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A Large Pressurized Cerenkov Counter*

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ABSTRACT

The design, construction, and operation of a large Cerenkov hodoscope are described. The radiator is normally Freon 12 at a pressure between one and four atmospheres and with a length of 293 cm. The primary mirror is arranged in ten segments covering an area of 275 cm x 140 cm, or, with reduced radiator length, twelve segments with an area of 330 cm x 140 cm. Wavelength shifter (pTP) is used on the pressure windows at the photomultiplier tubes.

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A large pressurized gas Cerenkov hodoscope (Canute) has been built to operate with the SLAC 1-meter fast cycling bubble chamber. The large emittance solid angle of the bubble chamber was to be matched as far as possible. Good particle identification characteristics were required while costs were a strong limitation on design possibilities.

As may be seen from Fig. 1, the bubble chamber is a cylinder 110 cm in diameter by 34 cm deep, with a horizontal axis. The 2.6T magnetic field is coaxial with the bubble chamber. The downstream particle exit windows of the bubble chamber and its vacuum tank define, to a first approximation, the emittance solid angle. Further constraints are imposed by parts of the field coils and the edges of the magnet steel. For particles originating at the bubble chamber center--and ignoring the effect of the magnetic field--the emittance limits are $\pm 8.5^{\circ}$ horizontally by $\pm 24^{\circ}$ vertically.

To match the capabilities of the SLAC beam line and the bubble chamber, particle identification was desired over a range up to about 15 GeV/c. Since there was a need to be able to separate pions, kaons and (anti-)protons over as broad a momentum span as possible, the counter could not operate simply as a threshold device. Further, the possibility of more than one particle penetrating to the counter suggested that the optics be divided into as many independent cells as practical to allow independent examination of the Cerenkov emissions.

Information from the counter would be used not only in the final analysis of the data but also in an "on line" mode. In conjunction with trajectory information from proportional chambers in the bubble chamber magnet gap, a fast algorithm in the facility's NOVA 840 computer would reach a decision within $\sim$ 2 ms on whether to flash the bubble chamber lights and record an event of possible interest.

Preliminary study indicated that a 3 meter path length of Freon 12 would be adequate, and the gas pressure range should reach 4 atmospheres absolute. This implied the use of approximately 10 mirrors in two parallel vertical banks. Total geometrical light collection was enforced for the experimental acceptance, and this was facilitated by the use of Winston-Hinterberger type[1] collecting cones with 110-mm diameter photomultiplier tubes, one for each mirror.

Analysis by hand allowed the parameters of all the optical components and their layout to be obtained to a good approximation. In several ways the solutions to the design criteria have differed from previously reported designs.[2,3] To contain the optical components within a practical pressure vessel, it was decided to use an all welded aluminum cylinder, Fig. 2, with vertical axis. All the working components of the counter would be encased in the vessel and access would have to be by means of a manhole at the top. Analysis further suggested that the use of wavelength shifter[4,5] near the phototube faces would allow the use of inexpensive components for the phototubes and their pressure windows.

The vessel need not be built to withstand operating pressures below atmospheric, and so it would not be possible to evacuate it before charging with gas. For environmental reasons it was decided to implement a Freon recirculation system to purify the gas on filling and to recover it on depressurization--the volume of the pressure tank was 2.8×10^4 liters ($\sim$ 1000 ft^3).

The remainder of the design was more conventional. It was found possible, however, to provide the option of increasing the acceptance solid angle of the counter by about 60% at the expense of reducing the effective radiator length by about 30%. To use this alternative configuration it is necessary to move mirrors and detectors approximately 1 meter upstream, add two extra detector-mirror units and realign the optics.

Optical Design

The preliminary hand calculations for the mirrors were optimized by the use of a Monte Carlo program. As input data, track measurements from bubble chamber pictures were extrapolated out through the magnetic field to the position of the Cerenkov counter. In addition, some specific interaction channels were simulated and treated the same way.

The program was written quite generally and has since been used for the design of other counters.[6] The trajectories of about 5% of photons usefully emitted in Freon 12 were traced. The entrance apertures of the collecting cones were taken as targets and the positions and incident angles of the reflected rays were examined at these planes. The orientations of the mirrors and the positions, orientations, diameter and limiting acceptance angle of the cones were adjusted by trial and error. Allowance was made for optical distortions of the mirrors to confirm the adequacy of their specifications, and the effects of alignment and positioning errors were investigated. Multiple scattering and optical dispersion were treated by hand, but since the program showed that the optical design was conservative even at the highest refractive indices, these effects had little importance.

All mirrors were designed to collect light from a rectangular area of 70 cm x 55 cm with overlaps above and below to prevent light loss at mirror boundaries. The gap between the two vertical banks of mirrors was specified to be less than 2 mm wide. Thus the overall collecting area in the ten mirror case is 275 cm vertically by 140 cm horizontally

(27° by 14° from the bubble chamber center). The nominal focal length of the mirrors is 84 cm. The maximum allowed deviation of the mirror normal from its nominal direction was ±5 mr.

The collecting cones have front and rear diameters of 26 cm and 11 cm respectively, with a length of 79 cm, corresponding to a maximum acceptance angle of 25°. The horizontally mounted cones are aimed at a specified point near the center of their objective mirrors from a distance of 98 cm and at an angle of 24° from the vertical counter symmetry plane--as close to the prereflection light envelope as possible without interfering with it. A radiator length of 293 cm could be fitted into the pressure vessel. The relative positions are modified slightly for the case of 12 mirrors with 217-cm radiator length. In this case the light collecting area is 330 cm by 140 cm, or 36.5° by 16° from the bubble chamber center.

Construction of Reflector Surfaces

Conventional techniques[3] were capable of giving adequate results for the mirrors and cones. The emphasis was on minimizing effort and expense, in part by emphasizing reproducibility of production conditions. Selected material for the mirrors was 0.68 cm thick black acrylic sheet whose surfaces were cleaned only if necessary and only with very soft material. Oversize sheets of the plastic were slumped into a female mold to produce the spherical shape.

The mold was a machined aluminum block with 1.6-mm diameter holes on a 5-cm square grid which were used for evacuation purposes. A cover was used to prevent deposition of dust and to prevent local deviations in the plastic from the uniform temperature of the mold. Heating was performed in a circulating air oven. To prevent wetting of the mold surface by the plastic and consequent imprinting, a fluorocarbon release agent was applied to the mold surface before slumping each mirror.

The initial shaping was carried out with the mold temperature cycle shown in Fig. 3. In this case gravity and not vacuum was used for the deformation. The edges of the acrylic were then taped to the mold for the annealing cycle. A temperature of 87°C was reached and held for twenty-four hours after which cooling proceeded to 40°C in twelve hours. During this period the mirror was constrained against the aluminum surface by a vacuum of 13 cm Hg. The vacuum was released for two minutes every fifteen minutes to allow the acrylic to "creep" without local stretching. After forming, the mirrors were stored vertically to minimize bending stresses.

Optical tests on the unaluminized surfaces were performed using two methods.[3] A grid was placed between the mirror and a pinhole camera at the center of curvature. Comparison of this grid and its image in the mirror provided a detailed map of the mirror distortions. A surface deviation in excess of 5 mr caused rejection. A photographic record was also kept of the image of a point source mounted close to the center of curvature.

Acceptable mirrors were attached to their mounts while supported on a similarly slumped male vacuum mandrel of thick plexiglas. Mirror and mandrel were separated by a layer of soft paper tissue. Only the outside 20 cm of the 70 cm length of the mirror was available for mounting, so that the amount of material directly in front of the particle exit window could be kept as small as possible. Acrylic brackets, bonded to the mirror ~~by~~ 1 mm thick flexible silicone adhesive performed the task without distorting the optical surface. Mirrors were subsequently trimmed to their individual shapes on the male mandrel. Aluminization without overcoating followed standard procedures.

The collecting cones were initially spun from aluminum sheet over a steel mandrel of the correct shape. Considerable difficulty was experienced in obtaining a good polish on the inside surfaces, but adequate results were obtained on a lathe by a strict regimen of decreasing the abrasive particle diameter and repeatedly flushing with kerosene. The cones were then lacquer dipped, baked and aluminized. Surface quality and reflectivity were tested by a small reflectometer made for the purpose using a silicon PIN light diode and filtered tungsten filament light. Reflectivity better than 85% was acceptable, but the results were usually close to 90%.

Photomultiplier Mounting and Pressure Windows

Although photomultiplier tubes of smaller diameter could withstand the pressure, it was necessary to mount the chosen 110-mm diameter tubes in atmospheric pressure containers within the Freon pressure vessel. A transparent pressure window was therefore necessary. The design chosen, Fig. 4, used a 6.4-mm thick window of U.V. transmitting acrylic sheet, slumped to a spherical inside radius of 17.55 cm, to correspond to the average curvature of the faces of the photomultipliers. The spherical design allowed the use of thinner material and gave better optical coupling to the photomultiplier tube than would a plane pressure window.

With the use of wavelength shifter the system was considerably less expensive and of somewhat superior Cerenkov light collecting efficiency than a flat quartz window.

The low modulus of elasticity and comparatively high thermal expansion coefficient of acrylic sheet meant that there could occur displacements of the window centers of up to 0.6 mm with changes in the operating conditions. To allow for this, the phototube was mounted by spring compression, and a space of 0.6 mm was provided between the tube face and the window. The space was filled with optical coupling liquid of refractive index and dispersion intermediate between those measured for the tube face and the window.

The optical transmission of the optical coupling liquid and the pressure window material (after slumping) were tested to ensure compatibility with the emission spectrum of the wavelength shifter pTP (350 to 440 nm). The paraterphenyl was coated on the gas side of the pressure windows to a thickness of 0.25 mg/cm^2, and overcoated with 25 nm of MgF_2. The deposition rates were respectively 0.01 $mg/cm^2/min.$, and 10 mm/min.. Beam tests carried out on a complete assembly agreed with the previous calculations that in Freon 12 it should be about 10% better than a quartz window assembly, and about equal with a tube without pressure window or wavelength shifter.[5]

A further complication in the design was the necessity to provide for magnetic field cancellation. The P.M. tubes required shielding against stray magnetic fields with both axial and transverse components of up to 20 Oersted. The large aperture of the collecting cone did not facilitate this, but an appropriate layout of available high permeability sheet metal was found experimentally. Coupled with an axial field cancelling coil and an external steel cylinder, the shielding could cancel the field in all of the critical P.M. tube volume to within 0.1 Oersted.

Pressure Vessel Design

The dimensions of the pressure tank are 335 cm diameter by 406 cm high. It is formed of plates of aluminum 1.9 cm thick. The torispherical end caps were formed by a process of altering the metal temper by heat treatment, then spinning and reannealing. The cylinder wall plates were shaped on a press brake. The 1.9-cm wall thickness was required because of the weakness of aluminum after welding. It was possible, however, to provide particle entrance and exit windows 5.7 mm thick by the expedient of machining two of the plates so that 25-cm wide welding margins of full thickness remained. These windows are 102 cm wide by 204 cm high. The thickness of the entrance window corresponds to 2.2% of a nuclear collision length or 6.4% of a radiation length. The corresponding values for the bubble chamber exit windows are 3.2% of a collision length and 19% of a radiation length. The vessel is not designed to operate below atmospheric pressure.

The tank is supported on a 2-meter diameter ring welded to the bottom cap. The internal framework of aluminum tubing which supports the mirrors and P.M. tube assemblies is attached to the pressure vessel on the inside at four places on the circle where the support ring intersects the tank floor. Consequently, the optics are immune to flexure of the tank caused by pressure changes.

The internal framework secures each mirror by nine screws which afford the angular and positional adjustment for alignment. The manifolds containing the two banks of P.M. tubes at atmospheric pressure are connected to the outside world by flexible bellows through which the electrical cables pass.

Because of vibration caused by the bubble chamber, there are four small vibration damping legs, which also serve as levelling jacks, which support the base ring above the floor.

Gas System

A simplified diagram of the gas system is shown in Fig. 5. After closing the counter, it is purged with dry nitrogen. The liquid Freon reservoir is filled and cooled to 180°K, about 2×10^{-2} atmospheres vapor pressure. With the help of heaters, Freon vapor is admitted to the bottom of the counter. Nitrogen is vented from the top until an admixture of Freon is detected in it. At this point batches of the exhaust gas are compressed in the reservoir to about 6 atmospheres, cooled to 180°K, and the uncondensed fraction vented. This process is repeated until the nitrogen content is below about 25%. A continuous cycle of recirculation through the liquid phase in the reservoir then becomes practical with the help of a heat exchanger to assist in condensation and evaporation.

When purification is complete, the required operating pressure is reached by bleeding gas from the Freon reservoir to the counter or recondensing some of that in the counter. It should be noted that the system is not restricted to the use of Freon 12.

Photomultiplier Tubes

The tubes used are Amperex 58DVP type with 110-mm useful photocathode diameter and Corning 9741 (or equivalent) extended U.V. response windows. The tubes were degaussed and the bases tuned for the most uniform response over the photocathode surface with the help of Monsanto MV5253 green light emitting diodes. It was found possible to select a tune condition that was essentially independent of the range of operating voltages (1900 V to 2300 V) for which the tubes gave a linear response to the encountered light levels. It was found that the uniformity could be checked in position after carrying out the magnetic field cancellation, by shining the diodes through the pTP on to the face of the tubes.

Some Physical Considerations

Light generation curves for π, K, and p are given in Fig. 6. The ordinate scales are consistent with the counter performance discussed below.

The total scattering effect of the counter for particles entering and leaving through the windows is illustrated in Fig. 7 in terms of interaction lengths. Multiple Coulomb scattering is shown in both displacement and deviation in Fig. 8 for particles of 10 GeV/c.

The thickness of the counter can produce pions from interactions of the rarer kaon or proton trajectories, or produce low energy (and hence low light emitting) pions from fast pion interactions. The resulting losses are strongly dependent on the operating pressure and particle momentum. In the present experiment with an 11.6 GeV/c beam and 1.5 atmospheres pressure, this effect causes approximately 2% of pions to appear to generate insufficient light and thus to be selected initially as K's.

The counter is normally used with a scintillator hodoscope that matches, counter for mirror, its geometrical layout. In this way, penetrating particles can be flagged whether or not they generate Cerenkov light. Initially it was planned to mount the scintillator hodoscope inside the pressure vessel directly behind the mirrors, thus improving trajectory matching between mirror and scintillator, and reducing particle interaction effects in the aluminum rear window or walls of the Cerenkov counter. It was discovered, however, that pressurized Freon 12 quickly causes the precipitation of one of the components of the supersaturated solid solution forming the NE 110 scintillator. This appeared as a white coating on the surface. Until this difficulty can be circumvented, the scintillator will remain outside the pressure tank.

Serious damage to acrylic components has been noted[7] elsewhere when CO_2, a gas of high permeability, was pressure cycled to 20 atmospheres. Tests have yet to be carried out to show whether CO_2 can be used in this counter at the comparatively low pressures involved.

Results of Operation

The counter has been in operation for about a year at the time of writing and has performed quite stably during this period. It has been used to select $K^{\pm}$ and $\overset{(-)}{p}$ trajectories of momentum greater than 5 GeV/c from interactions of an 11.6-GeV/c π^{+} beam incident on the bubble chamber. Pulse height distributions are shown for monoenergetic pions and kaons from the beam, Fig. 9.

For the data in this figure the beam particles were required to pass through a 25 cm x 7 cm scintillation counter behind the Cerenkov counter.

This was positioned to ensure that Cerenkov light was split between two cells in the counter, and also served to minimize the effect of interactions in the bubble chamber. The particles were independently identified by a beam-line Cerenkov counter. The beam contained $\sim$ 1.5% kaons. The large pulse height tail of the K's (8 ± 1.5% in excess of statistical expectations) can be partially accounted for in terms of K decay-in-flight after the beam line Cerenkov counter (3 ± 0.5%), and δ-rays (1.5 ± 0.5%). The threshold for δ rays is 9 MeV/c. The remainder is probably caused by interactions of the kaons.

Although the pulse heights from each tube are recorded separately, the tube gains have been balanced as far as possible by deflecting the beam and adjusting the tube voltages to equalize pulse heights. This simplifies the fast computer program which triggers the bubble chamber lights.

From the shapes of the pulse height distributions the effective number of photoelectrons can be derived. The tubes give an average of 37 photoelectrons for $\beta = 1$ particles, one atmosphere of Freon 12, and a mean radiator length of 293 cm. The R.M.S. deviation of the various cells about this is 3.7 photoelectrons. Light sharing between neighboring mirrors does not lead to any measurable losses. Using these figures, an illustration of the identification power of the counter is given in Fig. 10. Allowing 1% of pions of any momentum to contaminate the pulse-height-selected kaons, the fraction of identified kaons is plotted as a function of momentum for various pressures. At the higher pressures and momenta, the light emitted by kaons becomes comparable with that of pions and so the kaon identification efficiency falls (see Fig. 6).

Summary

The counter described is an unusually large pressurized Cerenkov hodoscope of useful differential identification ability. Several techniques not commonly used have been applied to achieve good performance at modest cost.

Acknowledgements

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7. C. Peck, Private Communication.

Figure Captions

1. Isometric view of the SLAC Hybrid Facility detector layout.
2. Cutaway drawing of the Cerenkov counter Canute. Some details are omitted in the interests of clarity. One detector cell is shown with its magnetic shielding removed.
3. Temperature cycle for forming mirrors.
4. Cross-sectional drawing of the pressure window--photomultiplier region. Some details are omitted. Magnetic shields of mumetal are labelled S1, S2, S3, and the steel magnetic shields are labelled S4 and S5.
5. Simplified diagram of gas purification system.
6. Pulse height generation curves for 1.5 and 3.0 atmospheres Freon 12 filling the counter, assuming 293 cm radiator length. Lines at the 5% probability contour for π's (---) and K's (-·-·-) are shown at the lower pressure.
7. Interaction probability for hadrons penetrating the counter.
8. Multiple scattering of particles penetrating the counter. The graphs show displacement and angular deviation of 10 GeV/c trajectories.
9. Pulse height spectra for 11.6 GeV/c pions and kaons penetrating Canute. Gas pressure was 1.51 atmospheres. Light was split between two cells.
10. Statistical probability of identifying K's if pulse height cuts are applied to exclude 99% of π's. Radiator lengths of 293 cm are assumed and pressures of 1.5 and 3.0 atmospheres are illustrated.

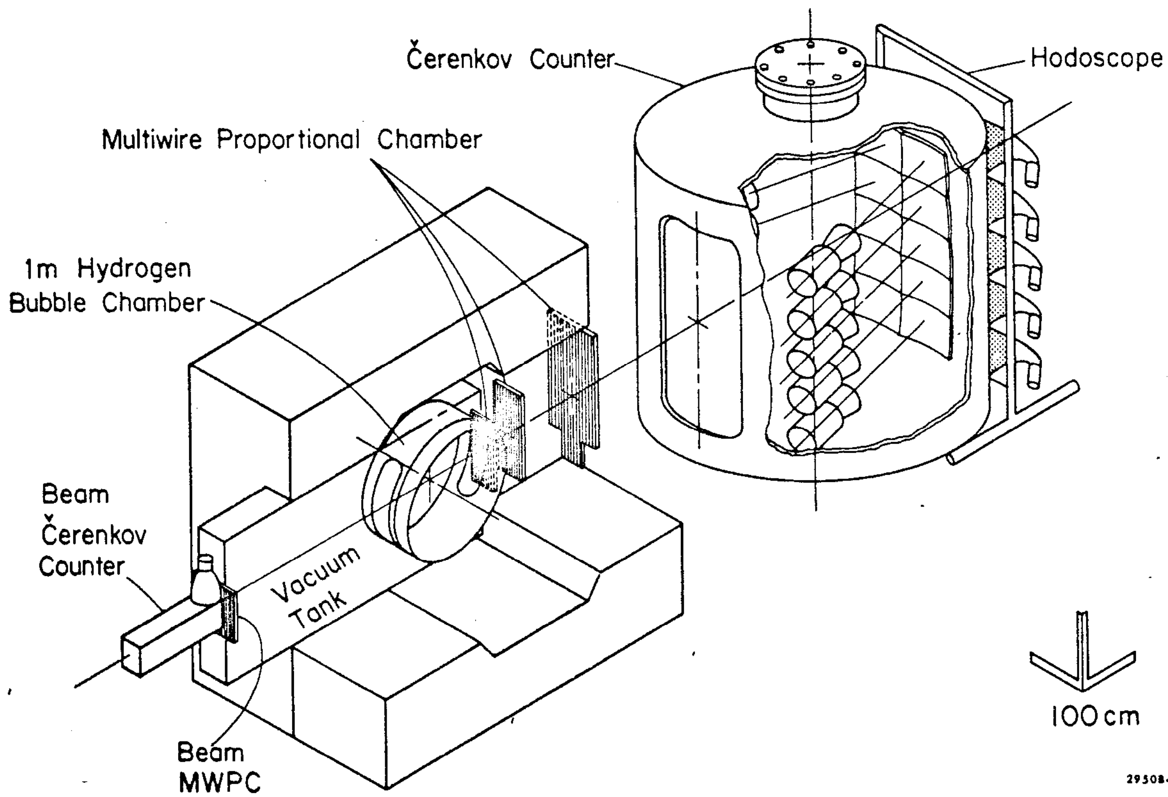

Čerenkov Counter
Hodoscope
Multiwire Proportional Chamber
1m Hydrogen
Bubble Chamber
Beam
Čerenkov
Counter
Vacuum
Tank
Beam
MWPC
100cm
295084

Fig. 1

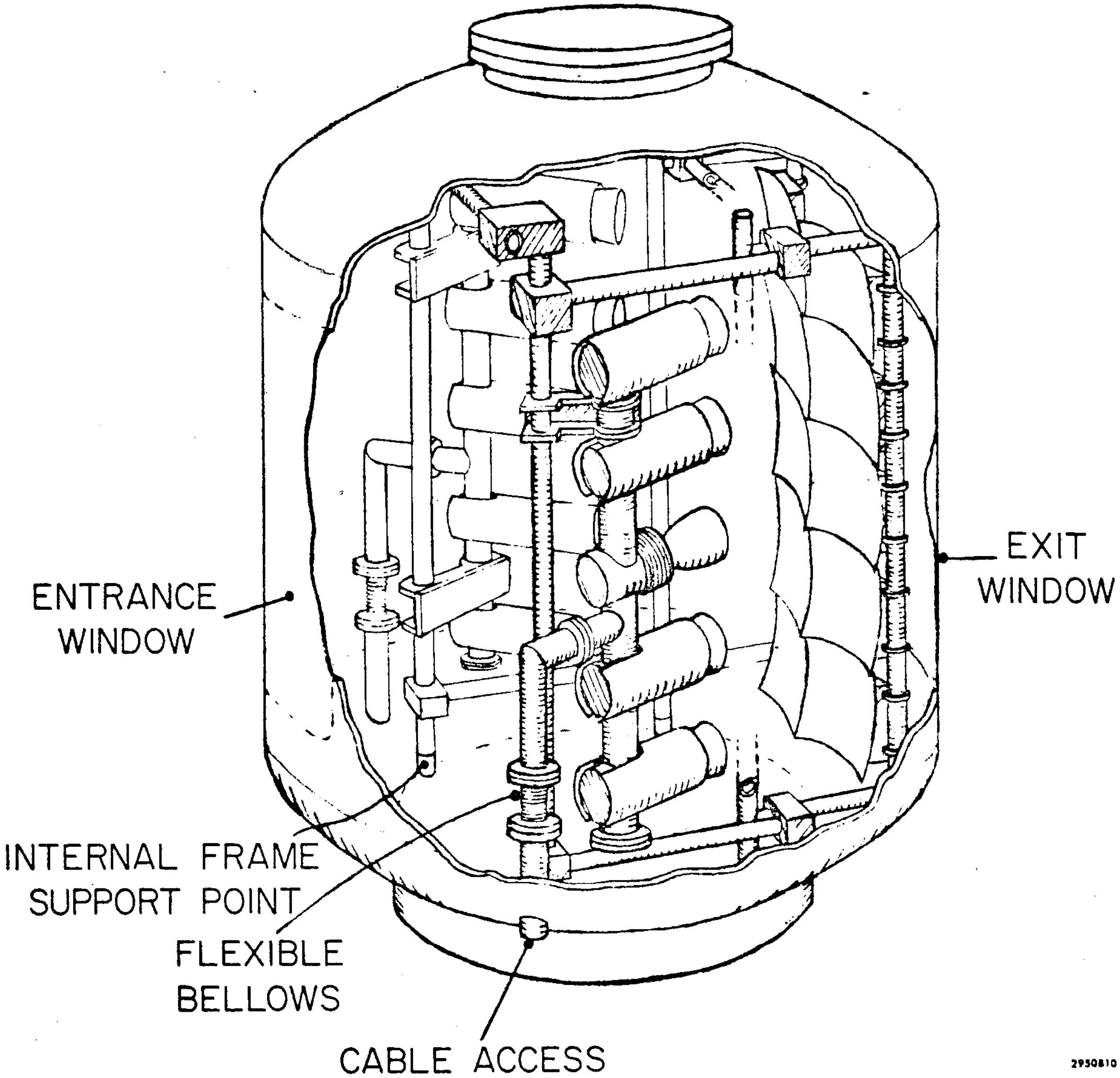

EXIT
WINDOW
ENTRANCE
WINDOW
INTERNAL FRAME
SUPPORT POINT
FLEXIBLE
BELLOWS
CABLE ACCESS
2950810

Fig. 2

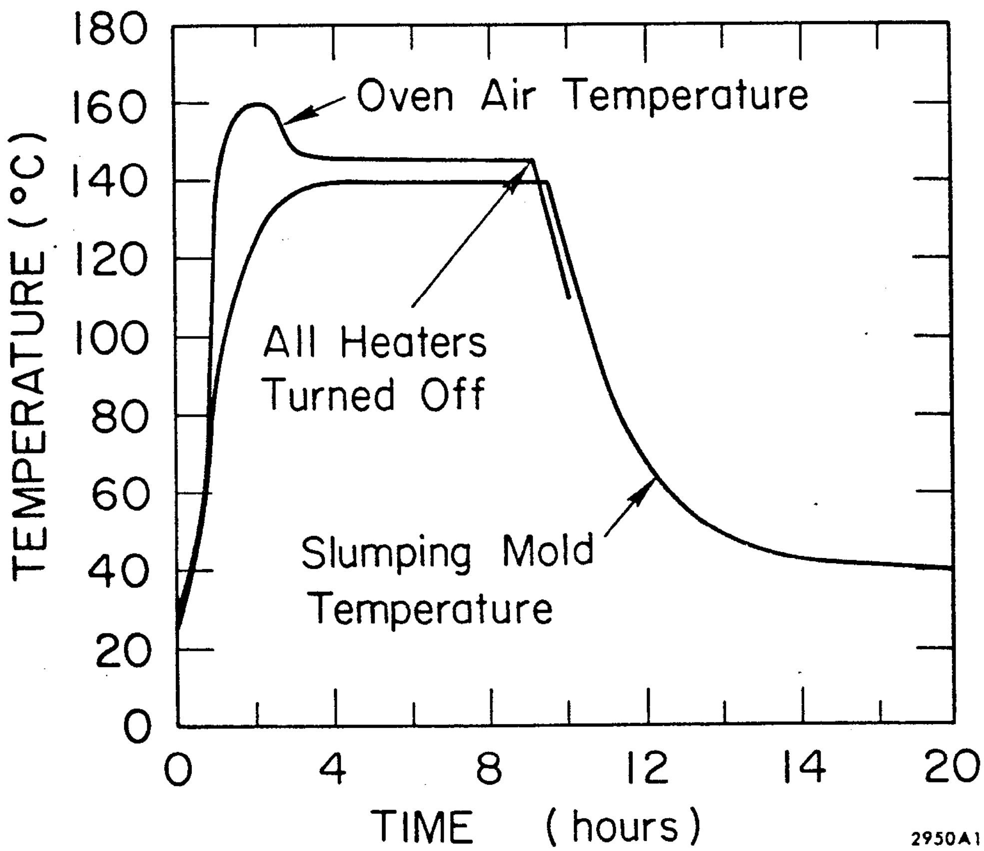
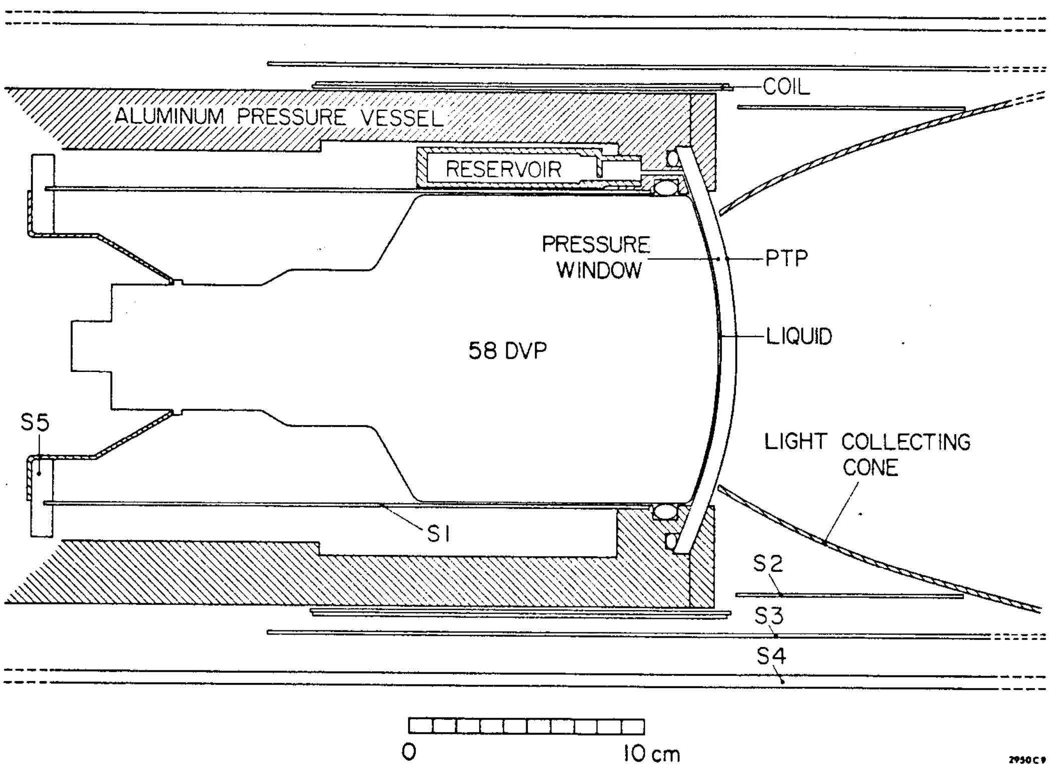

180
160
140
120
100
80
60
40
20
0
0
4
8
12
14
20
TEMPERATURE (°C)
TIME (hours)
Oven Air Temperature
All Heaters Turned Off
Slumping Mold Temperature
2950A1

Fig. 3



COIL
ALUMINUM PRESSURE VESSEL
RESERVOIR
PRESSURE WINDOW
PTP
LIQUID
58 DVP
LIGHT COLLECTING CONE
S5
S1
S2
S3
S4
0
10 cm
2950C9

Fig. 4

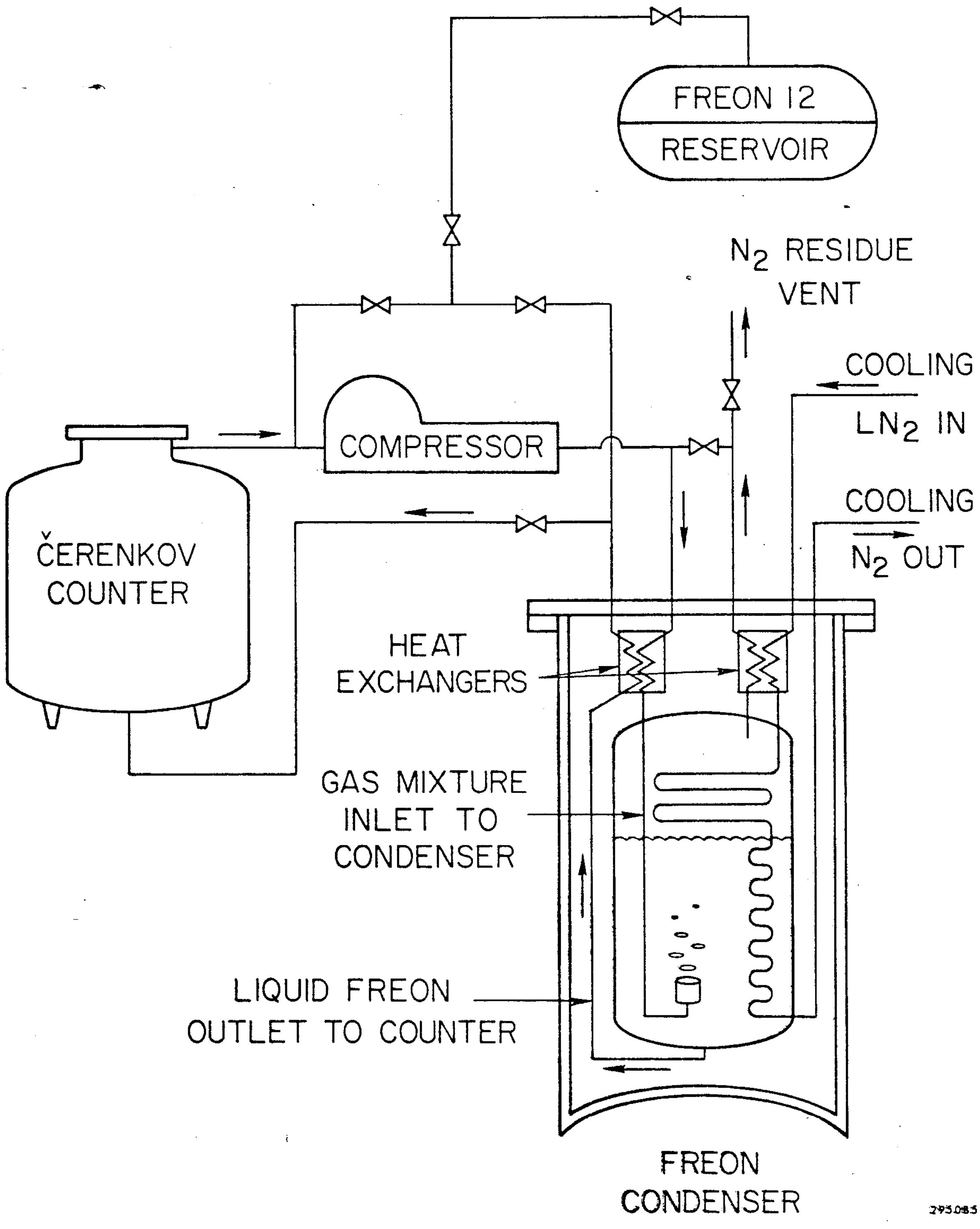

FREON 12
RESERVOIR
N_2 RESIDUE
VENT
COOLING
LN_2 IN
COMPRESSOR
COOLING
N_2 OUT
ČERENKOV
COUNTER
HEAT
EXCHANGERS
GAS MIXTURE
INLET TO
CONDENSER
LIQUID FREON
OUTLET TO COUNTER
FREON
CONDENSER
295085

Fig. 5

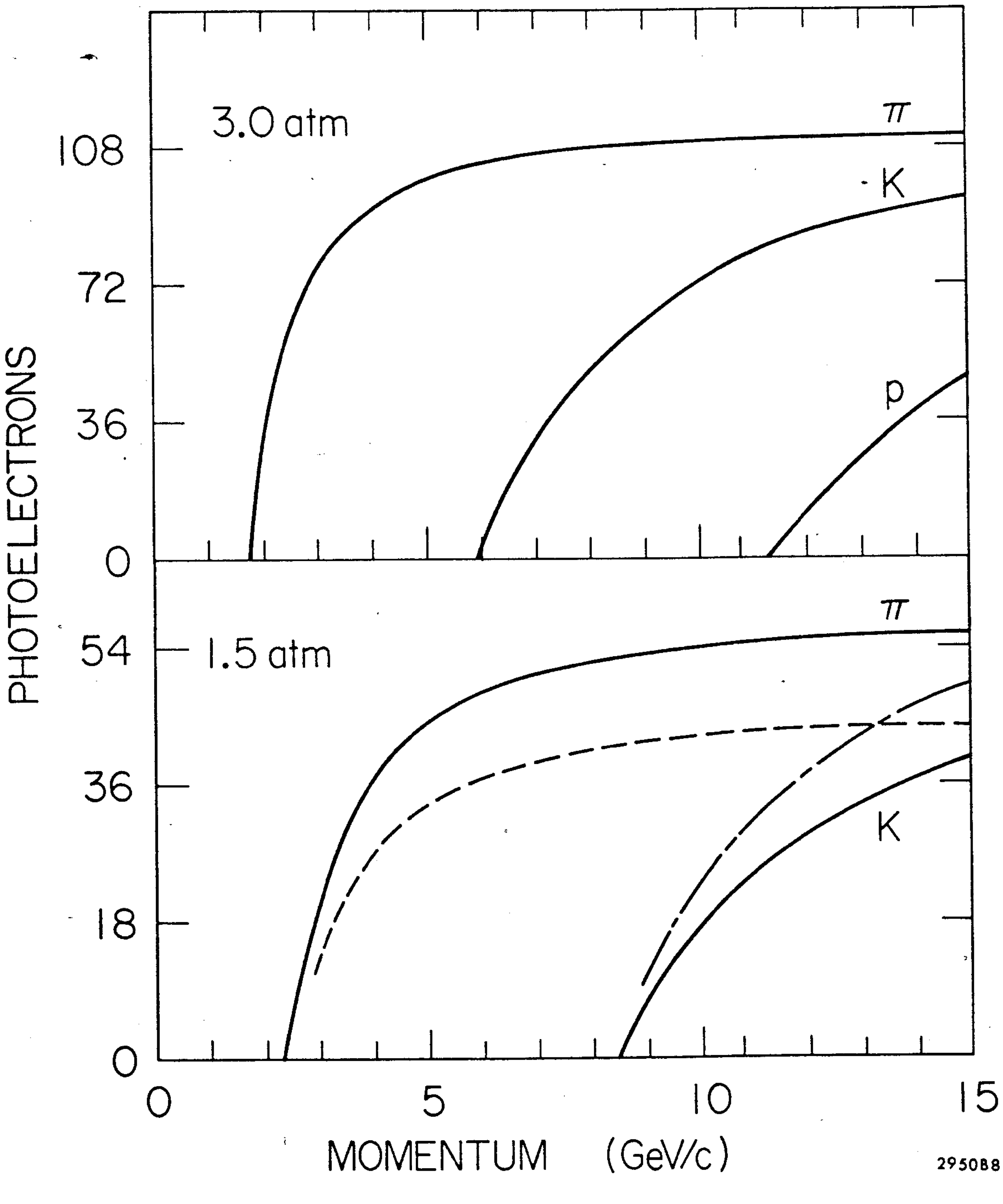

3.0 atm
π
K
p
108
72
36
0
1.5 atm
54
36
18
0
PHOTOELECTRONS
0
5
10
15
MOMENTUM (GeV/c)
295088

Fig. 6

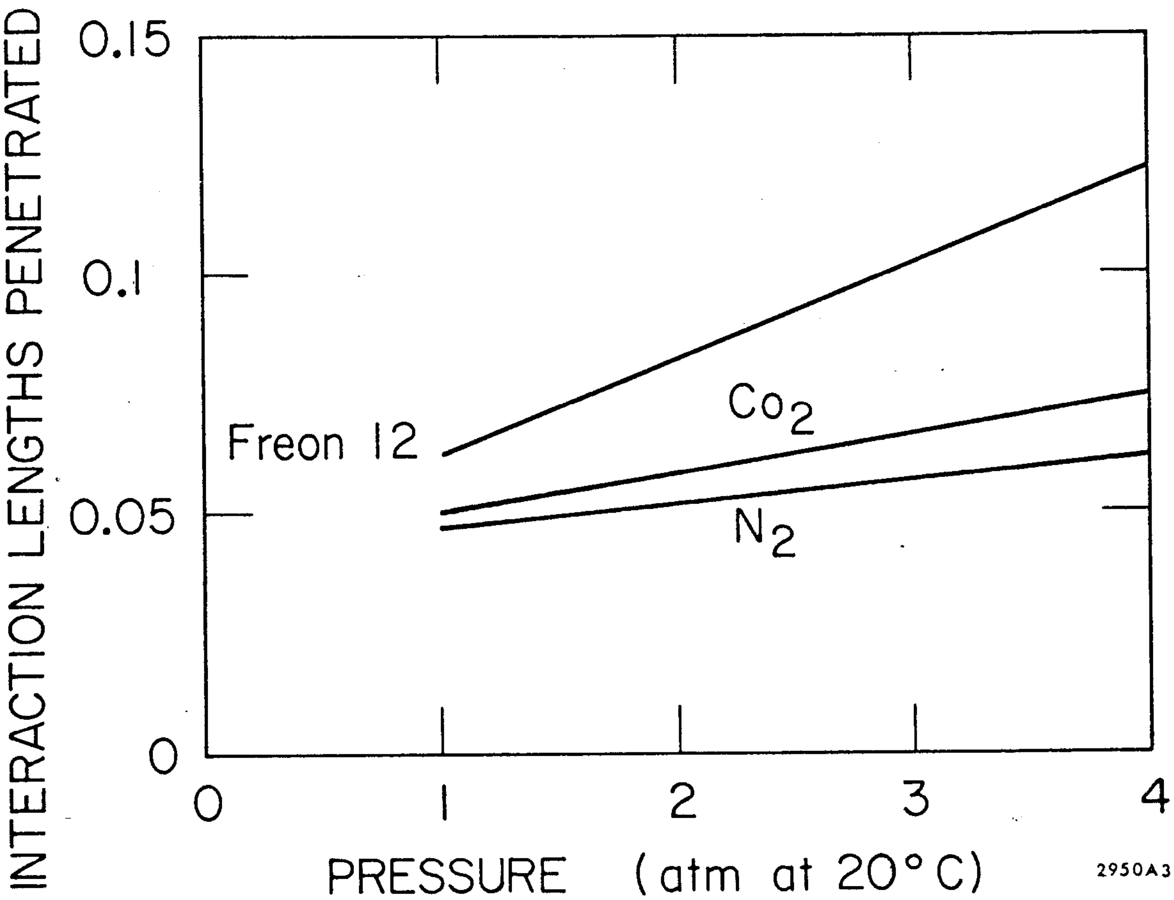

INTERACTION LENGTHS PENETRATED
0.15
0.1
0.05
0
0
1
2
3
4
PRESSURE (atm at 20° C)
Freon 12
Co2
N2
2950A3

Fig. 7

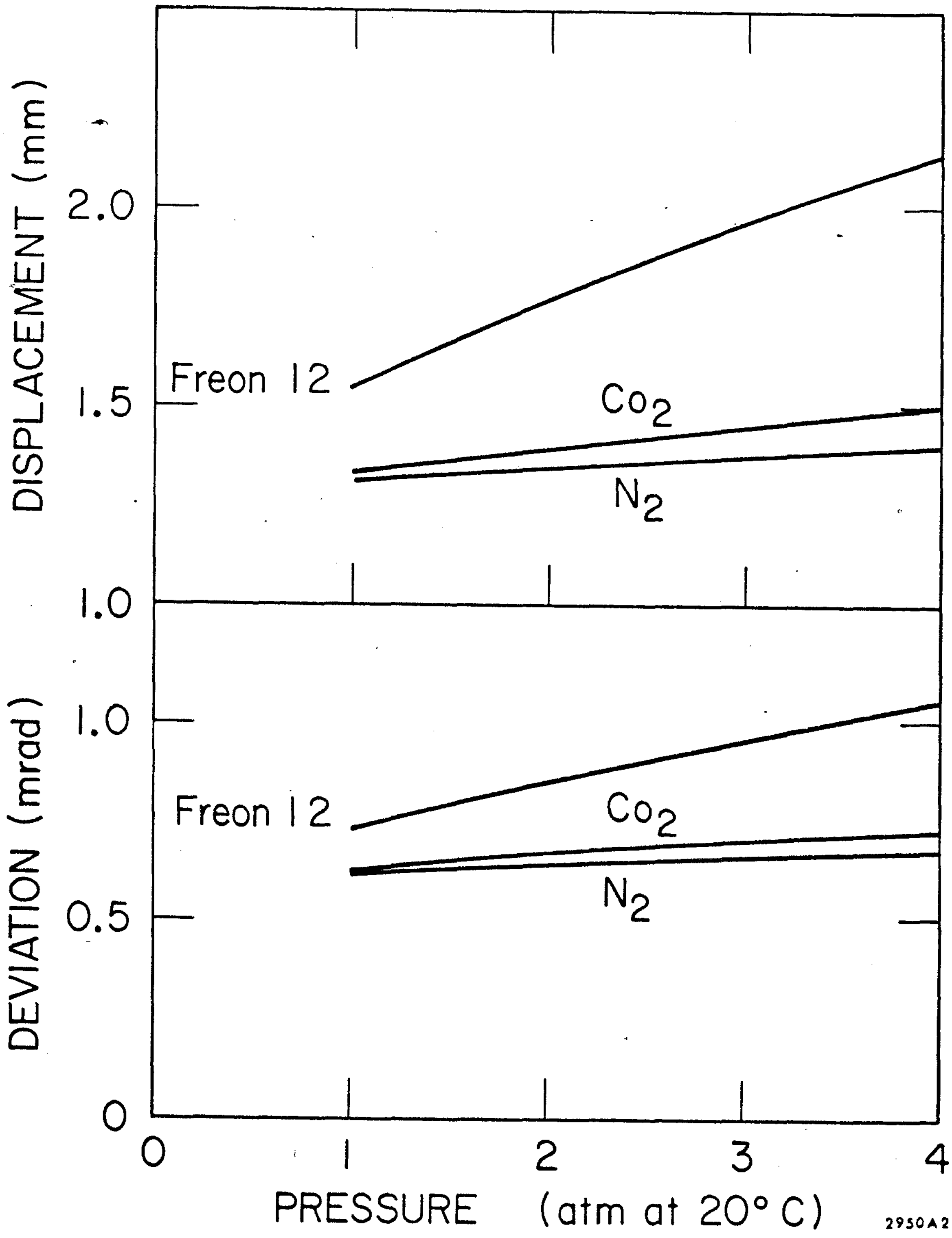
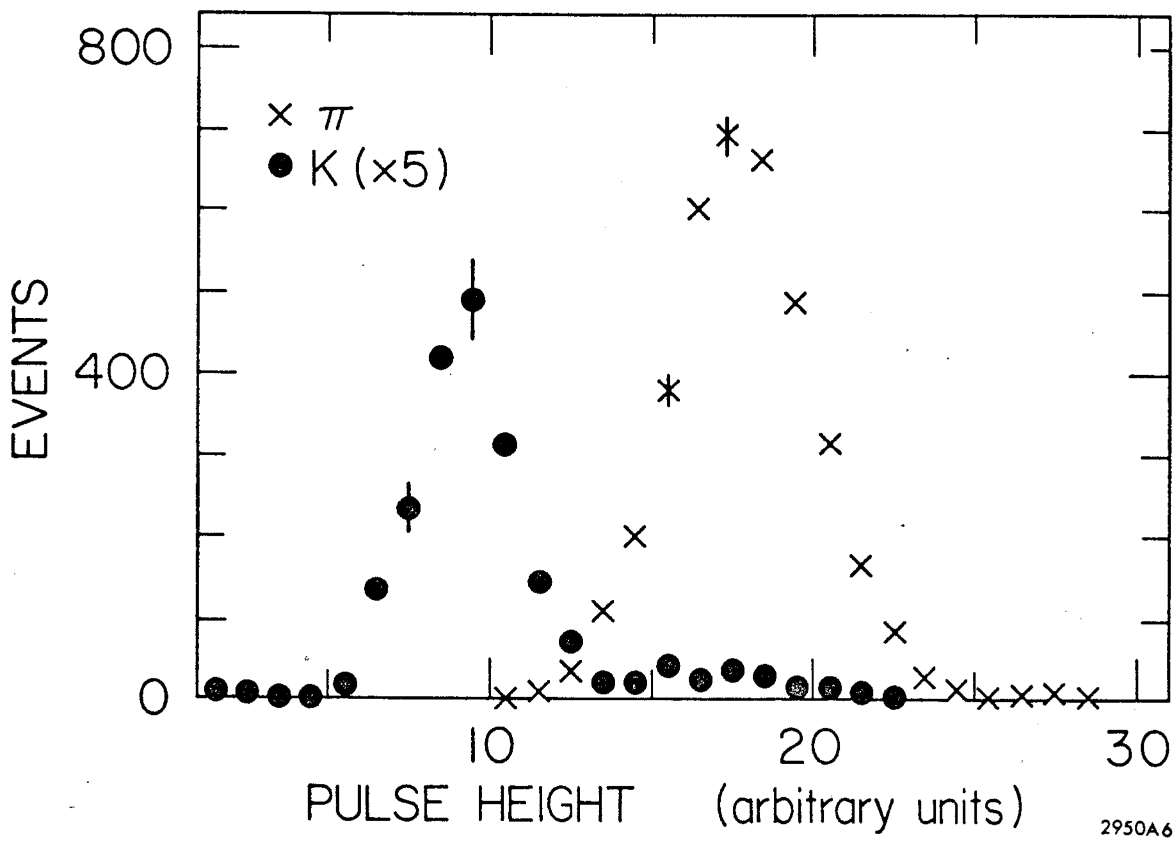

DISPLACEMENT (mm)
2.0
1.5
1.0
Freon 12
CO_2
N_2
DEVIATION (mrad)
1.0
0.5
0
Freon 12
CO_2
N_2
0
1
2
3
4
PRESSURE (atm at 20° C)
2950A2

Fig. 8



800
400
0
EVENTS
× π
● K (×5)
10
20
30
PULSE HEIGHT (arbitrary units)
2950A6

Fig. 9

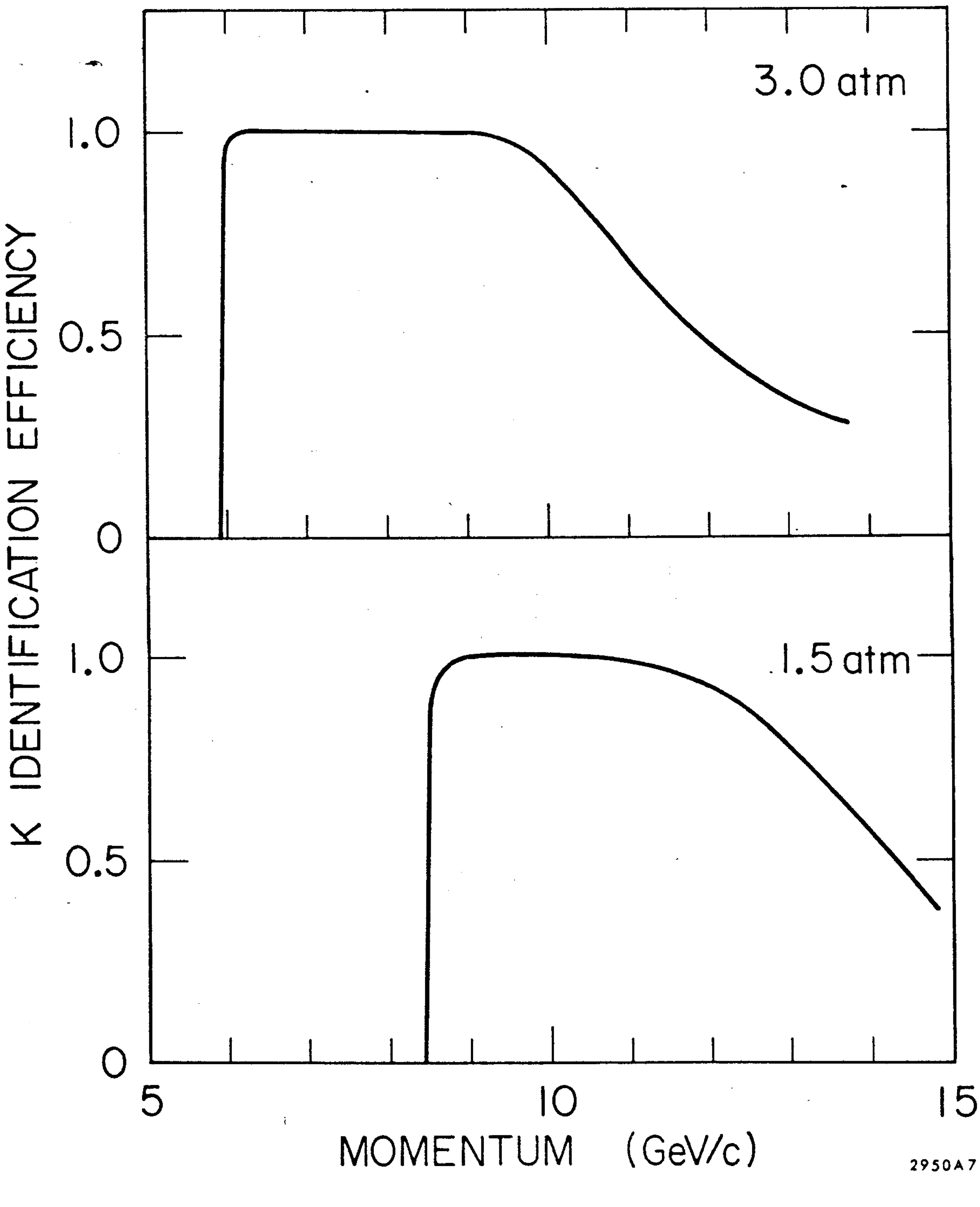

3.0 atm
1.5 atm
K IDENTIFICATION EFFICIENCY
1.0
0.5
0
1.0
0.5
0
5
10
15
MOMENTUM (GeV/c)
2950A7

Fig. 10