Incident Report

HEALTH AND SAFETY EXECUTIVE

RESEARCH AND LABORATORY SERVICES DIVISION

Broad Lane, Sheffield S3 7HQ

The Hillsborough Incident 15 April 1989: An Investigation into Various Technical Aspects prepared for the Court of Inquiry

by

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IR/L/ME/MM/89/1

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1 INTRODUCTION

1.1 Following an incident on 15 April 1989, I visited Sheffield Wednesday Football Club's (SWFC) Hillsborough Stadium on 16 April 1989 at the request of Mr M S Nattrass, Area Director of South Yorkshire and Humberside Factory and Agricultural Inspectorate of the Health and Safety Executive (HSE). Subsequently I was appointed to head the HSE team investigating the incident following correspondence between the Court of Inquiry and the Deputy Director General of the HSE, Mr J D G Hammer.

1.2 This report contains details of examinations performed on site and in the laboratory. The work was carried out by me and by other staff of HSE working on my instructions and under my general supervision.

2 SURVEY OF PENS 3 AND 4

2.1 Using the drawings prepared by Ralph Brade & Associates, 1340/02 and 03, and comparing with figures stated in the Guide to Safety at Sports Grounds 1986, the following assessments were made.

2.2 The heights of crush barriers should be 1.02m to 1.12m with a preferred height of 1.1m. In Pen 3 four out of five barriers do not conform. In Pen 4 six out of nine barriers do not conform.

2.3 The alignment of gaps in successive rows of barriers on a terrace should form an angle of less than 60° to the barriers. Of the four 'paths of gaps' in Pen 3, two do not conform. Of the eleven 'paths of gaps' in Pen 4, one does not conform.

2.4 Gaps in the line of crush barriers should be at least 1.1m and not more than 1.4m in width. In Pen 3, four out of five gaps do not conform. In Pen 4, nine out of ten gaps do not conform.

2.5 For a terrace slope of approximately 14° the interpolated maximum horizontal distance between barriers is 3.9m. In Pen 3 only one spacing does not conform. In Pen 4 only two spacings do not conform.

2.6 Gates or other access points should have a minimum width of 1.1m. The gate to Pen 3 has a clearance width of 0.81 to 0.82m and the gate to Pen 4 has a clearance width of 0.77 to 0.79m. Both therefore do not conform.

2.7 The aim is for every spectator on the terraces to be within 12m of a gangway or exit. If the perimeter gaps are not considered as exits then approximately 40% of the spectators in Pens 3 and 4 will not be within 12 metres of an exit.

3 EXAMINATION OF THE BROKEN BARRIER - NO 124A

3.1 Barrier 124A was examined by HSE staff at Hillsborough Football Ground on 17 April 1989. Various parts of this barrier and 3 core samples of concrete were taken to the Sheffield Laboratory on 24 April 1989 for detailed assessment.

3.2 It was deduced that barrier 124A had consisted of a continuous horizontal tube, made from wrought iron, and four vertical supports each made from two lengths of steel angle section joined at the top by a steel gusset

plate. Five of the eight support feet were reinforced by additional angle sections which appeared to be let into the concrete terrace steps. Two of the rear support legs were braced by further angle sections. A reconstruction is shown in Figure 1. The barrier had failed apparently by partial collapse and fracture of supports 3 and 4, and by fracture of the horizontal tube at supports 2, 3 and 4, as shown in Figure 2. The portion of the tube which had been located between supports 2 and 3 had been bent uniformly to give a maximum permanent deflection of 133mm at midspan. The portion of the tube which had been located between supports 3 and 4 had been bent uniformly to give a maximum permanent deflection of 200mm at midspan. Barrier 124A was estimated to be approximately 60 years old, although it had received a number of modifications during its lifetime.

3.3 The tensile strength of the wrought iron tube material was measured at 365MPa (23.6 tonf/in^2) with an estimated elastic limit of 150MPa (9.7 tonf/in^2). The tensile strength of the mild steel angle used for the supports was measured at 360MPa (23.3 tonf/in^2) with a yield stress of 288MPa (18.6 tonf/in^2).

3.4 The tube fractures had occurred in areas which had been located under the metal straps designed to retain the tube. At these locations the tubes had not been painted, and the tube wall thicknesses, nominally 4.5mm, had been reduced significantly by corrosion. At the fracture surface corresponding to support 2 the residual thickness of the tube wall was found to vary from 0.4mm to 4.4mm around the circumference. Similarly at the fracture surface corresponding to support 3 the wall thickness was in the range 1.6mm to 4.5mm. At support 4, however, there was evidence that the tube wall had been perforated by corrosion at two locations producing holes which would have been approximately 10mm and 20mm in diameter before the collapse. Elsewhere, around the fracture corresponding to support 4, the wall thickness was in the range 1.1mm to 4.5mm.

3.5 In general the appearance of the tube fractures was typical of wrought iron which had fractured in a single-stage bending/tensile mode. Fracture of the tube adjacent to support 3 appeared to have initiated on the uphill side of the barrier at a position approximately 90° from top dead centre. The other tube fractures had suffered some post-failure damage and the origins were not readily identifiable.

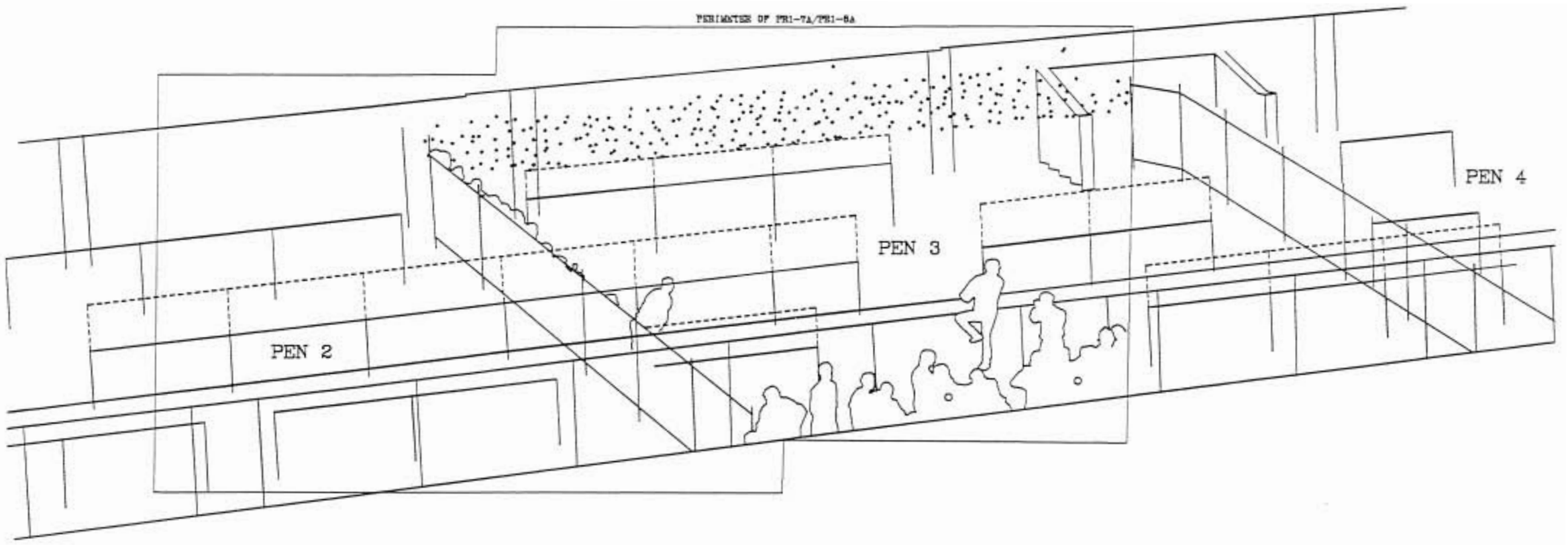
3.6 The failed supports had been corroded, particularly at the junction with the concrete steps and/or reinforcement angles. In these regions residual thicknesses in the range 3.1mm - 5.9mm were measured compared with a nominal thickness of 6.3mm.

3.7 Large amounts of metal had been lost by corrosion from supports 3 and 4 near, what would have been, the original junctions between the support feet and the terrace. In one case (rear leg support 4) a ligament of metal 8mm wide was all that remained of the original angle section (50 x 50mm). On two of the four feet this region had been reinforced by the addition of a length of metal angle which had been bolted on top of the original angle from which the support had been made. The height of the concrete terrace had been raised at some stage and this had concealed the previous corrosion damage. The appearance of the concrete cores, extracted from near the support feet, was consistent with this observation.

3.8 Calculations to establish the force required to cause the collapse of barrier 124A, and the collapse sequence are currently underway.

DIGITISED DRAWING OF PHOTOGRAPHS PR1-7A & PR1-8A
SUPERIMPOSED ON
DIGITISED DRAWING OF PHOTOGRAPHS PR10A-2 TO PR10A-5, SCALED ETC TO MATCH

PEN 3
OCCUPANTS OF ROW 4 ONLY SHOWN



HEADCOUNT - 268

PHOTOGRAPHS TAKEN 15.03

FIG.6

HSE SHEET PR17BC/PP1131

3.9 One of the remaining barriers in the Central Pen will be tested to destruction in the near future in order to validate the calculations.

4 INVESTIGATION OF TURNSTILES AT THE LEPPINGS LANE END

4.1 On 25 April 1989 HSE staff made tests on turnstiles at the Leppings Lane end of the stadium to investigate how the application of a force to a 'gate' affected the release of a turnstile. On 28 April 1989 tests were made to assess the accuracy of the computerised system for counting and recording the admissions through the turnstiles. Calculations were made to compare the average admission requirements of turnstiles serving the designated zones of the stadium. Counts of people passing through the turnstiles A to G were made from video recordings.

THE EFFECT OF A HORIZONTAL FORCE PUSHING ON THE 'GATE' OF A TURNSTILE

4.2 Turnstiles C to G appeared to be of the same pattern, whilst turnstiles A and B were of a different pattern. In the tests a known force measured by a load cell was applied to the 'gate' of the turnstile. Standard test weights were then placed gently on the pedal until the spindle was released. The tests showed that turnstiles C to G were likely to be more difficult to release than turnstiles A and B.

4.3 A turnstile operator having a weight of 750 N (12 stone) or less might have difficulty in releasing turnstiles in the group C to G if a force of 480 N (110 lbf) or more was applied to the 'gates'. The same operator might have difficulty in releasing turnstiles A and B if a force of 1340 N (300 lbf) or more was applied to the 'gates'.

THE ACCURACY OF THE COMPUTERISED SYSTEM FOR COUNTING AND RECORDING ADMISSIONS

4.4 Turnstiles were checked by rotating the 'gate' a known number of times and then recording the count measured in the control room. Tests of turnstiles in the group 9 to 16 indicated that they recorded the correct number of admissions.

4.5 Tests indicated that turnstiles A, B, C, D, E and F were likely to record the correct number of admissions. In my opinion turnstiles A to F, as a group, would indicate the correct number of admissions to within 1%.

4.6 Tests indicated that there could be a persistent error in the recorded number of admissions through turnstile G. It is my opinion that this turnstile might continuously register less than the correct number of admissions during a period of operation. It was concluded that the error was probably attributable to the roller of the roller-plunger micro-switch fitted to this turnstile only just making contact with the upper boss of each 'gate'.

4.7 Additional detectors were installed across each turnstile passageway at positions above the gates. Examination of these devices indicated that some appeared to be disconnected and in some cases the wiring had been cut.

AVERAGE ADMISSIONS REQUIRED FROM THE TURNSTILES

4.8 By reference to Eastwood & Partners Drawing No 8945/1A dated 16/4/87 figures were obtained for their estimates of the capacity of the various

zones of the stadium. On 28 April 1989 HSE staff surveyed the outside perimeter of the stadium to identify the numbers of turnstiles used by each zone. Six groups of turnstiles served the six zones of the stadium. These are summarised in the following Table.

Zone of ground	Capacity	Turnstile Designation	Number of Turnstiles	People per Turnstile
West Terrace Standing	10,100	A to G	7	1443
North Stand Seating	9,882	1 to 10	10	988
West Stand Seating	4,465	11 to 16	6	744
South Stand Covered Seating	5,567	23 to 32	10	557
Spion Kop Standing	21,000	37 to 78	42	500
South Stand Uncovered Seating	3,310	(19 to 22 (33 to 36	8	413

4.9 The three groups of turnstiles having the highest average admission requirements were sited at the Leppings Lane end of the stadium, i.e. West Terrace Standing, North Stand Seating and West Stand Seating.

4.10 The average admission requirement of the turnstiles serving the West Terrace was the highest for any zone of the stadium. It was almost 3.5 times the lowest average admission requirement which is that for the South Stand Uncovered Seating and approximately 2.9 times the average admission requirement for Spion Kop.

COUNTING OF PEOPLE ADMITTED THROUGH TURNSTILES A TO G FROM VIDEO RECORDINGS

4.11 The video recordings used for the counting were delivered by West Midlands Police and were identified RJH2/E/Part 1, RJH2/E/Part 2, RJH2/E/Part 3, RJH2/F/Part 1, RJH2/F/Part 2, RJH2/F/Part 3. They showed the exits of turnstile booths A to G from approximately 12.55pm until 3.10pm on 15 April 1989. The continuous reference timings on the video recordings were with respect to the start of each recording, and not to British Summer Time (BST), but the relationship between the recording times and BST was determined from the observation of specific events in conjunction with West Midlands Police.

4.12 The method of counting used a micro-computer and specially developed program. A push-button was depressed every time a person was seen to emerge from an identified turnstile booth and the computer recorded the signal and its time. People emerging from turnstiles A and B were counted together because it was not always possible to differentiate between people emerging from these individual turnstiles.

4.13 The analysed data provided the relationship between the total number of people seen to emerge from turnstiles A to G and the time that they emerged. Figure 3 shows the total number of people that had emerged from turnstiles A to G over the relevant period of time.

4.14 I was informed by West Midlands Police that the turnstiles were opened before the start of the video recordings. At approximately 2.00pm just over 2,000 people had been counted and at 2.52pm this number had risen to approximately 6,000. **The final total count was 7247 people.**

The HSE count totals are summarised in the following table and compared with the SWFC computer print-out, taken on 15 April 1989, a copy of which was provided by West Midlands Police.

Turnstiles	HSE Count	SWFC Computer	Difference
A+B	1930	2004	-3.7%
C	1168	1206	-3.3%
D+E	2130	2196	-3.0%
F+G	2019	1632*	
TOTAL	7247	7038*	

* See paragraph 4.15

Turnstiles A and B, D and E and F and G had common exits, and hence the HSE and SWFC counts of these pairs of turnstiles have been combined.

4.15 Paragraph 4.6 of this report referred to a persistent error in the count obtained from turnstile G. This could result in no signal being sent to the computer even though a person had passed through the turnstile and could account for the discrepancy between the HSE count of 2019 for F plus G and the SWFC count of 1632.

4.16 Based on the assumption that the SWFC computer printout accurately recorded A to E and that the HSE count for F and G was less than the number who actually passed through F and G by a similar percentage to that obtained from A to E, the estimate for the total number of people that entered through turnstiles A to G is 7494. **In my opinion the actual** number is unlikely to have exceeded this value by more than 2%, i.e. 7644.

4.17 The rate at which people were counted through all the turnstiles is shown in Figure 4. The rate is for a 3 minute time period and shows the number of people per hour per turnstile. The rate increases rapidly at about 1.40pm and remains fairly constant between 2.05pm and 2.50pm. The mean rate for this period was about 660 people per turnstile per hour. Between 2.55pm and 3.00pm the rate increased and reached a maximum of about 1150 people per turnstile per hour. **This increased rate coincides with the** time Gate C was opened and could therefore be a result of decreased crowd pressure allowing a faster flow through the turnstiles.

4.18 If the rate of 660 had been maintained from 2.50pm onwards and no gates had been opened I estimate that it would have taken until about 3.40pm to bring the total number of people admitted through turnstiles A to G to 10,100. (The quoted capacity of the West Terrace standing area.)

ESTIMATE OF PEOPLE ADMITTED THROUGH 'GATE C' TAKEN FROM VIDEO RECORDINGS

5.1 A video recording labelled RJH2, delivered by West Midlands Police, was used for this analysis. It was copied by HSE photographers and a timing reference added. This copy was given the identification DF1/B. It showed the exits of turnstile booths A to G, Gate C and the general area on the West Stand side of these turnstiles. The continuous reference timings on the video recording related to the start of the tape and not to BST.

5.2 I was told by West Midlands Police that, following scrutiny of synchronised video recordings, the 'First Opening' of Gate C had occurred at approximately 14.48pm for a duration of ~30 seconds. I was also told that the 'Second Opening' of Gate C had started at ~14.52pm and finished at ~14.58pm, a duration of ~5½ minutes. A 'Third Opening' then occurred approximately one minute later when the gate was opened for approximately 8 minutes, sufficient to allow the entry of people in single file.

5.3 The method of assessment for the first two openings was to count the number of people passing a reference line for a period of 3 seconds and then to repeat this process at intervals of no greater than 15 seconds. At times when the rate was seen to vary rapidly, and for the whole of the 'First Opening', samples were taken more frequently than at 15 seconds. Figure 5 shows a graph of the number of people who entered through Gate C during the 'Second Opening'.

5.4 Estimates of accuracy are based on the possibility of missing one in ten of the people passing the reference line and the unlikelihood of missing more than two in ten.

5.5 The estimate of the number of people passing through Gate C during the 'Second Opening' based on the counting was 1800 but this should be regarded as a minimum. The best estimate would be 10% higher than 1800 i.e. about 2000, and in my opinion the actual number was unlikely to be greater than 2200.

5.6 The estimate of the number of people passing through Gate C during the 'First Opening' based on the counting was 130 but this should again be regarded as a minimum. The best estimate would be about 150, and in my opinion the actual number was unlikely to be greater than 180.

5.7 In the 'Third Opening' entries were much slower and a more accurate count was possible. A total of 90 were counted over a period of about 8 minutes, and in my opinion the actual number is unlikely to be greater than 100.

5.8 The following table is a summary of the estimates of both Gate C and turnstile A to G entries.

	HSE Count	Best Estimate	Maximum
First Opening Gate 'C'	130	150	180
Second Opening Gate 'C'	1800	2000	2200
Third Opening Gate 'C'	90	90	100
Turnstiles A to G	7247	7494	7644
TOTAL	9267	9734	10124

6 ESTIMATES OF THE CAPACITY OF THE WEST TERRACE

6.1 Drawing 1340/02A by Ralph Brade & Associates gives dimensions of Pens 3 and 4. Both Pens are shown as being 13.1m deep; Pen 3 is shown as being 14.350m wide and Pen 4 as being 14.645m wide. Based on these dimensions the areas are 188.0sq m and 191.8sq m.

6.2 The 1986 "Guide to Safety at Sports Grounds" states

"222 The extreme allowances for packing density are as follows:

a. 54 persons per 10 square metres when the terrace or viewing slope is in good condition (as set out in Chapter 8); and

b. 27 persons per 10 square metres when it materially deviates from the recommended guidlines, so as to constitute a possible hazard to individuals closely packed.

223 It may be necessary to interpolate between these figures where conditions fall between the two extremes. When ..."

6.3 If 54 people per 10 sq m is assumed as the allowable packing density for the West Terrace then the capacity of Pen 3 is 1015 and the capacity of Pen 4 is 1036 making a total of 2051 for the combined area.

6.5 The above calculations of capacity must therefore be assumed to be the maximum allowable capacity for this terrace area. The guide also gives examples of how this maximum capacity figure should be reduced when certain factors do not conform to the guide. Examples include

a) When the strength of crush barriers conform with the guidelines but the spacing of such barriers does not ...

b) When perimeter wall and crush barriers do not comply with strength or spacing requirements ...

c) When the positioning and width of gangways do not meet with the recommendations of Chapter 8. ...

6.6 It also states that when crush barriers do not meet the guidelines on strength .....but are well constructed, consideration may be given to allowing a lower packing density figure for the purpose of calculation.

ESTIMATES OF THE PACKING DENSITIES OF THE WEST TERRACE

7.1 West Midlands Police provided me with several albums of photographs, taken at Hillsborough on 15 April 1989, and several of these photographs were identified as providing material for the estimation of the numbers in Pen 3. Enlargements of photographs PR1/7A and PR1/8A were provided by West Midlands Police and these two photographs were analysed in detail. The time identification marking on both these photographs was 15.03.

7.2 The method of assessment entailed mounting the photographs on an electronic digitising table (Digitiser) and then marking the head of each person who was discernible. The Digitiser was linked to Computer Aided Drafting software and the act of marking each person on the photograph enabled the physical points on the photograph to be placed on an electronic grid which could then be displayed, under computer control, on a VDU screen or printed out on a graphics plotter. Actual counting of the number of those identified within a specified area was carried out automatically and no allowance was made for people that were hidden from view.

7.3 On 22 May 1989 photographs were taken of the empty pens by the same photographer, using the same camera and camera position. This enabled the boundaries and barrier locations in Pen 3 to be transposed onto the computer image of photographs taken on 15 April 1989. PR1/7A and PR1/8A covered about 75% of Pen 3 and it was assumed that the density of people in the remaining 25% was similar to that in the photographed area of Pen 3.

7.4 The estimated headcount for the whole of Pen 3 was 1408 people but areas at the front of the pen were masked by people outside the pen and heads in the area forward of the first barriers were generally less discernible than those behind the first barrier; 1408 is therefore a minimum estimate.

7.5 The results from a more detailed analysis, in which Pen 3 was sub-divided into four rows, bounded by the perimeter fence and the rows of crush barriers, are summarised in the Table overleaf. Figures 6, 7 and 8 illustrate the four rows and the numbers counted in rows 2, 3 and 4.

	Distance to Perimeter Fence		Width of row	Area of row	Capacity at 5.4 /sq m	Count	Packing Density /sq m
Back Wall	13.1m						
		4th Row	2.5m	35.88	194	268	7.5
3rd Barrier	10.6m						
		3rd Row	3.5m	50.23	271	382	7.6
2nd Barrier	7.1m						
		2nd Row	3.5m	50.23	271	409	8.1
1st Barrier	3.6m						
		1st Row	3.6m	51.66	279	(517)*	(10.0)*
Fence	0.0m						
TOTAL				188.0	1015	(1576)*	

* The number of spectators in the First Row was estimated from the plan area and an assumed packing density of 10.0 spectators per square meter. This density has been shown to be the maximum achievable without undue discomfort in tests at HSE's Sheffield Laboratories and has been corroborated by crowd density measurements in a selected area of the first row on photograph PR1/10A.

7.6 The estimated total for Pen 3 of 1576 is about 55% greater than the value calculated from a packing density of 5.4 people per square metre.

7.7 An estimate of the packing density in Pen 2 was also made from photograph PR1/7A. The area selected showed an overall packing density of 5.0 people per square metre.

ESTIMATE OF POSSIBLE NUMBERS OUTSIDE THE LEPPINGS LANE TURNSTILES

8.1 I was asked to make estimates of the number of people which could have gathered outside the turnstiles at Leppings Lane but within the outer perimeter gates. The area between the Leppings Lane End turnstiles and the outer perimeter gates is illustrated in Figure 9. The Figure is based on Ralph Brade & Associates' Drawing No 1340/04. The area has been sub-divided into three separate areas (Area 1, Area 2 and Area 3) and the approximate area of each has been calculated by scaling from the Drawing.

8.2 The number of people that could stand in the areas has been calculated using a packing density of 8 people per square metre and also using 10 people per square metre; the estimates are tabulated overleaf.

	Area in square metres	People at density of 8.0 per square m	People at density of 10.0 per square m
Area 1	65	520	650
Area 2	160	1280	1600
Area 3	260	2080	2600
Area 1+2	225	1800	2250
Area 1+2+3	485	3880	4850

9 SUMMARY

9.1 Various aspects of the crush barriers and perimeter gates in Pens 3 and 4 did not conform to the 'Guide to Safety at Sports Grounds 1986'.

9.2 The broken barrier, 124A, was made from wrought iron tube and mild steel angle section. Both tube and angle sections were heavily corroded in some areas. Calculations on the mechanism and force required to cause the collapse of the barrier are proceeding.

9.3 Examination of turnstiles A-G indicated that there was a fault in the counting mechanism of G. From assessment of video recordings, a best estimate of people entering through A-G was 7494, with a maximum of 7644.

9.4 If Gate C had not been opened, HSE estimate that it would have taken until about 3.40pm to admit 10,100 people through turnstiles A to G.

9.5 Assessment of the numbers of turnstiles allocated to various zones of the stadium revealed that the average admission requirement of the turnstiles serving the West Terrace was the highest for any zone of the stadium, and was approximately 2.9 times the requirement for Spion Kop.

9.6 HSE's best estimate of the total number of people who entered the ground during the three openings of Gate C was 2240 with a maximum of 2480.

9.7 HSE's best estimate of the total number of people who entered the ground through gate C (3 openings) and turnstiles A-G was 9734, with a maximum value of 10124.

9.8 Even if the strength and spacing of the barriers had complied with the 'Guide to Safety at Sports Grounds 1986', HSE's calculations showed that the capacity of Pens 3 and 4 was 1015 and 1036 respectively.

9.9 Since the barriers did not comply in all respects with the Guide (see 9.1) the estimated capacity of Pens 3 and 4 would be less than in 9.7 above.

9.10 The best estimate, based on photographs, of the number of people in Pen 3 at 15.03 was 1576.

9.11 The number of people who could be accommodated theoretically between the perimeter gates and the turnstiles at Leppings Lane was estimated to be 3880 and 4850 for crowd packing densities 8.0 and 10.0 per square metre respectively.

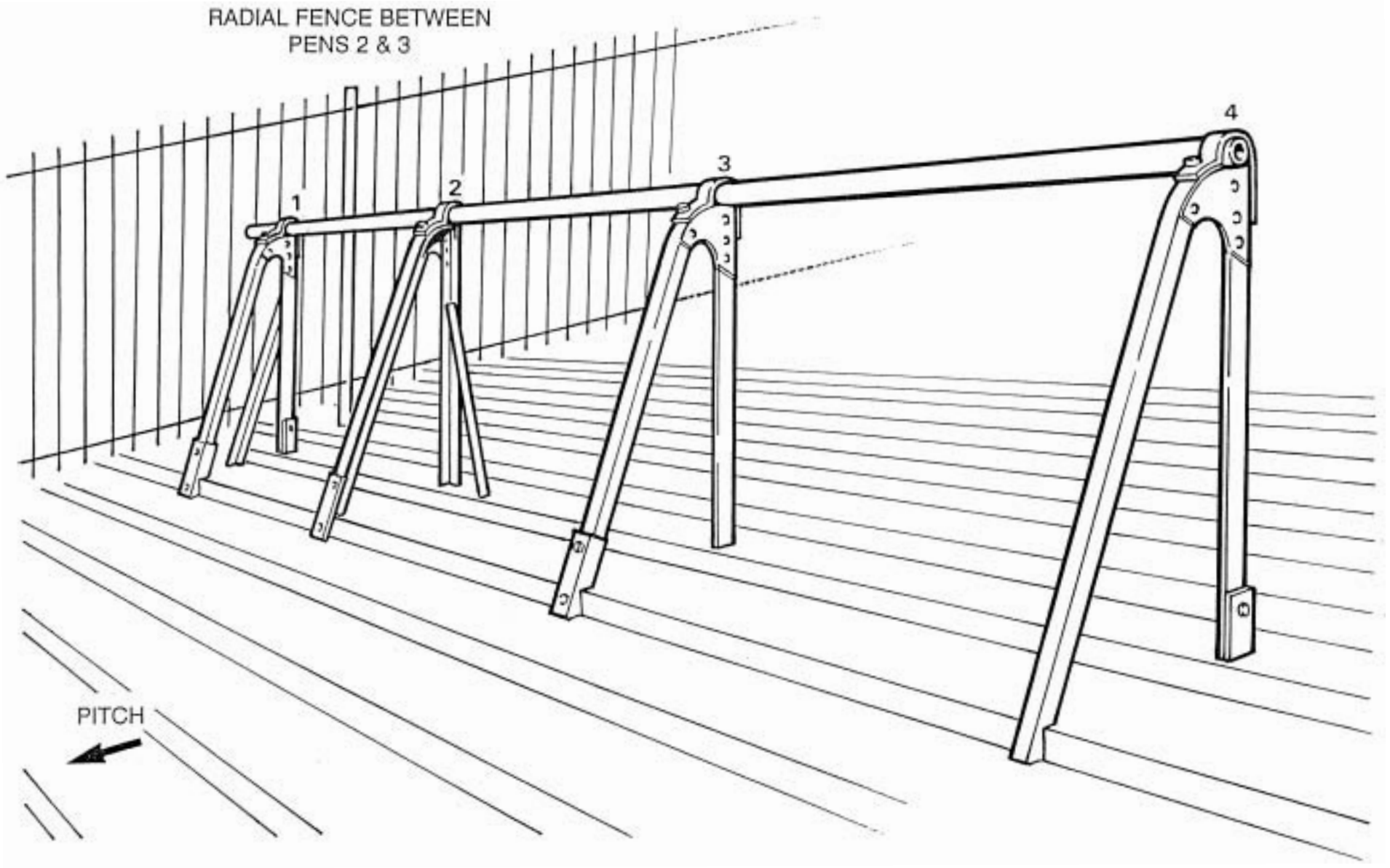


Fig. 1 - Reconstruction of Barrier 124A

Fig. 2 - Barrier 124A as photographed 17/ 4 /89

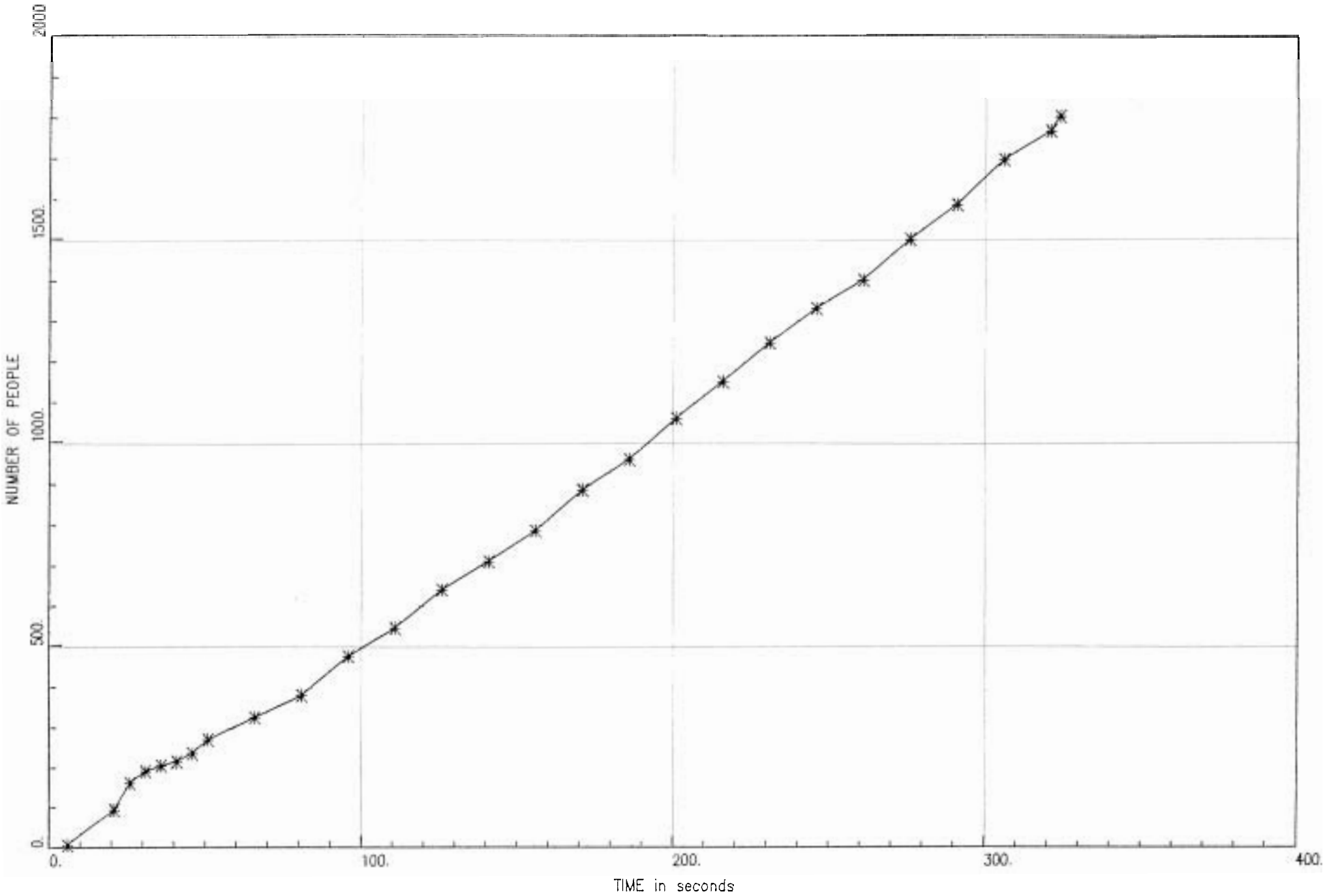
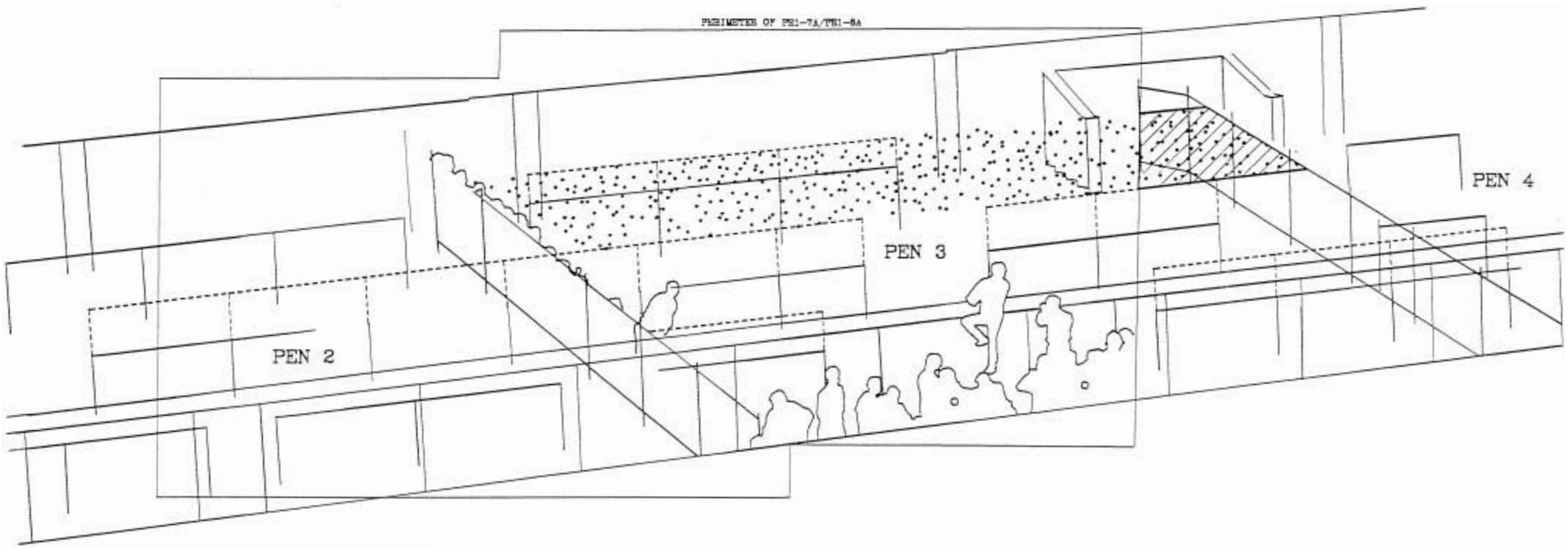


FIG. 5 NUMBER OF PEOPLE EMERGING FROM GATE 'C' AT THE "SECOND OPENING"

DIGITISED DRAWING OF PHOTOGRAPHS PR1-7A & PR1-8A
SUPERIMPOSED ON
DIGITISED DRAWING OF PHOTOGRAPHS PR10A-2 TO PR10A-5, SCALED ETC TO MATCH

PEN 3
OCCUPANTS OF ROW 3 ONLY SHOWN
(NB ESTIMATED CROWD - 60 OCCUPANTS - SHOWN HATCHED)



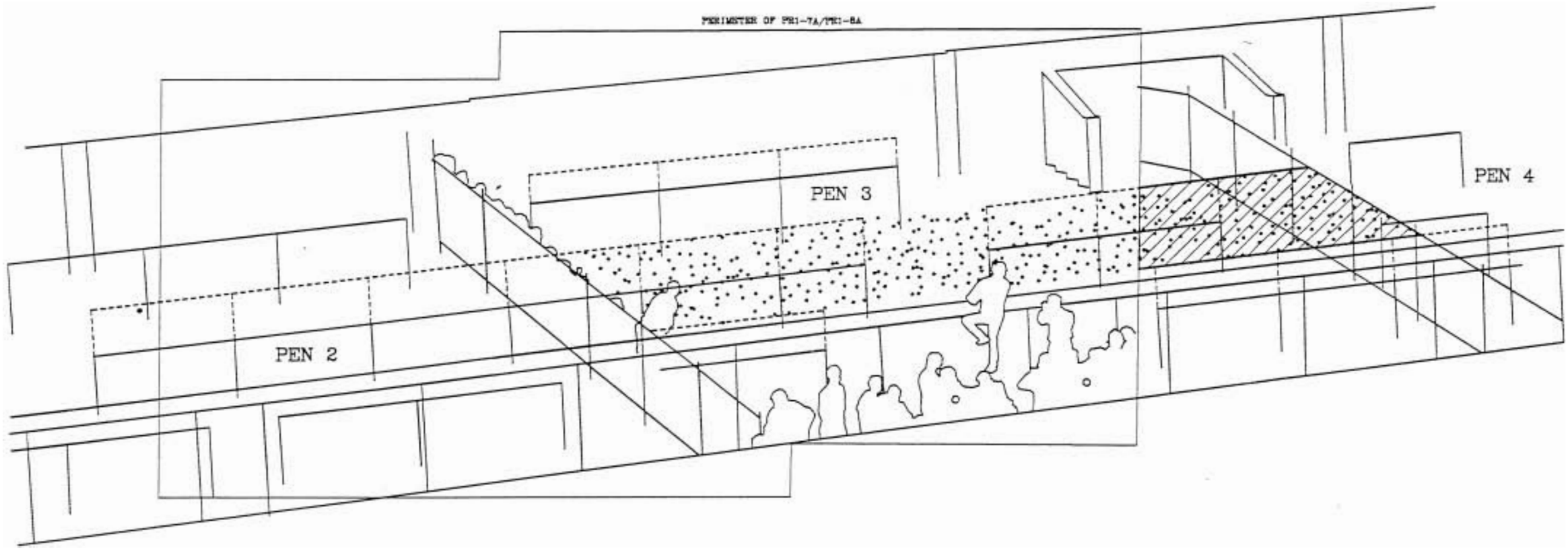
HEADCOUNT - 382

PHOTOGRAPHS TAKEN 15.03

FIG.7

DIGITISED DRAWING OF PHOTOGRAPHS PR1-7A & PR1-8A
SUPERIMPOSED ON
DIGITISED DRAWING OF PHOTOGRAPHS PR10A-2 TO PR10A-5, SCALED ETC TO MATCH

PEN 3
OCCUPANTS OF ROW 2 ONLY SHOWN
(NB ESTIMATED CROWD - 118 OCCUPANTS - SHOWN HATCHED)



HEADCOUNT - 409

PHOTOGRAPHS TAKEN 15.03

FIG.8

HSE SHEET PR178E/FP1131

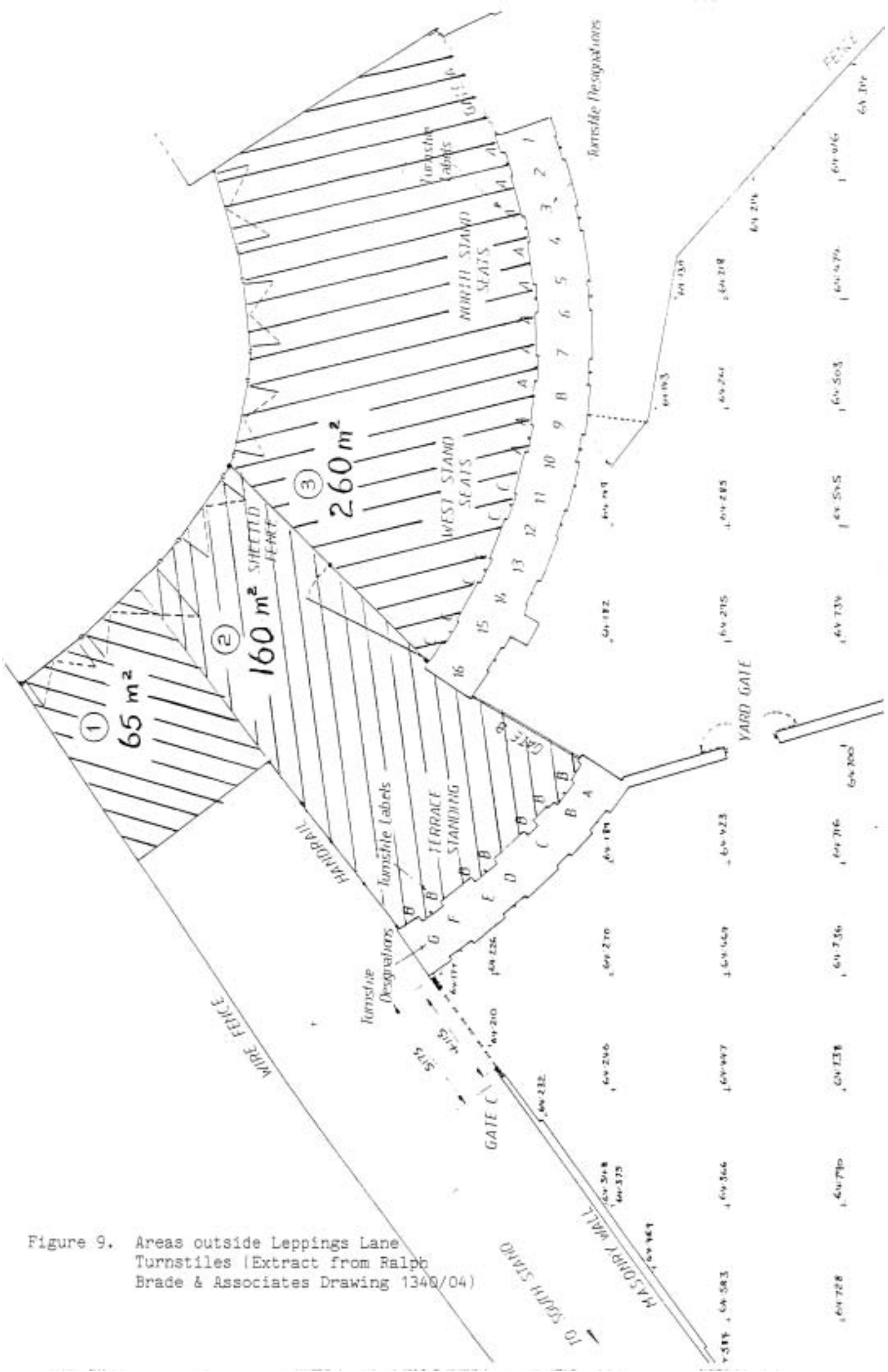


Figure 9. Areas outside Leppings Lane Turnstiles (Extract from Ralph Brade & Associates Drawing 1340/04)