

HEALTH AND SAFETY EXECUTIVE

RESEARCH AND LABORATORY SERVICES DIVISION

Broad Lane, Sheffield S3 7HQ

Examination of Crush Barriers from Pens 3 and 4

by

P F Heyes and J G Tattersall

IR/L/MM/89/11

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1 INTRODUCTION

Following the incident on 15 April 1989, staff of the Health and Safety Executive visited Hillsborough Football Ground. The crush barriers in Pens 3 and 4 (central pen), at the Leppings Lane end of the ground, were examined on 16 and 17 April 1989 and identified with a paint marker in accordance with a drawing supplied by Mr Paul Jackson, Sheffield Environmental Health Department. *On* each barrier the support locations were numbered sequentially from left to right when viewed from the pitch.

Barrier 124A appeared to have collapsed and a length of the horizontal tube had become detached. This detached length of tube had been found on the pitch in front of gate 3 in the perimeter fence at the Leppings Lane end on 16 April 1989 by Dr Nicholson. It was kept in a secure place by Club Officials and was placed in Pen 3 on 17 April 1989 so that it could be examined in conjunction with the rest of the barrier. Subsequently on 17 April 1989 it was taken to the Sheffield Laboratory of the Health and Safety Executive together with another small piece of tube found by Dr Nicholson on 17 April 1989 (see 2.1, page 3 below).

On 24 April 1989 the damaged parts of barrier 124A, consisting of two lengths of tube and two supports, were removed from Pen 3, under the supervision of the authors of this report, and taken to the Sheffield Laboratory of the Health and Safety Executive for metallurgical assessment. The remainder of barrier 124A was removed by Mr P F Heyes and HSE staff on 7 July 1989.

This report contains details of examinations performed both on site and in the laboratory. The work was carried out by the authors and by other staff of HSE working on their instruction and under their general supervision.

2 ON SITE EXAMINATION

2.1 BARRIER 124A

Barrier 124A was located on the seventh, eighth and ninth steps of Pen 3 adjacent to Pen 2. The overall length of this barrier before collapse was estimated to be 7.5m including a tube overhang of 0.6m near the radial fence adjacent to Pen 2. The horizontal distance from this barrier to the perimeter fence at the front of Pen 3 was approximately 3.5m, and the distance of the tube end from the radial fence, separating Pens 2 and 3, was 28mm. There were no other barriers between barrier 124A and the perimeter fence. A sketch of this barrier, showing our opinion of its appearance before the incident, is shown in Figure 1.

The evidence suggested that, prior to the collapse, barrier 124A had consisted of four vertical supports with a horizontal tube between them. HSE staff numbered the supports 1,2,3 and 4, beginning at the end nearer Pen 2.

Each vertical support had consisted of two lengths of 52mm wide metal angle, having a thickness of 6mm, inclined at an angle of 20 degrees to one another. During manufacture each front support leg had been curved near the top to form a horizontal surface and had been joined to the rear support leg by a triangular gusset plate. The latter had been rivetted to the two lengths of metal angle. The horizontal tube had been made from hollow circular section metal with an outside diameter of 60mm. An inverted U-shaped strap, approximately 50mm wide, had been bolted to the top of each support, and this was presumably intended to retain the horizontal tube.

Figure 2 shows barrier 124A viewed from the pitch as it appeared on the morning of 17 April 1989. The detached length of tube had a transverse fracture at either end. One of these fractures matched the fracture on the length of tube in contact with support 2 and the other matched the fracture on the length of tube in contact with support 3. Hence it was possible to locate this detached length of tube in the correct position between supports 2 and 3. This detached length of tube had been bent symmetrically about its mid-point where the maximum deflection was 133mm.

Support 4, shown in the foreground of Figure 1, had been moved forward and twisted towards the front left-hand corner of Pen 3, viewed from the pitch. The lower portion of the front leg had remained straight, although by comparison with the front legs of other barriers, it appeared to have moved forward through an angle of 25 degrees approximately. In so doing the front leg had broken away from the edge of the concrete step in which it had been supported. Several pieces of detached concrete were observed nearby, two of which matched the fracture on the step, shown in Figure 3. The upper portion of the front leg had suffered localised bending and it had been twisted inwards with respect to the other supports on this barrier.

The rear leg of support 4 had been deformed and kinked at the lower end near the junction with a piece of reinforcing steel angle which had been bolted on top of the original angle section. The latter had been thinned by corrosion in the area where this deformation had occurred. The rear leg also exhibited localised deformation and cracking in the vicinity of the lowest gusset plate attachment hole. The gusset plate appeared to be relatively undeformed but had been moved inwards towards the other supports. The tube retaining strap appeared to be intact and still in position.

Support 3 had been deformed extensively and flattened so that it was almost horizontal. The general direction of deformation was towards the front left-hand corner of the pen, viewed from the pitch. At its lower end the front leg had been deformed adjacent to a piece of reinforcing angle, but both the latter and the surrounding concrete were undisturbed. The rear leg had been bent forward and the majority of the deformation had occurred at the junction with the concrete step. The step itself was intact. The gusset plate was undeformed but it had been torn from the upper part of the rear leg and moved forward. The strap retaining the tube at support 3 had been straightened partially but the tube appeared to be captive at this position. A transverse fracture of the tube, in the vicinity of some tube wall corrosion, was visible under the strap.

The length of tube in contact with support 3 had been bent by 200mm at midspan and it had a ragged fracture in a corroded region near the end further from support 3, i.e. the free end. The latter had presumably been located under the strap on support 4 before collapse occurred. The fracture in the tube corresponding with support 4 was partly transverse and partly longitudinal, the original manufactured end being deformed but not fractured. At some stage the tube had also been partially crushed at this location.

During the visit on 17 April, a small piece of metal, roughly semi-circular in section, was found in Pen 3 by Dr C Nicholson amongst the debris near gate 3 in the perimeter fence. The fracture on this small piece matched that at the end of the tube corresponding to support 4. This end of the tube had apparently moved a distance of 1.4m in the horizontal plane before coming to rest on the steps. In total, the collapsed part of barrier 124A occupied an area measuring 4m along the terrace and 1.6m down the terrace in Pen 3.

Supports 1 and 2 were free from damage and the length of tube between them had not been deformed significantly. This length of tube contained two circumferential welds positioned as follows when viewed from the pitch side: one approximately 0.2m left from the strap on support 2; the other 0.05m right from the strap on support 1. The tube had fractured transversely under the strap on support 2 and a smaller diameter tube insert was observed protruding a distance of 25mm from this fracture. There was evidence of considerable corrosion of the original tube under this strap. The tube insert appeared to be approximately 150mm in total length. The strap on support 2 had been welded to the tube on the left side only. This was the only location on barrier 124A where a strap had been welded to the tube.

Support 1 had a piece of reinforcing angle attached to each foot and the rear leg had been braced by an additional piece of angle acting as an outrigger. Support 2 had a piece of reinforcing angle attached to the front foot only with an outrigger on the rear leg.

2.2 OTHER BARRIERS IN PENS 3 AND 4

The remaining barriers in Pen 3 and those in Pen 4 were examined. The layout of all the barriers in Pens 3 and 4 is shown schematically in Figure 4. On each barrier the supports were numbered sequentially from left to right as viewed from the pitch. Several barriers had been fabricated with rectangular hollow section supports and these appeared to be somewhat newer than the rest. Most of the old-style barriers had been modified in some way, for example by reinforcing of the support legs and welding of the horizontal tubes. Corrosion was evident at all joints and intersections, and rust "jacking" had occurred at many of the gusset plate/support leg junctions.

Most of the horizontal tubes on the older barriers were open-ended and in two cases (barrier 125 near support 1 and barrier 128 near support 1) holes in the tube wall, caused by corrosion under the support strap, were clearly visible. An example of this is shown arrowed in Figure 5 which depicts the end of barrier 125 adjacent to barrier 124A in Pen 3. The hole is approximately 25mm in diameter and its centre is 60mm from the end of the tube.

2.3 EXCAVATION OF BARRIER 124A SUPPORTS 3 AND 4 ON 24 APRIL 1989

It was agreed by the Inquiry that supports 3 and 4 on barrier 124A could be removed for laboratory examination. Three cylindrical cores, measuring 0.1m in diameter and 0.4m in length, were cut from the concrete steps at positions specified by Mr C Pertee, a Principal Specialist Inspector in the Technology Division of HSE, before excavation of the supports commenced. These cores, from steps 7, 8 and 9, were identified by the letters P, Q and U respectively. After cutting, core P was found to contain a piece of the front foot from support 4 and core U was found to contain a piece of the rear foot of support 3.

It became apparent during excavation that each support leg had been flattened and shaped to form a foot which had been positioned horizontally in the ground and bolted to a base plate. The supports were freed by unscrewing, or grinding off the nuts in contact with the feet of the supports. In all cases the boundary between the support and the concrete was marked using yellow paint.

When the front foot of support 4 was exposed, considerable thinning and loss of metal was observed in the vicinity of the bend between the upright and the foot. This area was further weakened during core drilling and the remaining ligament of metal, approximately 5mm wide and 0.8mm in thickness, became detached during removal of the support. Part of the front foot was found to be in contact with a reinforcing wire in the concrete and a length of this wire was removed for possible future examination.

The pieces of reinforcing angle, noted previously on the rear leg of support 4 and the front leg of support 3, were observed to extend below the surface of the concrete to the bend at the start of the foot.

The length of tube remaining in contact with support 3 slipped out of the strap during lifting of the support. It was apparent that this length of tube had not been fixed intentionally to the strap and it had been held temporarily in position by accumulated rust and debris only.

2.4 REMOVAL OF INTACT PART OF BARRIER 124A ON 7 JULY 1989

The feet of supports 1 and 2 were excavated to a depth of 50mm approximately and subsequently cut using an angle grinder. This permitted both supports, and the length of tube between them, to be removed in one piece.

3 LABORATORY ASSESSMENT

3.1 ITEMS RECEIVED

The following items were taken from Pen 3 on 17 April 1989 and transported to HSE's Sheffield Laboratory:

Exhibit No	Description
CEN/1	A piece of metal tube found by Dr Nicholson in Pen 3 near gate 3 in the perimeter fence

CEN/2 A length of metal tube found by Dr Nicholson on the pitch in front of gate 3 in the perimeter fence

The following items were taken from Pen 3 on 24 April 1989 and transported to HSE's Sheffield Laboratory:

- PFH/1 A length of metal tube, one end of which had been located in the strap of support 3 on barrier 124A
- PFH/2 Support 4 from barrier 124A
- PFH/3 Support 3 from barrier 124A
- PFH/4 Items from the front foot of support 4 on barrier 124A comprising: two nuts; a slice of metal from the foot and a piece of reinforcing wire.
- PFH/5 Two nuts from the rear foot of support 4 on barrier 124A
- PFH/6 Two pieces of concrete found by Mr Heyes near the front foot of support 4 on barrier 124A
- PFH/7 A concrete core, identified as "P", cut from step 7 in Pen 3 near the front foot of support 4 on barrier 124A
- PFH/8 A concrete core, identified as "Q", cut from step 8 in Pen 3 between the feet of support 4 on barrier 124A
- PFH/9 A concrete core, identified as "U", cut from step 9 in Pen 3 near the rear leg of support 3 on barrier 124A

The following item was removed from Pen 3 on 7 July 1989 and transported to HSE's Sheffield Laboratory:

- PFH/10 A piece of barrier 124A consisting of supports 1 and 2 and the length of tube between them.

Exhibits PFH/4,5 and 6 were not included in the present examination.

3.2 CONCRETE CORES

The three cores are shown schematically in Figure 6. They were taken at different positions along the terrace but, for convenience, they are shown here in the same plane. Core P was extracted in three pieces: a cylindrical upper piece, approximately 85mm in length, which was composed of an upper layer (27mm in thickness) containing relatively fine aggregate, typically a few millimetres in section and a lower layer (52mm in thickness) containing coarser aggregate, typically 5-10mm in section; an irregular shaped intermediate piece, with a maximum length of 120mm, which contained the coarsest aggregate, typically 20-30mm in section, and bore an impression of a section of barrier support foot; a cylindrical lower layer, 180mm in length also containing the coarsest aggregate (20-30mm in section)

Core Q was extracted in two cylindrical pieces: an upper piece, approximately 138mm in length, which was composed of an upper layer (23mm in thickness) containing relatively fine aggregate, typically a few

millimetres in section, a middle layer (65mm in thickness) containing coarser aggregate, typically 5-10mm in section, and lower a layer, 50mm in thickness, of loosely bound coarse material; a lower piece, 245mm in length containing the coarsest aggregate, typically 20-30mm in section.

Core U was extracted in two cylindrical pieces: an upper piece, approximately 141mm in length, which was composed of an upper layer (26mm in thickness) containing relatively fine aggregate, typically a few millimetres in section and a lower layer (115mm in thickness) containing coarser aggregate, typically 5-10mm in section; a lower piece, 200mm in length, containing the coarsest aggregate, typically 20-30mm in section. The lower layer contained a slice through a barrier support foot consisting of, in descending order, a nut, a piece of foot, a piece of bolt and a piece of base-plate.

3.3 LENGTHS OF TUBE FROM BARRIER 124A

3.3.1 Visual examination

The two detached lengths of tube (CEN/2 and PFH/1) are shown in Figures 7 and 8 respectively. The length of tube which had been between supports 3 and 4 was designated "tube 3/4" by the authors and the length of tube which had been between supports 2 and 3 was designated "tube 2/3". Each length measured 2.3m and had an external diameter of 60mm. The length of tube between supports 1 and 2 was designated "tube 1/2" and its overall length was approximately 3m. The outside diameter of this tube was 60mm.

Bottom dead centre of tube 2/3 and 3/4 was located by examination of paint runs and an accumulation of dried paint. It was deduced that both lengths of tube had been deformed towards the pitch in a horizontal plane.

Visual examination of the fractures indicated that in general the failure of the tube had occurred in a fibrous, ductile manner. On the two matching fractures which had been coincident with support 3 there was however a region of bright crystalline fracture, shown arrowed in Figure 9, consistent with a more brittle failure mode. This crystalline fracture had occurred where the remaining wall thickness of the tube was at a maximum.

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 at right angles to top dead centre. The other tube fractures had suffered some post-failure damage and the origins were not readily identifiable.

At all the fracture positions much of the wall thickness of the tube had been reduced, mainly by external corrosion. The corrosion had occurred under the locating straps in areas, approximately 65mm wide, which were unpainted. The end of the tube at the position of support 4 had been open to the environment and additional corrosion at the internal surface of the tube had occurred. This had resulted in the formation of two holes through the wall approximately 10 and 20 mm in diameter under the strap. One of these holes, shown arrowed in Figure 10, appeared to have initiated the fracture and led to the detachment of the small piece of tube (arrowed in Figure 11) found on the steps, item CEN/1. These holes

were location at the 4 o'clock and 8 o'clock positions and their centres would have been approximately 50mm from the open end of the tube at support 4 before failure.

The extent of corrosion of tube 1/2 under the strap at support 2 was disclosed when the strap was removed (Figure 12). Tube 1/2 was removed subsequently from supports 1 and 2 to permit closer examination. This revealed that two pieces of tube had been joined beneath support 2 by a part circumferential weld which also served to join the strap to the tube at this support. A 150mm long tubular insert (arrowed in Figure 12), with an outside diameter of 49mm and a wall thickness of 5mm, was located inside the main tube at a position corresponding with support 2. This reinforcement was retained by means of a tack weld on the inside of the main tube between support 2 and the adjacent circumferential weld in the main tube, which had been noted on site. Hence, neglecting the insert, the tube between supports 1 and 2 apparently consisted of three pieces joined by: a circumferential near support 1; a circumferential weld near support 2; a part circumferential weld beneath support 2.

An oval hole, shown in Figure 13 and measuring 35 x 15mm, was revealed in the tube under the strap on support 1, at the 4 o'clock position when viewed from the end nearer support 1. This hole had apparently been formed by external corrosion of the tube under the strap.

A rolled-up newspaper was found inside tube 2/3. This was part of a copy of the "Yorkshire Telegraph & Star", dated Saturday 24 October 1931. A piece of another newspaper, "The Star" dated Saturday 26 September 1959, was found in tube 1/2. Various other items of debris were found elsewhere in the lengths of tube.

3.3.2 Tube wall thickness measurements

The wall thickness of the tube at the fracture positions was measured at various locations around the circumference. The thickness range recorded at each fracture is shown below:

Support 2	0.4 to 4.4 mm
Support 3	1.6 to 4.5 mm
Support 4	1.1 to 4.5 mm (ignoring the edges of the holes)

Measurements taken along the lengths of tube using an ultrasonic instrument showed that the wall thickness remote from the fractures was in the range 3.2 to 4.9 mm. Corrosion was confined to regions about 70-75mm wide, centred on the support straps, and there were no areas of pronounced thinning elsewhere. The ultrasonic thickness reading was 5.0mm throughout the length of tube between the circumferential welds on tube 1/2.

3.3.3 Microstructural examination

A transverse ring section was cut from tube 3/4 at a distance of 65mm from the fracture corresponding to support 3. Microexamination showed that the tube had been manufactured from wrought iron and that it contained a longitudinal, forged lap weld.

A microsection of a sample of paint removed from a similar position showed that the paint consisted of 13 coats plus an initial metal loaded primer coat. The total thickness of these coats was approximately 0.5 mm. Various microsections from tube 1/2 indicated that this length of tube consisted of both wrought iron and low carbon steel as follows: the length between the end nearer Pen 2 and the circumferential weld near support 1 was wrought iron; the length between the circumferential welds was low carbon steel; the length between the circumferential weld near support 2 and the part circumferential weld beneath the strap on support 2 was low carbon steel; the length between the part circumferential weld beneath the strap on support 2 and the fracture was wrought iron.

3.3.4 Tensile tests

Two longitudinal tensile test pieces, identified as T343/1 and T343/2, were machined from tube 3/4 near the end corresponding to support 3. Two further longitudinal tensile test pieces, identified as T1221 and T1222, were machined from the central portion (low carbon steel) of tube 1/2. In order to minimize the effects of previous work hardening, all test pieces were taken as near as possible to what would have been the neutral axis during bending.

These test pieces were tested in accordance with BS 18:1987 "Method for tensile testing of metals (including aerospace materials)", and the following results were obtained:

	Elastic Limit (limit of proportionality)	Rp0.2	Rp0.5	Rm	A%
T343/1	142 MPa 9.1 tsi	255 MPa 16.6 tsi	271 MPa 17.5 tsi	371 MPa 24.0 tsi	17
T343/2	159 MPa 10.3 tsi	261 MPa 16.9 tsi	269 MPa 17.4 tsi	358 MPa 23.2 tsi	17
T1221	282 MPa 18.3 tsi	342 MPa 22.2 tsi	360 MPa 23.3 tsi	488 MPa 31.6 tsi	27
T1222	301 MPa 19.5 tsi	356 MPa 23.1 tsi	372 MPa 24.1 tsi	499 MPa 32.2 tsi	27

None of these test pieces exhibited a yield phenomenon.

3.3.5 Hardness testing

Hardness tests were carried out on the ring microsection from tube 3/4 and on the microsections from tube 1/2 in accordance with BS 427:Part 1:1961(1981) "Method for Vickers hardness test: Testing of metals". The following results were obtained:

Tube 3/4, wrought iron	142 - 145 HV 10
Tube 1/2, low carbon steel	146 - 152 HV 10
Tube 1/2, weld metal at support 2	161 - 171 HV 10

3.4 SUPPORTS FROM BARRIER 124A

3.4.1 Visual examination

Supports 1 and 2 had not been deformed. Supports 3 and 4 are shown after excavation in Figures 14 and 15 respectively. Although the extent of the deformation of supports 3 and 4 was noted on site (see section 2.1 of this report), a number of additional features became apparent in the laboratory.

The legs of supports 3 and 4 had been corroded, particularly at the junctions with the concrete step and/or additional reinforcing angles. At these locations the residual thickness was in the range 3.1mm to 5.9mm, compared with a nominal thickness of 6.3mm elsewhere. A considerable amount of metal had been lost by corrosion from the sub-surface region of the supports. For example, on the rear leg of support 4, a ligament of metal 8mm wide and 2mm in thickness was all that remained of the original nominal 50 x 50mm angle section at a distance of 150mm below the surface.

The front leg of support 3 and the rear leg of support 4 had been reinforced with additional sections of steel angle. Both these reinforcements spanned areas of corrosion on the sub-surface region of the supports. In general on the collapsed supports, the most severe sub-surface corrosion was located at a distance which varied from 50mm to 170mm below the surface depending on which step the barrier had been located.

3.4.2 Dimensions

In general, the width of the steel angle from which the support legs had been made was in the range 49 - 52mm and the thickness remote from corroded regions was in the range 6.0 - 7.4 mm. In some above surface regions of supports 3 and 4 the thickness of the angle had been reduced by corrosion and buckling had occurred during collapse. This can be seen in Figures 14 and 15 in which the thickness of the angle at the positions indicated was:

Support 3	(a)	4.6 to 5.9 mm
	(b)	5.9 mm
Support 4	(c)	1.5 mm
	(d)	5.6 to 5.8 mm

The thickness of the steel angle in the sub-surface regions of supports 3 and 4 varied from zero, where through-thickness corrosion had occurred, to 6.4mm.

3.4.3 Microexamination

Microsections were cut and prepared for examination from each of the legs on supports 3 and 4 only. The following microstructures were observed:

- Support 3 Front leg - 100% ferrite
- Rear leg - small amount of pearlite in ferrite in central region; ferrite at edges.

Support 4 Both legs - small amount of pearlite in ferrite in central region; ferrite at edges.

These microstructures were typical of low carbon or rimming steel.

3.4.4 Tensile tests

One tensile test piece was machined from each leg of support 3. The test pieces were identified FL3 and RL3 and were tested in accordance with BS 18:1987 "Method for tensile testing of metals (including aerospace materials)", and the following results were obtained:

	ReH	Rm	A%
FL3	267 MPa 17.3 tsi	343 MPa 22.2 tsi	32
RL3	308 MPa 19.9 tsi	376 MPa 24.3 tsi	31

Both test pieces exhibited yield phenomenon and hence the upper yield stress (ReH) was determined.

3.4.5 Hardness tests

Vickers hardness tests were carried out on the microsections taken from the support legs. These tests were conducted in accordance with BS 427: Part 1:1961(1981) "Method for Vickers Hardness Test - Testing of metals" and the following results were obtained:

Support 3	Front leg	105 - 109 HV
	Rear leg	113 - 125 HV
Support 4	Front leg	112 - 140 HV
	Rear leg	121 - 141 HV

These results are typical of low carbon steel.

4 ASSESSMENT

Barrier 124A had consisted originally of a horizontal tube and four vertical supports. 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. The length of tube which had been located between supports 2 and 3 (tube 2/3) had been bent uniformly to give a maximum **permanent** deflection of 133mm at midspan. The portion of the tube **which** ~~been~~ located between supports 3 and 4 (tube 3/4) had been bent uniformly to give a maximum permanent deflection of 200mm at midspan. Tubes 2/3 and 3/4 had been deformed in a horizontal plane towards the pitch. Tube 1/2 and supports 1 and 2 had not been deformed.

Laboratory examination showed that most of the tube had been made from wrought iron and each support had been made from two lengths of steel angle section joined at the top by a steel gusset plate. Part of the original wrought iron tube between supports 1 and 2 had been replaced at some time by a 2m length of low carbon steel. In addition, the tube had

been strengthened at support 2 by insertion of a internal tubular reinforcement. Thus tube 1/2 was probably stronger than the rest of the tube and this may, in part, explain the lack of deformation in this region. In addition, supports 1 and 2 had been strengthened by reinforcement with angle section at three of the four feet and by bracing of the rear legs with outriggers.

The tube fractures had occurred in areas which had been located under the metal straps designed, presumably, to retain the tube. The tube wall thickness, nominally 4.5mm, had been reduced significantly by external corrosion under each strap. In some cases holes had been present in the tube at these locations before collapse occurred. Corrosion here appeared to be a highly localised phenomenon which was confined to a distance of 30mm to 35mm either side of the centreline of the strap.

In general the appearance of the tube fractures was typical of ductile failure of wrought iron in a single-stage bending/tensile mode. The region of brittle fracture, noted in the tube near support 3, was the last part of the tube to fracture at this location. The change in fracture mode can be explained in terms of increased constraint as the fracture entered thicker material and an increase in strain rate as the fracture propagated round the tube. Both these factors would tend to promote brittle fracture.

Corrosion at the tube/support junctions was predictable because liquid would have been retained in crevices under the strap and the surface of the tube under the strap had not been painted. At the open end of the tube, near support 4, internal corrosion had also contributed to deterioration of the tube since there was access for rainwater. Here the tube wall had been perforated by corrosion under the strap at two locations producing holes which we estimate would have been approximately 10mm and 20mm in diameter before the collapse. The centres of these holes would have been located approximately 50mm from the open end of the tube at support 4. They would have resembled the hole in the tube on barrier 125 (Figure 3) and, in our opinion, they would have been readily visible to the naked eye.

The direction of collapse of supports 3 and 4 appeared to be towards the front left-hand corner of Pen 3, as viewed from the pitch. For the most part the supports had been buckled and bent at locations which had been weakened by corrosion. Although there was considerable sub-surface corrosion of these supports, this played no part in the collapse. The concrete which broke away at the front foot of support 4 did so because this support had been positioned along the riser of a step in the terrace.

In all cases the most severe sub-surface corrosion on the feet of supports 3 and 4 had been located near the lower end of the region of concrete containing the coarser aggregate. One possible explanation for this could be that the height of the terrace had been raised at some stage and the sub-surface corrosion may have occurred at or near the original junction between the support feet and the terrace. This would have reduced the effective height of the barriers.

The use of wrought iron tube, and the method of tube fabrication, suggests that barrier 124A was many years old. British Standards governing the use of wrought iron tube were in use in the 1920s and 1930s but are now obsolescent. The discovery of dated sections of newspaper in the tube indicates that parts of barrier 124A were at least 58 years old, although clearly this barrier had received several modifications during its lifetime.

5 CONCLUSIONS

5.1 The tube on the collapsed part of barrier 124A had been made from wrought iron.

5.2 The tube on the collapsed part of barrier 124A had fractured at supports 2, 3 and 4 in regions where considerable localised corrosion had occurred.

5.3 The legs of supports 3 and 4 on barrier 124A had been made from low carbon steel angle section which had been corroded in some areas.

5.4 Two other barriers in Pens 3 and 4 contained tubes which had been perforated by corrosion at support locations.

In our opinion,

5.5 The general direction of collapse of barrier 124A was towards the lower left-hand corner of Pen 3, as viewed from the pitch.

5.6 Two holes, caused by corrosion, had been present in the tube of barrier 124A at the junction with support 4 before the collapse occurred and these would have been visible to the naked eye.

RADIAL FENCE BETWEEN
PENS 2 & 3

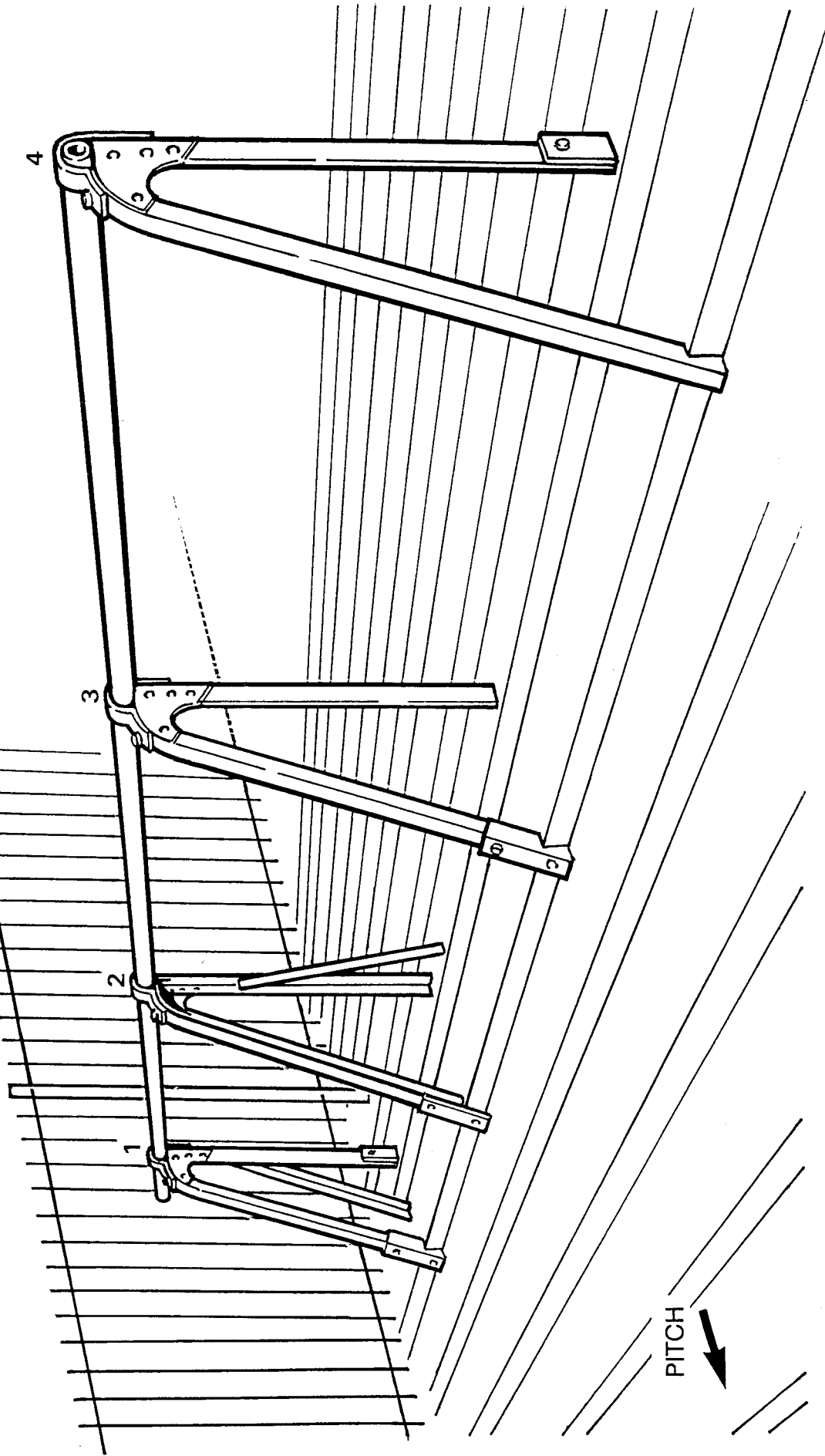


Fig. 1 - Reconstruction of Barrier 124A



89 04-073/17

Fig. 2 - Barrier 124A on 17/4/89.



89 04-073/84

Fig. 3 - Front leg of support 4 on barrier 124A.

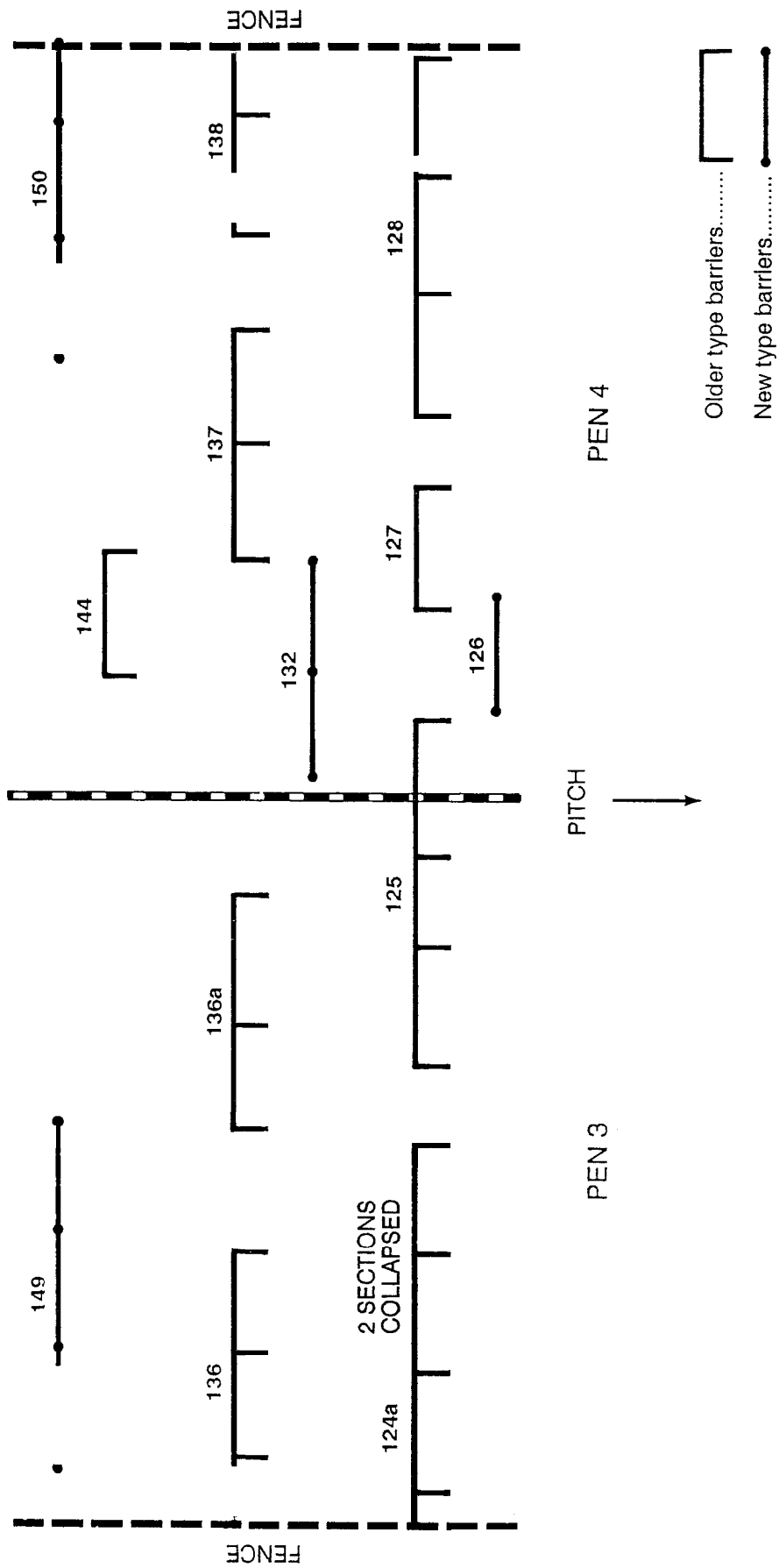
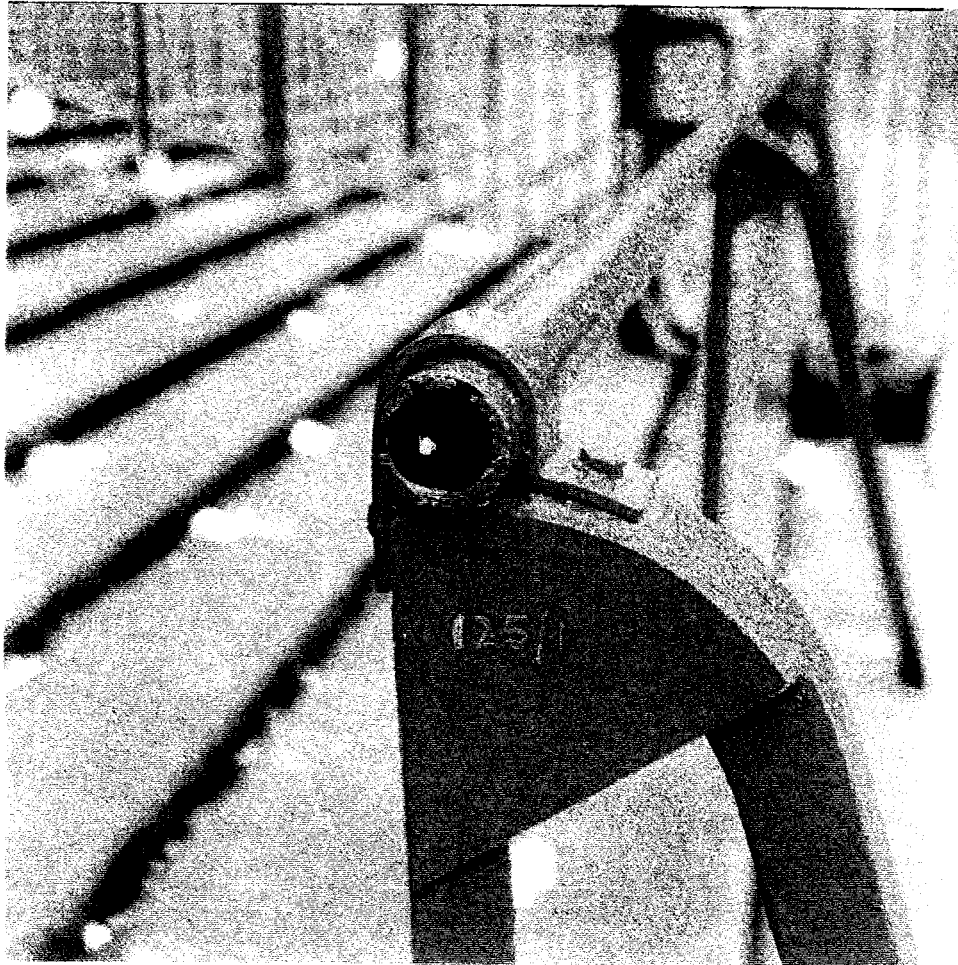
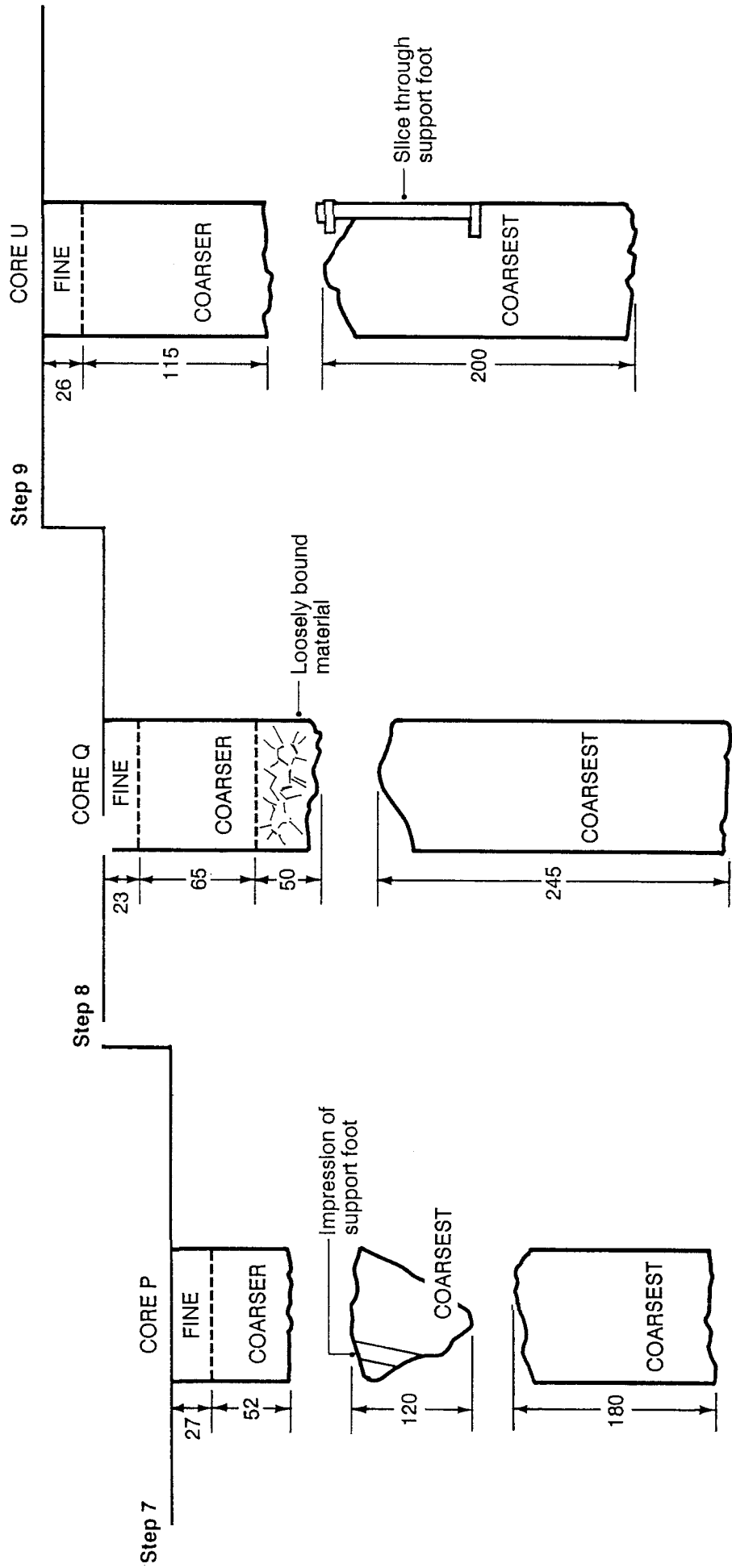


Fig. 4 - Layout of barriers in PENS 3 & 4



89 04-073/6

Fig. 5 - Barrier 125.



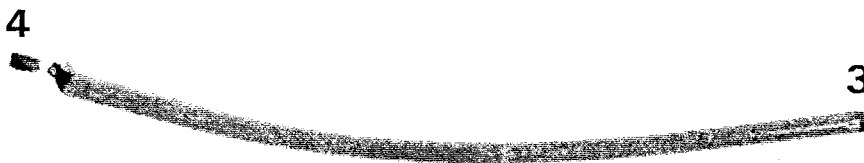
Fine..... Aggregate : 1-2 mm
 Coarse... Aggregate : 5-10 mm
 Coarsest Aggregate : 20-30 mm

Fig.6 - Concrete cores



8904-117/25

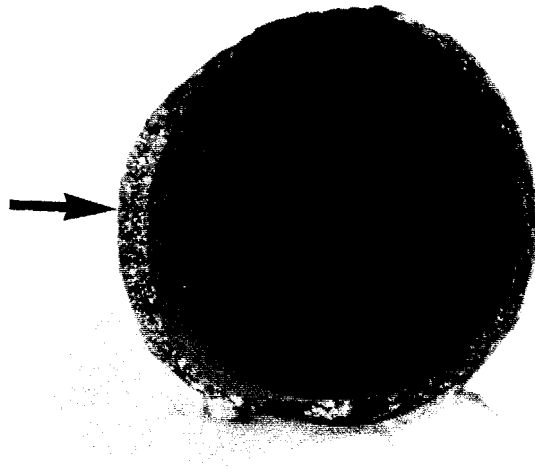
Fig. 7 - Tube 2/3 from 124A.



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Fig. 8 - Tube 3/4 from 124A.

124A/3



8905-033/2

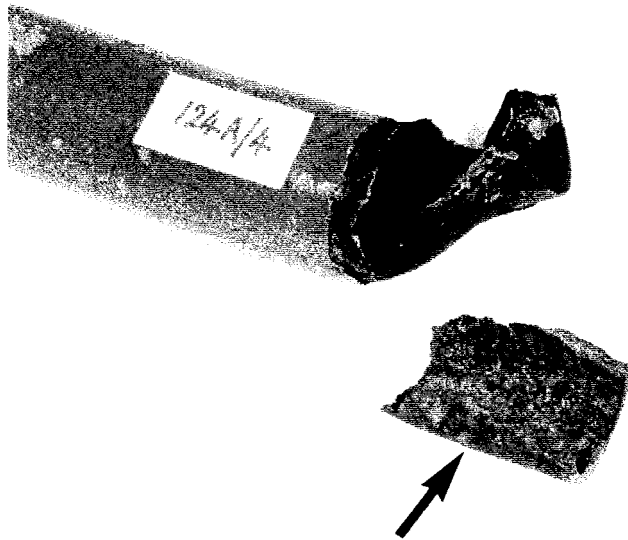
Fig. 9 - Fracture of tube at support 3.

124A/4



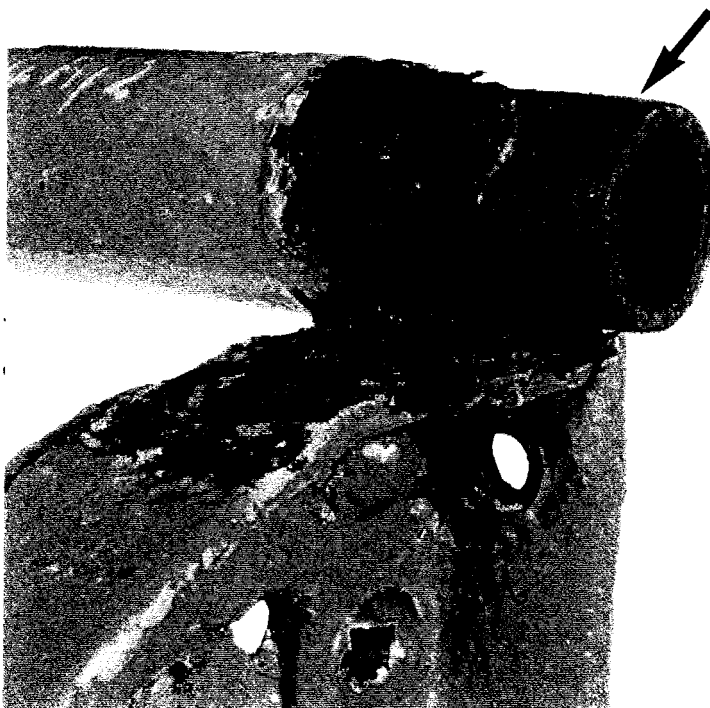
8905-033/5

Fig. 10 - Fracture of tube at support 4.



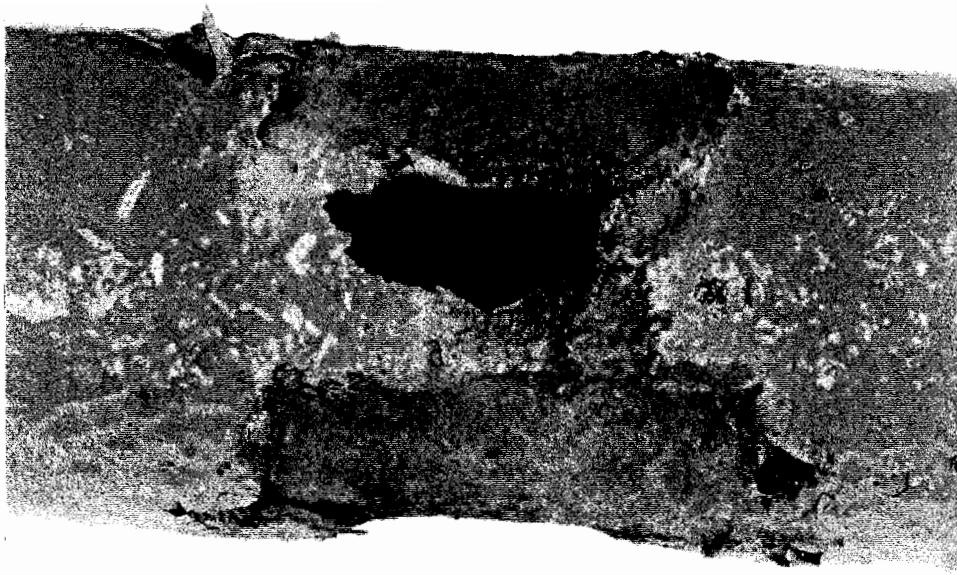
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Fig. 11 - Tube at support 4 + CENII.



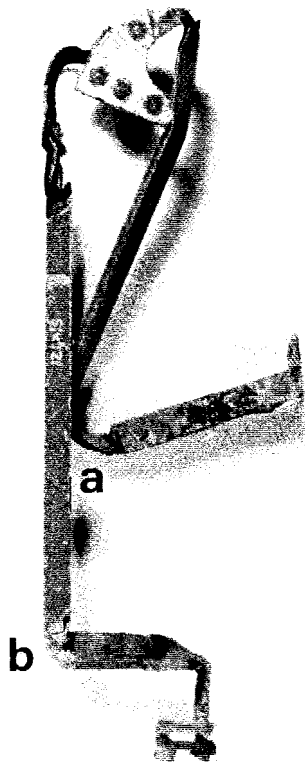
8907-048/13

Fig. 12 - Tube on support 2.



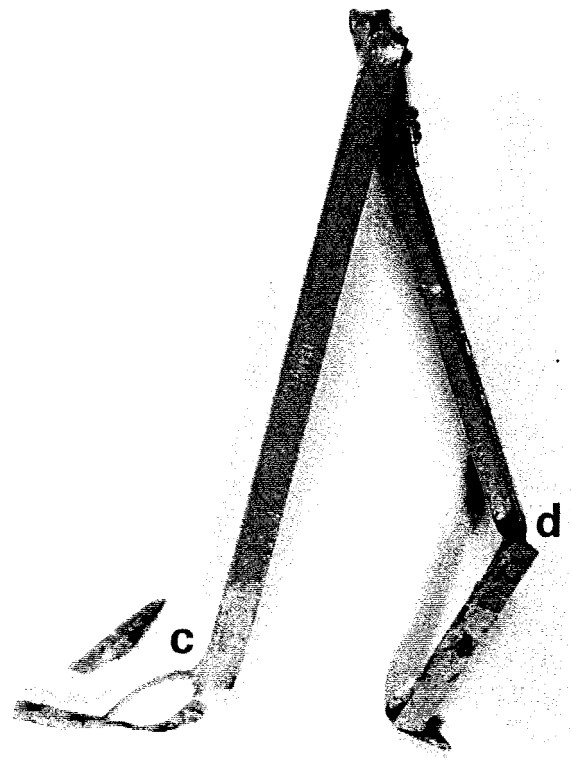
8907-063/4

Fig. 13 - Hole in tube at support 1.



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Fig. 14 - Support 3.



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Fig. 15 - Support 4.