the PVC yielded a tensile strength of $9.65 \times 10^5 \text{ N/m}^2$. Separation resulted from a cohesive failure of the coating itself, rather than detachment from the PVC substrate.

We will now discuss in more detail the operational difficulties encountered. Initial testing [6,7,8,9] showed that the great majority of the problems observed when

operating the chambers were associated with the cathode quality and not with errors made in wiring and assembly. The principal problem encountered was current instability, either spontaneously occurring or induced by a radiation from a radioactive source.

The major cause of instabilities was inhomogeneity in the cathode resistivity even over a small area. In most cases visual inspection of the cathodes of problem chambers did not reveal any clear imperfection, such as uncoated spots, etc. This made visual selection of "good" coated profiles before wiring very difficult. Even when our experience in coating was well established, we found that different failure rates could arise without any apparent reason in batches of chambers produced at different times. There are several critical parameters in the coating technique which could account for inhomogeneities, and which are difficult to keep under control.

- i) The sponges for the pen are cut and shaped using a specially made punch. Nevertheless, one cannot guarantee complete reproducibility because the assembly of the three (or four) flexible layers of sponge that form a pen is done by hand. Furthermore, the sponges used are of commercial quality and have large tolerances. The frequent replacement of worn-out sponges is a possible cause of non-uniformity among different samples.
- ii) The quality of the coating on the side walls is generally worse than that on the cell bottom. After a single pass with the pen, the resistivity is usually much higher on the side walls resulting in a greater chance for coating imperfections.
- iii) The upper part of the walls separating adjacent cells are sometimes thinly coated because of the faster deterioration of the pen in this region.
- iv) The graphite suspension in the reservoir bottle tends to settle out, leading to a variable concentration during the coating operation.
- v) Ambient temperature and humidity also play a role.

These factors may account for the differences observed in the resistivity of different profiles coated during a week production run. The distribution of resistivities measured for two of these profiles are shown in Fig. 4. A considerable difference is noted.

Since fluctuations in the thickness of the carbon deposit, hence in resistivity, are more important when the thickness of the layer is small, it is reasonable to suppose that heavy coating of the side cell-wall would significantly reduce inhomogeneities in the cathode. (In our case the bottom of the cells cannot be heavily coated because good transparency is required).

The final technique aimed at obtained a uniform high resistivity coating of the bottom of the profiles and a heavy uniform coating of the side walls. In the work done at Frascati, this was achieved by a second pass through the coating machine with the pen raised so as not to touch the bottom of the cells. After this operation, the resistivity per square of the side walls ranged from 0.02 M Ω /square to 0.1 M Ω /square, thus partially solving the problems mentioned in point ii). Furthermore, the difficulty mentioned in point iii) was eliminated.

Profiles were accepted if they had a cell bottom resistivity ranging from 0.1 M Ω /square to 5.0 M Ω /square and passed a careful visual inspection for coating imperfections. Tests on doubly coated chambers showed a decrease by about a factor of three in the rejection rate due to current instabilities. The overall rejection fraction in coating the profiles was about 30%.

3.2 Breox Treatment

The effectiveness of treating carbon-coated cathodes with Breox B-35 [10], a very low vapour pressure polyalkylene glycol oil, was first investigated by a Russian group [11] and has been verified by the OPAL hadron calorimeter group at CERN and at Maryland. Breox has a volume resistivity of 10^{10} Ohm cm, and can be used as an antistatic dope. This property first prompted its use in improving the high voltage stability of carbon coated cathodes. It was found to considerably reduce the chamber rejection rate due to current instabilities, and also to improve the lifetime of chambers exposed to high integrated doses of radiation [6].

Before Breox application, the profiles were cut to the appropriate length. The last 2 cm at both ends of each profile were shaped to a suitable form to fit the board-holders. In order to avoid discontinuity in the cathode and to guarantee a proper electrical connection to ground, concentrated carbon solution was painted over the bottom of the shaped profile at one end, where contact with the ground connection was made.

Breox coating was done manually with a sponge shaped to fit the profile and impregnated with a 10% by volume solution of Breox in ethanol. A second pass was made using a dry sponge of similar shape; in this way a more uniform deposit of oil was obtained. With this procedure it is estimated that the quantity of Breox deposited was about 1 gram per square meter. It should be noted that after evaporation of the ethanol, the treated profiles could not usually be distinguished from the untreated ones.

The high contact resistance after Breox treatment prevented spot resistivity measurements of the treated cathodes. However, on average the treatment caused the resistance per unit length of whole profiles to increase, while staying well within the acceptable range ($0.1 \text{ M}\Omega$ – $5 \text{ M}\Omega$). No change was observed if ethanol alone was used. The increase observed following Breox treatment was generally small ($\sim 30\%$ in a typical batch). However, increases up to a factor 10 have been seen [8], indicating sensitivity to the process of carbon coating and the fine details of the Breox application technique. The measurements show that small changes in the distribution of resistance per unit length can continue for a few weeks at most following Breox treatment. After that, the individual values remain extremely stable.

4. CHAMBER ASSEMBLY

To minimize contamination, the wiring and completion of batches of chambers took place immediately after the Breox treatment of their graphite-coated profiles. Plastic board-holders were inserted at both ends of each profile. One of these was fitted with a ground electrode which made contact with the graphite of the profile through a piece of conducting sponge. The board-holders were normally equipped

with boards before insertion in the profile. One had a simple board with solder pads for wire attachments. The other had a printed circuit board with 220 Ohm limiting resistors in series with each wire and a bus which brought H.V. to the chamber. The standard ceramic boards were designed to be used with a hot air soldering device and were found to be too delicate to be soldered with a conventional hot iron. It was very easy to produce small cracks in the ceramic and thus damage the high voltage bus. Since hand soldering was necessary for all the shorter chamber lengths, G10 fiber glass epoxy boards were used throughout.

Wires on the 8 cell profiles were strung at Frascati in a single step by an automatic wiring machine using a single spool of wire. The Maryland machine used a separate spool of wire for each cell, with the profile moving rather than the stringing head. Systematic checks of the wire tension show a range of tension from 180 gr to 210 gr (at Frascati) and from 150 gr to 180 gr (at Maryland). The 100 micron silver-plated Be-Cu wires were double soldered to the boards and PVC spacers placed every 500 mm were used to keep the wires centred in the cells to within ± 0.2 mm. An automatic heat sealing machine was used to seal the wires in position in the spacers. After passing through a final vacuum cleaning head, the profiles were inserted into PVC gas envelope cut 50 mm longer than the profile to allow just sufficient space for the endplugs. Two identically shaped PVC endplugs were used. One had two brass gas fittings only, while the other also had connection pins for H.V. and ground. The wires connecting these pins to the H.V. board and the ground electrode were soldered with a heat dissipator attached to protect the plastic. Finally, both caps were welded to the envelope with a heat-sealing machine.

Cutting errors and creep during heat-sealing produced an error of $^{+3}_{-1}$ mm in the intended length of each chamber.

Some fraction (5% to 10%) of all chambers were tested for leaks immediately after production to give rapid quality control feedback. Each chamber tested was pressurised to 50 mb overpressure using nitrogen, and each end was then placed under water to observe possible bubbling. (All chambers were later extensively tested at CERN or at Maryland as described in the next section). One batch of endplugs had serious leaks around the gas fittings and the electrical pins. To identify such

problems, a sample of endplugs from each batch was checked using a specially built device. All plastic pieces were individually checked for mechanical imperfections such as occlusion of the gas fittings by excess material. All parts (with the exception of the profiles and the envelopes) were cleaned in a bath of freon-113 using ultrasound.

5. SUMMARY OF TESTING PROCEDURES AND RESULTS

Testing of chambers from both manufacturing facilities was divided approximately equally between testing stations at CERN and Maryland. Details can be found in refs. [7,8,9]. The tests ensure that all chambers were gas-tight and operated safely.

Underground safety considerations for the 22 m^3 gas volume of the hadron calorimeter dictate a maximum allowable gas leakage of less than 1% of total flow at an operating pressure of 1 - 2 m bar. For an individual chamber, this translates into a loss of less than 1.5 mL/hour. Several different techniques were found to be capable of this sensitivity. For individual chambers, the chosen methods were constrained pressurisation or submersion of pressurised chambers under water. In the former, leaks were detected by observing the rate of pressure loss from 100 m bar in chambers whose volume was held constant in a massive clamp, while, in the latter, a visual search for bubbles revealed leaks directly. Layer assemblies of 3 - 6 chambers were all tested by comparison of input and output flows under 10 m bar overpressure and very small input flow ($\sim 3 \text{ mL/min}$).

The success of this leak-testing program is demonstrated by Fig. 5, which shows the distribution of leak rates from 52 of a total of 192 gas circuits in the barrel calorimeter. There were typically 12 chambers of 5 m length in each circuit. The measurements were made by observing the pressure loss over a period of days after sealing each circuit at an overpressure of 10 m bar. The arrow indicates the value corresponding to a loss of 1% of the flow in each circuit. The average loss in the measured circuits corresponds to only 0.7%. Therefore even at the average overpressure of this test, which exceeded the normal operating overpressure by a factor of 6, the total leakage is less than the 1% criterion.

All chambers which passed the individual leak-test were filled with the gas mixture chosen for use in OPAL (Argon 25%, Isobutane 75%), flushed for 20 volume changes, and tested at a voltage of 4850 V for at least 10 days. The current flowing in each chamber was limited to about 300 nA while increasing the voltage, and throughout the test period. This individual chamber current was closely monitored for the whole period of the test. For normally operating chambers, the value is less than 10 nA/m. Chambers which exhibited instability (typically current spikes above 100 nA) were rejected. An example of the current record of a good chamber is shown in Fig. 6.

To complete testing, wire signals from each chamber were examined (either using an oscilloscope or by measuring counting rates above a suitable voltage threshold). Finally, the current limit was removed and a source was scanned along the length of each chamber, so as to progressively irradiate all parts of all cells. The induced current (≥ 300 nA) was required to be stable, and to vanish once the source was removed.

Detailed accounts of the test procedures used and the results obtained can be found in refs. [7,8]. Approximately 10% of the chambers manufactured failed to satisfy the testing criteria.

Each of the 24 modules comprising the barrel calorimeter was operated for at least 1 month after assembly. Over 97% of chambers were performing satisfactorily after completion of this final test.

6. CONCLUSION

The construction, testing, and installation of about 6700 plastic limited streamer chambers for the OPAL hadron calorimeter has been satisfactorily accomplished. The preparation of the resistive carbon cathodes was found to be the most crucial step in chamber manufacture. Double carbon coating of the side cell-walls and application of Breox B-35 were vital in reducing the number of rejects. After considerable effort in mastering the labour-intensive and relatively imprecise manufacturing techniques, the great majority of chambers (90% or more) worked well. The average construction rate for a team of seven technicians was about 350 chambers per week, and the cost per functional 8-cell chamber of typical length 3.5 m, was about \$50 (1987).

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FIGURE CAPTIONS

- Fig. 1 Exploded view of a plastic limited streamer chamber.
- Fig. 2 Mechanical structure of the OPAL hadron calorimeter iron showing supports.
- Fig. 3 Barrel and End Cap sub-assemblies.
- Fig. 4 Distribution of the resistivity (in M Ω m per square) of the bottom wall of the cathode for the 8 cells measured along the coated profile every 50 cm. The top and bottom part of the figure refer to two different representative profiles coated at different times. Both profiles are accepted even if they show a different spread of resistivity values.
- Fig. 5 Distribution of leak rates in 52 separate gas circuits of the barrel section.
- Fig. 6 Record of the current flowing in a good chamber sampled for 10s every 3 mins. over a test period of 1 month. Plotted is the current (full scale = 200 nA) vs time (full scale = 1.5 months).

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6