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EXPERIMENTAL DETERMINATION OF THE SERVICE LIFE OF A VULCAN PRESSURE CABIN

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Introduction

The tests described in this report were carried out in order to investigate the fatigue life of the Vulcan pressure cabin and its associated structure. The object was to simulate as closely as possible all the loads which would appear to influence the strength of the pressure cabin. These include both ground manoeuvring and flight conditions.

1. Conclusions

The service life of the pressure cabin has been shown to be more than adequate to meet the 3900 hours flying required by the M.O.S. The structure will withstand 2100 pressurisations to the maximum differential pressure of 9 p.s.i. In terms of flying hours this should be well in excess of the life required since short duration flights would not approach maximum altitude.

The life has been quoted in terms of pressurisations, since it is basically the differential pressure as opposed to gust and undercarriage loading which has been the primary cause of all the failures. The pressurisation cycle is assumed to have been completed if the differential pressure during a flight exceeds 6 p.s.i.

These conclusions have been reached after consultation with the Royal Aircraft Establishment and are based on the attainment of a life for the test specimen which is five times as great as that for which the aeroplane is guaranteed. Since the flight cycle included de-pressurisation to combat level an adjustment has been made to take account of this when estimating the life in terms of pressurisations so that

$$\text{No. of safe pressurisations} = \frac{\text{No. of flights completed on test} \times 1.5}{5}$$

The safe life quoted is subject to certain stipulations as follows :-

1) Modifications are carried out to the canopy, cockpit rail, and front pressure bulkhead to Mod. numbers 354, 367, 368, 405, & 449 before the aeroplane enters service.

2) The following items are "lifed" and must be changed after they have completed the number of safe pressure cycles given.

Item	Test Life No. of flights	Safe Pressurisations
Rear cockpit rail top member	4148	1200
Former 302 attachments to cockpit rail	4148	1200
Rear canopy release unit housings	5028	1510
D.2 pressure release valve support structure	5167	1560
Pressure bulkhead access door skin	5577	1675
Stringer brackets (Front Bulkhead)	5614	1680
Rear canopy release unit sealing boxes	6365	1910

Conclusions. Contd.

Listed below are parts, which having been replaced or modified during testing, have not completed the total number of flights but, not having failed, have a life of something in excess of the figure given in the table.

Item	Test Life No. o Flights	Safe Pressurisations
Front pressure bulkhead access door frame	4786+	1440+
Attachment of Former 316 to cockpit rail	4786+	1440+
Canopy attachment lugs and dowels	4786+	1440+
Stringer brackets (Rear bulkhead)	5940+	1790+

After 2100 pressurisations there is a possibility of fatigue cracks developing in the skin pa rticularly round the crews entrance door and the attachments to the front pressure bulkhead. Final failure occurred at the latter position (Plate 22) and this governs the life limitation.

All the failures on the modified structure are fail safe since the cracks were observed whilst the specimen would still react the full differential pressure.

2. Loading conditions.

2.1 General.

At a meeting at A. V. Roe on 23rd November 1954 representatives of the R.A.E. expressed the opinion that the programme of applied loads should be based on an average flight plan and not purely on an operational sortie i.e. account should be taken of other flights such as circuits and bumps, engine testing etc. They therefore suggested that flights of 2 hours duration would be appropriate. As the nosewheel is mounted ontthe rear pressure bulkhead it was decided that, as well as gust inertias during the flight, the undercarriage reactions during ground manoeuvring should be applied. It was agreed that these ground reactions should be based on the mean value of the take-off and landing weights to simplify the loading. This value was estimated to be 140,000 lbs.

2.2 Undercarriage Loads

Little information on the magnitude and frequency of under-carriage reactions during taxying was available so a large number of nosewheel accelerometer readings were taken during taxying, take-off and landing of Vulcan prototype aircraft. These indicated that, whilst the frequencies were high, the magnitudes of the reactions were very low and little fatigue damage to the pressure cabin would result. However, in order to simulate these effects to some degree, it was decided to apply a limited number of representative loads to the nosewheel. These were to include two simulated engine runs against the main wheel brakes which apply twice the normal static reaction to the nosewheel. Also two opposite side loads of 0.5 times the normal static reaction were to be applied during each taxy run, and drag and rebound drag of 0.8g during the landing.

2.3 Gust loadings

During the "flight" the crew's nacelle floor and the retracted undercarriage were to be loaded 24 times to the loads corresponding to the effects of a 10 ft. per sec. gust. This gust is considered to be the most damaging from a fatigue point of view and the frequency of its occurrence was based on R.A.E. knowledge of the gust spectrum for a typical Vulcan sortie.

2.4 Aerodynamic Loading

The aerodynamic suction on the canopy at M = 0.9 increases the loads on the canopy catches to something of the order of 1.15 times that due to cabin pressure alone. This was considered to be an amount which would significantly affect the fatigue life of the attachments. This suction was to be applied as a steady load during the flight.

2.5 Pressurisation Loading

During an operational sortie the maximum cabin pressure differential of 9 lbs/sq.in. at cruising altitude will be reduced to to approximately $3\frac{3}{4}$ lbs/sq.in. in combat zone and then increased again to 9 lbs/sq.in. for the return flight. These pressures were to be reproduced in the test programme.

2.6 Summary of programme of loads

The following is a summary of the sequence of loads which was finally accepted as being most representative of an average Vulcan flight.

APPLIED LOADS

Load No.	Extended Undercarriage					Retracted U/C.	Cabin Inertia	Aero Suction	Cabin Press.
	Drag	Rebound Drag	Side −	Side +	Vert.				
1					0-2g		0.7-1.3g	-	
2				0-0.5g	0.7-1.3g		0.7-1.3g	-	
3			0-0.5g		0.7-1.3g		0.7-1.3g	-	
4						0.7-1.3g	0.7-1.3g	-	0
5						0.7-1.3g	0.7-1.3g		
6						0.7-1.3g	0.7-1.3g		
7						0.7-1.3g	0.7-1.3g		
8						0.7-1.3g	0.7-1.3g		
9						0.7-1.3g	0.7-1.3g		
10						0.7-1.3g	0.7-1.3g		
11						0.7-1.3g	0.7-1.3g		
12						0.7-1.3g	0.7-1.3g		9
13						0.7-1.3g	0.7-1.3g		
14						0.7-1.3g	0.7-1.3g		
15						0.7-1.3g	0.7-1.3g		
16						0.7-1.3g	0.7-1.3g		$3\frac{13}{16}$
17						0.7-1.3g	0.7-1.3g		
18						0.7-1.3g	0.7-1.3g		
19						0.7-1.3g	0.7-1.3g		
20						0.7-1.3g	0.7-1.3g		9
21						0.7-1.3g	0.7-1.3g		
22						0.7-1.3g	0.7-1.3g		
23						0.7-1.3g	0.7-1.3g		
24						0.7-1.3g	0.7-1.3g		
25						0.7-1.3g	0.7-1.3g		
26						0.7-1.3g	0.7-1.3g		
27						0.7-1.3g	0.7-1.3g		0
28	0-0.8g				0.7-1.3g	-	0.7-1.3g	-	
29		0-0.8g			0.7-1.3g	-	0.7-1.3g	-	
30			0-0.5g		0.7-1.3g	-	0.7-1.3g	-	
31				0-0.5g	0.7-1.3g	-	0.7-1.3g	-	
32					0-2g	-	0.7-1.3g	-	

CONSTANT

Note.

Actual values are as follows:-
Extended undercarriage 1.0 g = 12500lbs.
Retracted undercarriage 1.0 g = 9361bs. at 57.2 inches aft of M/W.pivot.
Cabin inertia 1.0 g = 3.0 tons S.F. and 340 ton inches B.M. at rear pressure bulkhead.
Canopy aerodynamic suction - constant 2.34 tons.
such that:- the front hooks carry 0.54 tons.
the rear hooks carry 1.58 tons.
and the hinge arms carry 0.22 tons.

Description of Specimen.

The specimen was a structurally complete Vulcan pressure cabin which is of circular section approximately 8 ft.6 inches diameter and 14 ft. long. The structure is comprised basically of channel section formers rolled top hat section stringers and a DTD 687 skin. Practically the whole of the top of the cabin is cut away for the canopy and cockpit rail structure whilst the bottom of the fuselage between the two heavy keel longerons comprises the bomb aimers' blisters and crew's entrance door. (see Fig.1)

The front pressure bulkhead is of a dome shape 7 ft.3 inches spherical radius formed of eight segments of 20 swg.DTD.610 Aluminium Alloy joined by 20 swg. DTD.610 butt straps In the centre of the bulkhead is an opening, 2 ft. diameter, for access to the radar in the nose. This opening was framed initially by a magnesium alloy (spec.DTD 88C) forged ring but this was later changed to spec DTD 410 aluminium alloy of a thicker section as a result of the tests (see fig 2) The opening is covered by an inward opening circular door formed from a fluted DTD.610 skin edged by a DTD.88C forging.

The rear pressure bulkhead consists of a flat skin reinforced on the forward face (inside the cabin) by horizontal top hat stiffeners and on the rear face by vertical top hat stiffeners rivetted to the bulkhead skin. At the bottom of this bulkhead on the rear face are the two nosewheel pivot forgings which are bolted through the bulkhead to the aft end of the pressure cabin keel longerons. Running vertically up the bulkhead from these two forgings are two heavy extruded channel diffusion members which carry the nosewheel drag link bearings approximately on the vertical centre line of the fuselage.

All the holes and cut-outs for hydraulic couplings, electrical plugs and sockets, flying control rods and pressurization valves were present and were in some cases blanked with their correct fittings and in the others with light alloy plates. All the brackets for the internal fixed fittings and the trim scheme were fitted.

To simulate the correct fixation at the rear pressure bulkhead a further 11 feet of fuselage including the nosewheel bay and Number 1 fuel tanks as far aft as Former 75 were added.

The specimen, less canopy windscreen and bomb aimer's window was pressure tested during normal production first to 9 lbs/sq.inch and eventually to 12 lbs/sq.inch.

All the magnesium alloy components in the cabin were protected by the standard dichromate treatment to Specification DTD.911 which was followed by two coats of chromate rich primer. To prevent corrosion due to the presence of water 3 further coats of bitumastic paint were applied after assembly.

Description of Test Rig.

To simplify the loading arrangements the specimen was mounted upside down and cantilevered from Former 75 which was bolted onto one end of a rectangular frame composed of steel joists and channels with the weight of the specimen and dummy undercarriage counterpoised by lead weights. All the inertia loads were applied by means of hydraulic jacks attached to the test frame and the whole rig was assembled in a water tank and submerged.

/The

Description of Test Rig. Cont'd.

The sequences and combinations of hydraulic loading were selected by means of a uniselector switch operating electro-hydraulic valves which supplied their respective jacks from a fluctuating pressure supply.

This same switch also selected other valves controlling a supply of water to the specimen for pressurization purposes. When the cabin pressure reached 9lbs/sq.inch a pressure switch reversed these valves to allow the cabin to depressurize.

The whole operation was completely automatic and continued until failure occurred.

Test history and procedure.

Testing was commenced on the 20th June 1956 and after 163 flights had been completed, the starboard canopy side window failed. This was due to the inner pressure bearing toughened glass becoming delaminated from the vinal interlayer and allowing the cabin pressure to be applied to the combined vinal and outer annealed glass. The result was a shear failure of the vinal around the periphery of the frame. In practice the delamination would have been observed long before it became dangerous and the window would have been replaced. A new window of the same type was fitted and testing continued.

After 1063 flights the front bulkhead access door frame failed (see Plate 2) but after examination it was generally considered that this failure was probably caused more by corrosion than by the high stress level in the magnesium alloy forging. In particular the inner edge of the ring from which the failure commenced was extremely badly corroded and apart from the ultimate failure, a large number of smaller cracks starting at corrosion pits were evident. Associated with this failure was the tensile failure of one of the segment joints in the front pressure bulkhead which continued right out to the fuselage skinning and caused failure of six of the magnesium alloy brackets attaching the fuselage stringers to the front bulkhead. Examination of these broken brackets revealed further severe corrosion, and it was apparent that the steps taken to prevent this occurring were inadequate. As a result of these observations a new door frame of basically the same design but with a larger edge radius was coated with Araldite 985 and fitted into the bulkhead which was repaired by replacing the two segments adjacent to the failure. All the stringer brackets in the pressure shell were replaced by identical items treated with Araldite 985 and then heavily coated with Bostik after assembly.

However, after 1510 flights the access door frame failed again and examination showed that, notwithstanding the Araldite protective treatment, the specimen was again badly pitted by corrosion and had numerous small cracks starting at the inside edge of the ring. As before one of the segment joints in the front bulkhead had failed and two of the panels had to be replaced. The stringer brackets were, however intact

A new magnesium alloy ring coated with Araldite was fitted in order that testing might continue but strain gauges affixed to this ring indicated that at 9lbs/sq.inch cabin pressure, stresses(Fig.2) of the order of 11 tons/sq.inch were induced in the edge of the ring from which the failures had commenced. Additional stresses of between 2 and 3 tons/sq.inch could be induced in these points by tightening the door clamping screws. Thus a total stress of between

Test history and procedure. Contd.

13 and 14 tons/sq. inch was being induced in material with an ultimate tensile stress of 18 tons/sq.inch so that an extremely low fatigue life could be expected.

After 1605 flights two failures occurred simultaneously.

1) The port canopy side window delaminated in an identical manner to the starboard window earlier in the tests. This was replaced.

2) Failure of the countersunk head tension bolts attaching the port aft canopy catch lugs to the canopy structure. A microscopic examination of the bolts attaching all the four canopy lugs was made with the following observations

	BOLT NUMBER (FROM FRONT TO REAR)			
LUG	1	2	3	4
Port Aft	Head broken off from crack in radius under head	Broken off at start of thread, crack under head.	Broken off at start of thread, crack under head.	Broken off at start of thread
Stbd Aft	Broken off at start of thread	Severe crack under head.	Severe crack under head.	No visible damage.
Port Fwd	No visible damage.	Slight crack under head.	Slight crack under head.	No visible damage.
Stbd Fwd	No visible damage			

n.b. These bolts were standard High Tensile Steel bolts.

The two forward canopy locating dowels had also failed and Plate 3 shows a photograph of these dowels together with the broken bolts from the two rear lugs. Also shown in this photograph is the port aft locating block in which the 2 B.A. bolts attaching it to the underside of the cockpit rail had failed in tension probably due to the fact that, when the lug bolts failed, the locating dowel was withdrawn from its socket and, on releasing the load, did not return directly. This was borne out by marks on the edges of the socket, and the failure is thus secondary to the lug bolt failures.

All these items were replaced by identical components pending design modifications.

Further inspection of the specimen revealed a crack across the upper surface of the starboard cockpit rail immediately aft of former 302. Two rivets attaching the top decking to the diagonal cross member in the immediate vicinity of the crack had sheared (see Plate 4). On the port side there was a 2" long crack in the underside of the cockpit rail in the corner of the cut-out for the periscope sextant about 4 inches aft of former 302 (see Plate 5). The brackets attaching former 316 to the underside of the cockpit rail on both port and starboard side were cracked at their inboard edges (see Plates 6 & 7).

Strain gauges were affixed to the top surface of the port cockpit rail in the exact position of the crack on the starboard /rail

Test history and procedure. Cont'd.

rail and these indicated that, with 9 lbs/sq.inch cabin pressure and aerodynamic suction on the canopy, a stress of 22.9 tons/sq.inch was induced in the position from which the starboard rail had cracked. Full results and gauge positions are shown in Fig. 3. This stress is high due to the aforementioned crack on the underside of the rail (Plate 5). The stress on an undamaged section is given in report D.O.798.

During a routine inspection after 1862 flights it was noticed that the port cockpit rail had cracked on the upper surface in exactly the same position as the starboard rail had. It is considered that this crack occurred after approximately 1820 flights as it passed through one of the strain gauges which ceased to read about that time. Examination of the access door frame in the front pressure bulkhead revealed three well developed cracks and rather than risk further serious damage to the bulkhead, the ring was replaced again.

On flight 2075 bubbles were observed to be coming from the centre of the crew's entrance door, and a visual examination showed severe cracking across the outer magnesium alloy door skin (See photograph Plate 8) Since this skin was not considered to be load carrying during the original stressing calculations, it was decided not to replace it

Further failures observed after flight 2075 were :-

i) A delamination failure of the second port canopy side window which was replaced.

ii) Failures of both port side canopy locating dowels. All four dowels were replaced by similar items with larger fillet radii at the base of the pin.

iii) Two of the bolts attaching the port rear canopy catch to the canopy structure were slack and a microscopic examination showed that both bolts had cracks in the start of the threads. However these bolts were refitted.

iv) There was a 1 inch long crack running forward and outboard from the outboard forward corner of the cabin skin cut-out for the starboard entrance door hinge It was thought that this was due to over-opening the door and the crack was located with a 3/16" dia. tear hole.

A further major failure of the pressure cabin occurred during flight 2217 when the differential pressure dropped instantaneously from 5 lbs/sq.inch to zero. On inspection two major failures were found :-

Firstly, a delamination failure of the starboard canopy side window which left the toughened glass intact but sheared the vinal interlayer for more than half of its circumference.

Secondly the port side of the cockpit rail had failed completely at station 302 (see Plate 9) and had fractured the bracket attaching former 302 to the rail. The rail had also pulled away from the fuselage skinning locally around this area shearing about 50 of the 1/8" diameter rivets forming the joint. The bracket attaching the diagonal cross member to the cockpit rail had fractured across its bend radius and this member had its other attachments to the rail torn out (see Plate 10).

/On

On the starboard side this bracket had failed in an identical manner (see Plate 11) but the remainder of the attachments, and the rail itself, were substantially intact except that the rivets attaching the rail to the fuselage skinning were very severely strained, two being actually sheared off.

The port canopy side window had two large areas of delamination covering approximately half of the window area and was replaced (see Plate 12).

The strength of the cockpit rail and canopy attachments now became the subject of a more detailed investigation and extensive strain gauge testing of a production pressure cabin and canopy has been reported in Test Report Number D.O.798.

As a result of these tests the following modifications were incorporated in the fatigue test specimen before any further testing was carried out :-

1) The front pressure bulkhead access door frame was replaced by a solid section ring in aluminium alloy spec.DTD.410 (Vulcan Mod.No.354).

2) Retaining clamps were fitted to the canopy and cabin side windows to prevent the pressure bearing toughened glass from becoming displaced in the event of delamination.

3) The canopy lugs and attachments to the canopy were completely redesigned to eliminate tension bolts. (Vulcan Mod.No.367).

4) The canopy dowels and sockets were replaced by redesigned and strengthened items (Vulcan Mod.No.367).

5) The rear top member of the cockpit rail was replaced by a new member in DTD.546 aluminium alloy having a more gradual contour and a deeper flange (Vulcan Mod.No.368).

6) The diagonal cross members at the rear of the cockpit rail were redesigned so that their top flanges were continuous (Vulcan Mod No.368).

7) The attachments of former 316 to the cockpit rail were replaced and strengthened by the addition of a gusset plate (Vulcan Mod.No 368).

8) The attachments of former 302 to the cockpit rail were replaced by identical items.

Prior to recommencing the fatigue testing a large number of stress measurements were made by means of electric resistance strain gauges at various points on the canopy and cockpit rail and, as a result, further modifications were incorporated as follows:-

1) A reinforcing angle was fitted to the cockpit rail at station 330 to embrace an existing cut-out (Mod.405).

2) The reinforcing channels in the diagonal cross members were extended to embrace the cut-outs for the canopy release mechanism. (Mod.405).

3) The rear top member of the cockpit rail was reinforced by two 16 swg. plates in stainless steel specification F.V.520. (Mod No.449). These tests are described and results tabulated in Test Report No.Addendum 1 to D.O.798.

Test history and procedure. Cont'd.

Fatigue testing was recommenced on April 11th 1957 and a further 2811 flights were completed before the rear canopy release unit housings failed (see Plate 13). These components are DTD.683 forgings and had not been changed since the commencement of the tests. Each one had thus completed 5028 flights. Since there were no completed release units available from Production the housings only were replaced by new items.

After a total of 5577 flights the skin of the front pressure bulkhead access door failed along two of the stiffening flutes (see Plate 14). This item is made from 20 swg. L.72 aluminium alloy and, although the stress level is generally very low, the forming of the flutes under a drop hammer process had evidently introduced serious stress raisers and residual stresses. No modifications were incorporated at this stage but a new door skin was fitted to allow the tests to continue. A general inspection of the specimen at this stage revealed no further damage.

During a routine inspection after a total of 6365 flights serious cracking was observed in the rear cockpit rail. This was the new portion of the rail fitted in line with Mod.368 after 2217 flights and had thus completed 4148 flights The cracks, which were almost identical port and starboard, ran from the forward corner of the rear canopy catch cut-out to the inboard edge of the rail and similarly from the rear corner of the cut-out to the outboard edge of the rail (see Plates 15 & 16) When this portion was dismantled it was observed that the steel sealing boxes on the underside of the rail had also cracked in the front inboard and aft outboard corners (see Plate 17).

There was a crack in the edge of the cabin skinning on both port and starboard sides just aft of the rear canopy catches and running from the edge of the skin to the first of the 1/4 inch dia. rivets attaching the diagonal cross member (see Plate 15).

The angle brackets attaching Former 302 to the underside of the cockpit rail had cracked on both port and starboard sides. The cracks were in the centre of the flange attaching to the rail and were continous from the inboard edge to the second of the three bolts forming this joint.

The rear cockpit rail, former 302 attachment brackets and the rear canopy catch sealing boxes were replaced by identical items and testing was recommenced. After a further 312 flights (total 6677) cracks were observed in the entrance door hinge cut-outs and it was decided to make a thorough inspection of the entire specimen. The paint had to be removed to render the cracks visible.

This inspection revealed the following damage :-

1) The rivets in the fairing strip around the periphery of the bomb aimers' blister, in the region between former 330 and 358 were severely pulled and one rivet in each side had actually sheared off. Failure of several others appeared imminent.

2) There were circumferential cracks in the fuselage skinning between the aft row of the two rows of rivets attaching this skinning to former 372 (front pressure bulkhead). All the cracks were in the region above the centre line of the aircraft and the sum total of their length was approximately 14½ inches.

The cracks were as follows:-

/Above

Port Side.

Above the skin joint at stringer 7 the first two rivets were completely sheared and between stringers 7 and 8 there was a 4 inch crack. See Plate 18.

Directly in line with stringer 9 there was a 1" crack and directly in line with stringer 10 a 1/2" crack.

Between stringers 10 and 11 ------ a 3" crack.
Between stringers 11 and 12 ------ a $1\frac{1}{2}$" crack.
See Plate 19.

Starboard Side.

Above the skin joint at stringer 47 the first two rivets had completely sheared and there was a $1\frac{1}{2}$" crack in the skin.

Below the skin joint and between stringer 47 and 48 there was a $2\frac{1}{2}$" crack.

3) The stringer brackets attaching stringers 8, 9, 10 and 11 to the front pressure bulkhead on the port side had failed. All the bracket to stringer rivets were intact but on each bracket all three legs were broken off. These items are magnesium alloy forgings and had been replaced after 1063 flights when they were severely corroded. Although there was some evidence of corrosion this time it is not known to what extent this accelerated the failures and consequently the stringer brackets should be considered to have a fatigue life of 5614 flights.

4) There were numerous small cracks across the rivet holes in the pressure cabin skin at each of the four corners of the crews entrance door frame (see Plate 20).

5) There were cracks in the corners of the cut-outs for the entrance door hinges. These cracks ran forward and outwards from both hinges for a distance of approximately $3\frac{1}{2}$ inches (see Plate 20).

6) There were cracks in both rear corners of the cabin skin cut-out for the bomb aimers' blister. These cracks ran aft and outboard. Plate 21 shows the crack in the port side with the rear fairing removed from the blister.

7) There was a small crack in the aft outboard corner of the cabin skin cut-out for the starboard canopy hinge arm.

8) Two of the rivets attaching the upper diaphragm of the support structure for the D.2 pressure release valve had sheared at the attachment to the pilots floor. This diaphragm was replaced originally after 1510 flights when damage occurred which was thought to be secondary to the door frame failure.

9) There was a crack in the inside skinning in the bottom of the cabin on the edge of the lap joint just aft of former 316 about 24 inches from the centre line of aircraft on the port side.

10) There was a crack in the port front corner of the skin cut-out for the bomb aimers' blister. This crack was about 1/4 inch long and extended from the edge of the cut-out to one of the rivets attaching the skin to the blister longerons. Strain gauges were fixed to a production aircraft in the positions of these cracks and the measured stresses are shown in Appendix I.

Test history and procedure. Contd.

Before recommencing testing the skin cracks at the entrance door hinge cutouts were patched with plates of 16 gauge specification L.73 material. The extent of the patching can bee seen on Plate 20. The four broken stringer brackets on the port side were not replaced as they had failed completely. The redundant holes were plugged with bolts and rivets as appropriate to effect a pressure seal.

After a further 224 flights had been completed, bringing the total to 6901, an inspection of the specimen was carried out. This was principally to make note of the rate of propogation of the skin cracking discovered after 6677 flights. No new cracks were discovered and with one exception the cracks noted after 6677 flights had not increased in length. The exception was the large crack at the port forward corner of the crews entrance door which had increased from $2\frac{1}{2}$" after 6677 flights to 3".

A further 102 flights were completed, bringing the total to 7003, when a major failure occurred. The circumferential cracks in the fuselage skin at the Front Pressure Bulkhead had merged together so that a continuous crack about 36" long ran from stringers 7 to 14 on the port side. A photograph of the failure is shown on Plate 22. The skin cracks on the starboard side of the Front Pressure Bulkhead were no worse than after 6677 flights. The large skin crack at the port forward corner of the crews entrance door had increased to $3\frac{1}{4}$", all other cracks were no worse than when first discovered after 6677 flights.

APPENDIX I.

MEASUREMENT OF STRESS LEVELS AT FATIGUE CRACKS.

Introduction:-

In order to determine the intensity of stress in the cabin skinning where cracks were discovered in the fatigue test specimen, strain gauges of the electrical resistance wire type, were cemented to a production line pressure cabin and the gauge readings noted during the routine pressure testing of the cabin.

Positioning of the Strain Gauges :-

The areas to be investigated were :-

(i) The four corners of the crews entrance door.

(ii) The skin cutout for the entrance door hinge.

(iii) The front and rear end of the bomb aimers blister.

(iv) The skin cutout for the canopy hinge arm.

(v) The termination of the cabin skinning to the front pressure bulkhead former.

(vi) The flutes pressed into the front pressure bulkhead access door skin.

A careful note was made of the position and direction of the cracks in the fatigue test specimen and the gauges were cemented to the production line cabin so that the strain measuring grid of the gauge was at right angles to the line of the crack.
Figs. 4 to 13 show the positions of the gauges.

Test Results:-

The strain gauge readings obtained have been tabulated in Table No.1 and plotted on Figs.14 to 16.

From the plotted results, the stress at each gauge position for 9 p.s.i cabin pressure has been calculated and marked on Figs.4 to 13.

With regard to gauge numbers 18 and 19 which measured the bending stresses induced in the fluted portion of the Front Pressure Bulkhead Access Door, the gauge readings were factored by 0.60 before converting to stresses. This was because the active elements of the gauges were not in direct contact with the metal surfaces but removed from them by a layer of cement and the backing paper of the gauges which together total about .012". Since the door material was 20 swg. (.036") the active elements of the gauges were appreciably further from the Neutral Axis than the extreme fibres of the door material hence the factor.

Gauge numbers 11, 12 and 13 showed a compressive stress which rose to a maximum midway between stringers thus indicating that the skin was in bending. This was probably due to bellying between formers, together with skin bending due to the moment from the offset load from the front pressure bulkhead.

As the longitudinal tension in the cabin skin between stringers is calculated at 2.0 tons/sq.inch the stress on the inside face of the skin at gauge number 12 position is in the order of 10 tons/sq.inch.

/Table

TABLE No:1. - STRAIN GAUGE RESULTS

GAUGE NUMBER	CABIN PRESSURE - LBS/SQ.INCH.							
	0	2	4	6	8	6	2	0
1	0	.035	.072	.120	.170	.129	.043	.004
2	0	.050	.102	.157	.207	.170	.072	.006
3	0	.081	.166	.275	.384	.308	.135	.026
4	0	.089	.180	.291	GAUGE U/S			
5	0	.046	.128	.240	.372	.252	.058	.007
6	0	.038	.081	.142	.211	.149	.037	-.009
7	0	.060	.122	.181	.239	.183	.058	-.006
8	0	.092	.182	.278	.371	.286	.097	.014
9	0	.072	.142	.210	.281	.198	.063	.004
10	0	.005	.010	.018	.023	.020	.006	.001
11	0	-.038	-.082	-.135	-.193	-.152	-.061	-.018
12	0	-.043	-.097	-.165	-.239	-.191	-.077	-.025
13	0	-.032	-.069	-.108	-.151	-.120	-.050	-.012
14	0	.062	.131	.209	.289	.219	.080	.009
15	0	0	-.005	-.015	-.021	-.015	-.002	-.003
16	0	.010	.017	.016	.015	.009	0	-.010
17	0	0	.002	.002	0	.001	0	-.001
18	0	.458	.799	1.120	1.440	1.223	.656	.200
19	0	-.562	-.930	-1.286	-1.617	-1.402	-.839	-.336

+ ve sign means tension, - ve sign compression.

Conversion of Strain Gauge Readings into Stress

The results obtained from the strain gauges were the percentage change in the resistance of the gauge, and the strain in the gauge is given by :-

$$\text{Strain} = \frac{\% \text{ change in resistance}}{\text{Gauge factor} \times 100}$$

$$\therefore \quad \text{Stress} = \frac{\% \text{ Change in resistance} \times E}{\text{Gauge factor} \times 100}$$

The gauges used had a factor of 2.16 and were cemented to light alloy material for which $E = 10.5 \times 10^3$ lbs/sq.inch. Therefore the stress at a gauge position is given by :-

$$\text{Stress} = \% \text{ change in gauge resistance} \times 21.8 \text{ tons/sq.inch.}$$

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REPORT No.

SHEET No.

TYPE No.

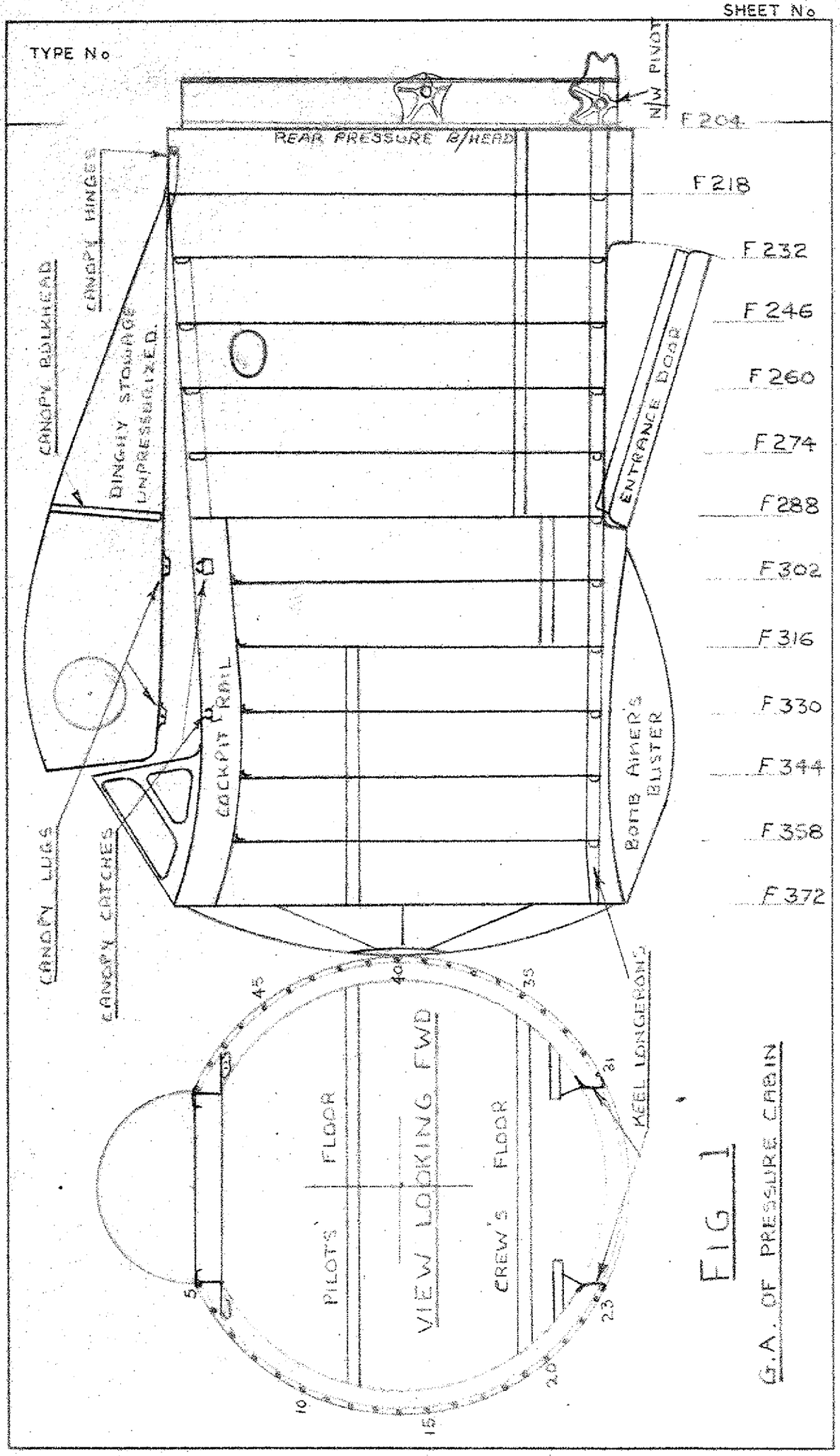


FIG 1

G.A. OF PRESSURE CABIN

ISSUE No.	
DATE	

PREPARED BY DATE

CHECKED BY DATE

RP 3287/1

GAUGE N°	CLAMPING STRESS	STRESS DUE TO SPECIFIED PRESSURE
1	-1·11	0·542
2	0·68	4·10
3	2·27	8·07
4	1·12	5·29
5	0·28	2·84
6	-0·12	6·6
7	-0·62	-0·75
8	-0·38	1·93
9	0·67	8·0
10	0·39	5·4
11	0·33	2·39
12	0·27	3·48

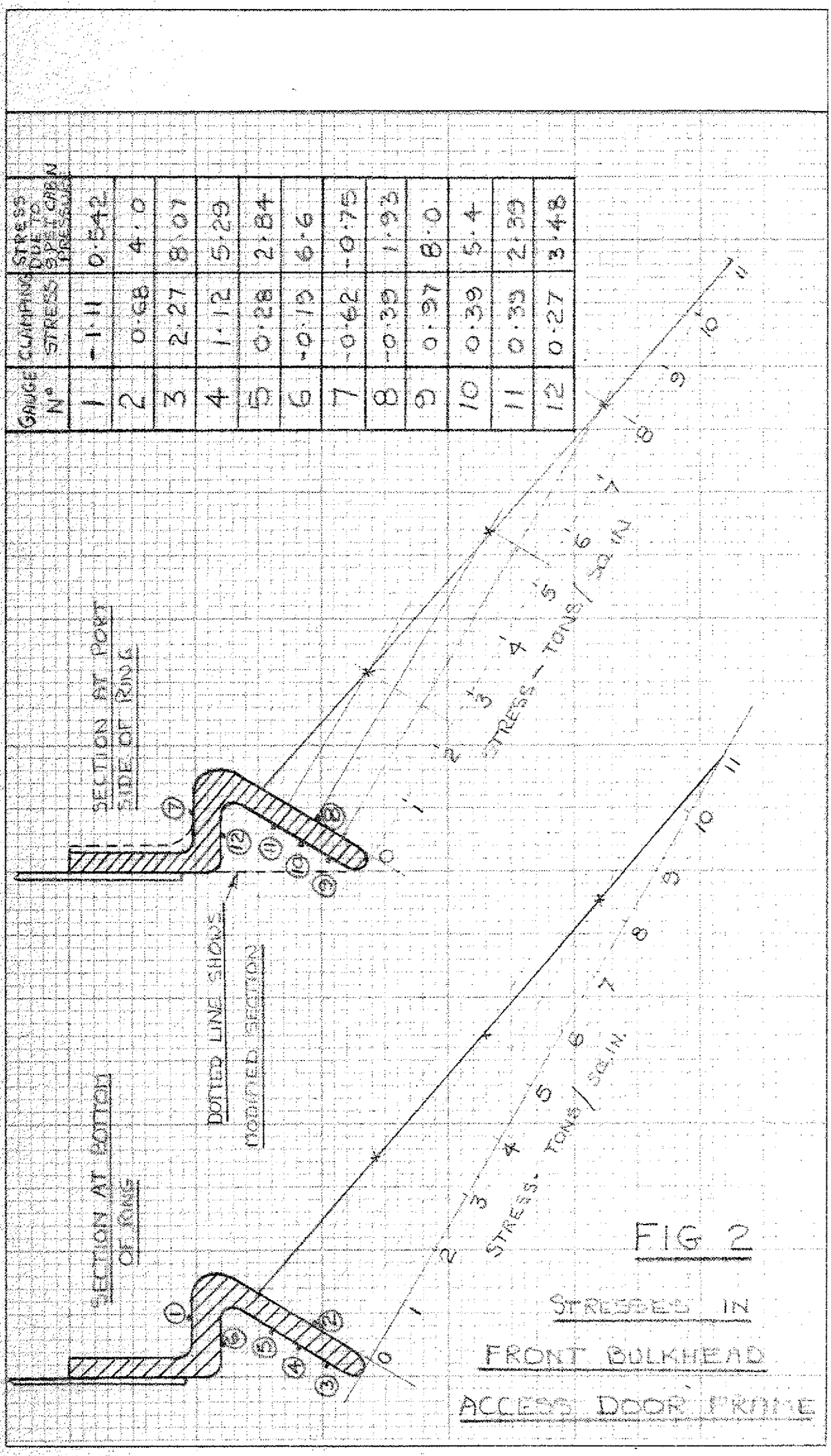


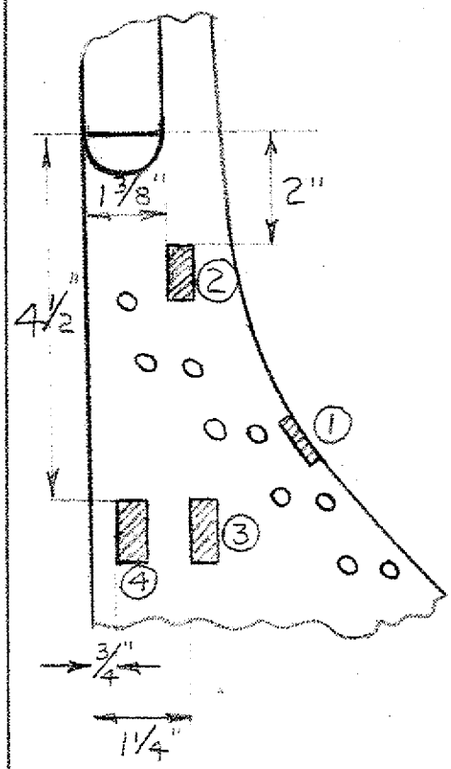
FIG 2

STRESSES IN FRONT BULKHEAD ACCESS DOOR FRAME

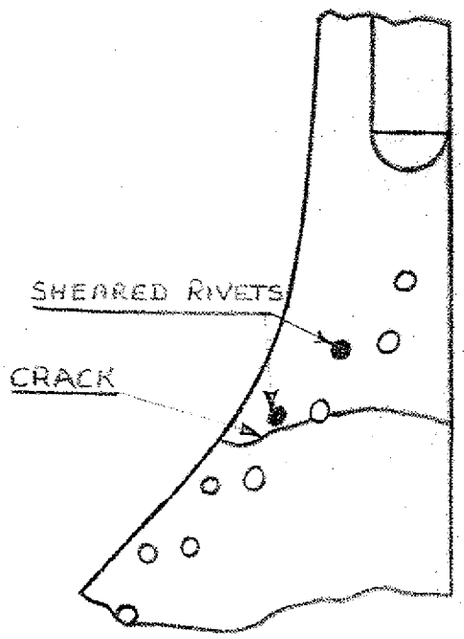
ISSUE N°	
DATE	

RD 3287/2

TYPE No



PORT RAIL SHOWING
STRAIN GAUGE POSITIONS



STARBOARD RAIL SHOWING
POSITION OF CRACK

GAUGE No	CANOPY AERO SUCTION ONLY	9 P.S.I CABIN PRESS ONLY	CANOPY AERO + CABIN PRESS.
1	+1·9	+21·7	+22·9
2	+0·95	+13·0	+13·7
3	+0·22	+1·17	+1·19
4	+0·12	−0·85	−0·64

FIG 3

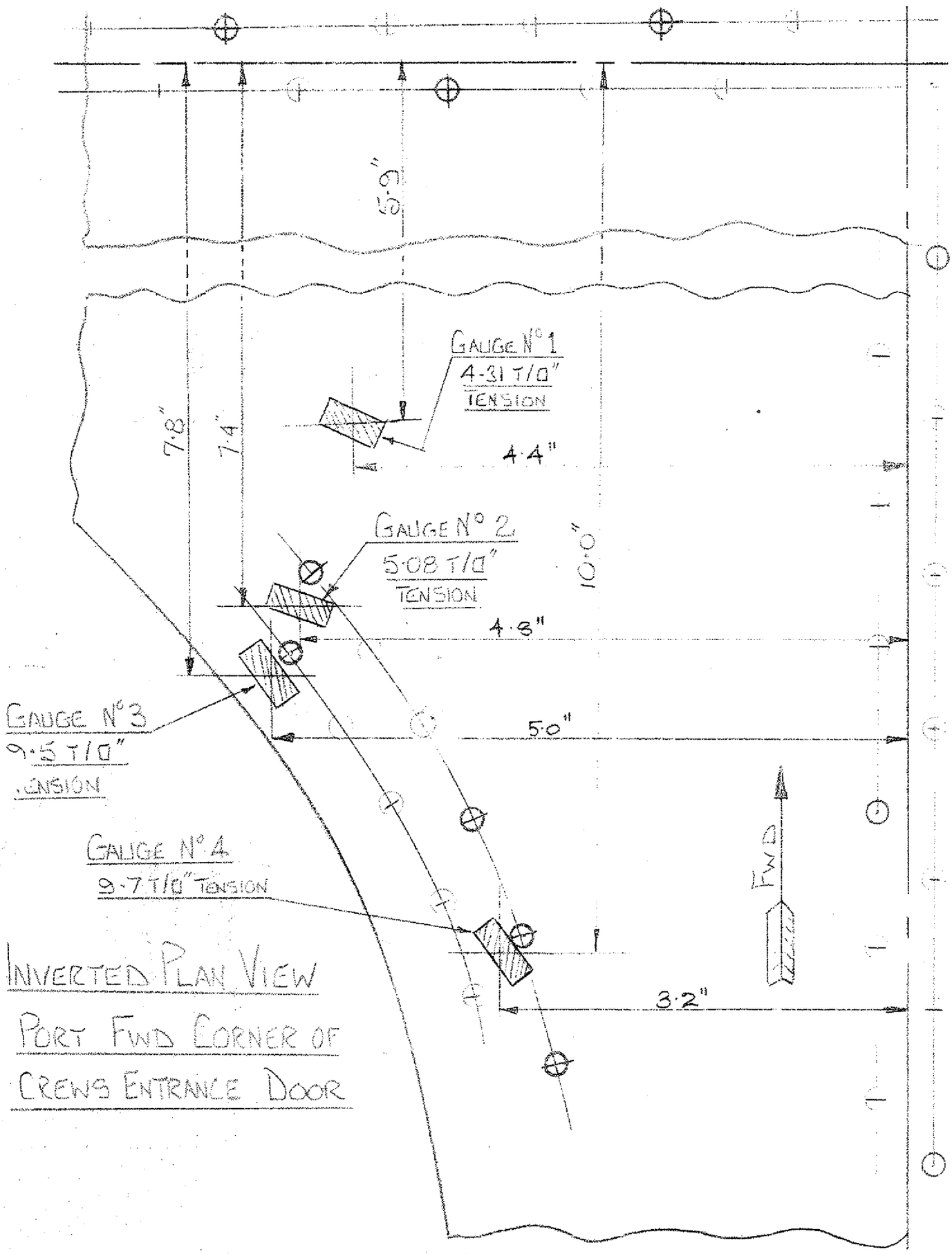
GAUGE POSITIONS AND STRESSES (TONS/SQ IN)
IN CRACKED COCKPIT RAIL

ISSUE No.	DATE

PREPARED BY DATE

CHECKED BY DATE

RD 528/15



INVERTED PLAN VIEW
PORT FWD CORNER OF
CREWS ENTRANCE DOOR

FIG 4

RD 3287/4

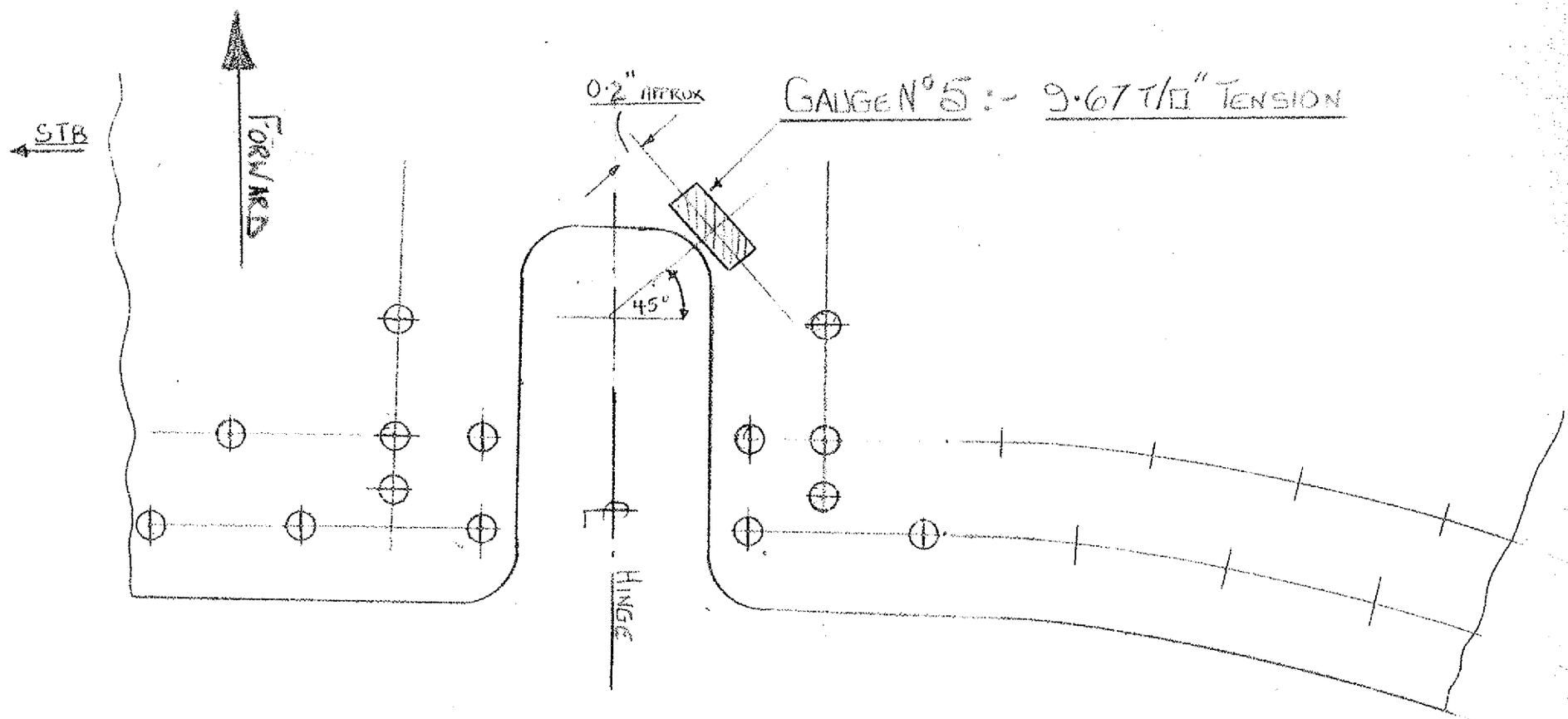
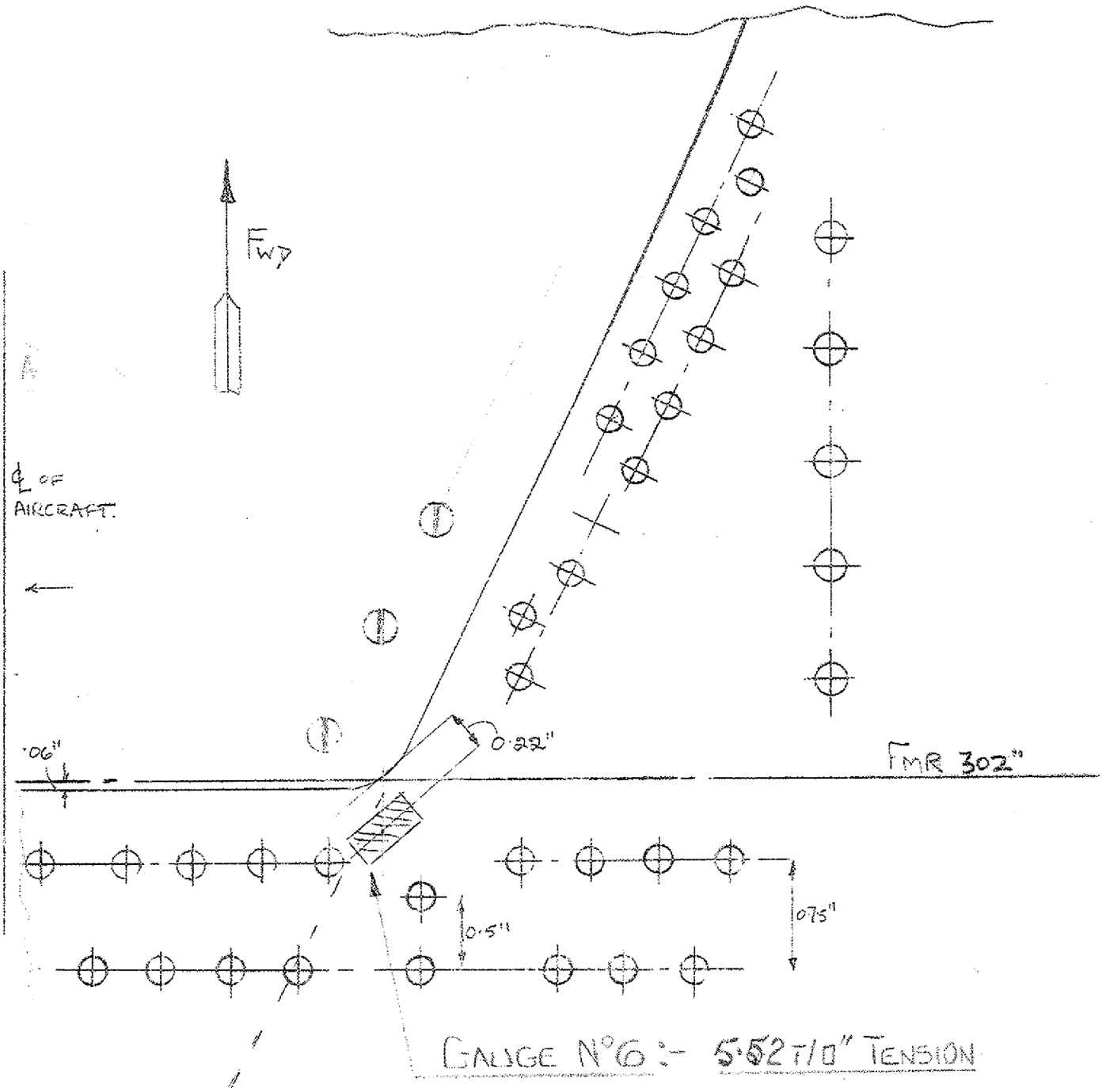


FIG 5

INVERTED PLAN VIEW OF SKIN CUTAWAY FOR CREWS ENTRANCE DOOR HINGE - PORT SIDE

RD 3287/5



POSITION OF GAUGE N°6 AT AFT END OF B/A BLISTER (PORT SIDE)

FIG 6

RD 3287/6

FIG. 7

INVERTED PLAN VIEW - STBD FWD CORNER OF CREWS ENTRANCE DOOR

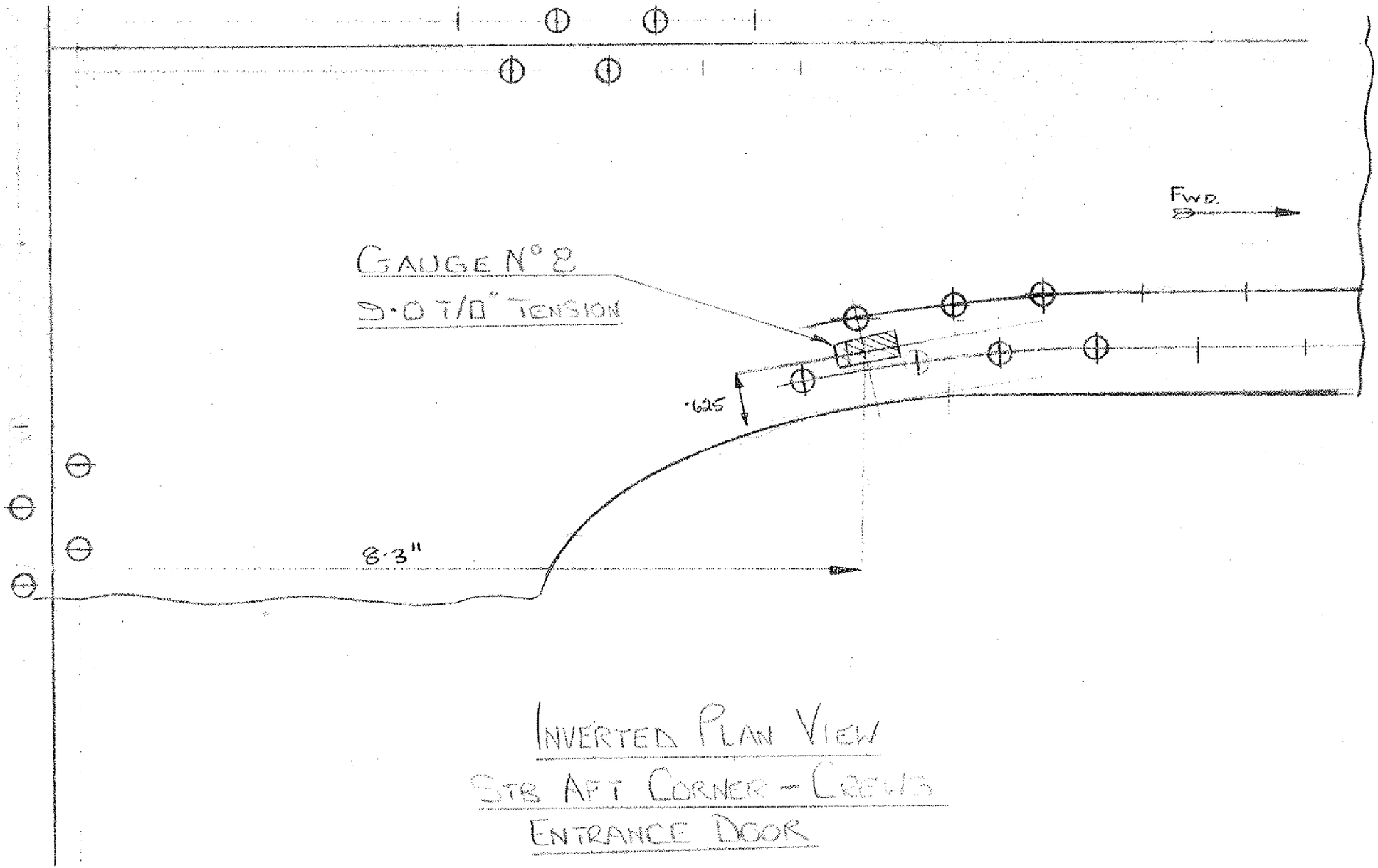
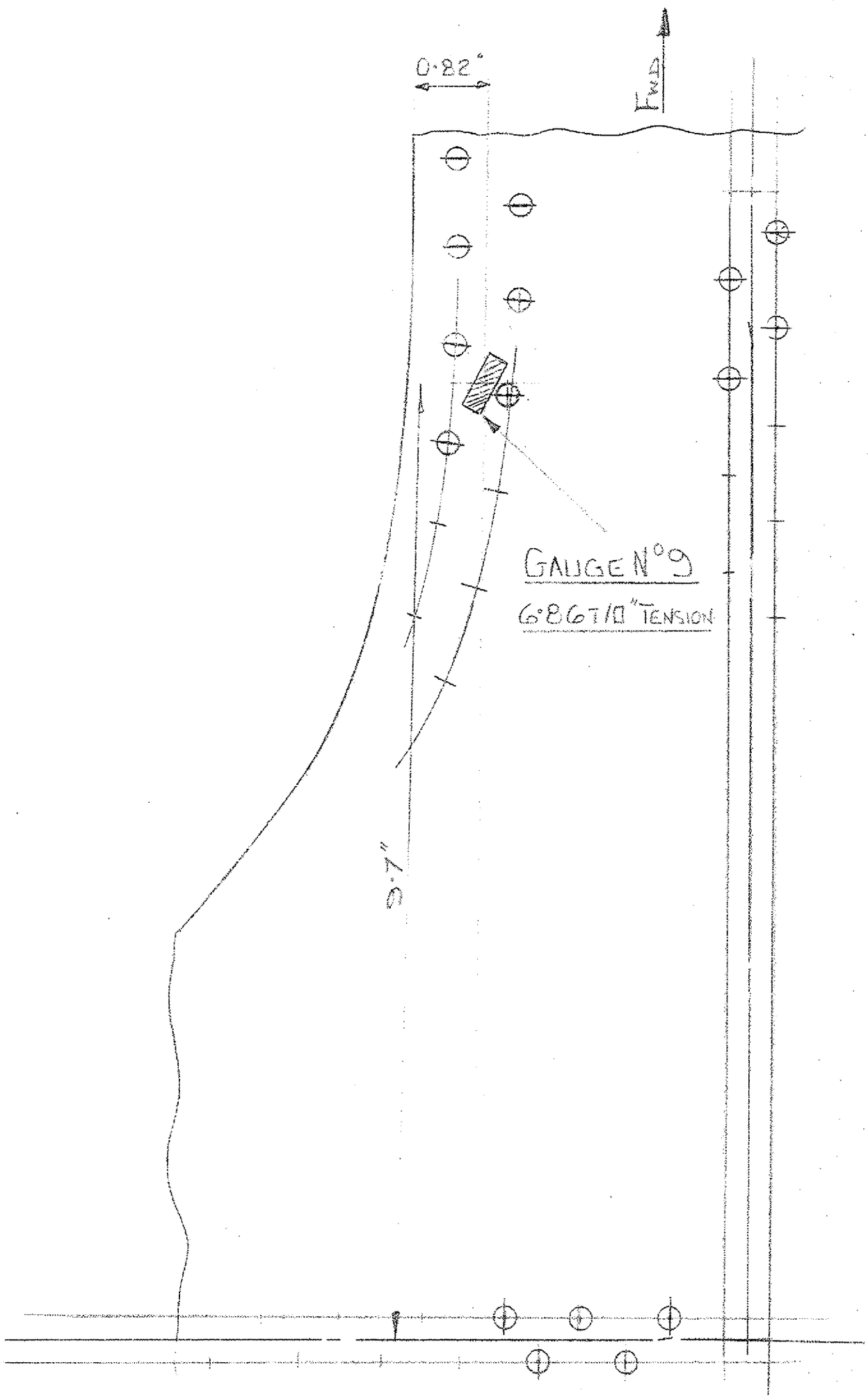


FIG. 8

INVERTED PLAN VIEW
STB AFT CORNER - CREW'S
ENTRANCE DOOR

RD 3264/8

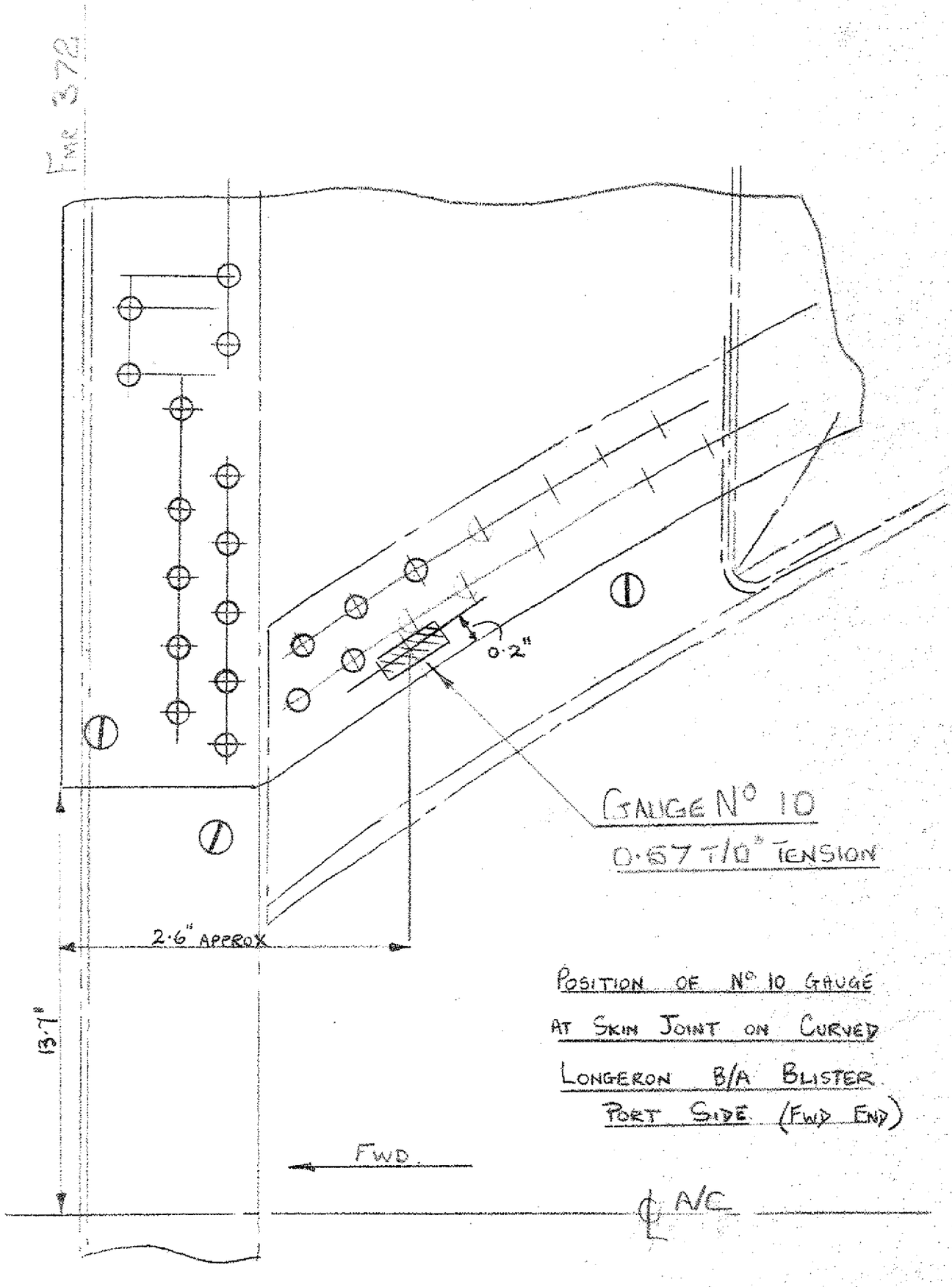


INVERTED PLAN VIEW

PORT AFT CORNER OF CREWS ENTRANCE DOOR

FIG 9

RD3287/9

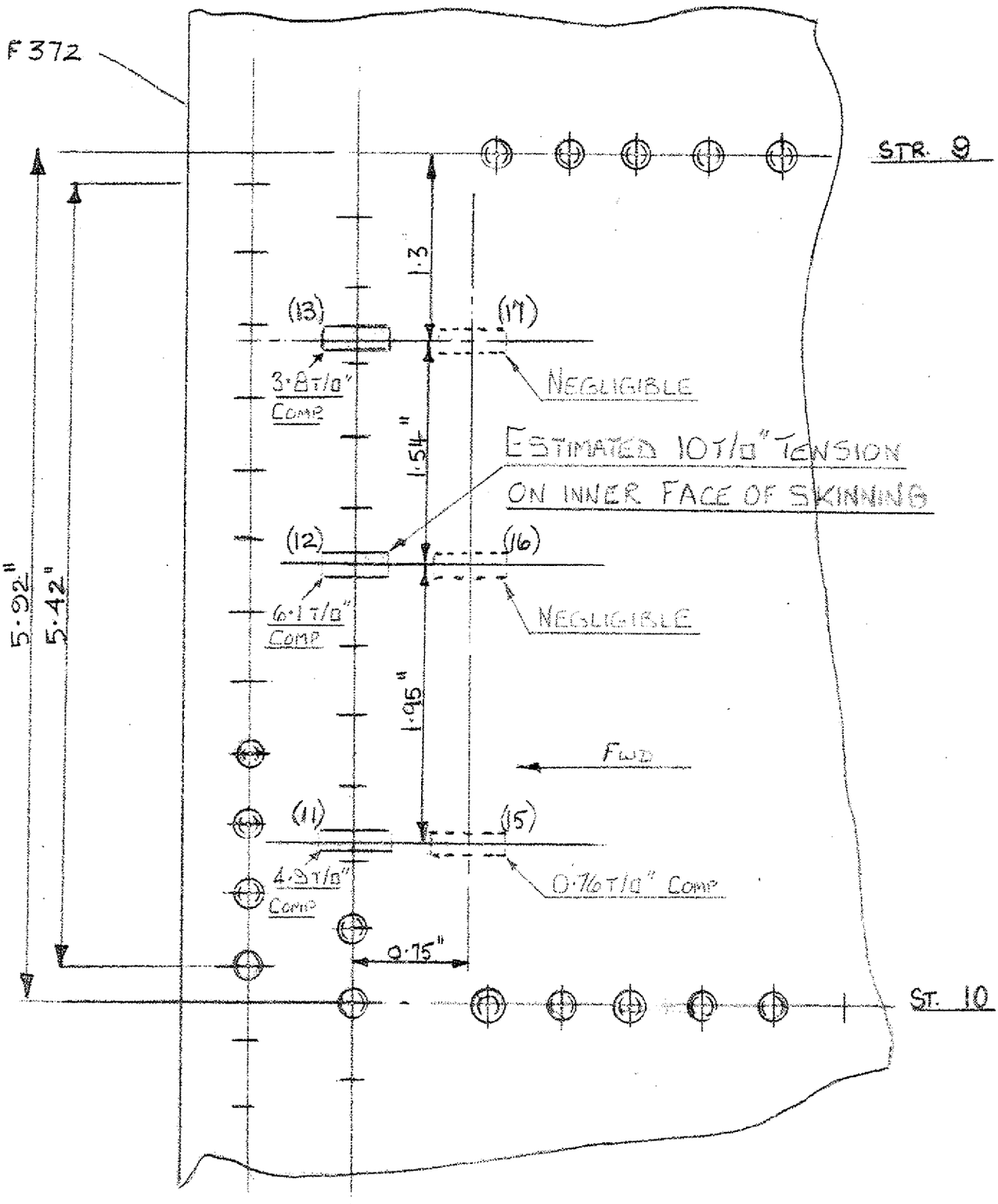


POSITION OF N° 10 GAUGE
AT SKIN JOINT ON CURVED
LONGERON B/A BLISTER
PORT SIDE (FWD END)

FIG 10

RD 3287/10

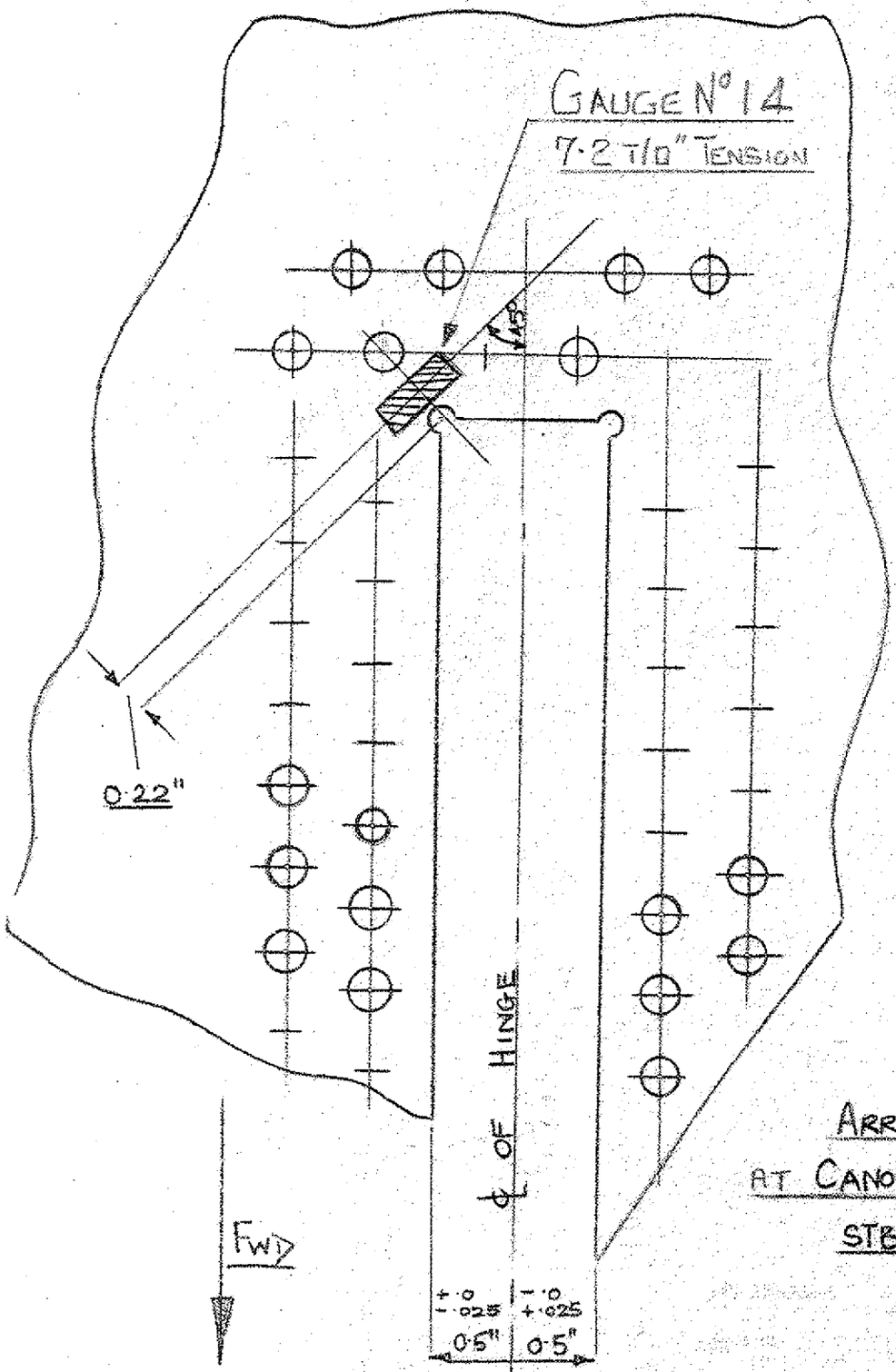
NOTE/ FIGURES IN BRACKETS ARE GAUGE NUMBERS
GAUGES SHOWN DOTTED ARE ON THE INSIDE SURFACE OF THE CABIN SKINNING



ARRG^T OF GAUGES ON CABIN SKINNING ADJACENT TO FRONT PRESSURE BULKHEAD – PORT SIDE

FIG 11

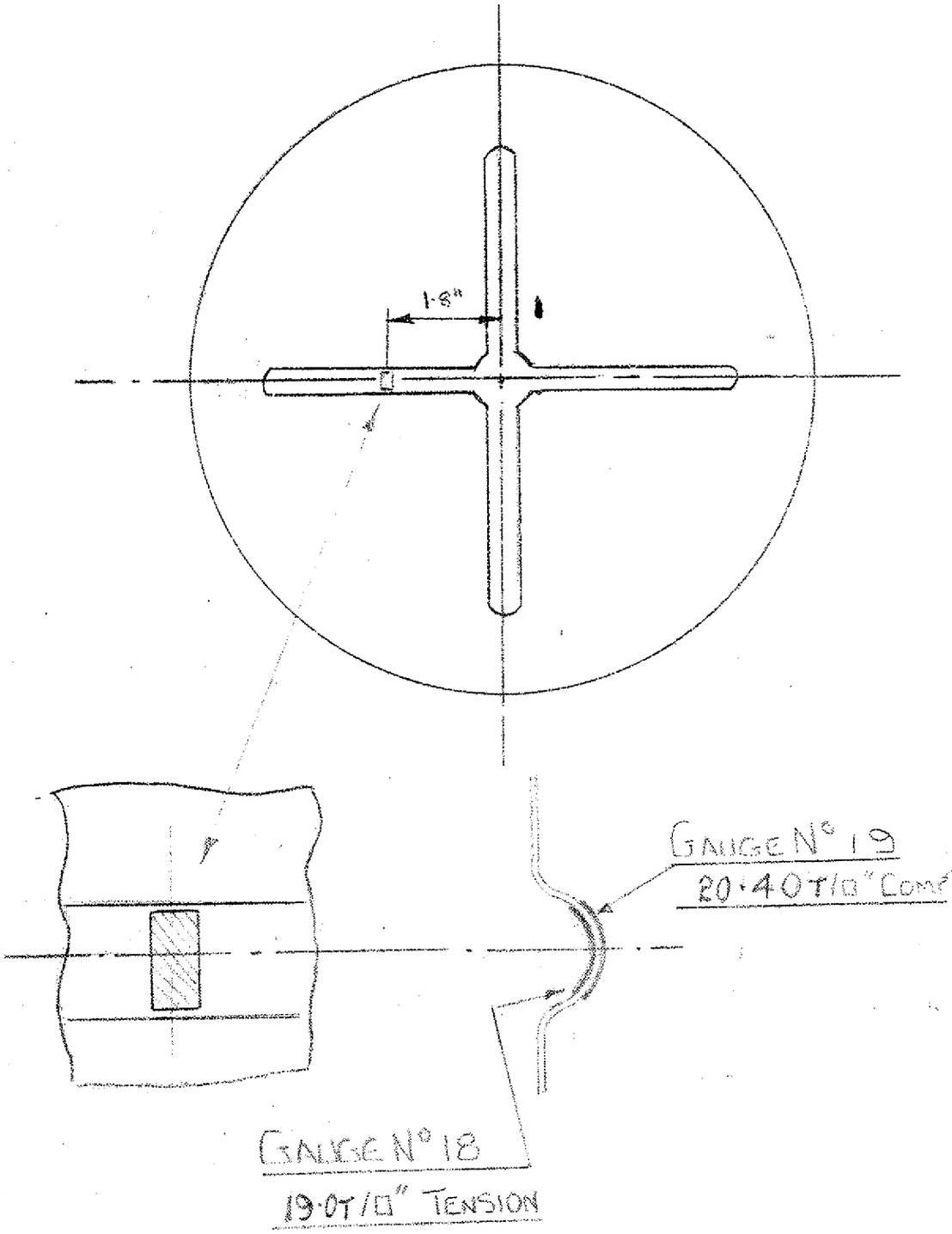
RD 3287/11



ARRG^T OF STRAIN GAUGE AT CANOPY HINGE CUT-OUT STBD. SIDE

FIG 12

RD 3287/12

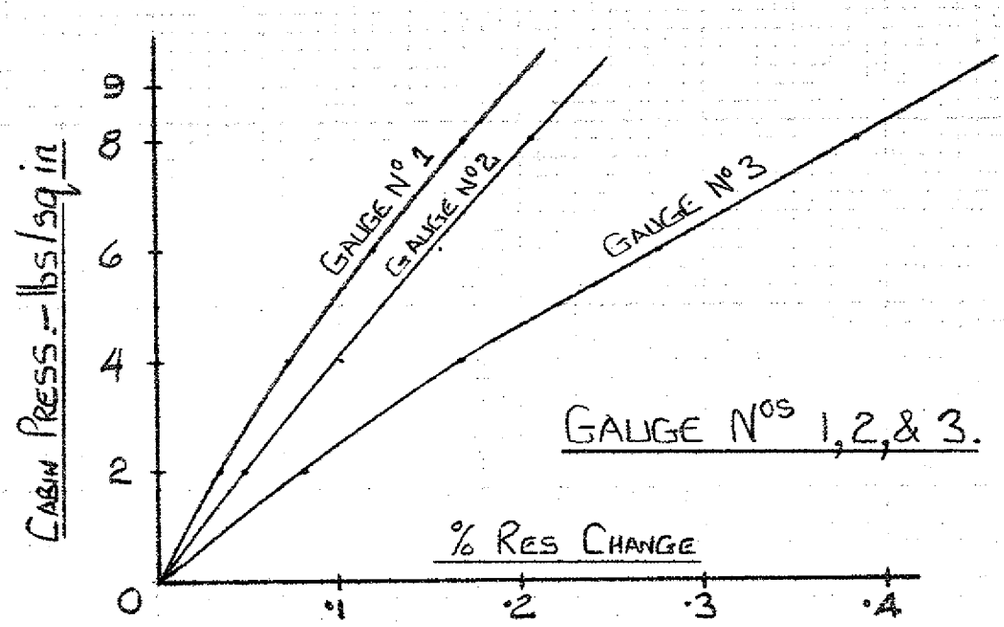


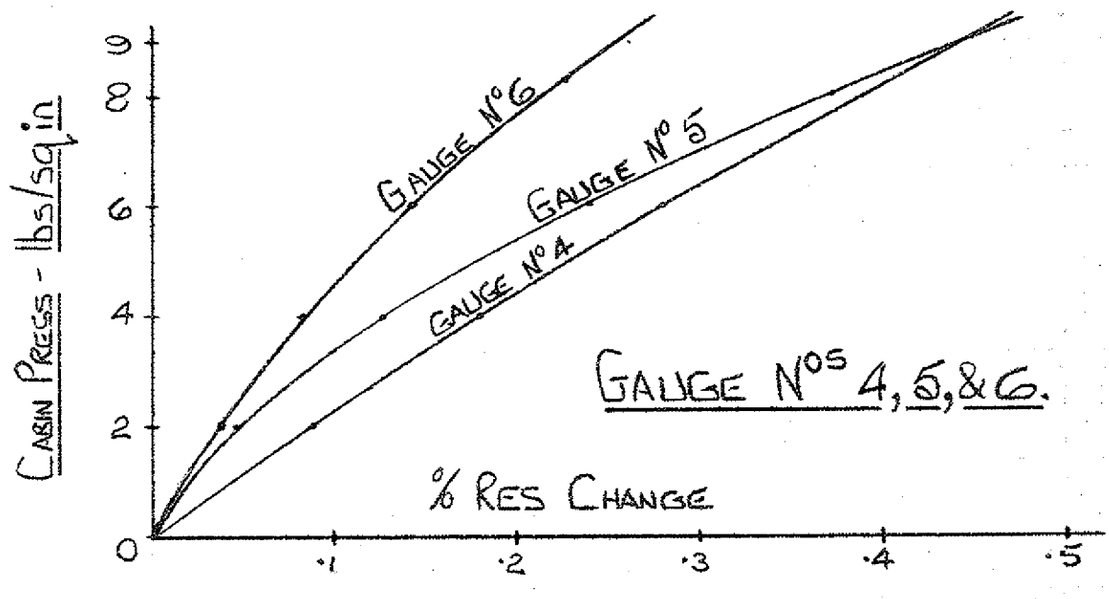
ARRG^T OF STRAIN GAUGES ON FRONT PRESS.
BULKHEAD ACCESS DOOR FLUTE

FIG 13

RD 3287/13

STRAIN GAUGE RESULTS





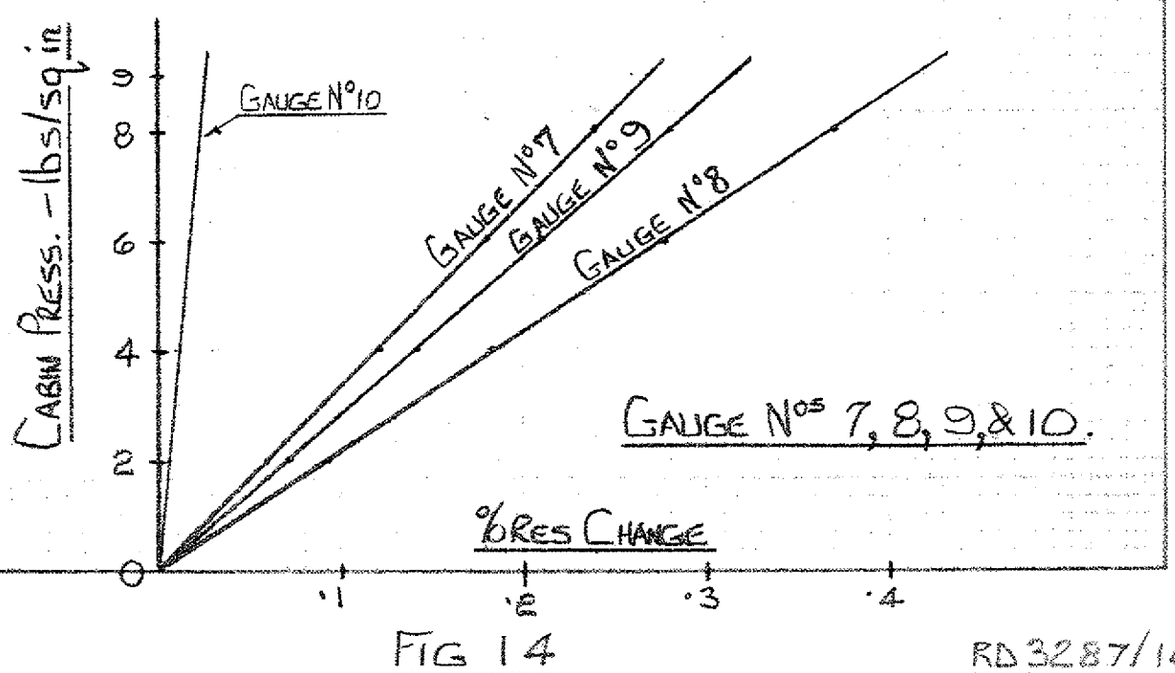
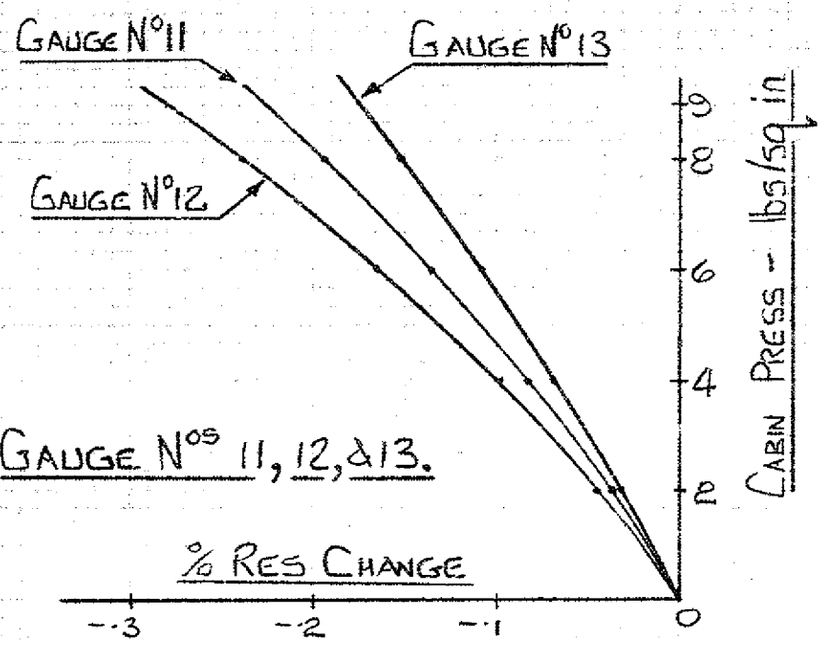


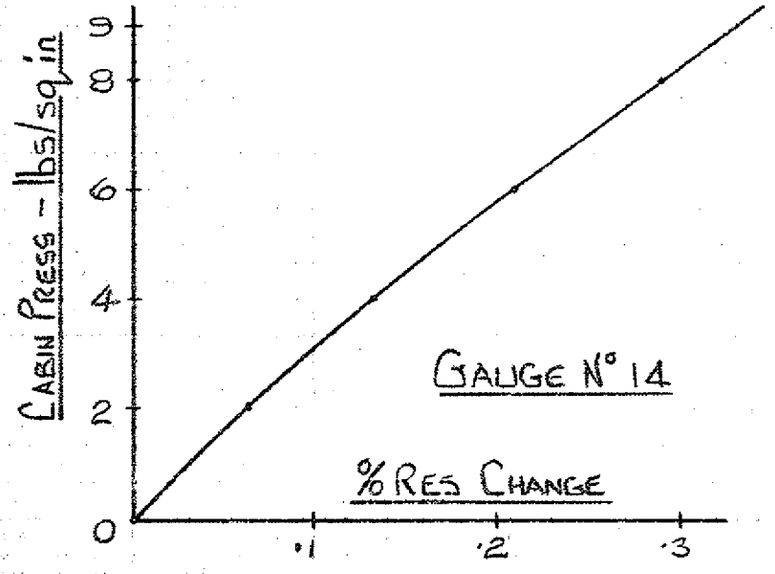
FIG 14

RD 3287/14

ISSUE No.	
DATE	

STRAIN GAUGE RESULTS





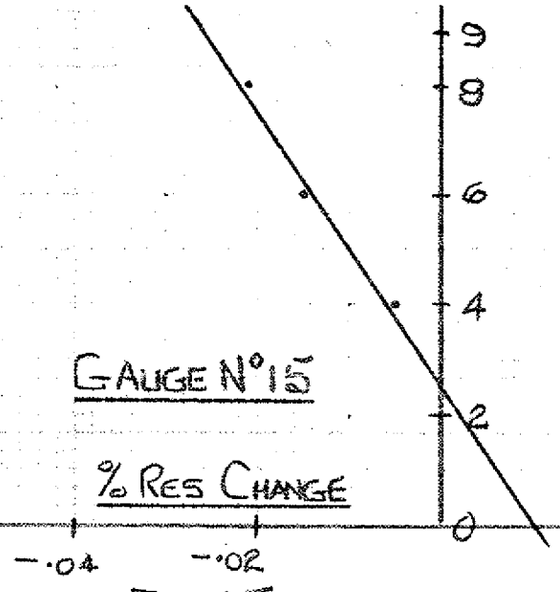


FIG 15

RD 3287/15

ISSUE No.	
DATE	

ISSUE No.						
DATE						

STRAIN GAUGE RESULTS

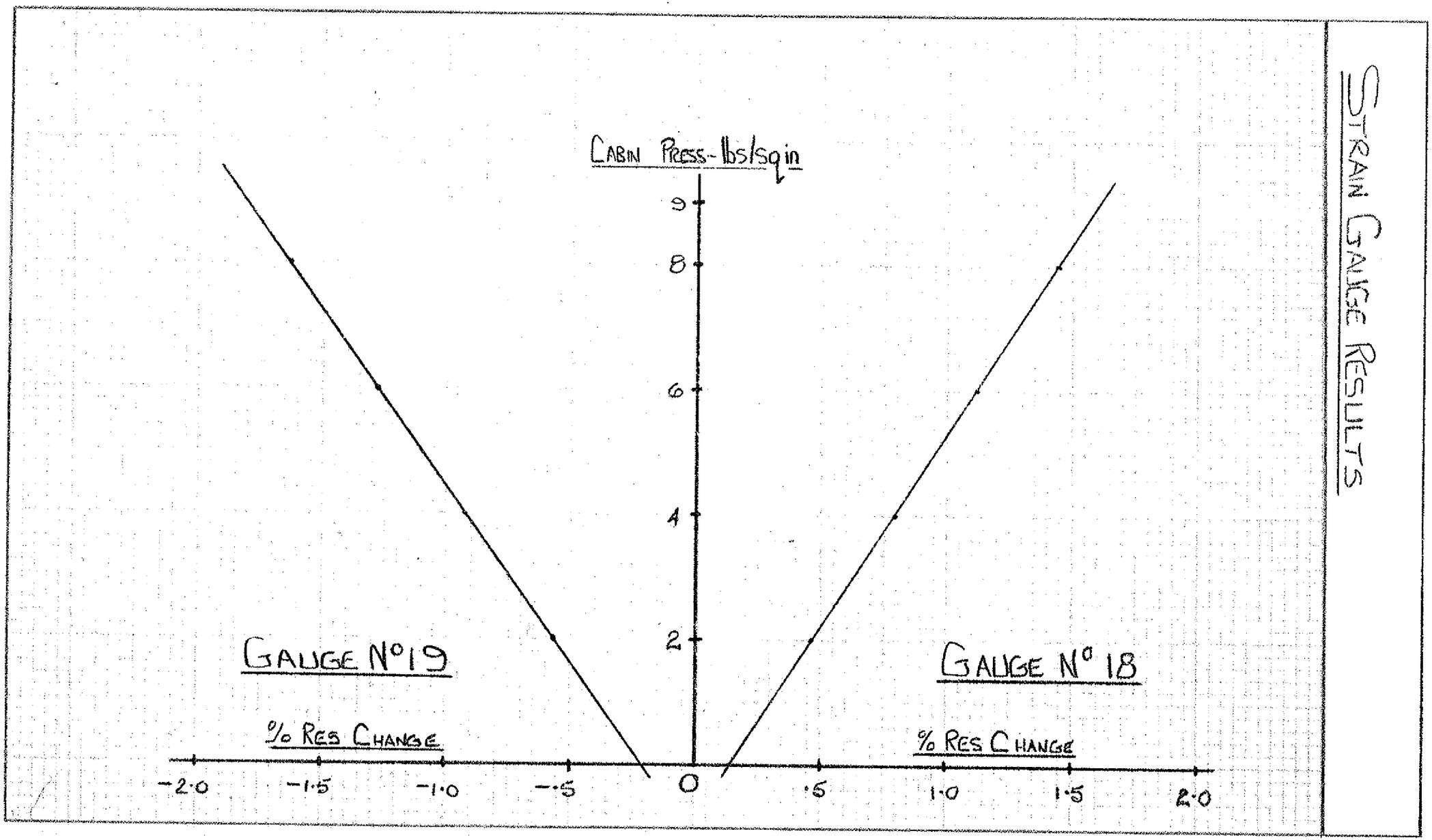
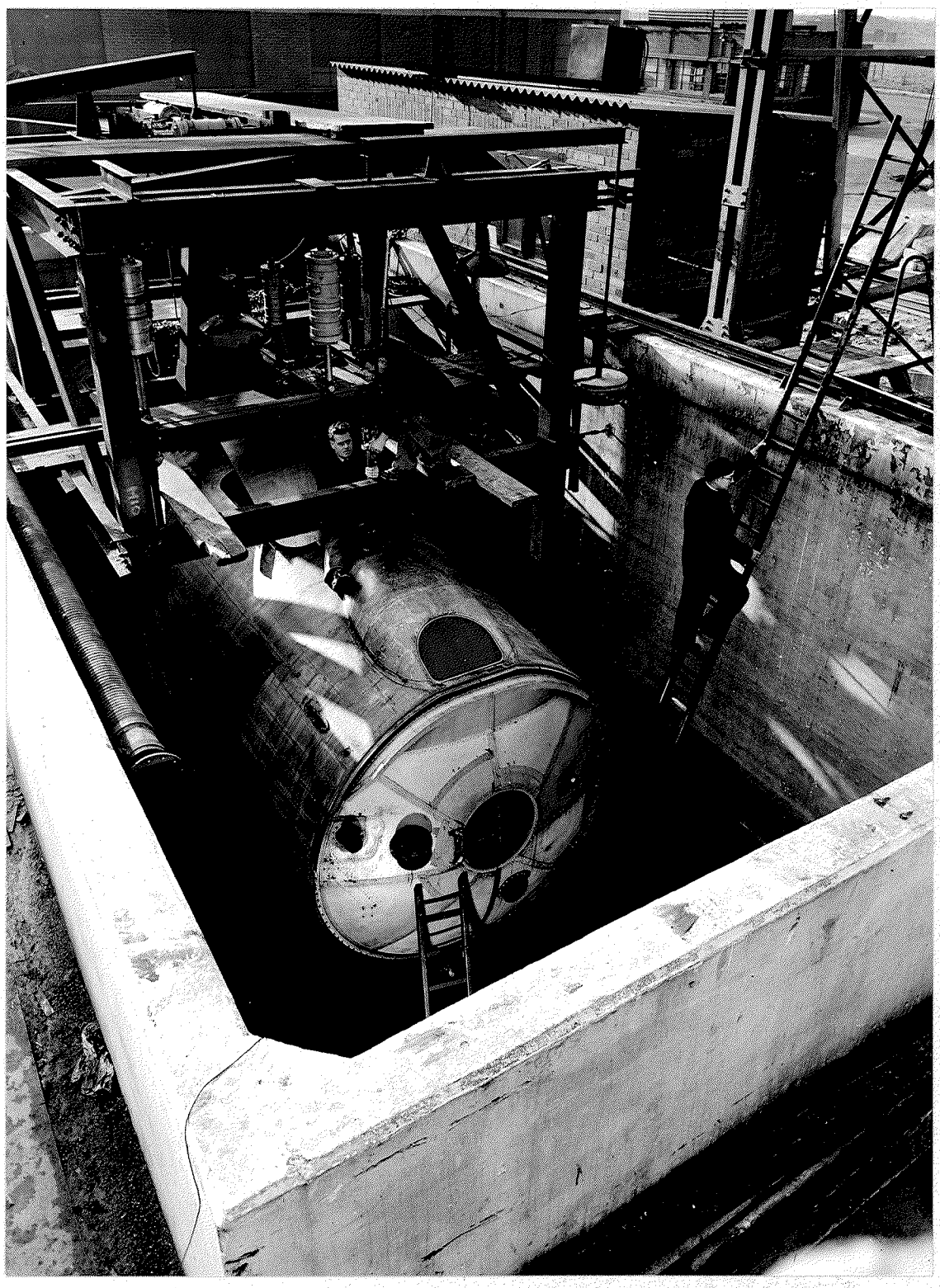
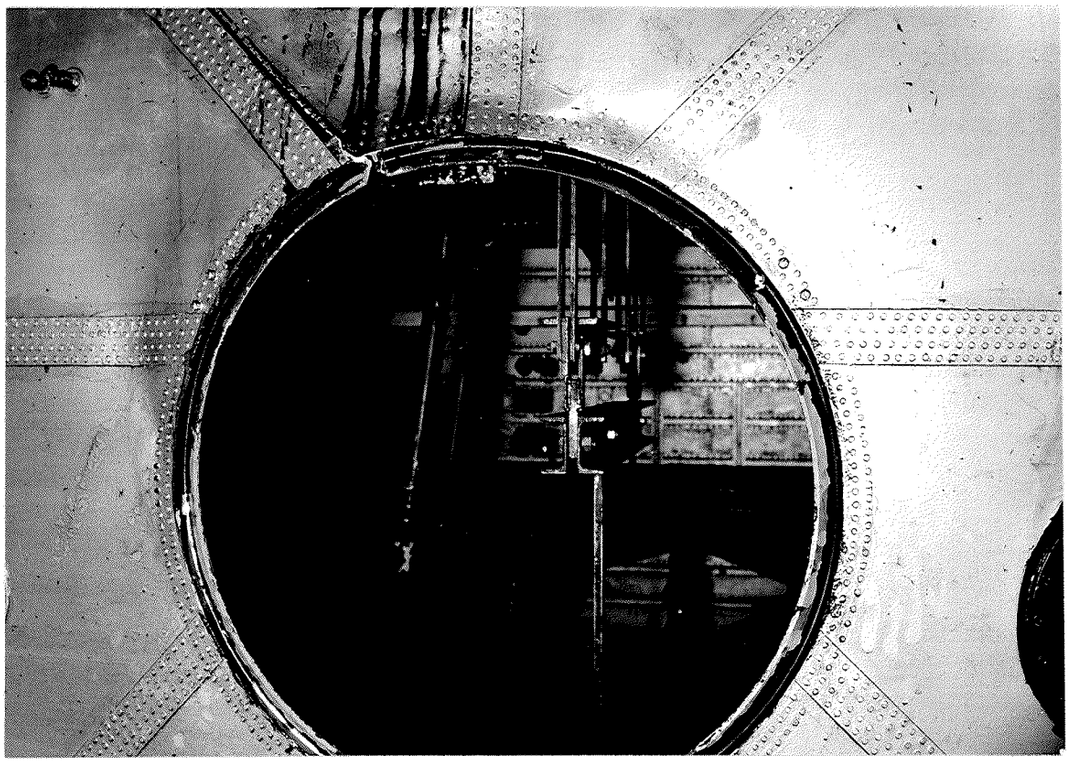


FIG 16

RD 3287/16

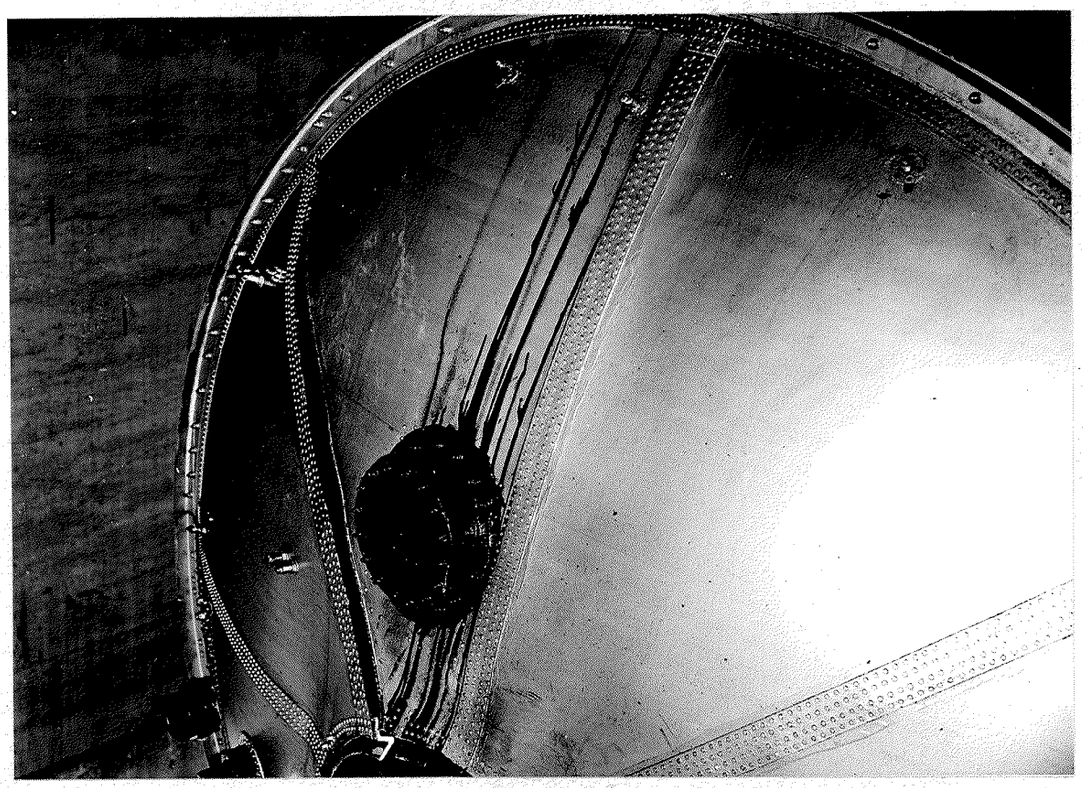
A. V. ROE & CO. LIMITED AVRO MANCHESTER





FAILURE OF ACCESS DOOR FRAME IN FRONT PRESSURE BULKHEAD (1063 FLIGHTS)

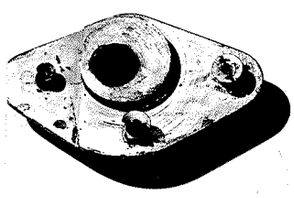
PLATE II



FAILURE OF PRESSURE BULKHEAD SEGMENT JOINT

SECONDARY TO ACCESS DOOR FRAME (1063 FLIGHTS)

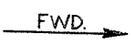
PLATE IIA

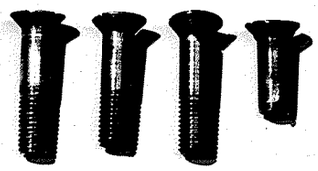


PORT AFT LOCATING BLOCK

PORT AFT BOLTS

PORT FWD. LOCATING PIN





STARBOARD AFT BOLTS

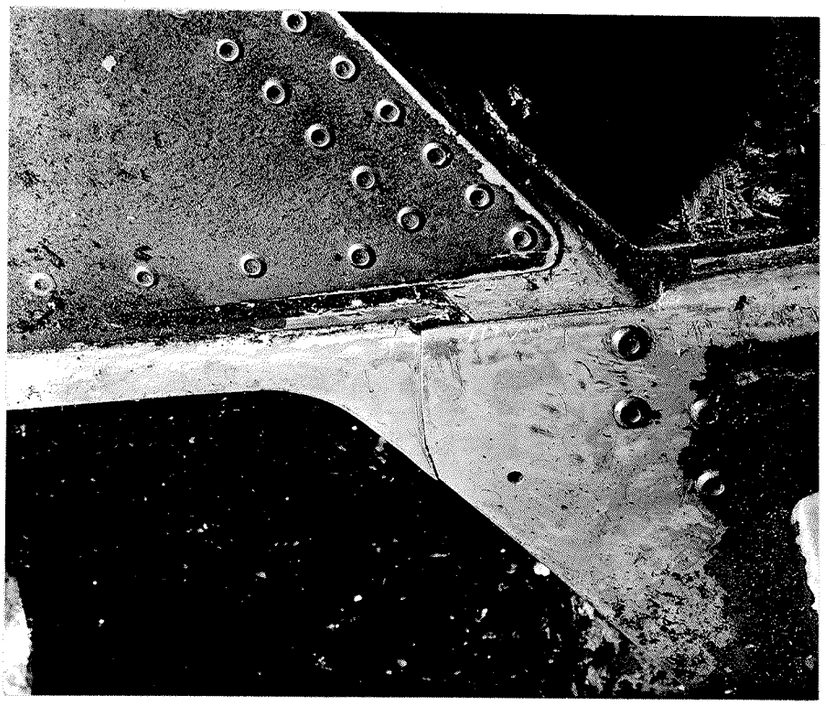
STBD. FWD. LOCATING PIN

FAILURES OF CANOPY CATCH BOLTS AND DOWELS (1605 FLIGHTS)

PLATE III

CRACK IN STARBOARD REAR COCKPIT RAIL UPPER SURFACE (1605 FLIGHTS)

PLATE IV



CRACK IN PORT REAR COCKPIT RAIL LOWER SURFACE (1605 FLIGHTS)

PLATE V

CRACK IN FORMER 316 ATTACHMENT TO COCKPIT RAIL STARBOARD (1605 FLIGHTS)

PLATE VI

CRACK IN FORMER 316 ATTACHMENT TO COCKPIT RAIL PORT (1605 FLIGHTS)

PLATE VII

CRACKING ACROSS CENTRE OF CREW'S ENTRANCE DOOR SKIN (2075 FLIGHTS)

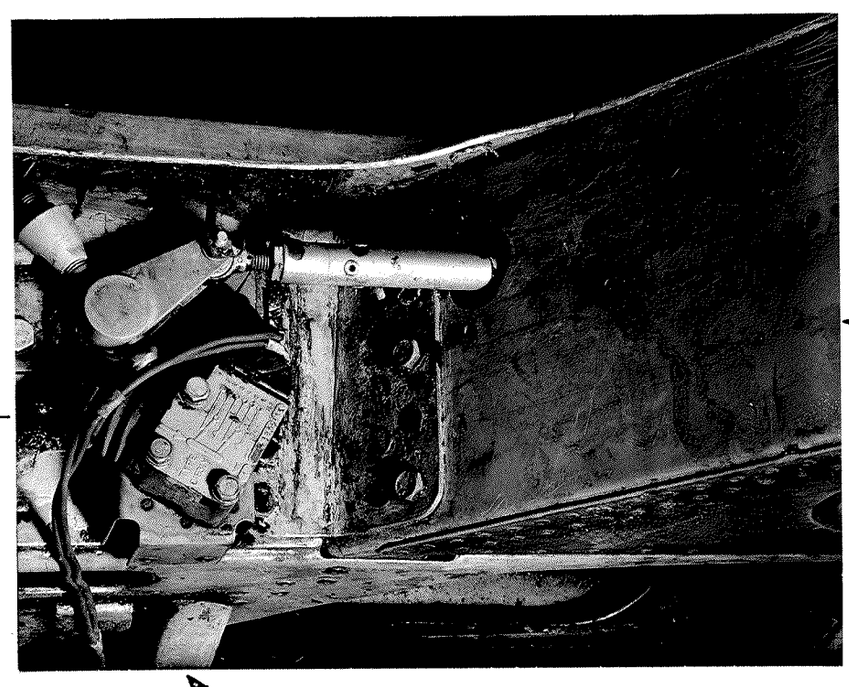
PLATE VIII

FAILURE OF PORT REAR COCKPIT CORNER OF COCKPIT RAIL (2217 FLIGHTS)

PLATE IX

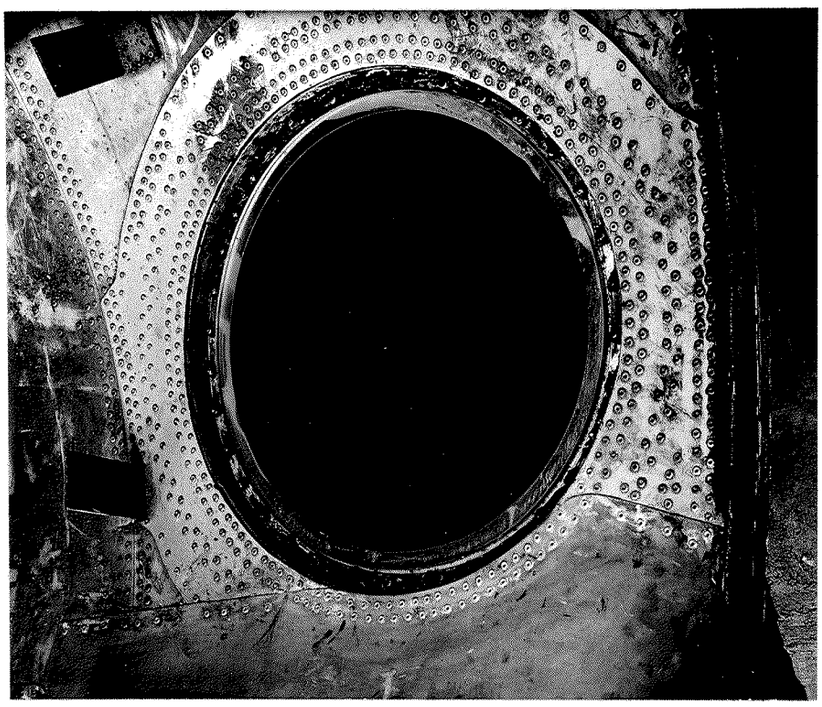
VIEW ON UNDERSIDE OF PORT COCKPIT RAIL (2217 FLIGHTS)

PLATE X



REAR CORNER OF STARBOARD COCKPIT RAIL (2217 FLIGHTS)

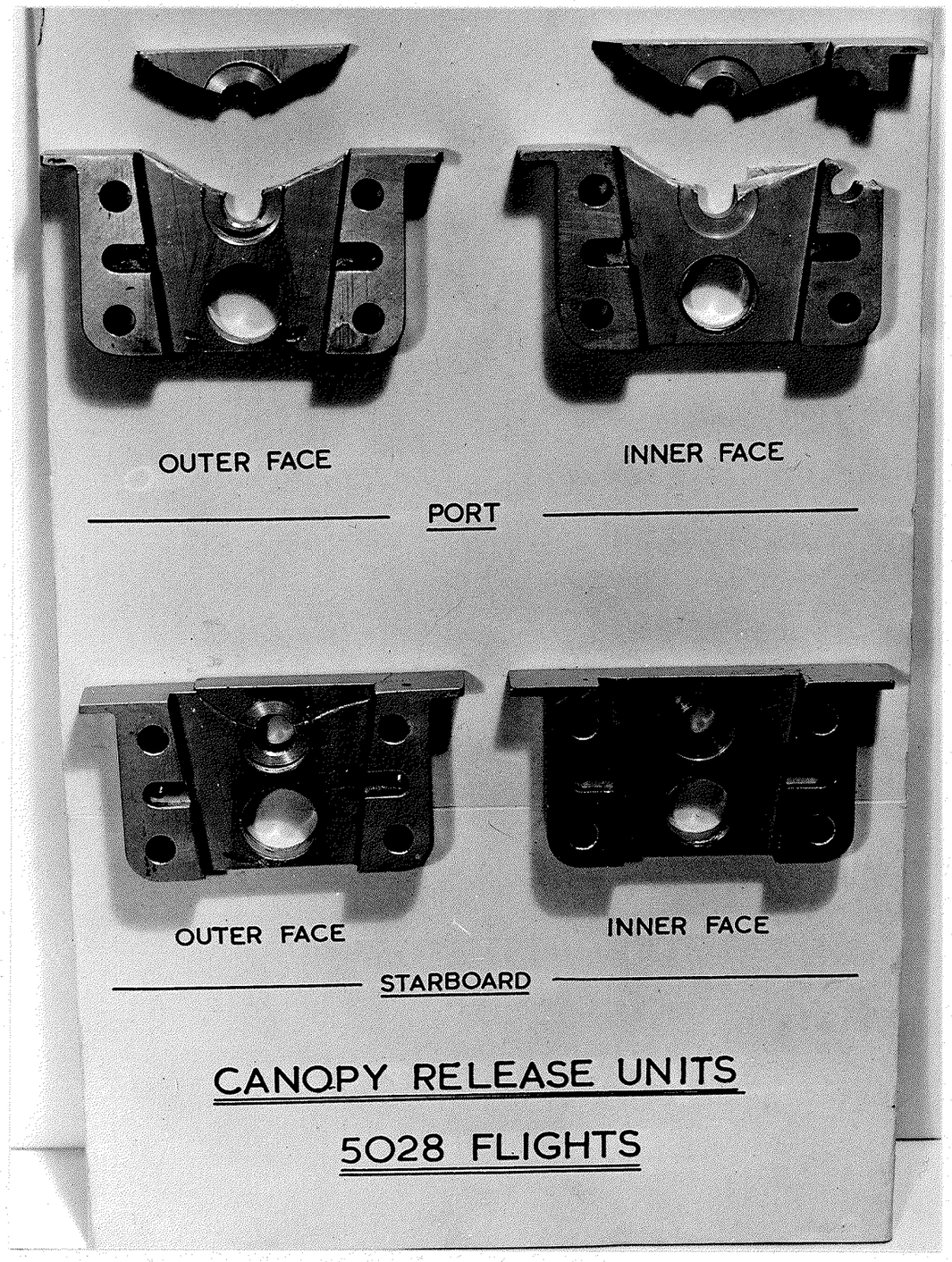
PLATE XI



PORT CANOPY SIDE WINDOW AFTER 2217 FLIGHTS

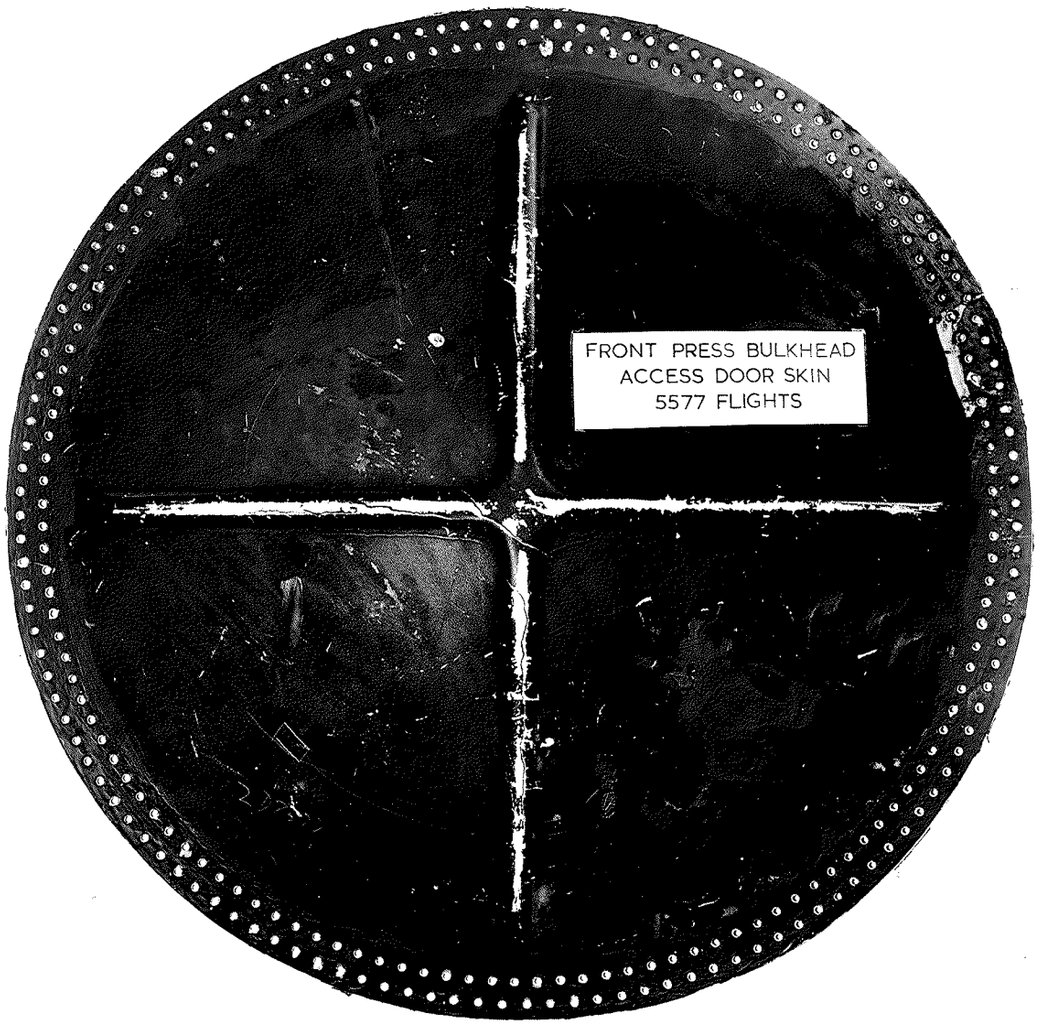
SHOWING TWO LARGE AREAS OF DELAMINATION

PLATE XII



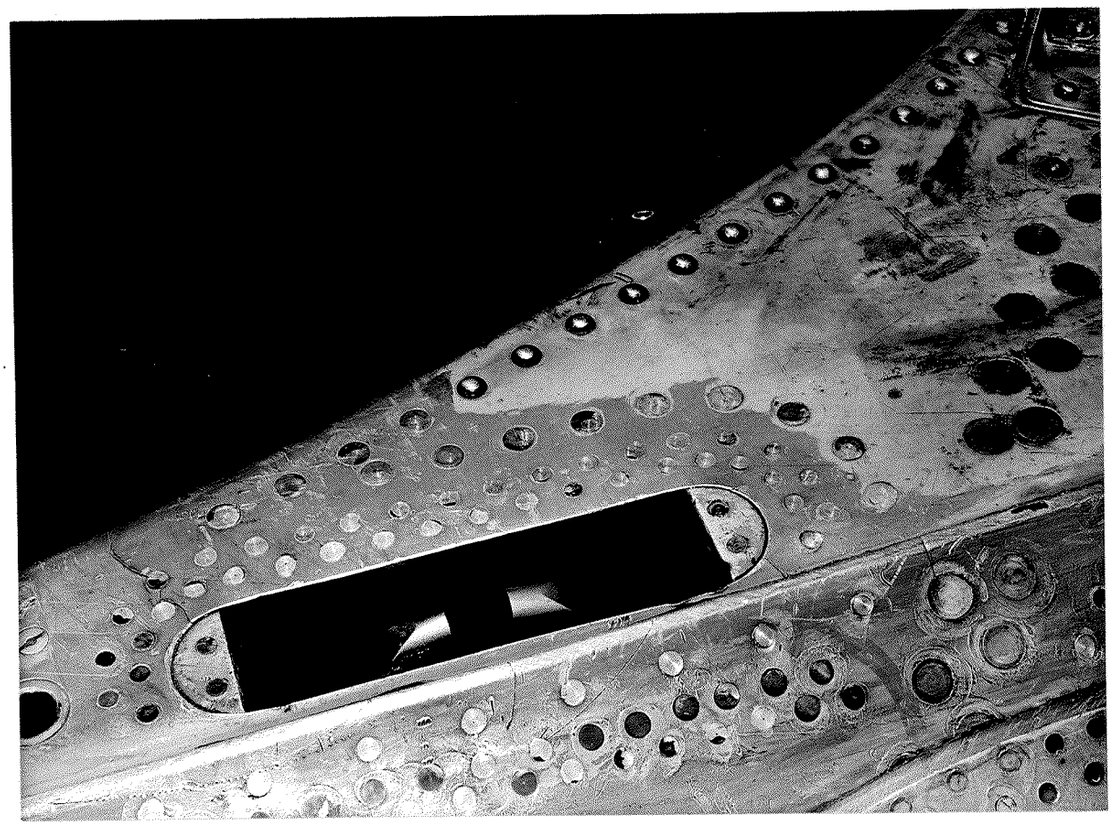
REAR CANOPY RELEASE UNIT HOUSINGS AFTER 5028 FLIGHTS

PLATE XIII



FRONT PRESSURE BULKHEAD ACCESS DOOR SKIN AFTER 5577 FLIGHTS

PLATE XIV



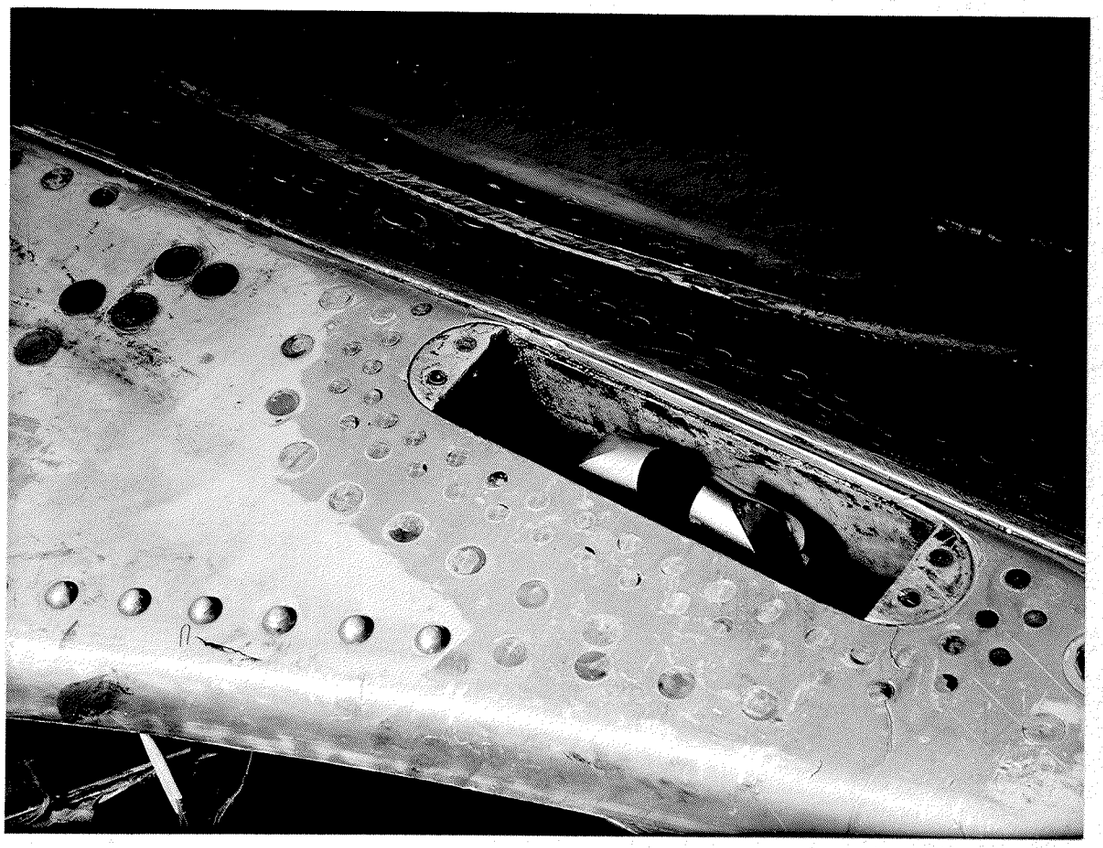
MODIFIED PORT COCKPIT RAIL (MOD 368) AFTER 4148 FLIGHTS.

NOTE FUSELAGE SKIN CRACK IN BOTTOM RIGHT HAND CORNER

AFTER 6365 FLIGHTS.

FAILURE IS IDENTICAL ON STARBOARD SIDE.

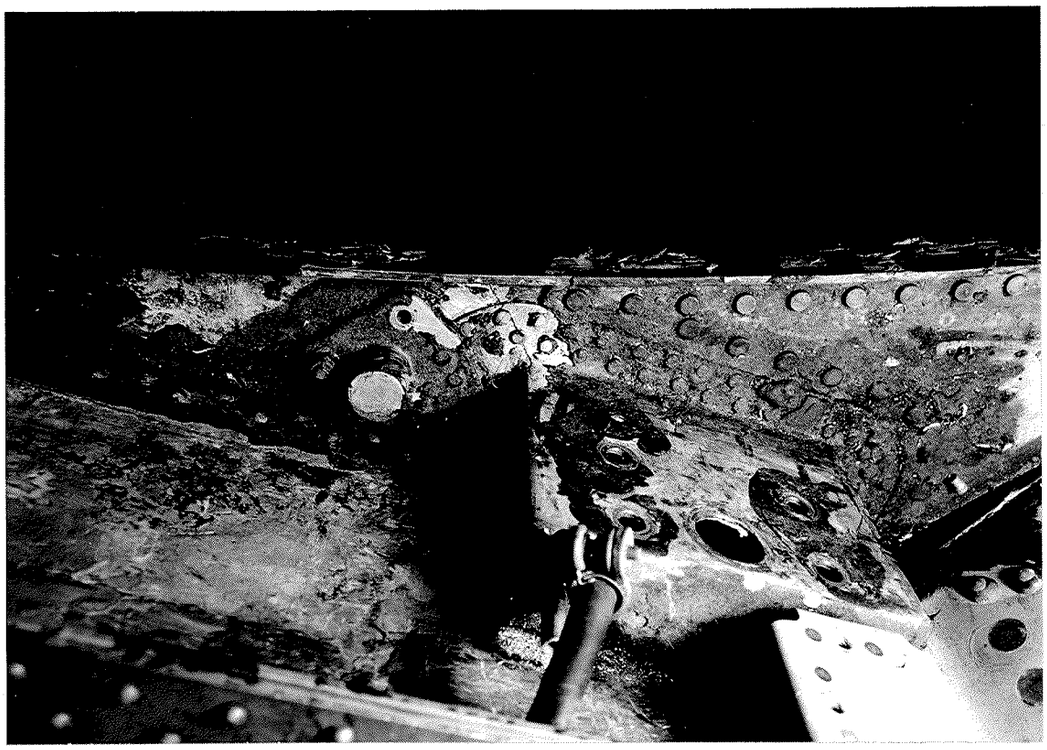
PLATE XV



VIEW OF PORT COCKPIT RAIL (MOD 368)

FROM INSIDE CABIN AFTER 4148 FLIGHTS.

PLATE XVI

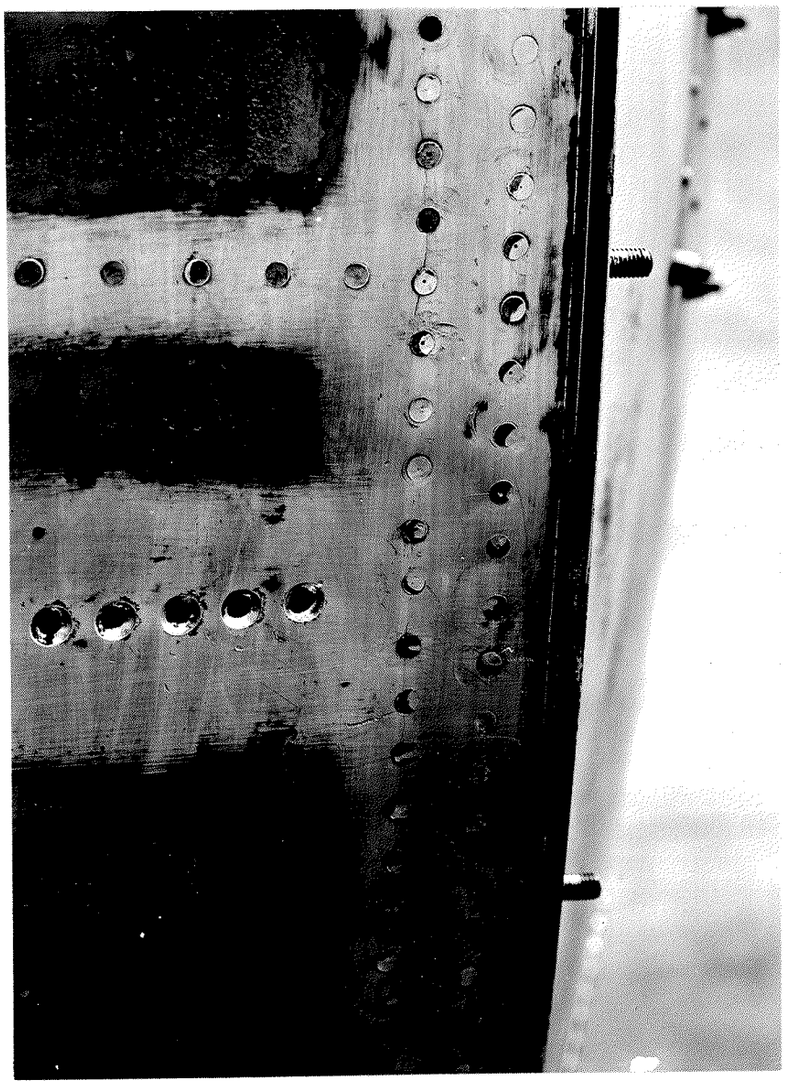


VIEW ON UNDERSIDE OF MODIFIED COCKPIT RAIL SHOWING CRACKING OF CANOPY CATCH SEALING BOXES AFTER 4148 FLIGHTS.

PLATE XVII

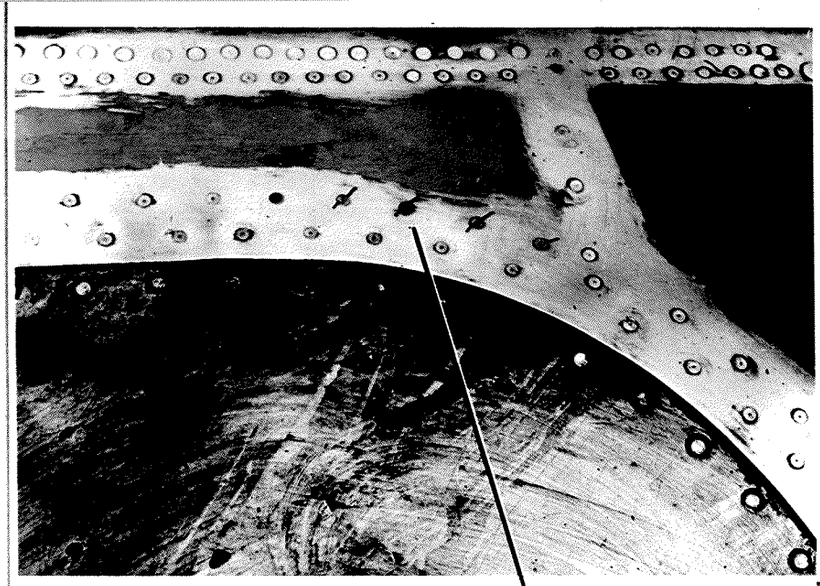
RIVET FAILURE AND CRACK AT STRINGER 7 (6677 FLIGHTS)

PLATE XVIII

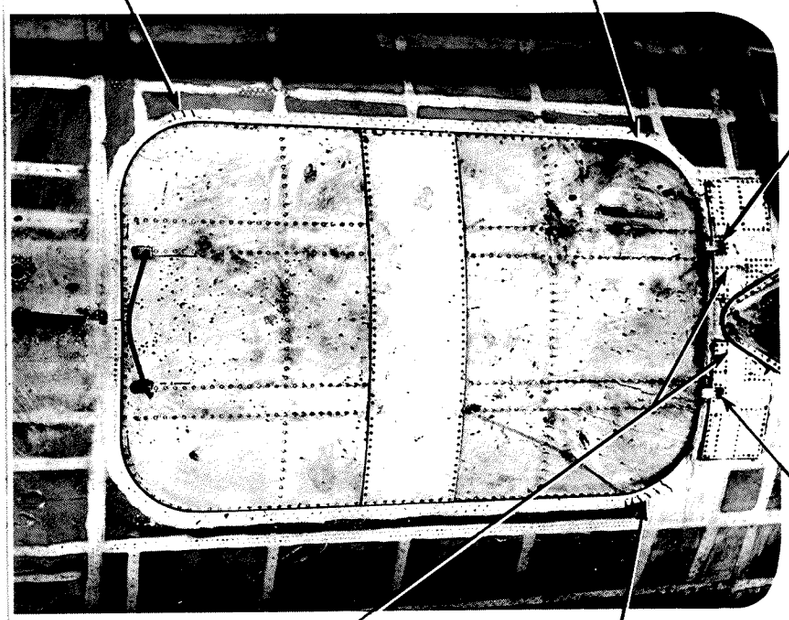


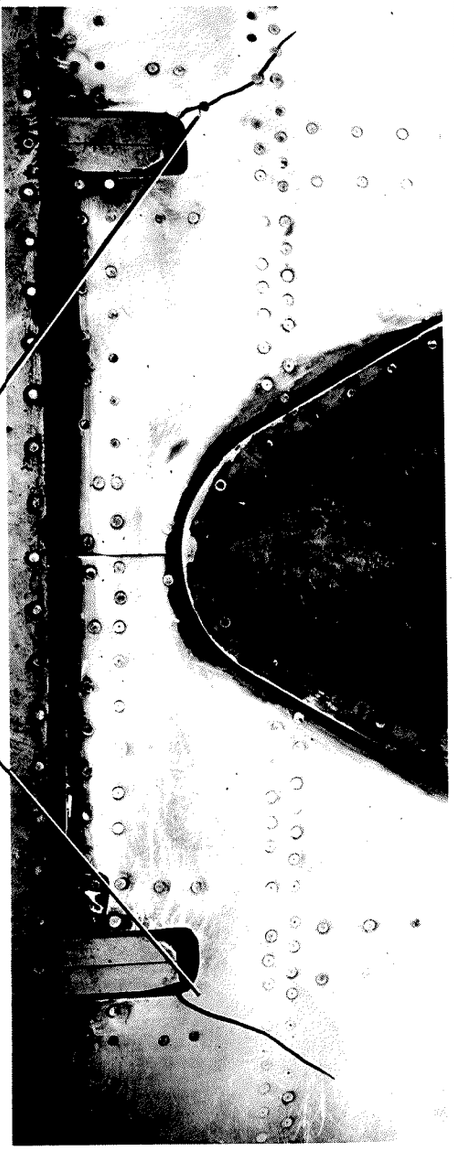
SKIN CRACKS BETWEEN STRINGERS 10 AND 12 (6677 FLIGHTS)

PLATE XIX



NOTE SIMILAR CRACKS AT AFT CORNERS.





THESE PATCHES FITTED OVER CRACKS

SHOWN IN RIGHT HAND PHOTOGRAPH.

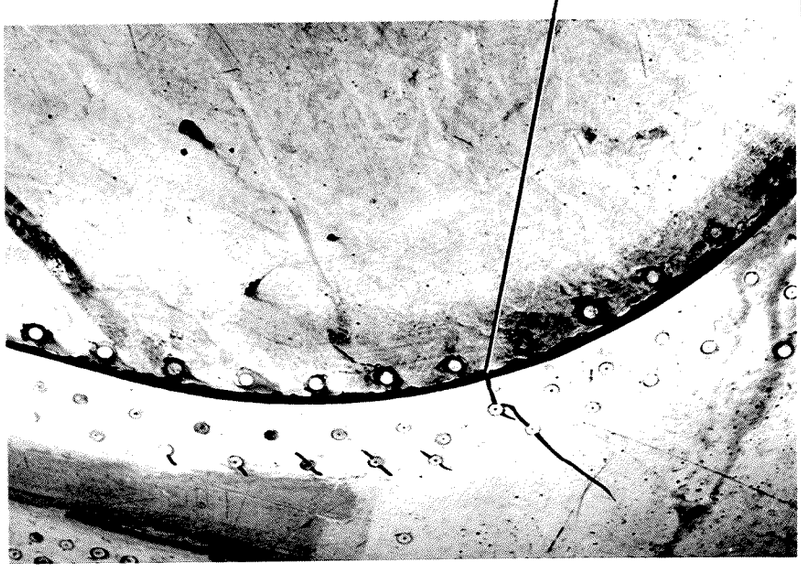


PLATE XX

CABIN SKIN CRACKS AROUND ENTRANCE DOOR. 6677 FLIGHTS.

CRACKS IN FUSELAGE SKINNING AT REAR END

OF BOMB AIMER'S BLISTER. (6677 FLIGHTS)

PLATE XXI

CRACKS IN FUSELAGE SKINNING AT REAR END

OF BOMB AIMER'S BLISTER. (6677 FLIGHTS)

PLATE XXI

FAILURE OF CABIN SKINNING AT PORT SIDE OF FRONT PRESSURE BULKHEAD. (7003 FLIGHTS).

PLATE XXII

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