RAL-85-014

Science and Engineering Research Council
Rutherford Appleton Laboratory
CHILTON, DIDCOT, OXON, OX11 0QX

The Design of the Optical Components and Gas Control Systems of the CERN Omega Ring Imaging Cerenkov Detector

R J Apsimon et al

June 1985

RAL-85-014

© Science and Engineering

Research Council 1985

The Science and Engineering Research Council does not accept any responsibility for loss or damage arising from the use of information contained in any of its reports or in any communication about its tests or investigations.

THE DESIGN OF THE OPTICAL COMPONENTS AND GAS CONTROL SYSTEMS OF
THE CERN OMEGA RING IMAGING CERENKOV DETECTOR

(Submitted to Nuclear Instruments and Methods)

R J Apsimon, J Cowell, P S Flower, K A Freeston, G D Hallewell¹,
J A G Morris, J V Morris, C N Paterson, P H Sharp, C N Uden and R M Young
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK.

M Davenport and J Eades
CERN, 1211 Geneva 23, Switzerland.

P A Coyle

University of Manchester, Schuster Laboratory, Manchester M13 9PL, UK.

S Danaher², R H McClatchey³ and L F Thompson

University of Sheffield, The Hicks Building, Sheffield S3 7RH, UK.

Present Addresses:

¹Stanford Linear Accelerator Center, PO Box 4349, Stanford,
California 94305, USA

²Department of Electrical Engineering, Leeds Polytechnic, Leeds, UK.

³CERN, 1211 Geneva 23, Switzerland.

A B S T R A C T

A large Ring Imaging Cerenkov Detector (RICH) has been commissioned for use at the CERN Omega Spectrometer. In the first of a series of reports we begin by discussing the general design of the device and illustrate the dependence of the attainable spatial resolution and range of particle identification on its optical parameters. We then describe in detail the construction and performance of the major optical components and gas systems of the detector.

1. INTRODUCTION

The CERN Omega Spectrometer supports an active and important series of fixed target high-energy physics experiments. Crucial to this program of high precision measurements is the development and introduction of a series of new and advanced particle detectors including a large acceptance Ring Imaging Cerenkov detector (RICH). This detector has been designed to provide secondary particle identification over a large momentum range and to have a spatial resolution sufficient to resolve particles with an angular separation as small as one milliradian. This single detector is capable of identifying pions from 5 GeV/c to 80 GeV/c and of providing kaon-proton discrimination up to 160 GeV/c. Figure 1 shows the position of the detector in the WA69 high-energy photoproduction experiment which began data taking in July 1984.

2. GENERAL DESCRIPTION

High-energy particles entering the detector produce ultraviolet Cerenkov radiation in a 5 m atmospheric pressure gas radiator. In this report the spatial resolution and particle identification ranges are computed for a nitrogen radiator, with which data was taken in the WA69 and WA71 experiments in July, August and September 1984. In addition a gas recirculation system is under construction to allow the radiator to be filled with more expensive gases of higher refractive index for use in experiments where lower secondary particle momentum thresholds are required.

The radiator contains less than 10 parts per million of oxygen and water vapour to ensure good transmission down to wavelengths of 160 nm. The Cerenkov radiation is focused into ring images by an array of 80 5 m focal length spherical mirrors. An array of 16 Time Projection Chamber (TPC) modules is arranged on the focal surface of this mirror. The

Cerenkov radiation enters the TPCs through 16 UV transmitting windows - which also serve to separate the radiator and TPC gas volumes - each of which is constructed from two sheets of fused quartz. A general view of the detector is shown in Figure 2.

Each mirror has good reflectivity⁵, down to a wavelength of 170 nm (Figure 3 and Section 4.2), and mirror distortions have been measured to contribute less than 1 mm to the RMS error on the fitted radius for a Cerenkov ring image. The mirrors have been aligned to have a common centre of curvature to within $\pm 1\%$ and to produce an essentially continuous mirror surface 7 m by 4 m in extent. Figure 4 shows some reflected images in the mirror system and Figure 5 shows the mirror mounting arrangement.

Thirty-two sheets of 3 mm thick fused quartz, each 800 mm by 200 mm are used to construct the UV transmitting window, which is 3.2 m by 1.6 m in extent. The measured transmission of the sheets is shown in Figure 6, and includes the geometric losses produced by the electric field shaping wires which are placed on both sides of the quartz sheets (Figures 7, 23).

A single TPC module is shown in plan and elevation in Figure 7, and a photograph of a TPC is shown in Figure 8. Each TPC has a 20 cm long drift space on either side of a proportional wire plane. This plane contains 200 cells each 8 mm by 4 mm by 100 mm, each with a 20 μ m sense wire at its centre. The TPCs were operated at an ambient temperature of about 20°C and contained methane (CH_4) with 20% isobutane (C_4H_{10}) and the organic photo-ionising vapour Tetrakis(dimethylamino)ethylene (TMAE: ionisation energy 5.3 eV). The drift gas was bubbled through liquid TMAE at a temperature of 10°C before entering the TPCs. At this temperature the fractional concentration of TMAE vapour in the drift gas gave an absorption length for ultraviolet photons of ~ 50 mm. Electrons produced from the conversion of Cerenkov photons entering the TPC through the quartz window drift up to 20 cm onto the proportional wire plane. One co-ordinate of the photon

conversion point is given by the wire number while the other co-ordinate is given by the drift time to the wire plane.

Each sense wire is connected directly to a sensitive preamplifier, which in turn is connected to a second stage amplifier, discriminator, and time-slice encoder, by 2.5 m of ribbon cable. After an event trigger, data from 192 wires in each TPC are strobed into a memory at time intervals which correspond to a drift of ~ 1.6 mm. When all the data has been collected for an event, the contents of the memory are encoded into wire number and time slice and read into CAMAC.

3. DESIGN CONSIDERATIONS

The detector was designed with the aim of providing secondary particle identification over a large momentum range. Figure 9 shows the variation of Cerenkov ring radius as a function of particle momentum for electrons, muons, pions, kaons and protons, with a 5 m atmospheric pressure nitrogen radiator.

It can be seen that at high momenta of the order of 80 GeV/c, the π and K rings differ in radius by only a few millimetres. In fitting a circle to a photoelectron ring however, the error on the fitted radius is reduced by the square root of the number of constraints in the fit. Hence having a large number of photoelectrons on a ring improves the determination of the radius, important at high energies, and helps reject background.

The overall detection efficiency for Cerenkov photons is the convoluted product of the mirror UV reflectivity $R(E)$, the quartz window UV transmission $T_w(E)$, the TMAE quantum efficiency $Q(E)$ (Ref 3) and the radiator gas transmission $T_g(E)$. Figure 10 shows the various efficiencies

plotted as a function of photon energy (E) and wavelength. The transmission of the nitrogen radiator gas is shown for 10 parts per million oxygen and water vapour contamination.

The mean number of photoelectrons converted in the detector from a Cerenkov cone of half angle θ developed in a radiator length of L (cm) is given by:

$$N_e = 370L \sin^2 \theta \int Q(E) R(E) T_w(E) T_g(E) dE$$

$$= N_0 L \sin^2 \theta$$

We have in our design^(1,2), assumed a value for the quality factor N_0 of 90. The numbers of photoelectrons produced by pions, kaons and protons are then as plotted against momentum in Figure 9. The dominant contribution to the error in reconstructing the position of a photoelectron in a ring image in the TPC is due to the chromatic dispersion in the radiator gas.

Figure 11 shows the variation of the refractive index of nitrogen at atmospheric pressure, plotted as a function of photon energy. This dispersion gives rise to smearing in the position of a reconstructed photoelectron of ± 1.8 mm. Other additional effects, which each contribute $\sim \pm 1$ mm to the position error, are the mirror distortion (Section 4.4), diffusion in the TPC drift process, the reconstruction errors due to the 4 mm wire spacing and the time slice resolution, and the effects due to the photon conversion depth in the TPC.

The various contributions from the TPCs to the overall spatial accuracy will be discussed in detail in a further report. However, adding the known errors in quadrature gives an estimate of the overall reconstruction accuracy of ± 2.7 mm in the position of a photoelectron,

which is in very good agreement with the 2.6 mm observed in an analysis of preliminary data taken with the RICH at Omega in December 1983⁴.

4. THE MANUFACTURE, EVALUATION AND PERFORMANCE OF THE RICH MIRROR

ARRAY

As can be seen in Figures 2 and 5, the RICH mirror array was built up from a mosaic of 80 individual hexagonal elements each 70 cm in diameter. The diameter of the mirrors was determined principally by the size of the equipment available to mould, grind and polish the glass blanks into a spherical surface, and the coating facilities capable of producing high reflectivity surfaces down to far ultraviolet wavelengths. The individual mirrors were attached to a low mass support frame via 3-point mountings, and could be separately aligned in both position and angle.

4.1 The Production of Spherical Mirror Substrates

The first operation in the production of the mirrors was the preforming of circular glass blanks to the 10 metre radius of curvature. This was carried out at the UKAEA Culham Laboratory, Oxfordshire, England⁽⁵⁾. The blanks of 6 mm thick standard soda-lime float glass were heated to their softening temperature of 610° C and dropped under vacuum into concave stainless steel moulds (Figures 12 and 13). The time profile of the moulding process is shown in detail in Figure 14. When the furnace had reached the 610° C, the volume between the glass blank and concave mould was evacuated to begin the drooping process. The furnace was then kept at the forming temperature for 3 hours - the minimum time necessary to form mirror substrates with good spherical profiles - and then allowed to cool down over a 16 hour period so that extremely well annealed substrates were produced.

After moulding, the surface curvature of the glass substrates was examined at many points with a spherometer which allowed local radii of curvature to be calculated at numerous points from sagitta measurements over a preset chord length.

All mirror substrates needed some degree of grinding to achieve a surface quality suitable for our application, and were ground with varying grades of Axolite (Al2O3) powders before being finally polished with Cerium Oxide paste. Sphericity was frequently rechecked during the grinding process.

At the beginning of the project it was necessary, in collaboration with the mirror grinders[†] to develop techniques for the grinding of these relatively thin mirrors which were too flexible to be ground unsupported. By way of comparison, a telescope mirror of similar size is usually 70-100 mm thick, and a mirror blank of this type was in fact prepared by the manufacturers to act as a sphericity standard with which to compare the sagitta measurements taken from the production mirrors. After a series of trials a technique was evolved in which the glass substrates were ground while held in a slightly cushioned concave 5 cm thick aluminium support which had been machined to the correct radius of curvature. Once this technique had been successfully demonstrated, a total of 7 mirror grinding machines were commissioned - several of which are shown in Figure 15 - which gave an average production of 4 good substrates a week.

Each mirror blank was given a final optical inspection to make sure that there were no "grey" areas of under-polished glass which would have shown up as areas of low reflectivity after aluminising, when further polishing would have been impractical.

After grinding and polishing, each mirror blank was cut to a hexagonal shape and glued - using a flexible epoxy resin - to a mounting ring which would later be used to attach it to the mirror support frame. The mounting

rings were constructed by a spinning process from 2 mm thick mild steel sheet, a material with a similar thermal expansion coefficient to that of the glass.

4.2 The Mirror UV-Reflective Coatings

Reflective coatings were applied to the completed mirror blanks by a process of vacuum evaporation at the UKAEA Culham Laboratory, where there is considerable experience in the deposition of high reflectivity coatings at ultraviolet wavelengths.

The mirror substrates were suspended face downwards in a vacuum evaporation chamber, attached by their mounting rings to a workholder capable of rotating at 30 rpm.

After being glow-discharge cleaned for several minutes, a coating of 75 nm of high purity aluminium was evaporated onto the glass from an electrically-heated boat. To minimise oxidation of the freshly deposited aluminium surface, within 10 seconds a 22 nm protective layer of magnesium fluoride was evaporated onto it. The coating thicknesses were calculated from the change in frequency of oscillation of a crystal sited in the deposition zone. Great skill and experience were required on the part of the operator to accurately control the depths of the deposited layers. In particular, small variations in the thickness of the magnesium fluoride coating were found to have a critical effect on the reflectivity of the mirrors.

It proved essential to develop facilities to measure mirror reflectivities into the far ultraviolet so that the optimum coating thicknesses could be established. A vacuum UV reflectometer was designed and built at the Rutherford Appleton Laboratory for this purpose, and is described in Section 4.3. Once the optimum coating recipe had been established, careful monitoring of the reflectivities of mirrors in the

[†]A E Optics Ltd, Luton, England.

course of production ensured good quality control, allowing mirrors with defective surfaces to be identified and sent for recoating.

4.3 Measurement of Mirror Reflectivities

The reflectivity of the mirrors was measured at the Rutherford Appleton Laboratory with the specially designed reflectometer shown in Figures 16 and 17. This device is unique in design in that it allows the reflectivity of large curved mirrors to be measured at any point on their surfaces, and has an integral laser alignment system. The mirror under test is attached via its mounting ring to a moveable platform and sealed into a vacuum vessel, inside which it can be rotated through 360° and translated along half a diameter (Figure 18a). The "v" principle of operation of the reflectometer is shown diagrammatically in Figure 19. Ultraviolet light from a deuterium arc passes through a wavelength-selecting vacuum UV monochromator and enters the device, to be reflected - depending on the mirror configuration - between the moveable plane mirrors and the mirror under test before being detected by an intensity-measuring photomultiplier tube coated with p-terphenyl wavelength shifter. In the "w" configuration the UV beam - with a spot size of 5 mm - is reflected from the test mirror surface at an angle of 10 degrees from two points 44 mm apart.

Great care was taken to ensure that the moveable components in the reflectometer were correctly aligned so that intensity measurements were always made at the same point on the photocathode. Provision was made to inject a laser beam into the mirror system via a pair of 45° angled mirrors (Figure 18b). The alignment was adjusted until the laser beam crossed predetermined points on two translucent targets mounted near the output post. This meant that the reflectometer axis was correctly aligned in position and angle, and the two alignment mirrors could be swung out of the

path of the UV beam ready for measurements to begin. If necessary, as part of the alignment procedure, the plane of the test mirror could be adjusted by means of a 3-point mounting on the vacuum vessel support truck (Figure 17). This was fitted primarily to allow mirrors of different radii of curvature to be measured: the mirror plane could be tilted to compensate for the change in radius.

In normal operation, the reflectometer vacuum vessel was evacuated to 10⁻⁴ mbar to eliminate the absorption of UV by oxygen and water vapour, which become serious at wavelengths below 195 nm.

The mirrors were set up in the "v" reference configuration and the intensity measured firstly over a range 170-230 nm in 5 nm steps. The wavelength scan was then repeated in the "w" configuration with the UV beam being reflected from the centre of the test mirror, all data being transmitted to an on-line computer over a CAMAC dataway so that reflectivities could quickly be calculated at each wavelength. Reflectivity measurements were then taken at a further 9 points on each mirror; at 3 points spaced at 120° intervals at radii of 10, 20 and 25 cm. The two UV impact points on the test mirror were 22 mm tangentially equidistant from the nominal measurement positions.

Figure 3 shows the average reflectivity as a function of wavelength for the 80 mirrors, each of which has been measured at 10 positions. No systematic geometrical variation of reflectivity was seen in the mirror sample, and the variations between individual mirrors were generally less than 3%. Occasionally, however, a "bad coat" was applied to a mirror which showed up as a dramatic reduction in reflectivity, particularly below 200 nm. In these few cases it was, however, possible to remove the defective coating according to the following procedure:

- i. Wash with 1% nitric acid in distilled water to remove MgF₂ coating.

ii. Wash with 1% sodium hydroxide in distilled water to remove

aluminium coating.

iii. Wash with detergent.

iv. Wash with distilled water.

All mirrors recoated after being washed in this way gave "second pass" reflectivities entirely consistent with the curve of Figure 3. All the mirrors used in the RICH had a minimum average reflectivity of 75.5% at 170 nm and 88% at 230 nm.

Tests were made to establish whether mirror reflectivities

deteriorated significantly with time. Over a period of 15 months, no significant deterioration was seen in the reflectivity of a test mirror that had been stored in a protective wooden crate under normal laboratory conditions of temperature and humidity (Figure 20). We believe, therefore, that no deterioration of mirror surfaces is likely to occur in the clean atmosphere of the RICH (Section 5). At all times mirrors were handled with gloved hands, avoiding any contact with the coated surface, and care was taken never to breathe directly on them, since it would have been impossible to restore the reflectivity of a blemished surface without a complete recoat.

4.4 The Measurement of Mirror Optical Distortions

The design requirement that the point error on each Cerenkov photoelectron should not exceed 3 mm gave us a criterion with which to specify the maximum allowable optical distortion of each mirror. Given the likely contributions to the spatial resolution from other factors it was demanded that optical distortions at the focal plane contribute at most ± 1 mm to the point error on a single photoelectron. Techniques were therefore developed to measure the optical quality of the mirrors, as shown schematically in Figure 21.

The first stage in the procedure was to photograph on high resolution bubble chamber film a template onto which 7 circles of diameter 230 mm had been accurately machined with a numerically-controlled engraving tool. The radii of these circles was chosen to be similar to those of the rings produced by high momentum particles traversing the 5 m RICH atmospheric pressure nitrogen radiator, and the layout of the 7 rings formed roughly a hexagon of the same size as the mirror itself. For this photograph, the camera was focussed on the template 5 metres distant (Figure 21). The film negative was then projected in a bubble chamber film scanning machine and the positions of 25 equidistant points around each circle, together with the 7 centres, were digitised. These points were then fitted onto circles using the MINUIT⁶ minimisation program and the average RMS residual on the radius for the 175 points was calculated to be 0.17 ± 0.03 mm, representing the average accuracy with which a ring radius could be measured by this photographic technique.

In the second stage, the template was replaced with a test mirror and a second template - with a hole at its centre for this purpose - was positioned around the camera lens, which was refocussed at infinity (Figure 21). The resulting film negative was digitised and fitted as in the first stage. The RMS deviations of the measured points from the best-fitting circles represented the distortion in each of the seven sectors of the test mirror - taking into account the inherent accuracy of the technique in stage 1 - and were required to be less than 1% of the corresponding fitted radii. Less than 4% of the production mirrors failed this acceptance criterion. The average radius of the seven best-fitting circles for each mirror allowed its focal length to be conveniently calculated from the demagnification of the reflected template image.

With this technique, it was seen that the 4 mm thickness mirrors originally envisaged, of which a sample of 12 were built and tested, would

give a point distortion in the focal plane of 1.69 ± 0.53 mm. It was therefore decided to construct the RICH production mirrors from glass blanks 6 mm thick, which gave average point distortions of 0.85 ± 0.21 mm, and focal lengths of 501.3 ± 5.7 cm - well within the design specification.

4.5 Mirror Suspension and Alignment

The support rings of the 80 RICH mirrors were attached via 3 point suspensions to individual brackets which were then fixed in position on a low mass aluminium support structure (Figure 5). Each mirror bracket could be adjusted in position, while the angle of the mirror relative to the bracket plane could be varied with the 3 adjusting screws.

It is known to be impossible to tessellate regular hexagons onto an exactly spherical surface - slight gaps and discontinuities are unavoidable. This was not a serious problem in our application, since it was also necessary to space the mirrors to prevent their edges grinding and chipping one another when the RICH was moved.

The mirrors were mounted in 3 layers staggered by ± 1 cm about the nominal radius of curvature. This discontinuity was well within the $\pm 1\%$ variation in measured radius of curvature of the mirrors. With these mounting considerations in mind, a set of mirror positions and angular alignment constants was computed to minimise the discontinuities in the mirror array surface and to provide data for a preliminary coarse alignment of the individual mirrors. For each of the 80 locations, a computer program calculated the elevation and azimuthal angles at which a beam of light projected through a theodolite situated at the centre of curvature of the array would be reflected from the centre of the individual mirror back to the instrument.

Once all the mirror mounts had been initially set up, a first iteration of fine adjustments was made with the aid of several specially constructed plane hexagonal mirrors. A plane mirror was attached to each mounting in turn and adjustments made until the reflection of a projected image was seen correctly centred at the theodolite. In addition the radial distance of the mirror was measured and adjusted with the aid of an infra-red range finder accurate to ± 2 mm.

A slightly different technique was needed to make final adjustments to the alignment of the 80 spherical mirrors once they had all been mounted on the support frame. Clearly an extended image would be magnified to infinity at the radius of curvature, so a laser "auto-collimation" technique was used. A laser beam was shone through a theodolite and the reflected image observed on a rotatable translucent screen covering half the objective. Final adjustments were made to the mirror mounts until the reflected laser spot returned from the centre of each mirror struck the screen within 1 mm of the centre of the theodolite objective - defining an angular alignment accuracy for each mirror of 0.05 milliradians.

5. THE RICH GAS RADIATOR

5.1 General Construction

Cerenkov light is produced and focussed over a distance of 5 metres in an enclosure containing approximately 118 m^3 of gas near atmospheric pressure. In the first Omega experiments to use the RICH - WA69 and WA71 in July, August and September 1984 - the radiator vessel was continuously flushed with nitrogen. To increase the flexibility of RICH, however, a gas recovery and recirculation system is presently under construction to allow the radiator vessel to be filled with more expensive fluorocarbon gases of higher refractive index for use in experiments where lower secondary particle momentum thresholds are required.

It is planned to use the new radiator gas system in the second phase of the WA69 experiment in mid-1985.

The new gas system will be discussed in a future report - here the description will be confined to the nitrogen radiator.

5.2 The Control and Measurement of Impurities in the Radiator Gas

The essential requirement of the radiator gas was that its transmission was high into the far ultraviolet. In particular it was most important to keep it free from oxygen and water vapour contamination since both absorb UV strongly below 195 nm. The gas supply was of very pure nitrogen derived from liquid boil-off. The typical flow rate was 10 m³ per hour with an exhaust impedance which created an overpressure of 0.3 mbar. Under these conditions, the oxygen and water vapour contamination as measured with hot cell and dew-point meters were usually below 20 and 3 parts per million respectively for a corresponding input supply line purity of 10 and 1 part per million. With this level of contamination, the radiator gas was essentially 100% transmissive over our detection bandwidth, and it was not necessary to pass the nitrogen supply line through a purifier to further reduce the contamination.

The top, bottom and sides of the radiator vessel were assembled from seam-welded prefabricated sections of 1 mm and 3 mm stainless steel sheet. It was important - for the optimum performance of other detectors situated behind the RICH - to minimise the amount of material in the path of secondary particles in the Omega spectrometer. The rear panel of the radiator enclosure was therefore constructed from 1 mm thick aluminium sheet braced vertically at several points to resist bowing due to the hydrostatic pressure of the gas. The front of the enclosure was formed by a "bay window" frame constructed from 5 mm thick epoxy fibreglass ("PERMALI")[†] sheet, containing 16 apertures into which the TPC quartz

[†]Manufactured by PERMALI Ltd, Gloucester, England.

T A B L E 1 a

OUTGASSING RATES FROM THE PRINCIPAL MATERIALS USED IN THE

RICH RADIATOR VESSEL

Material	Approximate Surface Area Exposed to Gas (cm ² x 10 ³)	Outgassing Rate (mbar l cm ⁻² s ⁻¹)	Relative Contribution (%)
Stainless Steel	1080	10 ⁻¹⁰	<< 1
Aluminium and Al ₂ O ₃	622	10 ⁻⁹	<< 1
Quartz	51	10 ⁻⁵	8.3
Epoxy Fibreglass "PERMALI"	58	9 x 10 ⁻⁶	8.5
Glass and MgF ₂ (Mirrors)	509	10 ⁻⁵	83.1

T A B L E 1 b

OUTGASSING RATES FROM THE PRINCIPAL MATERIALS USED IN THE

CONSTRUCTION OF THE RICH TIME PROJECTION CHAMBERS

Material and Component	Approximate Surface Area Exposed to Gas (cm ²)	Outgassing Rate (mbar l cm ⁻² s ⁻¹)	Relative Contribution (%)
Quartz and glass windows			
Copper and Beryllium-Copper	6400	10 ⁻⁵	59
Copper (Drift region electrodes, drift field wires and MWPC cathode wires and separators)	6000	10 ⁻⁸	<< 1
Epoxy fibreglass and "PERMALI" (Framework and circuit boards)	4900	9 x 10 ⁻⁶	41

windows were permanently fitted. The thickness of the frame was reduced to 2 mm across a narrow band in the median plane, separating the middle quartet of windows, to minimise the amount of material in the path of non-interacting beam tracks. The TPCs could be detached from the quartz windows for servicing, so that the radiator gas seal was not broken whenever it was necessary to remove a TPC.

Detailed studies were made of the likely effects of outgassing - primarily of trapped water vapour - from the various materials of the radiator gas enclosure. Table 1a shows the outgassing rates for the principal materials, together with their respective surface areas exposed to the gas. It can be seen that the largest contributions come from the mirrors, TPC quartz windows and their support frame. The contributions from the much larger unbaked stainless steel and surface-oxidised aluminium panels are negligible.

All the materials listed in Table 1a are unbaked and unvarnished.

Outgassing rates are initial values for materials which, after having been initially cleaned with suitable solvents, have been stored for a period of several weeks under normal laboratory conditions of humidity, temperature and cleanliness prior to assembly.

Detailed measurements were made of the outgassing rate from samples of "PERMALI" fibreglass, as this material is known to be porous to water. The rate for an untreated sample was found to decrease roughly exponentially from 9.2×10^{-6} to 2.1×10^{-7} mbar ℓ cm $^{-2}$ s $^{-1}$ over a period of 20 hours after insertion into an inert atmosphere, while the rate for a sample coated with fully cured PZ820[†] epoxy varnish dropped from 7.9×10^{-6} to 6.8×10^{-7} mbar ℓ cm $^{-2}$ s $^{-1}$ over the same period. It was therefore concluded that it would be counterproductive to varnish the inner surface of the bay window frame. The outer surface, however, was sealed with epoxy

[†]Manufactured by Ciba-Geigy Ltd.

varnish to prevent water vapour diffusing through the fibreglass to reach the radiator gas.

From Table 1a an upper limit for the partial pressure due to the outgassing of water vapour can be estimated, integrated over the first complete change of radiator gas (approximately 12 hours). This is 2.2 mbar, or 0.22% of the normal operating pressure. This dropped very quickly however, and within three gas change periods, the water vapour contamination was measured to be only 30 parts per million.

As part of the RICH commissioning programme, nitrogen was flushed through the radiator enclosure for several weeks after final assembly before the whole detector was operated in a test beam⁴. This period was found necessary to dry out the various materials and reduce the water vapour contamination from an initially fairly constant level of about 30 parts per million to an acceptable level of 3. The radiator could then be opened up occasionally for a period of a few days for routine maintenance - during which access was through a small curtained hatchway in one of the sides - and be successfully brought down to acceptable contamination levels of 20 and 3 parts per million oxygen and water vapour respectively within about 10 gas change periods.

5.3 The Radiator Gas Pressure Control System

It was very important to prevent large pressure differentials arising across the fragile 3 mm quartz windows separating the TPC drift and radiator gases. The TPC gas pressures were well controlled by accurate flowmeters and referenced to the external atmospheric pressure by overpressure defining exhaust bubblers (Section 7.2). The radiator vessel normally operated at a controlled overpressure of 0.3 mbar - sufficient to reduce the ingress of oxygen to insignificant levels - sensed by an electronic transducer which measured the pressure difference on the two

sides of the radiator wall at a point near the bottom of the vessel. The transducer maintained a constant overpressure with the aid of a logic circuit and a set of electromagnetic valves which controlled the flow of gas into and out of the vessel (Figure 22).

The pressure transducer could detect pressure fluctuations of 0.01 mbar. Such sensitivity was necessary to quickly detect and react to possible faults in the high capacity gas supply stem, which if left unchecked might rapidly increase the pressure across the quartz windows. Although the enclosure was thermally insulated over most of its surface area with 4 cm of polystyrene foam, the pressure monitoring and control system prevented large variations in the refractive index of the radiator gas due to changes in the ambient temperature. Atmospheric pressure and temperature were continually monitored during running so that the radiator refractive index could be calculated at any time.

The overpressure in the vessel was coarsely defined by MV1, a manually adjusted telescopic exhaust throttle, while the main nitrogen supply was opened and closed by the electromagnetic valve EV1. A safety valve, SV1, protected the vessel against extreme pressure fluctuations (Table 2) - or against a failure in the electricity supply to the pressure control system and electromagnetic valves - by opening the radiator gas enclosure to atmosphere. In this event, the maximum differential pressure across each quartz window was 1.2 mbar, defined by the oil level in the TPC exhaust gas bubblers.

A complete list of the functions and settings of the electromagnetic valves is given in Table 2.

6. THE TPC ULTRAVIOLET-TRANSMITTING WINDOWS

The UV windows through which Cerenkov light entered each TPC were constructed from two 80 cm by 20 cm rectangular sheets of 3 mm thick

T A B L E 2

RICH RADIATOR PRESSURE CONTROL SYSTEM ACTION

Radiator Gas Pressure Range (mbar)	Condition of EM Valves "O" = Open "C" = Closed					Safety Valve	Ejection Pump	Remarks
	EV1	EV2	EV3	EV4	EV5			
> 0.58	C	C	C	C	C	O		Radiator Safety Valve Open, Fill Stopped, Alarms Sound.
0.47-0.58	C	C	C	C	C	C		Fill Stopped, Alarms Sound.
0.35-0.47	O	O	O	C	C	C	Pumping Hard	N ₂ Drawn Off Through Low Impedance to Quickly Reduce Pressure.
0.31-0.35	O	O	C	C	C	C	Pumping	N ₂ Drawn Off Through High Impedance To Reduce Pressure.
0.29-0.31	O	C	C	C	C	C		Normal Operating Conditions.
0.27-0.29	O	C	C	C	O	C		N ₂ From Emergency Supply Fed in Through High Impedance to Increase Pressure.
0.22-0.27	O	C	C	O	O	C		N ₂ From Emergency Supply Fed in Through Low Impedance Quickly to Increase Pressure.
0.11-0.22	C	C	C	C	C	C		Normal Supply Line Closed in Case of Supply Leak, Alarms Sound.
< 0.11	C	C	C	C	C	O		Radiator Safety Valve Open, Fill Stopped, Alarms Sound.

"SUPRASIL II"[†] fused silica. This material has a high transmission into the far ultraviolet, and is well matched to the spectral quantum efficiency of the TMAE photoioniser (Figure 10).

Each quartz sheet was wired on both sides (Figures 7, 23) with 99 Beryllium-Copper wires of 100 μ m diameter at 2 mm pitch. These were connected to a potential-grading resistor chain, and acted as drift field-defining electrodes along the 20 cm drift direction of the TPC. The electrical connections to the drift chain were arranged so that a TPC could be easily removed from its window for maintenance.

A 1.5 cm deep varnished PERMALI trough was sealed between the two quartz sheets in each TPC window (Figure 23). This recess was designed to contain the inner edge of the central sense plane support frame, which projected from the TPC body (Figure 8). In this way, the active area of the sense plane was extended down to the inner edge of the quartz where the majority of the photoelectrons were produced due to the exponential depth dependence of the gaseous photoionisation process. Techniques were developed at the Rutherford Appleton Laboratory to measure the UV transmission of the quartz sheets in their delivery condition and at several stages during their incorporation into TPC windows. Light of known wavelength from a monochromator was passed through an evacuated vessel containing a pivoting and sliding sample holder on which a quartz sheet could be mounted for measurement (Figure 24). The sheet could be swung into and out of the path of the UV beam, whose intensity was measured with a wavelength-shifted phototube. At each wavelength and position on the sheet, the transmission was calculated by an on-line computer from the ratio of the intensities with the sheet swung into and out of the beam.

Transmission measurements were generally made over the full wavelength range of 162.5 to 250 nm at 2 positions on each sheet ("A" in Figure 24),

[†]Manufactured by Hiraux & Co, West Germany.

while at a further 16 points ("B") the transmission was only measured at 190 nm.

Quartz sheets were delivered with their faces ground optically flat and polished. All newly-delivered sheets were measured and found to be within about 2% of the manufacturer's specified transmission curve.

To be installed in a TPC window, each quartz sheet was glued into a PERMALI and printed circuit board framework before being wired on both sides. Great care was taken in the handling of the quartz during these processes; the faces were covered to prevent adhesive and flux blemishes, and all wire was drawn through a solvent-soaked degreasing pad before stringing. The inner edges of each quartz sheet were painted with an opaque epoxy varnish before being glued to the central trough. This was a precaution designed to prevent the escape into the TPC sense plane of any multiply internally-reflected Cerenkov light that might be produced in the 3 mm of quartz by the passage of high energy particles.

During the wiring process, the field shaping wires on either side of the quartz were carefully aligned to be opposite one another. In this way, the attenuation in transmission due to the geometric shadowing effect of the wires was expected to be about 5%.

In spite of the care taken to keep the quartz sheets clean during these processes, the transmission of the finished windows was usually found to have dropped significantly, so that final cleaning was necessary before the windows were fitted onto the RICH radiator.

Each quartz sheet was washed with distilled water and wiped with a soft and lint-free cloth before being drenched with high-purity ethyl alcohol and allowed to dry by evaporation in a laminar filtered-airflow cabinet.

Figure 6 shows the final average transmission of the 32 quartz sheets over the range 162.5 to 240 nm (64 measurements per point). All

transmission measurements were made with a UV beam spot size of 1.0 by 1.5 cm. The average transmissions of Figure 6 therefore include the expected 5% shadowing due to the field shaping wires. At 190 nm, variations in transmission across the surface of prepared and cleaned windows were found to be less than $\pm 3\%$.

One of the main considerations in the design of the TPC gas handling system (Section 7) was the need to prevent the condensation of TMAE vapour on the inside of the quartz windows, which would have resulted in a catastrophic loss of transmission. It was equally important to study the effect on the quartz of prolonged exposure to TMAE vapour.

One window that had been exposed for a period of 28 days to a drift gas mixture of 80% methane and 20% isobutane bubbled through liquid TMAE at 15° C - in effect a TMAE concentration of 0.03% - was remeasured in several positions at 190 nm. Its transmission was found to have dropped on average by no more than 3%.

7. THE TPC DRIFT GAS DELIVERY SYSTEM

The function of the TPC gas system was to accurately mix the constituent drift gases in a ratio necessary to set up a desired photoelectron drift velocity in the TPC, and then to bubble the mixture through liquid TMAE at a known temperature. Accurate control of the temperature of the TMAE bubblers was essential, as the UV photon conversion depth - and hence the fraction of incoming UV photons detected - was strongly dependent on the fractional concentration of TMAE vapour in the drift gas.

As in the case of the radiator, it was necessary to minimise the contamination in the drift gas due to water vapour and in particular, oxygen. Not only do both molecules absorb UV, but the organic photoioniser TMAE is a powerful reducing agent, reacting in air to form oxidation products that are known to absorb ultraviolet radiation strongly

(Section 7.2). Likewise oxygen is known to have a strong affinity for free electrons, and its presence in large concentrations would cause many drifting photoelectrons to be absorbed before they reach the TPC sense plane. The incoming drift gases were passed through a purifier after being mixed. The oxygen and water vapour contamination was measured at the input and exhaust lines of the TPCs, and the UV absorption length of the input and exhaust gases was monitored with a monochromator and UV test cell. The following sections deal with the various aspects of the gas delivery system in more detail.

7.1 Gas Flow Control and the Measurement and Removal of Contamination

A simplified diagram of the TPC gas delivery system is shown in Figure 25. The normal TPC gas to be bubbled through liquid TMAE was a mixture of 80% methane and 20% isobutane, the relative concentrations chosen on the basis of the required drift velocity and the TPC gas gain conditions. Both these considerations are, however, outside the scope of this report and will be dealt with in a future publication. Stock methane and isobutane of 99.95 and 99.5% nominal purity respectively were supplied from batteries of cylinders and mixed together in a ratio determined by the settings of flowmeters A and B. The manufacturer's own specified upper limits for the various contaminants present in the two gases are shown in Table 3.

As several of these contaminants were known to absorb ultraviolet radiation strongly, it was necessary to establish whether the stock gases in their delivery condition would be too heavily contaminated for use in the TPCs. Their suitability was determined from measurements of their UV transmission at several wavelengths in the range 160-230 nm. The gas under investigation could be switched via electromagnetic valve A into the UV transmission measurement system shown in Figure 26. A monochromatic UV

TPC STOCK INPUT GASES SPECIFIED CONTAMINANTS

Gas	Cylinder Type	Nominal Purity (%)	Specified Contamination (Upper Limits in Parts Per Million)
Methane	9 m ³ of gas at 160 bar	99.95	Oxygen (20), Carbon Dioxide (10), Hydrogen (20), Nitrogen (200), Ethane (200)
Isobutane	Liquid below gas at 2 bar: 16.5 m ³ total gas volume	99.5	Oxygen (100), Water Vapour (20), Hydrocar- bons (1000), Rare gases and nitrogen (4000)

beam passed through 8.6 cm of sample gas contained in a test cell sealed at each end with calcium fluoride windows. The intensity of the beam was measured with a wavelength-shifted photomultiplier tube, and the transmission at a particular wavelength calculated from the ratio of intensities recorded when the test cell was filled with sample gas and when it was either evacuated or filled with nitrogen (100% reference transmission).

Figure 27a shows a typical UV transmission curve for methane in delivery condition. In particular, its transmission below 160 nm is very high - indicative of low levels of oxygen, carbon dioxide and heavier hydrocarbon contamination. Although this part of the UV spectrum was not detectable due to the cut-off of the quartz windows (Figure 27b), it was nevertheless useful as a gas quality indicator.

In general the isobutane was found to be contaminated with impurities that absorbed UV particularly strongly, and to have very large cylinder-to-cylinder variations in transmission. Isobutane cylinders were therefore routinely selected for use on the basis of their UV

characteristics (Figure 26). During the selection process it was found that the transmission of most cylinders was improved significantly after up to 10% of the gas volume had been vented off. The UV transmission of the isobutane was sampled at 176 nm, a particularly critical wavelength just above the natural cut off of the pure gas itself and at a point in the spectrum where the transmission is still sensitive to oxygen and water vapour contamination. In delivery condition, the typical transmission at 176 nm varied between 3 and 50%, but was usually improved by venting to about 95% - the acceptance criterion for cylinder selection.

Figure 27c shows a typical transmission curve for a vented sample of isobutane. This curve is very similar to that measured for a very much more expensive test cylinder of 99.95% purity isobutane that had been cleaned solely by passage through a molecular sieve and oxygen remover.

After the input gases had been mixed in the desired ratio, the drift gas mixture was passed through an "OXISORB" filter[†] which contained a 5 Angstrom molecular sieve and a chromium oxygen remover. Operating at normal laboratory temperatures, this filter could reduce various contaminants - including water vapour, oxygen and carbon dioxide - to below 2 parts per million and absorb a total of 9 litres of oxygen and water vapour before regeneration was required. Gas was passed through the filter at 320 litres per hour before being split between the 8 pairs of TPCs. At this flow rate, and with the contamination levels of Table 3, the minimum lifetime of the filter was 7 weeks under continuous flow conditions.

Before being filled with their normal drift gas, each pair of TPCs was first purged of air and water vapour by flushing for several days with clean nitrogen from the RICH radiator bulk supply. The exhaust line was closed with an oil bubbler to prevent air backstreaming into the chambers, and to help set up an overpressure to inhibit the ingress of oxygen through any small leaks. For a flow rate of 40 litres per hour - roughly one

[†]Manufactured by Messer Gaisheim & Co, West Germany.

volume change per TPC every 16 hours the bubbler oil level and exhaust line impedance maintained an overpressure of 1.2 mbar in each TPC.

The input and exhaust nitrogen from each pair of TPCs could be switched with the aid of a set of electromagnetic valves (Figures 25, 26) either into the UV gas transmission cell, or into the combination of a hot-cell oxygen meter and a dew-point water vapour meter. The difference in measured oxygen contamination between the input and exhaust lines of the 8 pairs of TPCs was observed to drop with time to a steady-state average of 14 parts per million - a level indicative of the leak rate at this overpressure. Table 1b shows the outgassing rates for the principal materials used in the construction of the TPCs, together with their respective surface areas exposed to the gas in a single chamber. From Table 1b, the upper limit for the partial pressure due to the outgassing of water vapour is estimated, integrating over the first complete TPC gas change of 1.6 hours, to be 19.5 mbar, or nearly 2% of the normal operating pressure. Within 24 hours of flushing with clean nitrogen, however, the average water vapour contamination was measured to be only 50 parts per million. Although it was not possible to directly measure the water vapour contamination during normal running (Section 7.2), it was later measured when data taking had finished - and the TPCs were again being purged with nitrogen - and found to be on average 3 parts per million. The contamination present during the period of RICH data taking between July and September 1984 is therefore believed to be below 10 parts per million in all TPCs.

Before data taking could commence, nitrogen had to be purged from the TPCs with the drift gas mixture of methane and isobutane. The absence of TMAE vapour at this stage allowed a number of important tests to be made. In particular, the UV transmission of the drift gas could be finally checked, and various sets of calibration data could be taken. In one test,

the front surface of the RICH was illuminated with a large sample of straight particle tracks from zero field interactions in the Omega spectrometer (Figure 1). The alignment of the 16 TPCs was deduced from an off-line comparison between the projected impact points of the tracks and the position of the signals detected in the TPCs themselves.

7.2 The TMAE Bubbling System

The position of a TMAE bubbler in the gas control system for a pair of TPCs has been shown in Figure 25. The methane-isobutane drift gas mixture was passed through the bubbler when the entry and output valves C and D were opened and the by-pass valve B was closed. Each bubbler was a thick-walled cylindrical stainless steel bottle (Figure 28) surrounded by a coiled heat exchanger through which water was circulated at a temperature controlled to an accuracy of within $\pm 0.1^\circ \text{C}$. The temperature inside the bubbler was itself measured by a thermocouple probe passed through the cylinder wall. At all stages during the handling of TMAE, great care was taken to prevent it coming into contact with oxygen. TMAE was supplied by the manufacturers[†] as a liquid under an inert gas atmosphere in sealed glass containers. 1 gm-mol (200 gm) of TMAE was transferred into each bubbler in a remote-handling enclosure filled with nitrogen. The bubbler lids were formed from UHV compatible glass observation windows which were sealed to the cylindrical vessels with chain clamps and metal seals. The bubbler output ports were protected with splash guards to prevent droplets of liquid TMAE entering the TPC input pipes. The bubblers were constructed entirely from materials known to be highly resistant to corrosive attack from liquid TMAE.

Before the bubblers were installed in the TPC drift gas delivery system, the UV absorption characteristics of their TMAE were examined, as these were expected to depend significantly on the presence of dissolved

[†]RSA Corporation, Ardsley, New York 10502, USA.

impurities - for example tetramethyloxyde, tetramethylurea and dimethylamine⁷. It was generally found that high impurity levels had accumulated after TMAE had been stored for several months in the manufacturer's bottles. Each bubbler was in turn connected to the UV gas transmission measurement system and flushed with nitrogen at a rate of 15 litres per hour while being maintained at a temperature of 14° C.

The transmission at a particular wavelength is given by

$$T = \frac{I}{I_0} = e^{-\mu \lambda}$$

where I_0 is the intensity recorded with the cell filled with nitrogen, and I is the intensity when the nitrogen is loaded with TMAE vapour. The ultraviolet absorption coefficient μ is given by

$$\mu = -\frac{1}{\lambda} \ln \frac{I}{I_0}$$

where λ is the length of the cell in cm.

The reciprocal of μ is the mean free path in cm of UV photons of a particular wavelength in TMAE vapour at this temperature.

Figure 29 shows the typical improvement in UV transmission with time as nitrogen is passed through a TMAE bubbler at 14° C. At first the rate of clean up is high, but after about 1 m³ of nitrogen has been bubbled through 1 gm mol of TMAE little further improvement in transmission is seen and the purging is stopped. At this point, the value of the TMAE absorption coefficient is in good agreement with other authors' measurements^(7,8) over most of the detection bandwidth.

As an alternative, the dissolved impurities could be removed by pumping on the TMAE vapour above the liquid via a third port that could be connected to a vacuum pump (Figure 28). The UV absorption coefficient

obtained after pumping away 0.1 gm mol of TMAE was approximately equal to that seen when 1 m³ of nitrogen had been passed through a bubbler. It was not easily possible with this technique, however, to monitor the absorption coefficient during clean-up, due to the difficulty in repressurising the bubblers to allow TMAE vapour to be transported to the UV transmission cell with a nitrogen carrier gas. The first cleaning method has therefore been almost exclusively used.

The vapour pressure of the TMAE in the TPC drift gas varies with temperature according to the Clausius-Clapeyron equation

$$P = P_0 \exp \frac{\Delta H}{R} \left(\frac{1}{T_0} - \frac{1}{T} \right)$$

where P_0 is the vapour pressure (torr) at the reference temperature T_0 (Kelvin), ΔH is the molar heat of vaporisation and R is the molar gas constant. At room temperatures of 20° C the vapour pressure of TMAE has been measured to be 0.35 torr⁸.

The UV absorption coefficient of TMAE is directly proportional to its vapour pressure. Figure 30 shows the temperature variation of the spectral UV absorption coefficient for samples of TMAE vapour in a nitrogen carrier gas, over the temperature range 0-15° C. The temperature dependence of μ has been fitted to the Clausius-Clapeyron form and compared with the fitted measurements of Reference 8. We believe that the difference in the fitted coefficients reflects the different wavelength intervals over which data were taken. We have only included measurements of μ at 176 nm in our fit, while the data of Reference 8 come from a broad bandwidth 170-195 nm, over which the spectral UV absorption coefficient is known to vary significantly (Figures 29, 30; Reference 7).

During normal running, the UV transmission of the methane-isobutane-TMAE input and exhaust gases of the TPCs were routinely compared as a

useful check for the development of leaks. At all times, however, the UV absorption characteristics of the input and exhaust gases were virtually indistinguishable, and were consistent with upper limits of 14 and 50 parts per million oxygen and water vapour contamination measured when the TPCs were being purged with nitrogen prior to running. It was not possible to directly measure oxygen and water vapour levels during normal running: the hot-cell oxygen analyser was unsuitable for use with flammable gases while there was also concern that the measuring instruments could be damaged by the known corrosive properties of TMAE⁸.

Efforts were made to build the TPCs and gas handling system from materials likely to be resistant to attack by TMAE, which has been found⁸ to react with various organic vacuum greases and O-ring materials. TPC O-rings were manufactured from Viton[†] as it was found that silicon rubber and Neoprene samples degraded seriously under immersion in liquid TMAE. All TPC PERMALI components were varnished and assembled using the most TMAE-resistant epoxy varnishes and adhesives tested: PZ/HZ 820[‡] and CY 1300/EM 308[#] respectively. All gas connections were made with solvent-cleaned stainless-steel and copper tubing. The gas delivery system was of modular construction, allowing various sections to be isolated and independently pumped down for leak testing.

It was extremely important to maintain temperature gradients in the gas delivery which prevented TMAE vapour condensing in the TPCs - particularly on the quartz windows whose UV transmissions would be destroyed. The TPCs were operated at ambient temperatures of 20-25° C - although they could be enclosed to run at higher temperatures if desired - while the TMAE bubblers were typically operated 10-12° C colder.

The first 3 metres of the TPC gas delivery piping was surrounded by a larger diameter plastic tube through which water was circulated, and led initially vertically out of the TMAE bubblers (Figure 32). The temperature

of the circulating water was controlled to within $\pm 0.1^\circ \text{C}$ by a water bath, and maintained typically 3 or 4° C higher than the bubblers themselves.

The heat exchanger was the coldest part of the piping to the TPCs to ensure that any TMAE condensation occurred in this region, and that the liquid droplets could return to the bubblers. The ambient temperature and that of all the bubblers and heat exchangers were continually monitored with a multichannel data logger so that the correct temperature gradient could be set up along the gas supply lines under varying ambient conditions.

The TPC exhaust gas bubblers were filled with about 3 cm³ of synthetic naphthalene oil^{*} that was of those tested the most resistant to TMAE degradation.

It was found that a number of silicon vacuum oils were irreversibly cracked by the passage of TMAE-vapour laden gas; the oil volume being seen to increase as the liquid took on the green hue of liquid TMAE. This effect can raise the effective chamber overpressure by an amount dependent on the density of the TMAE solution, putting additional strain on the quartz windows.

The volume of the chosen oil was found to increase by about 1.9 cm³ to a saturated maximum after about 0.5 m³ of drift gas had been bubbled through it. Taking this effect into account, however, the total operating overpressure was found to be within the 3 mbar test limit for the maximum differential pressure across the quartz windows. The oil could later be cleaned up by bubbling about 3 m³ of clean nitrogen through it, and the volume increase was found to be almost reversible.

[†]Registered trademark of Dupont Ltd.
[#]Manufactured by Ciba-Geigy Ltd.

^{*}"L9" diffusion pump fluid;
Edwards Vacuum Components Ltd,
Crawley, England.

ACKNOWLEDGEMENTS

We are indebted to the many people who have contributed to the design, construction and commissioning of this detector. The major structural components of the RICH were constructed by H S Marsh & Co Ltd, Reading, England, while time projection chambers and readout electronics were built at the Rutherford Appleton Laboratory. The mirror system was a collaborative project between A E Optics Ltd, Luton, England, the UKAEA, Culham Laboratory and the Rutherford Appleton Laboratory. We thank the SERC (UK) and CERN for financial support with this project.

REFERENCES

1. A proposal to build a ring image Cerenkov detector for use by the Omega Photon Collaboration in WA69, RAL PPSP/82/24, Proposal 231, Addendum 4.
2. M Davenport et al, "A ring image Cerenkov detector for the CERN Omega Spectrometer". IEEE Trans Nucl Sci Vol N-S 30, (1983) p35.
3. E Barrelet et al, "A Two-Dimensional, Single Photoelectron Drift Detector for Cherenkov Ring Imaging". Nucl Inst Meth 200 (1982) 219.
4. R J Apsimon et al, "A ring imaging Cerenkov detector for the CERN Omega Spectrometer II". IEEE Trans Nucl Sci Vol N-S 32 (1985) p674.
5. C N Uden, Physics Apparatus Group Technical Note 95, Rutherford Appleton Laboratory Internal Report, May 1984.
6. F James and M Roos, MINUIT, CERN Computer Centre Program Library Long write-up D506 (1977).
7. TMAE Absorption Length vs Wavelength. Private Communication from T Ypsilantis.
8. D F Anderson, "A Photoionisation Detector for the Detection of Xenon Light". IEEE Trans Nucl Sci Vol N-S 27 (1980) p181.

TABLE OF FIGURES

Figure 1 The RICH in the WA69 experiment at Omega.

Figure 2 General view of the RICH detector.

Figure 3 The reflectivity of the 80 mirrors used in the RICH.

Figure 4 Reflected images in the RICH mirror array.

Figure 5 The RICH mirror mounting system.

Figure 6 The transmission of the RICH TPC quartz windows.

Figure 7 Plan and elevation of a single TPC.

Figure 8 Photograph of a single TPC, showing the central MWPC.

Figure 9 Cerenkov Ring radius and number of photoelectrons as a function of secondary particle momentum.

Figure 10 Convoluted response curve.

Figure 11 Chromatic dispersion in the RICH radiator gas.

Figure 12 The mirror moulding former.

Figure 13 Photograph showing two mirror moulding formers in the furnace.

Figure 14 The mirror moulding cycle.

Figure 15 Photograph of several mirror grinding machines.

Figure 16 Photograph of the UV reflectometer with the vacuum vessel open showing a test mirror.

Figure 17 UV reflectometer - detail of elevation.

Figure 18a Method of measuring reflectivities at different points on a mirror surface.

Figure 18b Plan view of reflectometer showing the laser alignment system.

Figure 19 The "VW" principle of operation of the reflectometer.

Figure 20 Degradation of UV reflectivity with time.

Figure 21 Procedure for measuring mirror optical distortions.

Figure 22 The RICH radiator pressure control system.

Figure 23 Photograph of a TPC quartz window.

Figure 24 The quartz UV transmission measurement apparatus.

Figure 25 Simplified diagram of the RICH TPC gas delivery system.

Figure 26 The TPC gas UV transmission measurement system.

Figure 27 The UV transmission of various gases.

Figure 28 One gm-mol TMAE bubbler.

Figure 29 The improvement in TMAE UV absorption coefficient as nitrogen gas is bubbled through the liquid.

Figure 30 The variation in the TMAE spectral UV absorption coefficient with temperature.

Figure 31 Clausius-Clapeyron fit to the temperature dependence of the TMAE UV absorption coefficient.

Figure 32 General view of the TPC gas delivery system.

FIG.1. GENERAL LAYOUT OF THE WA 69 EXPERIMENT AT OMEGA

FIG.2. GENERAL VIEW OF THE RICH DETECTOR

REFLECTIVITY OF 80 MIRRORS USED IN RICH

Figure 3

FIG 4 REFLECTED IMAGES IN THE RICH MIRROR
ARRAY

FIG 5 THE RICH MIRROR MOUNTING SYSTEM

FIG. 6. TRANSMISSION OF 32 QUARTZ SHEETS USED IN RICH

FIG.7

FIG 8 PHOTOGRAPH OF A SINGLE TPC, SHOWING
THE CENTRAL MWPC

FIG.9. RADIUS AND NUMBER OF PHOTOELECTRONS v MOMENTUM FOR RICH

Q.T.R FOR RICH (WITH EFFECTS OF 10ppm H₂O AND O₂)

Figure 10

FIG 11 CHROMATIC DISPERSION IN THE RICH RADIATOR GAS

FIG.12. THE MIRROR MOULDING FORMER

FIG 13 PHOTOGRAPH SHOWING TWO MIRROR
MOULDING FORMERS IN THE FURNACE

FIG.14. THE MIRROR MOULDING CYCLE

FIG 16 PHOTOGRAPH OF THE UV REFLECTOMETER
WITH THE VACUUM VESSEL OPEN SHOW-
ING A TEST MIRROR

FIG.18a. METHOD OF MEASURING REFLECTIVITIES AT DIFFERENT POINTS ON MIRROR SURFACE

FIG.18b. LASER ALIGNMENT SYSTEM: PLAN VIEW OF REFLECTOMETER

FIG 19 PRINCIPLE OF REFLECTOMETER

FIG 19

$$\frac{I_1}{I_2} = R^2$$

FIG 20 DEGRADATION OF MIRROR UV REFLECTIVITY
WITH TIME

FIG.21. PROCEDURE FOR MEASURING MIRROR OPTICAL DISTORTIONS.

FIG. 22. RICH RADIATOR PRESSURE CONTROL SYSTEM.

FIG 23 PHOTOGRAPH OF A TPC WINDOW

FIG.24. THE QUARTZ TRANSMISSION MEASUREMENT APPARATUS.

FIG.25. SIMPLIFIED BLOCK DIAGRAM OF GAS SYSTEM FOR SINGLE PAIR OF TPC's.

FIG. 26. THE TPC GAS U.V. TRANSMISSION MEASUREMENT SYSTEM

FIG 27 THE UV TRANSMISSION OF VARIOUS GASES

FIG.28. TMAE BUBBLER

FIG 19 THE IMPROVEMENT IN TOTAL UV ABSORPTION COEFFICIENT AS NITROGEN GAS IS BUBBLED THROUGH THE LIQUID

FIG 30 THE VARIATION IN THE TMAE SPECTRAL UV ABSORPTION COEFFICIENT WITH TEMPERATURE

FIG 31 CLAUSIUS-CLAPEYRON FIT TO THE TEMPERATURE DEPENDENCE OF THE TMAE UV ABSORPTION COEFFICIENT

FIG 32 GENERAL VIEW OF THE TPC GAS DELIVERY SYSTEM