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METALLURGY/STRUCTURAL GROUP CHAIRMAN
FACTUAL REPORT
SEQUENCING STUDY
(57 pages)

NATIONAL TRANSPORTATION SAFETY BOARD
Office of Research and Engineering
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METALLURGY / STRUCTURES SEQUENCING STUDY

Report No. 97-38

1.0 BACKGROUND

1.1 Accident

Place	: East Moriches, New York
Date	: July 17, 1996
Airplane	: Boeing 747-131, N93119
NTSB No.	: DCA96-M-A070

1.2 Components Examined

Primary Focus:

Wing Center Section (WCS)
Keel Beam
Fuselage Red Area Pieces

Secondary Focus

Outboard Wing
Other Fuselage adjacent to and aft of WCS

1.3 Group Description

The Metallurgy and Structures Sequencing Group was formed to evaluate the sequence of structural breakup of the airplane and to correlate proposed scenarios with the structural observations. The primary focus of this report is to address the wing center section (WCS) breakup sequence and any potential interaction or relationship with the fuselage "red area" breakup sequence[1]. In addition the report addresses overall airplane breakup sequence in somewhat less detail. The Group examined the airplane structure from December 2, 1996 to December 13, 1996, from January 7, 1997 to January 22, 1997, and from April 2 to April 8, 1997.

[1] See Structures Group Notes for further description of the recovery areas.

1.4 List of Abbreviations

WCS	Wing Center Section
SWB	Spanwise Beam
STA	Fuselage Station
BL	Buttock Line (lateral distance from centerline of airplane)
RBL	Right Buttock Line
LBL	Left Buttock Line
RHS	Right Hand Side
LHS	Left Hand Side

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3.0 INTRODUCTION

3.1 Sequence Study Methodology

The observations used in documenting the breakup sequence included the following features:

Recovery positions of the structure from the ocean (red, yellow, or green areas[2]) gave a clear indication that (1) the red area pieces (from the forward portion of the wing center section and the fuselage directly in front of the wing front spar) were the

[2] Red area, yellow area, and green area refer to search areas in the Atlantic Ocean from which pieces were recovered.

earliest pieces to separate from the airplane, (2) the forward fuselage section departed simultaneously with or shortly after the red area pieces, landing relatively intact in the yellow area, and (3) the green area pieces (wings, including major portions of the wing center section, and the aft portion of the fuselage, including empennage) remained intact for a period of time after the separation of the forward fuselage section, and impacted the water in a relatively small portion of the green area.

Differences in fire effects (soot accumulation on surfaces and fractures, changes in electrical conductivity) across pieces that are normally mated or adjacent to each other also indicated that the green area structure was exposed to significant fire effects after separation of the red area pieces and the forward fuselage. As will be discussed in section 10.0, the differences in fire effects indicated that the aft fuselage and wings broke apart from each other (referred to as a major airplane breakup in the remainder of this report) and that portions of these green area pieces were subjected to widespread significant fire damage (referred to as a major fire) after this major airplane breakup and before water impact.

The overall, large-scale effects described above yielded a general pattern of breakup of the airplane. The Group felt it was important to understand the manifestations of the general airplane breakup and subsequent fire because, by doing so, the earlier damage could be more readily isolated and understood. In addition to examinations leading to an understanding of the overall, larger scale effects, the Group also conducted detailed visual examinations, occasionally with magnifications up to 30X, of the separated structure in the wing center section and fuselage pieces from the red area to determine fracture directions, deformations associated with adjacent pieces, and witness marks. Fracture directions were based on chevron marks, river patterns[3] and branching cracks and gave information on initial areas of separation; deformation associated with a fracture indicated how the pieces on each side of the fracture were moving relative to each other as the fracture occurred; and witness marks demonstrated the direction of motion of structure as it separated and deformed. These features assisted in a further understanding of the early portion of the breakup sequence. Stress analysis was also used to provide confidence that proposed scenarios were consistent with structural properties and expected failure modes.

The basic narrative of the main part of this document is intended to represent a summary report. The figures referred to in the basic narrative are found in Appendix A. A more detailed rationale for the sequence elements for most components may be found in Appendix B. This document refers to sooting patterns, fire damage, and structural damage and description throughout. Limited sooting diagrams and structural diagrams are provided in figures and appendices A and B. For a more detailed accounting of these features refer to the Fire and Explosion Group and Structures Group documentation.

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[3] Chevron marks and river patterns are visible fracture features that indicate local fracture propagation direction.

A summary of fatigue cracks discovered in the structure is found in appendix C. Stress analysis calculations supporting various portions of the developed sequence is found in appendix D. Boeing stress analysis of wing safety margins under various conditions and initiation of fracture of the fuselage in front of the wing center section is provided in appendix E.

3.2 Description of Wing Center Section

The wing center section (WCS) is a large box with an airfoil shape generally corresponding to the shape of the inboard wing. The WCS is bounded by the wing front spar, wing rear spar, side-of-body ribs, and upper and lower panels. Spanwise beams #1, #2, #3, and the midspar form intermediate inboard-outboard beams. There is a fore and aft beam at the airplane centerline between the rear spar and the midspar. Most of the internal volume of the WCS, the volume between the rear spar and spanwise beam #3, forms the center fuel tank on a 747-100. The remaining volume of the WCS, between spanwise beam #3 and front spar, is a dry bay and does not contain fuel in the 747-100. See figure 3-1 for a WCS schematic.

The Group examined wreckage that had been recovered and identified from the WCS in four separate reconstruction mock-ups. The WCS upper panel, rear spar, spanwise beam #1, midspar, centerline rib, spanwise beam #2, and spanwise beam #3 formed one reconstruction. The front spar, forward most lower panel pieces, keel beam, and adjacent fuselage pieces from the red area (minus the upper lobe pieces) formed a second reconstruction. The remaining WCS lower panel was reconstructed separately in a third area. Finally, the Sequencing Group reviewed the WCS as part of the reconstruction of the entire fuselage and WCS structure from STA 510 to STA 1630.

The upper and lower panels were more than 95% recovered and identified. Recovery and identification of other major components ranges from 95% to approximately 65% on spanwise beam #2 and less than 30% on the left side-of-body rib.

Approximately 70% of the front spar, 60% of spanwise beam #3 and the manufacturing access door from spanwise beam #2 were recovered from the red area indicating relatively early departure from the airplane.

3.3 Description of the Fuselage Red Area Pieces

The fuselage pieces recovered from the red area are enveloped between the wing front spar at fuselage station (STA) 1000 and STA 741. The fuselage red area pieces were examined in two separate reconstructions. Those generally below the main deck window level were included in the reconstruction mockup with the wing front spar bulkhead and pieces of fuselage from the green area. Upper lobe fuselage red area pieces were laid out on the floor relative to each other. The basic fuselage skin on the pieces recovered from the red area is more than 95% recovered. The discussion of the sequence for the fuselage red area pieces is contained in section 6.0.

4.0 WING CENTER SECTION SEQUENCE

4.1 Upper WCS Panel Sequence

The upper skin panel of the WCS is more than 95% recovered and identified with several missing areas on the far left side and two small missing areas in the middle. All identified pieces of the upper panel were found in the green area. However, there are dramatic differences between the left side (clean) and right side (sooted) on both the top and bottom surfaces of this panel. A close examination of sooting on both surfaces and mating fracture faces yields a definition (see figure 4-1) of material departing with the left wing (minimal sooting) versus right wing (fire damage or heavier sooting) at the time of major airplane breakup. Intermediate soot patterns indicate that there is an area of upper panel material between the left side of body and approximately LBL 34 that either separated independently during wing breakup or remained attached to the right wing / aft fuselage for a time after major airplane breakup.

The reconstructed upper panel showed a multiple wave shape, consistent with spanwise compression buckling. In addition, the longitudinal fractures in the upper panel are generally typical of bending (buckling) overstress separations. The longitudinal compression buckling fractures are directly adjacent to the left side of body rib over the aft portion of the upper panel. These fractures and the compression buckling are indications of upward bending loads on the wings at "G" levels beyond the structural capability. Stress analysis (see appendix D) would also indicate that early loss of the front spar and spanwise beam #3 would significantly reduce the ability of the more forward upper panel to carry compression loads but would not initiate overall panel collapse under nominal flight loads.

4.2 Lower WCS Panel Sequence

The lower skin panel is more than 95% recovered and identified with small missing pieces on the left side and right middle area. The sooting patterns on the lower surface of this panel varies from light to heavy in different areas over essentially the entire lower surface, but with the heaviest accumulation of soot on the right side of the lower surface. The upper surface shows more localized areas of heavy sooting with some areas clean. The soot patterns on the upper and lower surfaces and on the fracture faces also indicate a delineation between material separating with the left wing versus the right wing as shown in figure 4-2. Fracture features along this line of delineation are typical of a tensile and/or bending overstress, also consistent with wing up bending.

In addition to the presence of heavy soot accumulation associated with a major fire after major airplane breakup, there are two additional sooting patterns that suggest prior fire sources: (1) Sooting on the lower surface of the lower panel, including some heavy sooting adjacent to the left side-of-body, and (2) heavy sooting on the right portion of the upper surface of piece CW221 (generally between SWB#2 and the front spar, and right of BL0).

4.3 Right Side-of-Body Rib Sequence

The right side-of-body rib is more than 75% recovered and identified with a number of small pieces which cannot be accurately placed in the reconstruction. The rib has moderate to heavy sooting on the inboard surface of the areas between SWB#2 and the front spar. The rib stayed with the right wing on major airplane breakup with most fractures probably occurring on water impact.

4.4 Left Side-of-Body Rib Sequence

Only a small percentage (less than 30%) of the left side-of-body rib has been recovered and identified, essentially all of which is between the rear spar and SWB#2. Identified pieces are broken into small fragments with negligible sooting. The lack of sooting indicates that the recovered and identified portions of the left side-of-body rib stayed with the left wing following major airplane breakup. Breakup of the rib into a large number of fragments is consistent with water impact, similar to the fragmentation that occurred to the left inboard upper wing skin (see section 8.1). Both the side-of-body ribs and the wing upper skin are comprised of 7075 aluminum alloys with characteristic high strength and relatively low elongation properties compared to the lower skin.

4.5 Rear Spar Sequence

The rear spar is approximately 90% recovered and identified with missing pieces mostly on the left side (LBL 57 to LBL 98) and a small area on the right (RBL 22 to RBL 33). Both the forward and aft surfaces of the rear spar are sooted to the right of LBL 21 (very heavily between LBL 21 and RBL 63). A review of sooting, fracture morphology, and interface with upper and lower panels indicates that at major airplane breakup, the pickle fork fitting on the left side of the spar remained attached to the left wing, the lower chord and that the spar generally to the right of LBL 21.5 departed with the right wing (see figure 4-3). A portion of the spar between the left side pickle fork fitting and LBL 21.5 either separated independently or remained attached to the right wing/aft fuselage for a period of time. No identifiable indications of damage or sooting prior to major airplane breakup could be documented.

4.6 Spanwise Beam #1 Sequence

Spanwise beam #1 (SWB#1) is approximately 90% recovered and identified, with the majority of missing material on the right side and the remainder mostly distributed full span across the lower portion of the beam. Sooting varies from clean to heavy on both the forward and aft surfaces of SWB#1 with a number of mating fracture faces equally sooted. A review of sooting patterns, electrical conductivity readings, and crack morphology indicates there were likely multiple failures at the time of major airplane breakup (RBL 66 to LBL 57). The portion of SWB#1 between the left side of body and approximately LBL 57 either separated independently during wing breakup or remained attached to the right wing for a time after major airplane breakup (see figure 4-4).

The access doors on both sides of centerline have consistent edge band deformations between fasteners and consistent patterns of soot moving aft through the openings. This is indicative of an earlier event forward of SWB#1 involving overpressure while the wing center section was still relatively intact. The presence of sooting and its highly consistent nature are indicative of the presence of sustained fire and soot following initial overpressure and preceding major airplane breakup. Deformations and soot patterns on the left side door are more pronounced than on the right side door. This lack of uniformity suggests that the centerline rib between SWB#1 and midspar may have been at least partially present when an overpressure event occurred.

4.7 Midspar Sequence

The midspar is approximately 75% recovered and identified with areas missing on both left and right sides. Sooting (light to heavy) is generally present on the forward surface (RBL 67 to LBL 44) and aft surface (RBL 67 to LBL 98). Sooting of mating fracture faces, crack morphology, and deformation patterns indicate that the midspar failed at LBL 44 consistent with compression buckling during major airplane breakup, with the area to right going with right wing and remainder with the left wing (see figure 4-5). Relatively minor sooting outboard of LBL 44 on the aft surface is another indication of an earlier event involving fire/soot between SWB#1 and midspar (see discussion on SWB#1, section 4.6). The midspar did not contain indications of differential pressure between the forward and aft sides.

4.8 Centerline Rib (BL 0.00 Rib)

Approximately 90% of the centerline rib between the rear spar and SWB#1 has been recovered and identified but only 40% of the rib between SWB#1 and midspar (see figure 4-6). The section between rear spar and SWB#1 is heavily sooted on forward, aft, and upper fracture faces. The pieces between SWB#1 and midspar are equally heavily sooted on both the left and right surfaces and most fracture faces. Sooting and the location and features of fractures indicate the centerline rib remained with the right wing at major airplane breakup. Definitive damage or sooting prior to major airplane breakup could not be identified, however see the sections on SWB#1 (section 4.6) and the midspar (section 4.7) for discussion of indications of earlier damage on these components, which may have also related to the centerline rib. There were indications described of an overpressure acting aft on SWB#1 and early presence of fire or soot ahead of SWB#1, either of which might have affected the centerline rib.

4.9 Spanwise Beam #2

Spanwise beam #2 (SWB#2) is approximately 65% recovered and identified with most of the left side still missing (see figure 4-7). The manufacturing access door and a small attached portion of web above the door were recovered from the red area indicating early departure from the airplane. The door fasteners on the bottom and left (inboard) sides of the door were separated mostly in vertical shear (door along with upper and outboard surround structure moving up and the remaining surround structure moving down relative to each other). The remainder of the door fasteners were fractured in tension by the door peeling forward and upward, finally tearing out a small portion of the upper web above the door. Witness marks found on the upper panel corresponded to deformation in the lower inboard corner of the door, indicating that the door separated upward with enough velocity to create this damage. Final separation of the door (peeling upward in the forward direction) indicated that the pressure on the aft surface of the door was significantly greater than the pressure on the forward surface of the door at that time. The access door is only lightly sooted, while sooting is moderate to heavy over most of the other pieces of the beam, consistent with much more substantial fire exposure after separation of the access door. The soot patterns indicated that most of the identified pieces of SWB#2 (with the significant exception of the access door) remained attached to the right wing at major airplane breakup.

A large portion of the right side of SWB#2 remained attached to the upper skin panel. Soot patterns indicate that the lower chord remained attached to the web until water impact but was separated from the lower skin panel before major fire exposure. In general, the features on the right side of the beam indicated that this entire portion of the beam remained largely intact but had separated from the lower panel before fire exposure. Recontact damage and separation of the web from the lower chord occurred after fire exposure.

The right side of SWB#2 also contained "accordion" damage (folding directly inboard) from forces acting in the inboard direction on the outboard end of the beam. No soot accumulation occurred after the deformation was created (see appendix B).

Close attention was directed to the keel beam interface (see Appendix B) where fracture of the two major tension bolts was due to a tensile overload (consistent with downward motion of the forward piece of keel beam as described in section 5.1). Early events associated with SWB#2 included the previously discussed initial separation of the manufacturing access door surround structure in shear and tensile separation of the fasteners common to the SWB#2 lower chord and lower panel. These features could be consistent with either a large downward load imparted by the keel beam tension bolts or overpressure acting approximately in equal amounts in the bays ahead of and behind SWB#2.

4.10 Spanwise Beam #3

Spanwise beam #3 (SWB#3) is approximately 85% recovered with most of the missing area located between RBL 50 and RBL 90 (see figure 4-8). Pieces of the beam between approximately RBL 50 and LBL 80 were recovered from the red area indicating relatively early departure from the airplane. The part of SWB#3 from RBL 87 to right side-of-body is heavily sooted (burn damage) on both surfaces as well as most fracture faces. The pieces recovered from the red area are generally lightly sooted on both faces with occasionally more sooting on the front face. The pieces between LBL 80 and the left side-of-body (green area) are moderately sooted. Piece CW611 (adjacent to the left side-of-body) exhibits soot tails above the protruding fastener heads on the front surface. During major airplane breakup the pieces outboard of LBL 80 went with left wing and the pieces outboard of RBL 75 with right wing. The sooting on the aft surface on the left side and on red area pieces is indicative of an earlier event. Larger amounts of soot accumulation and fire damage on the right wing pieces indicate that this portion of the structure was involved in a later major fire. The soot and fire damage associated with the later major fire masked any possible features that may have been associated with a possible earlier fire affecting the pieces of SWB#3 to the right of RBL 57.5.

SWB#3 contains vertical stiffeners on the aft face of the web. Approximately every third stiffener is attached to the upper skin at a (forward to aft) floor beam location over the upper skin panel of the WCS. The upper chord of SWB#3 has a "Z" shape, with the upper horizontal leg pointing aft.

The upper chord for SWB#3 was fractured through the fillet radius between the vertical leg and the upper horizontal leg of the chord. The upper chord fracture initiated at multiple locations and progressed essentially the full width of the beam.

Witness marks and deformation associated with separated fasteners for the stiffener fittings at the top of the beam were indicative of both an upper motion of the upper skin panel and a forward motion of the upper portion of the beam as this area separated. Initial separation of the upper portion of SWB#3 was consistent with overpressure on the aft face of the beam, causing the upper panel of the WCS to move upward a small distance as the upper portion of the beam rotated forward.

Initial forward rotation of the upper portion of SWB#3 caused the upper chord of this beam to impact the aft face of the vertical portion of stringer 29, located 6 inches in front of SWB#3. This stringer also has a "Z" shape, with the upper horizontal leg pointing aft and the lower horizontal leg pointing forward. The upper horizontal leg of stringer 29 remained attached to the upper skin over most of the width of the WCS. The vertical leg had separated from the upper horizontal leg at the fillet radius. Only three pieces of the vertical leg of stringer 29 have been identified to date. These pieces extended from LBL 50 to RBL 36 and from RBL 55 to RBL 104. Except for small pieces attached to the vertical portion, no pieces of the lower horizontal leg were identified.

The aft surface of the recovered pieces of the vertical leg of stringer 29 contained an intermittent witness mark corresponding to impact from the upper edge of the upper chord of SWB#3. Closer to the centerline of the airplane, the witness mark was about 0.9 inch from the bottom of the vertical flange of the stringer. Geometrical layout of SWB#3 and the upper and lower skin panels indicated that the forward rotation of SWB#3 about its lower end would result in an impact on the vertical flange of stringer S-29 at a point approximately 1.8 inches above the lower edge of the stringer, assuming no relative vertical motion between the upper skin and SWB#3. The difference between these two values (1.8 inches minus 0.9 inch) therefore represents a vertical displacement of 0.9 inch between the upper and lower skin panels along the centerline of the wing center section at SWB#3 at the time SWB#3 impacted stringer 29. The distance of the witness mark from the bottom of the vertical flange of stringer 29 gradually increased at positions further outboard, to approximately 1.4 inch at BL 104, indicating lesser amounts of vertical displacement outboard of the centerline.

Vertical fractures through SWB#3 were found at various locations including near the respective sides-of-body. These fractures are also consistent with a forward acting overpressure on the aft surface of SWB#3. Separation of the top of the SWB#3 allowed the segments to rotate forward about the lower intercostals (or, in the case of the center segment, about the beam's lower chord) until the top of the beam impacted the stiffeners on the aft surface of the front spar approximately 12" below the upper skin panel. The impact broke off parts of the upper web and stiffeners of SWB#3. The remaining lower portion of SWB#3 continued rotating forward and down with upper stiffener ends tearing vertical holes in the front spar web at various locations down to about 1 to 2 feet from the lower panel.

Following separation of the upper end of SWB#3 from the upper panel of the WCS, the forward rotation of the upper end of SWB#3 resulted in tension fitting separation at the interface with the keel beam (see appendix B, page SWB3-3 and associated figures B-6 and B-7) without separating the tension bolts for these fittings. Separation of the fittings at this time resulted in free play of about 0.65 inch in the bolts. Downward movement of the keel beam (later in the sequence, as described in section 5.1) took up the free play and separated these tension bolts.

4.11 Front Spar Sequence

The front spar is more than 95% recovered and identified (see figure 4-9). Pieces of the front spar between approximately RBL 50 and LBL 110 were recovered from the red area indicating they departed the airplane as part of a relatively early event. One piece, CW 504 from left side was recovered to the west of all other major structure in the red area. There is localized heavy sooting on the forward surface of the lower right portion of the front spar outboard of the wing leading edge vapor seal rib and around the dry bay access opening, primarily below and outboard of the ring chord. The pieces of the front spar that were recovered from the red area have minimal sooting. The front spar outboard of RBL 66 went with the right wing during major airplane breakup while that outboard of LBL 110 went with the left wing.

As discussed in section 4.10, SWB#3 rotated forward impacting the vertical stiffeners on the aft surface of the front spar. The impact, along with possible overpressure from behind SWB#3 fractured the front spar upper chord in the radius between the horizontal and vertical legs of the chord. The horizontal leg of the chord remained attached to the upper skin panel, and the vertical leg remained attached to the web of the front spar. Continued forward and downward rotation of SWB#3 tore holes in the front spar web, at various locations down to about 1 to 2 feet from the lower panel. Geometric layouts (see Appendix B) indicate that SWB#3 probably rotated almost fully forward and down prior to full rotation of the front spar about its connection to the WCS lower panel. The potable water bottles (centered on the front surface of the front spar) sustained relatively minor damage on their aft sides from impact with pieces of SWB#3. The forward side of the right bottle contained impact marks and fractures roughly corresponding to cargo floor structure. A geometric layout indicates that only about 10 degrees of rotation of the front spar would be needed to force contact between the bottles and the cargo floor structure (see figure 4-10).

Forward rotation of the front spar about its lower end is consistent with overpressure loads released by SWB#3 as it rotated forward. Deformations in the upper chord of the front spar were in a symmetric "sine wave" shape, with a lobe bulged forward on each side of center. Forward deflection amplitude was maximum at approximately LBL 66 and RBL 66 and minimum at the approximate center of the span of the spar (corresponding to the potable water bottle locations). Tension separations of the vertical leg of the front spar upper chord were found in multiple locations (LBL 66 and RBL 48, see figure B-12 in appendix B) corresponding to the forward bulges on each side of center. These separations are consistent with tension generated by the stretching of the vertical leg of the upper chord as the upper portion of the front spar rotated forward. Vertical fractures through the front spar web progressed downward to the front spar lower chord. Compression buckling of the vertical stiffeners attaching the front spar to the lower pressure bulkhead (located below the front spar and above the ring chord, see figure 4-11) indicates that separation of the front spar pieces from the lower skin panel and the lower pressure bulkhead was as a result of forward rotation of the front spar pieces about the lower chord caused by impact loads and/or pressure loads on the aft surface of the spar.

The front spar is attached to the keel beam through four bolts (5/16" diameter) through fittings on the aft edge of the front spar stiffeners above the keel beam. Tension separation of these bolts is consistent with the forward rotation of the front spar.

Close examination revealed small pre-existing fatigue cracking areas in the upper and lower shear ties for the stiffeners on the aft surface of the front spar, in the front spar lower chord near the underwing longerons, and in a longitudinal floor beam detail. The shear tie fatigue cracks and front spar lower chord fatigue cracks are in areas subject to Service Bulletin directed inspections and/or modification.

A more detailed description and discussion of the fatigue cracking is provided in appendix C. Included in this appendix is justification as to why these fatigue cracks would not contribute to the initiation of the structural breakup or affect the breakup pattern.

4.12 Front Spar Lower Pressure Bulkhead and Local Interface Sequence

The front spar lower pressure bulkhead is an extension of the plane of the basic WCS front spar downward to the fuselage skin which starts at the bulkhead and extends forward. The lower bulkhead is bounded on left and right sides by the underwing longeron and associated fittings. The lower bulkhead web is spliced to the main WCS front spar web just below the front spar lower chord and joined to the fuselage skin by an angle "ring chord". The splice between the webs of the lower bulkhead and the front spar is reinforced by vertical stiffeners on the forward side which effectively form an extension of the upper WCS front spar web stiffeners on the aft side. The lower bulkhead is also directly connected to the keel beam at LBL 9 and RBL 9.

The lower pressure bulkhead has been essentially 100% recovered, and pieces between LBL 66 and RBL 66 are either from the red area or are unconfirmed. It is noteworthy that on both sides the portion outboard of BL 66 associated with the underwing longeron and adjacent fittings stayed with the airplane and were recovered from the green area. The aft surface of the lower pressure bulkhead pieces to the left of the keel beam had soot deposits, especially on the upper edges of protruding head fasteners and on other protruding objects. Some soot was also noted on the aft surface of the bulkhead to the right of the keel beam. Crack propagation directions have been identified and documented on Figure 4-11.

At RBL 66, LBL 26, and LBL 66 web cracks propagated down from the front spar web and reinitiated downward in the lower pressure bulkhead with eventual associated axial fracture of the ring chord. There are additional lower bulkhead fractures at RBL 9 and LBL 9 which are close to the keel beam interface. There is an additional vertical web crack at LBL 49 which is associated with the separation of piece LF55A. The stiffeners "splicing" webs of the front spar and lower bulkhead are uniformly buckled in the free flange consistent with the motion of the front spar rotating forward. The stiffener at LBL18 is not bent forward as far as the others indicating limited forward rotation of the front spar in this area prior to ring chord separation at the bottom of the stiffener. The fasteners common to the splice between the webs of the front spar and lower pressure bulkhead are consistently (left and right sides, BL26 to BL75) separated in shear with the lower web being pulled downward and somewhat inboard.

There are two bathtub fittings nested in the ring chord above the underwing longeron. These joints have fractured in a tension/bending mode consistent with the fuselage skin panels forward of the fittings rotating outward about the ring chord, applying a bending moment which is reacted between these fittings (tension) and the longeron fitting. The bathtub fittings appear to have separated first then the longeron joint in a manner consistent with being overloaded by the same bending moment.

The keel beam lower chords are spliced just ahead of the lower pressure bulkhead to the keel beam runout in the forward body. Each keel chord extension tang is fractured identically in a down bending mode (i.e. body panel with keel runouts rotating downward relative to the main keel beam aft of the front spar).

The integration of significant lower bulkhead fractures into the overall sequence is accomplished in Section 7.0.

5.0 KEEL BEAM AND OVERALL WING CENTER SECTION SEQUENCE

5.1 Keel Beam Sequence

The keel beam (see figure 5-1) is located along the centerline of the airplane under the WCS from below the front spar aft through the wheel wells to the STA 1480 bulkhead. The beam is a box structure with two vertical webs (at LBL 9 and RBL 9). Each web has a heavy chord along its lower edge and a smaller chord along its upper edge. The upper chord is attached to the lower surface of the lower skin panel of the WCS through a series of aluminum rivets forward of the midspar and titanium bolts aft of the midspar as well as stronger steel tension bolts at each transverse beam inside the WCS (front spar, SWB #3, SWB #2, midspar, SWB #1, and rear spar).

Almost the entire keel beam has been recovered and identified. The forward 13.5 feet of the beam (from the front spar to 22 inches aft of the midspar) separated from the remainder of the beam. The forward portion of the beam contains no confirmed sooting (as of the date of this report), and was recovered in the red area (indicating early departure from the airplane). The aft portion of the keel beam was recovered from the green area, and this section of the beam contained moderate to heavy sooting, indicating that it remained with the right wing for a period of time following major airplane breakup. The portion of the keel beam under the aft part of the WCS separated along the upper flange where it had been attached to the WCS lower panel. These fracture areas did not contain soot, indicating that this portion of the keel beam separated from adjacent structure after sooting conditions ceased, probably at water impact.

The forward keel beam piece separated from the aft piece with a similar fracture through the web and chord on each side of the beam. The web fractures progressed from the top of the webs to the bottom, consistent with a downward bending moment on the keel beam. The large chords at the bottom of the beam webs also fractured in downward bending (forward end of the beam moving down). Separation of the upper edges of the keel beam from the lower skin panel of the WCS involved fracture of the upper (smaller) chord or tension separation of the rivets over most of the beam and shear separations of the aluminum rivets near the aft end of the forward piece of the beam. The steel bolts between the keel beam and the front spar were separated when the front spar rotated forward (see section 4.11). The forward rotation of SWB#3 fractured the bathtub fittings before downward motion of the forward end of the keel beam completed fracture of these bolts (see section 4.10). The tension bolts at SWB #2 are separated in tension (threads stripped inside nuts). The tension bolts at the midspar failed in tension with the remaining bolts protruding over the keel beam upper chord and bent sharply in the aft direction, consistent with forward motion of the upper edge of the keel beam as the forward end moved downward (pivoting about the last point of fracture, which was the lower chord).

In summary the sequence indicated by the above features is as follows:

- 5.1.1 SWB#3 rotates forward separating the keel beam tension bolt fittings for this beam and generating about 0.65 inch free play in the joint.
- 5.1.2 SWB#3 impacts the front spar, causing buckling of the front spar stiffeners, separation of the front spar upper chord in the fillet radius of the chord, and tension separation of the keel beam tension bolts for the spar.
- 5.1.3 The keel beam is now effectively cantilevered off of SWB#2.
- 5.1.4 Downward loading on the front of the keel beam from fuselage piece LF6A and associated pieces (see section 7.0 for a more detailed discussion) causes the keel beam to peel away the attachments to the WCS lower skin panel, failing the tension bolts at SWB#3, SWB#2, and the midspar.
- 5.1.5 As the separation of the keel beam attachments progresses aft, the bending strength of keel beam is exceeded by the continually increasing bending moment causing the keel beam to separate midway between the midspar and SWB#1.

5.2 Overall Wing Center Section (WCS) Sequence

5.2.1 Background of WCS Sequence Development

The overall WCS breakup sequence and early departure of selected parts from the airplane must have been a very precisely orchestrated sequence involving not only the WCS but also the fuselage red area and the keel beam. The sequence integration with the keel beam has been discussed in some detail in Section 5.1 above. More detailed discussions supporting the WCS scenario were provided in Sections 4.1 to 4.11. A more complete integration of the WCS, keel beam, and fuselage red area will be provided in Section 9.0.

5.2.2 Overview of WCS Breakup Sequence

5.2.2.1 There are indications of an early overpressure event (see Section 5.2.3) occurring as far aft as the forward side of SWB#1 and as far forward as the aft side SWB#3 (then front spar after collapse of SWB#3).

5.2.2.2 The spanwise fracture along the upper chord and subsequent forward rotation of SWB#3 due to an overpressure may have been one of the earliest events.

5.2.2.3 SWB#3 impacted the back of the front spar which initiated multiple failures within the spar, setting the stage for lower bulkhead failure, fuselage fracture initiation, and forward keel beam overload.

5.2.2.4 The lower chord of SWB#2 separated from the lower skin either as a result of overpressure, or as a result of the downward separation of the keel beam, or as a combination of these two factors.

5.2.2.5 The WCS maintained wing bending continuity with the upper and lower panels mostly undamaged and the midspar, SWB#1, and rear spar still providing shear continuity. The main landing gear beams also assisted in carrying wing bending.

5.2.2.6 Some localized areas of fire and soot were sustained subsequent to initial events and prior to major airplane breakup (see Section 5.2.4).

5.2.2.7 At major airplane breakup the WCS failed in a manner consistent with up bending overload (the upper panel buckling in compression and the lower panel fracturing in tension).

5.2.2.8 During major airplane breakup the remaining WCS separated with some of the WCS structure remaining attached to the right wing and some remaining attached to the left wing (as described in sections 4.1 to 4.11).

5.2.2.9 WCS structure associated with the right wing became very heavily sooted as a result of a major fire after major airplane breakup.

5.2.2.10 Unsooted fracture faces adjacent to heavily sooted surfaces indicates that there was significant damage to the WCS structure during water impact.

5.2.3 Summary of Early WCS Overpressure Indications

Indications of overpressure related damage or deformation were cited in the detailed description of Sections 4.1-4.11. There was insufficient information to place these in a sequence. They are summarized below:

5.2.3.1 Overpressure acting forward on SWB#3 (reference Section 4.10)
5.2.3.2 Overpressure acting forward on the front spar after collapse of SWB#3 (reference Section 4.11).
5.2.3.3 Overpressure acting forward on SWB#2 to complete the separation of the manufacturing access door and to eject the door from the airplane very early in the breakup sequence (reference Section 4.9)
5.2.3.4 A possibility of overpressure acting equally on both sides of SWB#2 causing tensile separation of the fasteners between the lower chord of SWB#2 and the lower panel (reference section 4.9).
5.2.3.5 Overpressure acting aft on SWB#1 deforming access door edge bands (reference section 4.6).

5.2.4 Summary of Fire/Soot Indications Prior to Major Airplane Breakup and Major Fire

As discussed in the introductory material, the Group attempted to differentiate between structural damage and/or sooting which preceded major airplane breakup and major fire effects. It should be noted again that such effects cannot generally be isolated in structure associated with right wing following major breakup because sooting from the major fire was so dominant. There were three possible areas in which it appears earlier fire/soot indications might be present (see appendix B for possible alternate rationale for some pieces). No further interpretation is being made as to significance of these within this report. More detailed information has been provided in Sections 4.1-4.11. These are summarized below for increased visibility:

5.2.4.1 Heavy sooting over virtually the entire lower WCS skin exterior surface including left side-of-body region (reference Section 4.2)
5.2.4.2 The interior of the WCS ahead of SWB#2 to the front spar and right of centerline (reference Section 4.2)
5.2.4.3 The interior of the WCS ahead of SWB#1 possibly extending as far forward as SWB#2 on the left side (reference Sections 4.2, 4.7, and 4.10)

There was some light sooting associated with WCS pieces departing early into the red area. No clear pattern or trend was identified with regard to these pieces.

6.0 FUSELAGE RED AREA BREAKUP SEQUENCE

6.1 Fuselage Red Area - Below the Window Belt, FS740 to FS1000

The major pieces in this portion of the sequence include red area pieces LF6A, LF55A, RF32, LF24A, LF24B, RF1, LF95 and LF5, and the adjacent yellow and green area pieces. These pieces incorporate the skin, stringers, and frames associated with the aft portion of the forward cargo compartment and the structure above the cabin floor up to the main deck windows. The red area structural pieces from below the main deck window belts were realigned relative to each other in a mock-up of this portion of the airplane. Included in the mock-up were the recovered frame and cargo floor structure pieces from the aft end of the forward cargo compartment, the green area fuselage pieces forward of the wing center section, some of the adjacent yellow area pieces from the bottom of the airplane, the front spar pieces from the wing center section, and the pressure bulkhead below the front spar. The potable water bottles and the halon fire extinguisher bottles (attached to the forward surface of the front spar) were also examined.

Figures 6-1 and 6-2 are two drawings of oblique views looking aft and either left or right at the internal surface of the aft end of the forward cargo compartment and the forward surface of the front spar of the wing center section. The stringers and frames are labeled only as linear positions on the drawings. The major pieces are labeled with their investigation data base numbers. Heavier lines on the drawing indicate the locations of fractures in the fuselage skin between the pieces from this area.

Examination of the mock-up revealed that a few portions of the fuselage structure below the window belt and forward of the wing center section were either not recovered or recovered but not identified. Fuselage skin areas that were not recovered or not identified are crosshatched in figures 6-1 and 6-2. Frames and stringers recovered and identified from these areas of the skin are shown in bold lines in these drawings. Most of the stringers and frames were recovered and identified in the largest area of missing or unidentified skin (below piece LF5 and above pieces LF89 and LF24B).

The red area pieces on the bottom and right sides of the fuselage structure (pieces LF6A, RF32, and RF1) were relatively undeformed, with most frames and stringers remaining attached to the skin. Between LF6A and LF5 were a series of red area pieces (LF24A, LF24B, and LF95) from which all of the frames and many of the stringers had separated. The stringers and frames were retained on piece LF5, and the frames and stringers on this piece extended downward below the lower edge of the skin on this piece, into the area where the fuselage skin was missing or not identified.

The green area pieces on the right side of the fuselage forward of and adjacent to the front spar of the wing center section (pieces RF95 and RF67) were relatively intact. However, the corresponding pieces on the left side of the fuselage were broken into many small pieces. The skin on most of these smaller pieces contained multiple folds consistent with compression loading in a circumferential direction, with one piece (LF70A) showing crushing in the downward direction. Portions of stringers were trapped within some of these pieces. Damage to these pieces on the left side was consistent with water impact.

All of the fuselage skin fractures on the pieces from the areas shown in figures 6-1 and 6-2 were examined in detail. No evidence of fractures originating from pre-existing fatigue or corrosion damage was found. Some of the skin fractures progressed along a row of rivets, either longitudinally along a stringer or lap joint, or circumferentially along a frame attachment location. Others were in the skin away from a row of rivets. None of the fuselage pieces from below the window belt in this area contained signs of longitudinal compression buckling. Fractures that were along a row of rivet holes and were consistent with in-plane[4] loading (hoop or longitudinal tension with the possible presence of in-plane shear were sequenced as occurring before fractures bending or out-of-plane shear deformation. Three types of earlier fractures were identified:

(1) Longitudinally oriented tensile fractures[5] along a row of rivet holes for a stringer or lap joint with minimal features associated with directionality[6] (forward or aft). Features associated with this type of fracture are indicative of tensile separation of the area between rivet holes under high hoop loading and with minimal out of plane movement of the pieces on each side of the separation. In all cases where this type of fracture was found, nearby portions of the longitudinal fracture area were classified as the second type of early fracture, as defined below.

(2) Longitudinally oriented tensile fractures along a row of rivet holes for a stringer or lap joint with features associated with directionality in either the forward or aft direction. Features associated with these breaks are indicative of a running fracture under high hoop loads and with minimal distortion (out of plane movement) of the pieces on each side of the separation. Some of these fractures also had some amount of in-plane shear loading, based on cracking out of each rivet hole in a direction slightly offset from longitudinal.

(3) Circumferentially oriented tensile fractures along a row of rivet holes with features associated with directionality. Features associated with this type of fracture are indicative of a running fracture under high longitudinal tensile loads

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[4] In-plane deformation or fractures are a direct result of loads acting in the plane of the surface being addressed. Out-of-plane deformations or fractures are a direct result of loads other than in the plane of the surface.

[5] Tensile fractures are those that have little or no bending, shearing, or twisting deformation associated with the break.

[6] The direction of propagation of a fracture through a series of rivet holes was based on the length of the crack intersecting each side of the hole. When uniform fracture features suggested instantaneous separation of the entire element between adjacent rivet holes, it was assumed that there was no direction to the propagation.

and with minimal distortion (out-of-plane movement) of the pieces on each side of the separation.

Unlabeled arrowheads oriented parallel to skin fracture locations in figures 6-1 and 6-2 indicate the location and direction of propagation of the earlier fuselage skin fractures. In places where the earlier longitudinal fractures did not have features indicating a crack propagation direction, arrowheads perpendicular to the separation indicate the tension loading that is consistent with the fracture features. The earlier fuselage skin fractures discussed above separated the right edge, the forward edge, and a portion of the left edge of a combined piece from the bottom of the fuselage (pieces LF6A and LF24A). The earlier fractures also progressed nearly completely around the circumference of piece RF32 and circumferentially across the bottom of the fuselage from S33L to S32R.

Additional fuselage skin fractures with features indicative of separation under a combined tension and either bending or out-of-plane shear loads were found on the red area pieces from the left side of the fuselage and are indicated by the arrows labeled with a "1" or "2" in a circle in figure 6-2. These fracture areas stemmed from the earlier cracks or were along the bottom row of rivets at a lap joint. Fracture areas labeled with "1" contained bending deformation and fracture areas labeled with "2" contained out-of-plane shear deformation. These additional fractures nearly completed the separation of a large combined piece from the bottom of the fuselage (combined pieces LF6A, LF24A, LF95, and LF55A).

Fuselage skin fracture areas not indicated by arrowheads in figures 6-1 and 6-2 were classified as later fractures.

Many of the frames through this section of the airplane were separated in tension, especially the frames that were broken at or near the earlier fuselage skin fractures on the right side of the fuselage.

Nearly all of the stringers from S36L to S30R were separated in direct tension (with little or no bending) at or close to the boundary between the red and yellow area pieces (at STA 760, STA 780, or STA 800).

The larger pieces just below each window belt (pieces RF1 and LF5) each contained curling deformation created as these pieces peeled away from the window belt structure, with the final point of the peel (the upper aft corners) being the last point to separate. The curls associated with the peeling areas were each more than 360 degrees. The direction of motion of the pieces as the peeling occurred was outboard, aft, and up toward the top of the airplane. Separation of the large combined piece from the bottom of the fuselage, piece RF32, and the two larger pieces below the window belt on each side of the fuselage (pieces RF1 and LF5) completed the structural breakup of the fuselage red area pieces below the main deck windows.

6.2 Fuselage Red Area - Floor Structure and Selected Interior Parts, STA 600 to STA 1000

Less than 50% of the transverse floor beam structure ahead of STA 1000 has been recovered and identified. Identification was hampered by the high degree of fragmentation of the individual floor beams. Portions of floor beams as far forward as STA 760 were recovered from the red area with the remaining mostly being from the yellow area. The recovery location of the floor panels is undetermined as they were typically found floating. Seats from as far forward as row 11 (approximately STA 600) and galleys B and C were recovered from the red area. The service cart stowage cabinet from approximately STA 600 was also recovered from the red area, while the lavatories and galley directly forward of this cabinet were recovered from the yellow area.

Main cabin transverse floor beams in the portion of the fuselage forward of the wing center section (STA 980 to approximately STA 760) were examined for direction of separation at the most outboard fractures identified (primarily where the beams attached to pieces LF5 and RF1, but also on much smaller individual pieces of frames and beams). On the left side of the fuselage, upward separation directions were noted for the beams at STA 960, 920, 900, 880, 860, 840, 820, and 800, and a downward separation direction was noted at STA 940. Separation directions could not be determined on the left side at STA 980 and 780. On the right side, downward separation directions were noted at STA 900, 880, 840, 820, 800, and 780, and an upward twisting separation direction was noted at STA 920. Separation directions could not be determined on the right side at STA 980, 960, 940, 860, and 760. See appendix B for more detailed information on the separation directions of these beams.

Prevailing seat deformations were separately documented in the Medical/Forensic Investigative Group Field Notes. No apparent correlation could be determined when assessing the seat deformation observations in conjunction with the floor beam observations. The initial opening of the fuselage lower lobe (e.g. LF6A) would have the expected result of rapid cabin depressurization accompanied by collapse of the main deck floor for some distance forward of STA 1000. The red area recovery of interior components as far forward as STA 600 would not be inconsistent with this floor collapse and associated structural breakup.

The service cart stowage cabinet at STA 600, immediately behind lavatory units D and E, was recovered basically intact except for the stainless steel service cart base plates (left and right) which had been separated from the bin sidewall structure. The left base plate retained the bottom of service cart on the locking pedestal and the plate had been severely deformed (pillowed) upward into and around the wheels on the bottom of the cart. Impact forces were sufficient to separate the rubber portions of the cart wheels. The outboard one third of the right base plate was relatively flat, but the remaining portion of this plate was also pillowed upward.

The base plates were recovered from the same location within the red zone. The seats directly behind the service cart stowage cabinet were also recovered from the red zone. The recovery positions of the base plates and their damage are consistent with separation of the cabinet from the airplane early in the sequence and water impact with the cabinet approximately in the upright position, resulting in water pressure causing the upward deformation (pillowing) to the bottom of the cabinet.

6.3 Fuselage Red Area - Window Belt and Above

The red area fuselage skin from above the window belts was completely recovered with the exception of one small area between RF5 and RF7 and a portion of the area between RF46 and RF19. The major pieces included in this portion of the sequence are RF5, RF7, RF35, RF20, RF21, RF46, RF19, RF117[7], LF74, LF12A, LF12B, and LF12C. These pieces comprise a relatively narrow band[8] of fuselage structure that extends from the main deck window belt on the right side of the airplane, up across the airplane's top, and down to the left side main deck window belt. Adjacent yellow and green area pieces were also examined for damage that may have extended from the red area pieces into adjacent structure.

When the airplane is intact, the weight in the nose portion creates downward bending in the fuselage red area. This bending normally creates longitudinal compression loads in the bottom of the fuselage and longitudinal tension loads at the top of the fuselage. Both window belts and the skin above the belts exhibited buckling from longitudinal compression loads; corresponding longitudinal compression damage was not found in the fuselage structure below the window belt (with the exception of minor compression damage in the lower auxiliary door sills below the L2 and R2 passenger entry doors). Buckling at and just above the window belts is consistent with loss of structural integrity below the window belts, causing the longitudinal compression loads to move upward into the window belt area and to increase in magnitude. On the right side the compression damage was centered at STA 940 to 960 and also may be evident in the #2 passenger entry door. On the left side, the compression damage was centered at STA 920. The compression damage extended upward to S6R on the right side and to S6L on the left side.

Figure 6-3 shows a stringer diagram of the fuselage in the area above the main deck window belts. The fracture locations in this diagram are denoted by the dark lines. All fractures in these fuselage skin pieces were "later" fractures, as defined in the section addressing the structure below the main deck window belts. Fracture directions of the fuselage skin structure above the main deck window belts are indicated by the arrowheads adjacent to the fractures in figure 6-3.

Many of the red area fuselage structure pieces from above the window belts contained peeling deformation to the skin, with a decreasing radius of bend toward the end of the peel. Peeled areas were typically not attached to stringers or frames. The peels were created as if the main portion of the piece was moving outboard, away from the fuselage, with the point of the peel being the final point of separation. Both the fracture directions in the skin and the location

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[7] Piece RF117 was a green area piece found during trawling operations.

[8] Maximum extent of the red area band above the main deck window belts was from STA 740 to STA 1000, but over much of the top of the airplane the red area piece extended only from STA 820 to STA 940.

and direction of the peels are indicative of a sequential separation of the upper fuselage pieces from the right to the left, across the top of the airplane, concluding with pieces LF12A and LF12B.

7.0 OVERALL WCS, KEEL BEAM, FUSELAGE SEQUENCE

7.1 Background

The overall WCS and keel beam sequence has been documented in Section 5.0. The fuselage red area sequence has been documented in Section 6.0. In keeping with the building block approach used by the Group in both developing and documenting the sequence at an increasing level of integration, this section will present a sequence linking the WCS breakup to the fuselage red area breakup. Section 7.0 will therefore only focus on the WCS front spar and the lower pressure bulkhead as well as the fuselage lower lobe directly ahead of STA 1000.

7.2 WCS, Keel Beam, Fuselage Sequence Description

7.2.1 SWB#3 rotated forward and impacted the back of the front spar resulting in fracture between the horizontal and vertical legs of the upper front spar chord across the full span of the WCS front spar. (Refer to section 5.0 for more detail leading up to this point in the sequence and section 4.11 on more specifics regarding the front spar separations.)

7.2.2 Deformation of the front spar upper chord vertical leg indicates the front spar rotated forward about the lower WCS skin attachment with a greater amount of rotation centered at LBL 66 and RBL 66 and a smaller amount of rotation at the centerline, consistent with the center of the spar being partially restrained by the mass of the potable water bottles and the attachment to the keel beam.

7.2.3 Overpressure in the WCS (associated with prior fracture and rotation of SWB#3 as well as responsible for forward rotation of the front spar) acting downward on the WCS lower panel caused vertical downward loading of the forward portion of the keel beam.

7.2.4 This downward load on the forward portion of the keel beam would be reacted by shear loads in the front spar web and in the lower pressure bulkhead web.

7.2.5 Forward rotation of the front spar buckled the stiffeners splicing the lower pressure bulkhead to the main WCS front spar.

7.2.6 The front spar upper chord vertical leg separated in tension at RBL 48 and LBL 66. The front spar web separated immediately at these locations, and the web fractures progressed downward until they reached the lower chord at LBL 66 and RBL 66. The front spar upper chord vertical flange also separated in tension at LBL 114, LBL 18, RBL 66, and RBL 114, but the web at these locations contained bending deformation, indicating that separations at these locations are later than the separations at RBL 48 and LBL 66.

7.2.7 The fasteners common to the splice between the webs of the front spar and lower pressure bulkhead are consistently (left and right sides, BL 26 to BL 75) separated in shear with the lower pressure bulkhead web being pulled downward and somewhat inboard.

7.2.8 Downward loading of the forward portion of the keel beam was then carried only by the lower pressure bulkhead and the fuselage structure forward of the front spar. Stresses in the lower pressure bulkhead from the downward loading of the keel beam caused separation of the bulkhead (except for the ring chord) just inboard of the underwing longeron, at locations corresponding to the early front spar web fractures at RBL 66 and LBL 66 (see Section 7.2.3).

7.2.9 Downward loading of the forward portion of the keel beam was then carried only by the ring chord at the bottom of the lower pressure bulkhead along with the fuselage skin immediately forward of the ring chord at LBL 66 and RBL 66. This structure was also subjected to hoop loads from cabin pressurization and possible vented WCS overpressure.

7.2.10 The ring chord and adjacent fuselage skin at S40R (RBL 66) fractured due to the combined loads described in 7.2.9, initiating the early skin cracking that propagated dynamically forward (first along S40R between pieces LF6A and RF95, then S41R, S42R, and S44R until running to the centerline access cutout between STA 800 and STA 820) and then circumferentially (upward to both the left and right from the bottom center at STA 760 to STA 800), then aft from STA 800 along two cracks, one at S40L and S39L and one at S38R and S37R (reference figures 6-1 and 6-2).

7.2.11 Cabin pressurization as well as any vented WCS overpressure generated a downward load on an isolated or nearly isolated piece of structure from the lower lobe (combined pieces LF6A, LF24A, LF95, and LF55A). The load on this combined piece was transmitted as a downward load acting directly on the forward end of the keel beam through the lower pressure bulkhead web and the keel beam lower chord extensions that attach to the fuselage structure. Downward loading on the forward end of the keel beam was sufficient to peel the keel beam away from the underside of the WCS and fail the keel beam aft of the midspar (see section 5.1).

7.2.12 Separation of the forward portion of the keel beam from the lower WCS skin was accompanied by other fractures along the lower pressure bulkhead interface with the WCS.

7.2.13 A skin crack symmetric to the early crack on the right side (see section 7.2.10, above) initiated on the left side at the ring chord along S39L.

7.2.14 The left side skin crack propagated dynamically forward along S39L and joined up with an early crack progressing aft along S39L and S38L. This fully isolated combined piece LF6A, LF24A, LF95, and LF55A..

7.2.15 Continued downward motion of the isolated fuselage skin panel (LF6A and associated pieces) from the lower lobe separated the keel chord extensions in bending just as the forward keel beam piece was being finally separated from the airplane.

7.2.16 Separation of the keel beam to fuselage splice joint (keel beam lower chord extension) initiated fracture of the lower pressure bulkhead ring chord at LBL9. Completion of the ring chord fracture allowed the final separation of LF6A.

7.2.17 Because the skin cracking described in 7.2.10 was primarily a progression from right to left, cabin pressure loads peeled the skin and frames outward until the frames broke near the centerline. The further progression to the left (across the bottom) was by peeling the skin from the frames.

7.2.18 While fractures within the fuselage proceeded at the extremely fast rate associated with dynamic crack propagation, the front spar was still rotating forward about its lower chord from overpressure within the WCS. Note the loss of LF6A and associated pieces created an opening in the fuselage through which potable water bottles, halon bottles, and associated WCS pieces could have exited the airplane.

7.2.19 The vertical flange of the front spar lower chord was bent forward separating from the horizontal flange and freeing front spar pieces to exit the airplane.

7.2.20 The underwing longerons and adjacent fittings failed primarily in an outward bending/prying mode.

7.2.21 Some fuselage structure ahead of each side of the WCS remained connected to the terminal fitting area and/or was trapped in the adjacent wing leading edge, finally being recovered from the green area.

7.2.22 The remainder of the fuselage red area breakup sequence is described in detail in Section 6.0.

7.3 General Information

The scenario linking the WCS, keel beam, and fuselage breakup was by far the most difficult for the Group to develop and reach a consensus on. It is also an area where further examination of the pieces might provide more detailed insight in support of the sequence.

It is apparent that the proposed sequence demands a very closely orchestrated timeline between many events happening virtually at the same time. In fact, the extreme speed of crack propagation is a fundamental aspect of this type of event. The sequence calls for events starting in the WCS, progressing to the fuselage, with the fuselage rapidly overtaking the final WCS breakup.

The proposed sequence does not support a conclusion that the front spar piece CW-504 departed the airplane substantially before other red area pieces, as the recovery position of this piece suggests. However, the proposed sequence is generally consistent otherwise with the trend of identified pieces in the red area.

One noteworthy aspect of the structural breakup characteristics is the exceptional degree of symmetry between right and left sides. Starting with SWB#3 and forward in the sequence there is the suggestion of a very uniform driving force.

8.0 WING SEQUENCE

8.1 Left Wing Sequence

The left wing spars and upper and lower skins were broken just outboard of the #1 engine (referred to as the wing tip fracture) in a manner consistent with upward bending overload. The lower skin of the left wing remained in large pieces and is more than 95% recovered and identified. The upper skin inboard of the wing tip fracture was fragmented into many small pieces. Consequently, only a small percent of the upper skin has been identified out of the many pieces recovered. All of the reliably identified pieces[9] of left wing have been recovered from the green area. The fracture characteristics of the major left wing section are consistent with an extremely high strain energy release associated with water impact. Recovery positions suggest that the left wing engines remained attached to the left wing until water impact. The left wing engines and wing attach fitting showed indications of a 6 o'clock overload direction.

The wing tip fracture progressed primarily through the reserve tank, but also through the aft corner of the #1 main fuel tank. Stress analysis indicates that the loads required to separate the wing at this location would be consistent with a high angle of attack, high "G" condition and that the area of separation is a region of lowest margin of safety for this type of condition on the 747-100 (see appendix E). The left wing tip piece contained an additional fracture located approximately midway between the wing tip fracture and the wing tip. This additional fracture is consistent with damage produced by water impact.

The portions of the wing outboard of the wing tip fracture were not sooted, while the portion of the wing inboard of the fracture was moderately to heavily sooted on much of the exterior surface of the wing lower skin. This sooting pattern extended inboard toward the side of body and is consistent with a fire and soot source at the ruptured outboard end of the #1 main tank. There is also sooting on the underside of the WCS skin extending outboard to the wing body fairing seal (locally heavy sooting). Just outboard of the fairing seal there is a distinct reduction in sooting. However, obvious loss of paint in this area may have removed the evidence of soot on this portion of the outer skin surfaces. Otherwise, the demarcation at the wing/body fairing seal would be indicative of an earlier fire/soot event which was contained by the fairing

[9] Pieces of internal and external wing structure were recovered from the red area during recent trawling operations and are under review.

for a period of time. Sooting trends on surfaces and fracture faces of the lower WCS skin panels were instrumental in making a determination of which portions separated with the left wing and which remained with the right wing. There are some indications of sooting on internal fay surfaces within the lower side of body joint. This sooting is consistent with the progressive failure of the left wing. Following the upper surface panel buckling there was sufficient local bending in the lower joint prior to failure to selectively open up internal areas of the joint to smoke (while other areas remained sealed from the smoke) which was present under the WCS during left wing separation.

8.2 Right Wing Sequence

The right wing separated just outboard of the outboard engine in an up-bending overload mode very similar to the left wing. The portion of the wing inboard of this separation was largely intact (extending to the right side-of-body) and was still attached to pieces of the wing center section and fuselage when recovered from the green area of the ocean. For transportation to the hangar this piece was pulled apart (upper skin panel from lower) and cut into spanwise pieces. The upper surface of this major piece was uniformly heavily sooted over the entire upper surface out to and including the separation near the outboard engine. The sooting generally appeared to emanate from the forward inboard end and flow outboard over the wing upper surface including the leading and trailing edge control surfaces. Damage and soot patterns indicated that engine No. 3 remained attached to the right wing until water impact. This engine and its attach fittings sustained a frontal impact.

Nearly all of the pieces of the wing outboard of the wing tip fracture have been recovered and identified. One piece from this area not yet recovered is located over the reserve tank near the fracture. Most of the wing "tip" (outboard of the fracture) was found floating in the green area. The major wing tip piece is free of soot while some separated pieces of the trailing edge aft of this piece are moderately to heavily sooted. The sooting patterns on the right wing are a positive indication that the fire in this area occurred after the wing tip fracture with some trailing edge and internal wing box outboard pieces remaining attached to the inboard portion of the wing.

The extreme burning damage to portions of the fuselage attached to the inboard end of the wing indicates that a primary source of the fuel for this fire was the inboard main fuel tank (#3) for the right wing.

8.3 Combined Wing Sequence

Both wing tips separated in a nearly identical location under up-bending loads, and all portions of both wings that did not float were found within a relatively small portion of the green area[9]. These facts indicate that the wing tip fractures were caused by the same relatively symmetric flight condition just before major airplane breakup. The sooting pattern for the left wing indicates that this wing was largely free of fire damage before the wing tip separated. The sooting pattern for the right wing indicates that this wing was involved in a major fire after the wing tip separated and after major airplane breakup.

9.0 WING / FUSELAGE BREAKUP SEQUENCE

As discussed in the Introduction (section 3.1), the debris field locations and content of parts within those fields are consistent with the later stages of the incident involving a major "in-flight" breakup of the wings and aft fuselage. The Group reviewed sooting patterns on surfaces and fracture faces to gain a general understanding of the nature of the breakup. Detailed fracture morphology was not documented in support of this aspect of the study. The relevant sooting patterns have been documented in figures 10-1 through 10-7 and are intended to supplement previously documented data in the Fire and Explosion Group notes.

The separation of the left wing from the combined right wing and aft fuselage (including empennage) is associated with deformation and fractures through the left side of the wing center section consistent with an up bending overload (compression buckling in the upper panel, tension then upward bending in the lower panel). Reconstruction of the airplane showed the presence of an apparent hole (2 to 3 feet longitudinally by about 5 feet circumferentially) in the fuselage structure above the main portion of the pickle fork fitting at the left rear corner of the wing center section. Most of the fuselage skin from the hole was located on folds attached to adjacent structure. All of the recovered structural pieces in the vicinity of this hole were from the green area. At the time just prior to separation, the wing is loaded in up bending, up shear, aft shear, and pitch down torsion (leading edge down and trailing edge up) at the side of body. Fracture of the upper and lower surfaces just inboard of the left side of body will result in a major release of stored energy and accompanying motion of the separating wing. The partially separated left wing is expected to first travel inward at the buckled upper surface, taking with it attached fuselage skin panels. Then, following completed separation of the lower skin, the wing would be expected to rotate upward at the rear spar and translate aft as a result of the shear and torsion loads before finally pulling away from the remaining structure. Inward folding of the skin panels (attached to the pickle fork fitting) is consistent with the expected initial wing motion. Enlargement of the hole and impact with the lower, forward corner of the L3 door is consistent with the expected rotation and translation of the separating wing. The unsooted surfaces and fracture faces of the heavily distorted panel directly below the L3 door (piece LF67A) would be consistent with this portion of the fuselage skin separating at the same time as the left wing.

The compression buckling in the left side of the wing center section upper panel continued aft through the left side of the horizontal pressure deck above the wing landing gear wheel well and into the body gear wheel well. The main landing gear beam was separated in upward bending below this area of compression buckling, at approximately LBL 75, indicating that the portion of the landing gear beam outboard of this fracture separated concurrently with or as a part of the left wing separation.

It can be seen from both the external and internal sooting patterns (figures 10-1 through 10-6) that there is a clear distinction between structure that departed with the left wing and the remainder of the right wing and aft fuselage. Lack of soot accumulation on the large fuselage piece (LF38) above the wing and fuselage pieces along the crown (RF34, RF41, and LF69) indicate that these pieces separated with the left wing. Soot accumulation on the remaining right wing and aft fuselage pieces indicates that this structure remained together for a period of time. However, distinct differences between these remaining pieces clearly indicate that the remaining right wing and aft fuselage pieces broke apart in stages.

The sooting patterns indicate that the continuing separation of the right wing/aft fuselage portion of the airplane initially involved separation of the aft fuselage from other structure along a plane forward of or near STA 1480, taking with it fuselage pieces LF2, RF10A, and RF65. During this separation, it appeared that a main body gear tire impacted the interior of the fuselage on piece LF39A, leaving a tire witness mark on the inner chord of the 1350 bulkhead. Severe upward crushing damage to the belly structure on the portion of the aft fuselage behind approximately STA 1480 is consistent with this portion of the fuselage remaining intact until water impact.

Following loss of the aft fuselage, some fuselage pieces (including major pieces LF39A, RF42, RF23) and some wheel well structure (including a portion of the keel beam and the STA 1350 bulkhead right of LBL 75 along with the right landing gear beam) remained with the right wing for a period of time and accumulated additional soot from a fire source on the right wing. See figure 10-7 for a diagram of the sooting patterns on the lower body structure between STA 1241 and STA 1480. These pieces subsequently separated before exposure to the major fire associated with the right wing. The right landing gear beam separated from the right wing at the outboard attach point liberating the right wing gear. Heavy soot accumulation and fire damage on pieces RF14 and RF37 indicated that they remained attached to the right wing for some period of time during the major fire. Fuselage piece RF17 was recovered attached to the right wing structure and was severely burned.

Severe fire damage on major portions of the WCS (for example the right side of SWB#3, the right two thirds of SWB#2, the right portion of the upper skin panel, and the rear spar near BL 0) indicates that these areas remained attached to the right wing during the major fire. Lack of fire damage and soot accumulation to the right rear corner of the WCS interior (including the right side of body) indicates that this portion of the WCS remained largely intact until water impact, preventing soot accumulation in this area.

10.0 OVERALL AIRPLANE SEQUENCE

10.1 Discussion

The basic approach used by the Group was to build up the overall airplane breakup sequence in components (sections 4.0 through 10.0) and then integrate into an overall sequence. The primary areas of interest in the wing center section and fuselage red area were treated in much more detail (sections 4.0 through 6.0). The purpose of this section is to summarize in one place the overall sequence without repeating the level of detail provided in the referenced sections.

10.2 Breakup Sequence Summary

10.2.1 In the WCS, the earliest identified event involved an overpressure.

10.2.2 Overpressure in the WCS resulted in fracture of portions of the substructure (spanwise beams, front spar, and integrity of the keel beam support).

10.2.3 The fuselage directly forward of the WCS initiated cracking in the lower lobe as a result of sustained overpressure in the WCS, structural damage to the front spar and lower pressure bulkhead, and the direct integration of the bulkhead into the adjacent fuselage. Cabin pressure differential as well as possible vented overpressure from the WCS also contributed to loading the lower fuselage lower lobe.

10.2.4 The earlier fuselage lower lobe fractures resulted in direct loading of the forward end of the keel beam separating the forward portion of the keel beam from the WCS.

10.2.5 Separation of red area fuselage pieces from the lower lobe progressed up to the window belt level on both sides.

10.2.6 Buckling of the window belt region reinitiated the breakup sequence which progressed over the upper lobe completing the separation of all red area pieces.

10.2.7 The forward fuselage separated away from the remainder of the airplane impacting the water relatively intact in the yellow area with a right wing low attitude.

10.2.8 The wings and aft fuselage remained intact for a period of time with some localized sustained fire as a result of an earlier center fuel tank event.

10.2.9 The left and right wing tips fractured symmetrically in upward bending.

10.2.10 The previously weakened WCS failed, with the left wing separating away leaving the right wing and aft fuselage attached for a brief time.

10.2.11 The number 3 main fuel tank is sufficiently ruptured to produce an escalating fire associated with the right wing and aft fuselage.

10.2.12 The right wing separated away from the main aft fuselage in stages with the right wing and some associated fuselage and WCS falling some portion of the remaining distance to the water enveloped in sustained, major fire originating from the side-of-body area.

10.2.13 Both wings (including engines), wing tips, and aft fuselage (aft of STA 1480) impacted separately but relatively closely dispersed in the green area.

11.0 SUMMARY

The Metallurgical and Structure Sequencing Group has spent 35 calendar days during December 1996, January 1997, and April 1997 assessing the wreckage of TWA Flight 800. As stated earlier on in this report the objective was "to develop scenarios for the sequence of structural breakup of the airplane and to correlate proposed scenarios with the structural observations". A number of scenarios were discussed by the team. Each step of each proposed scenario was held up to scrutiny with regard to as many as possible of the attributes described in section 3.1 "Sequence Study Methodology". In many cases a specific element of a particular scenario was given a "sanity check" also by conventional stress analysis. The basic approach taken was to systematically develop sequences at the airplane component or zone level then progressively build up to an overall sequence by correlating and integrating the separate elements.

The Group strove to fit a proposed scenario to all relevant observations in a given area. In some cases there was more than one identified possibility for a particular feature. In some cases, the Group had to accept that some feature(s) either could not be explained by the proposed scenario or might even be in conflict with the proposed scenario. A case in point of an apparent conflict is the recovery location of front spar piece CW504 in the earliest part of the red area. An example of a feature which was not explained in the breakup sequence is the localized recrystallization of portions of the rear spar cited in an NTSB Metallurgical Report.

The recovery operation is still underway but is probably within a few percent of being complete. There is still some significant missing structure in the key wing center section and fuselage red zone areas. It is therefore possible that new scenarios (sequences) may emerge as new information is acquired whether it be from newly identified parts or simply a new interpretation of current information. The Metallurgy and Structures Sequencing Group was not able to precisely locate the initiation of the center wing tank overpressure event and the Group's activities did not include addressing potential causes of the overpressure. At the present time in concluding its efforts, the Group did reach a consensus that the facts and data on the whole support the sequence documented herein.

James F. Wildey II
National Resource Specialist - Metallurgy

Metallurgy / Structures Sequencing Report

Appendix A: Figures

Table of Figures

747-100 WING CENTER SECTION

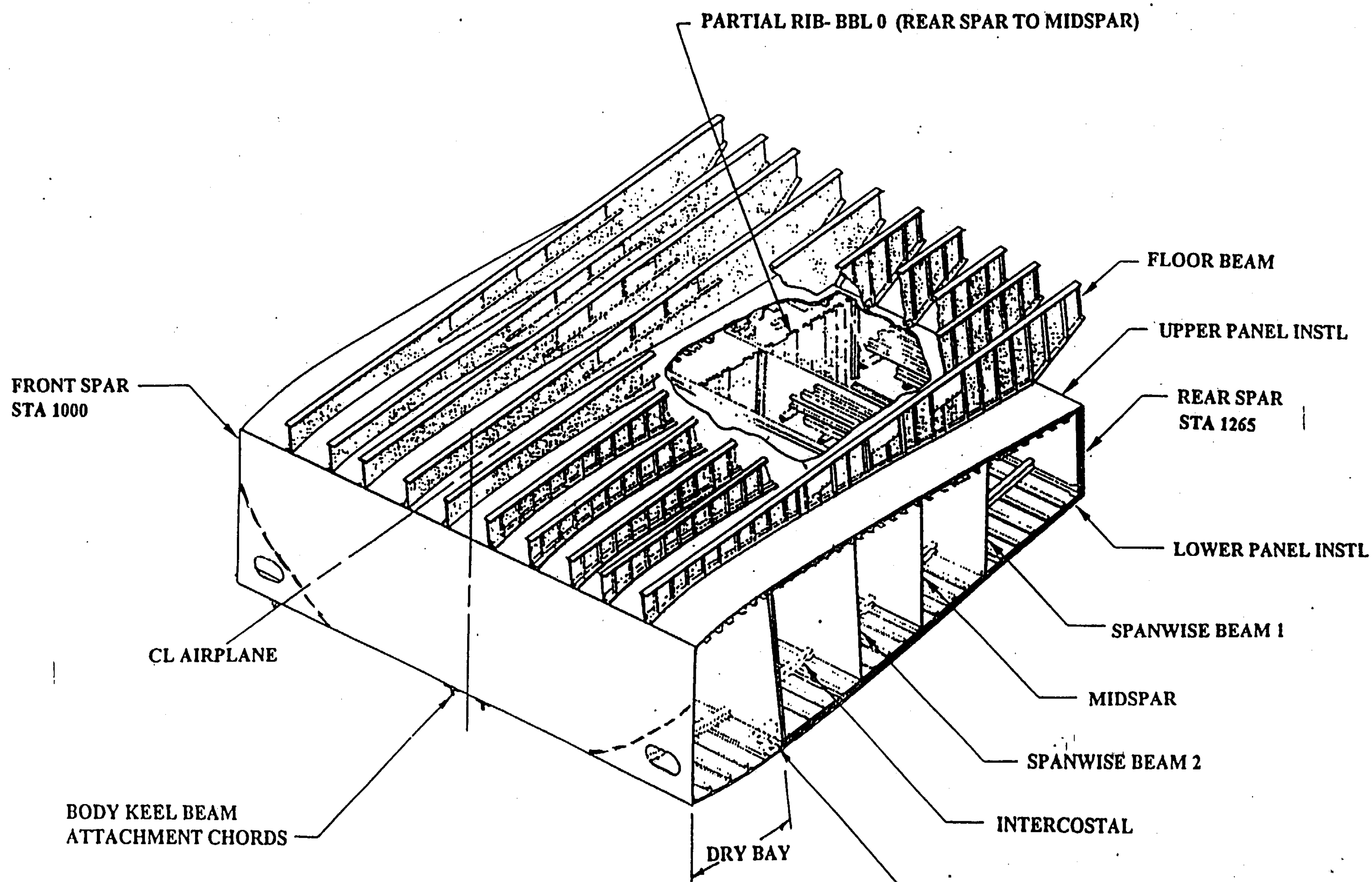


FIGURE 3-1

Wing Center Section - Upper Skin

Legend on Figure 4-3

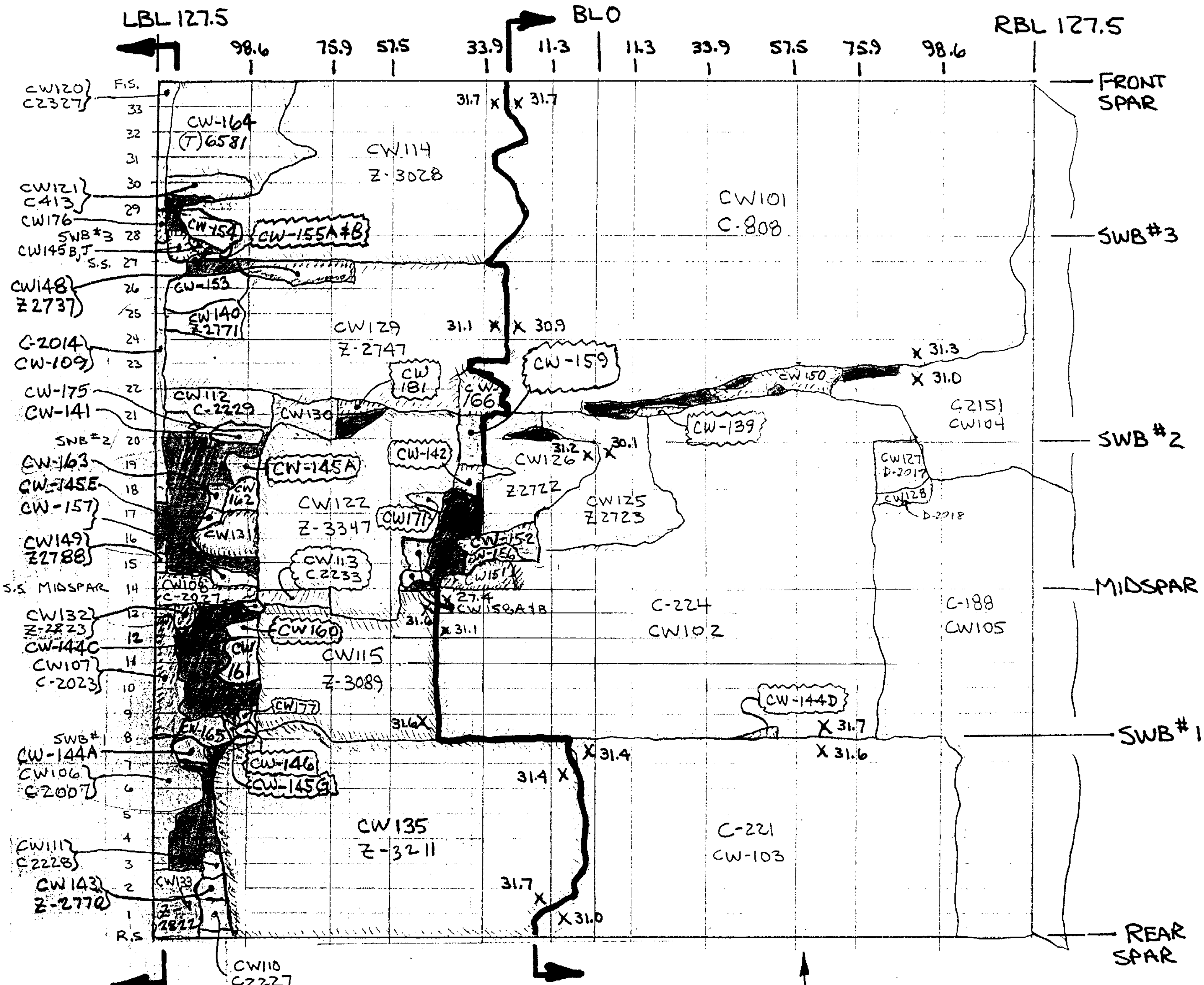
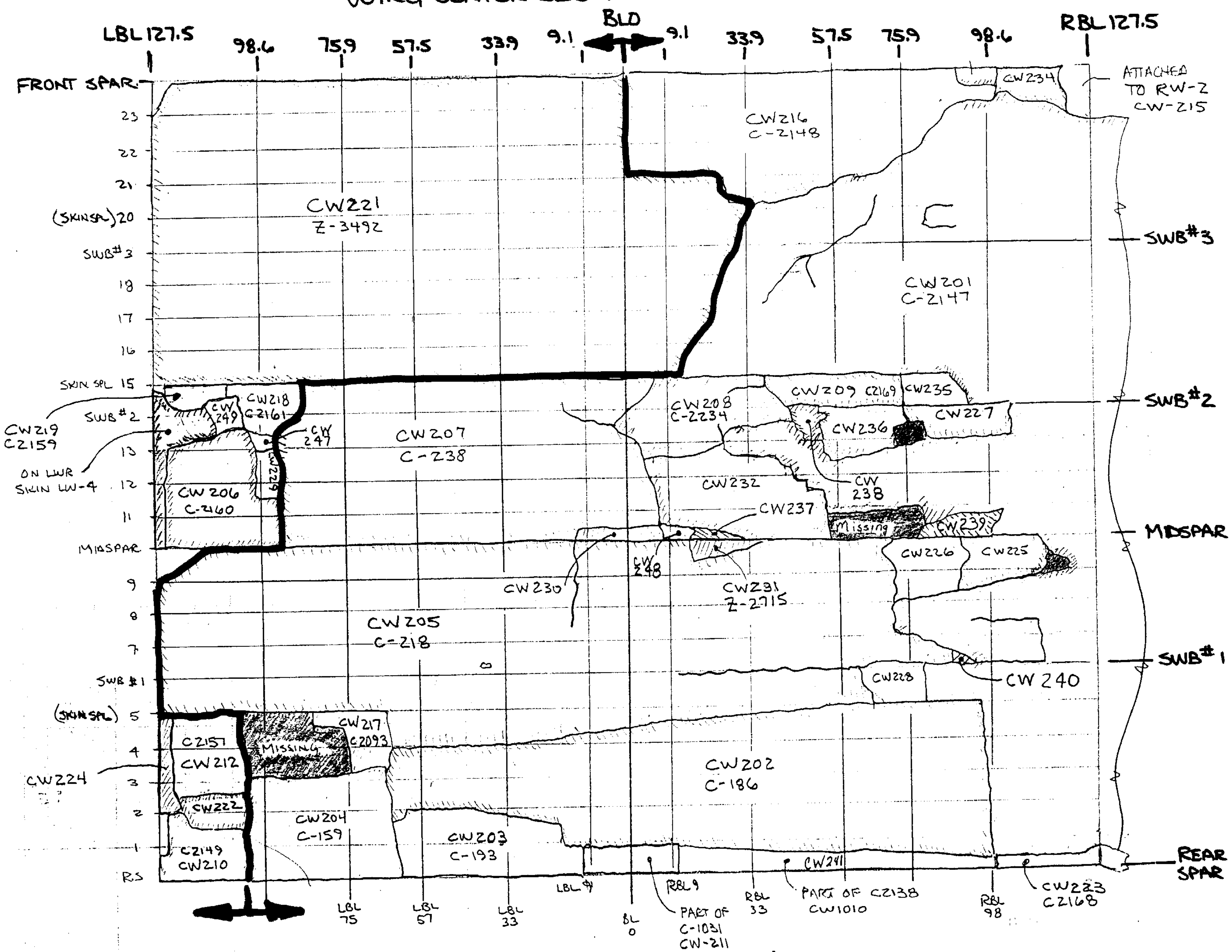


FIGURE 4-1

WING CENTER SECTION - LOWER SKIN



VIEW LOOKING DOWN
FIGURE 4-2

WING CENTER SECTION - REAR SPAR

Legend		
(shaded area)	=	Area not recovered or identified
X	=	Electrical conductivity measurement (%IACS). Used for comparison of relative thermal exposure between adjacent pieces.

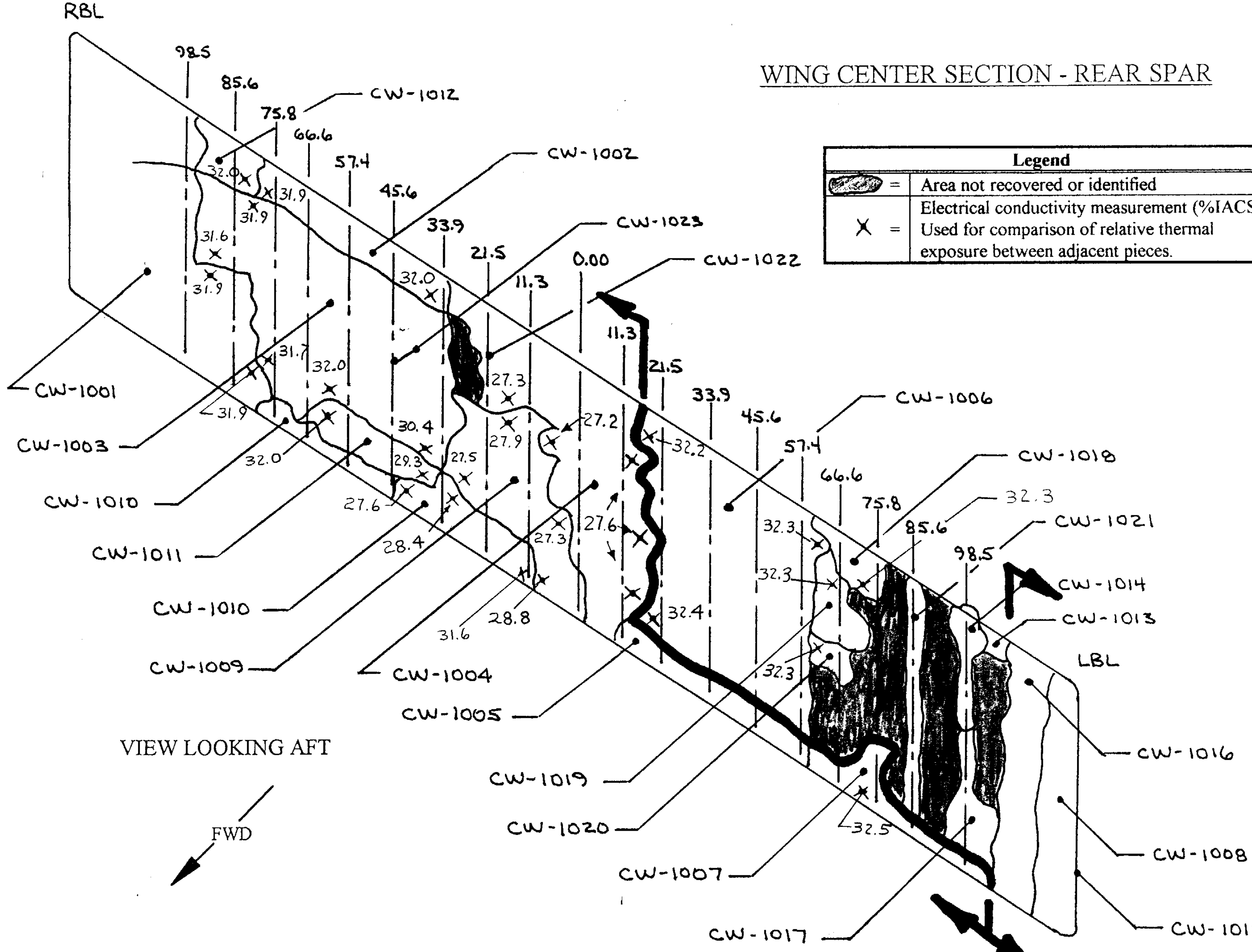


FIGURE 4-3

WING CENTER SECTION - SPANWISE BEAM #1

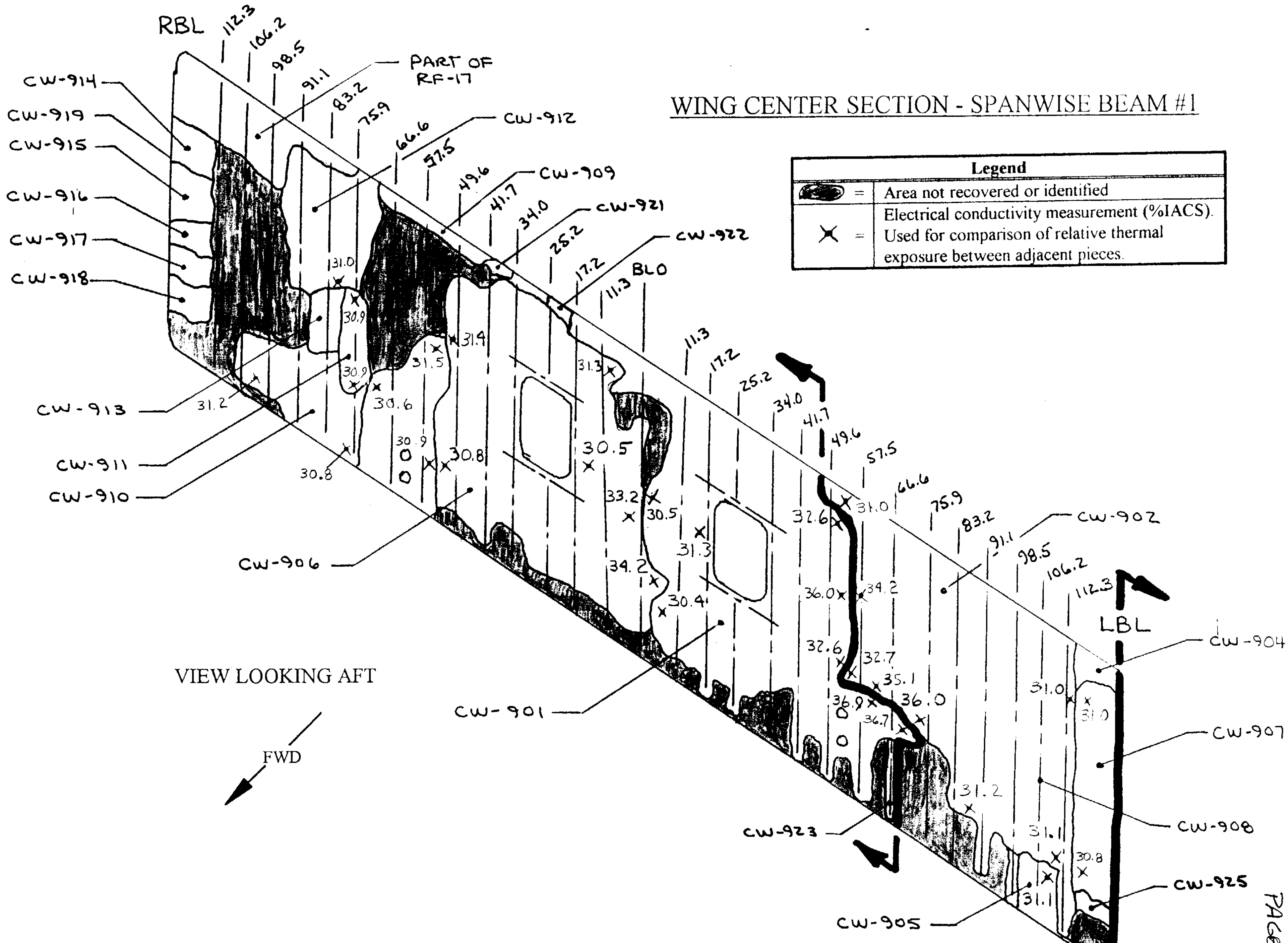


FIGURE 4-4

WING CENTER SECTION - MIDSPAR

Legend	
(dark area symbol) =	Area not recovered or identified
✕ =	Electrical conductivity measurement (%IACS). Used for comparison of relative thermal exposure between adjacent pieces

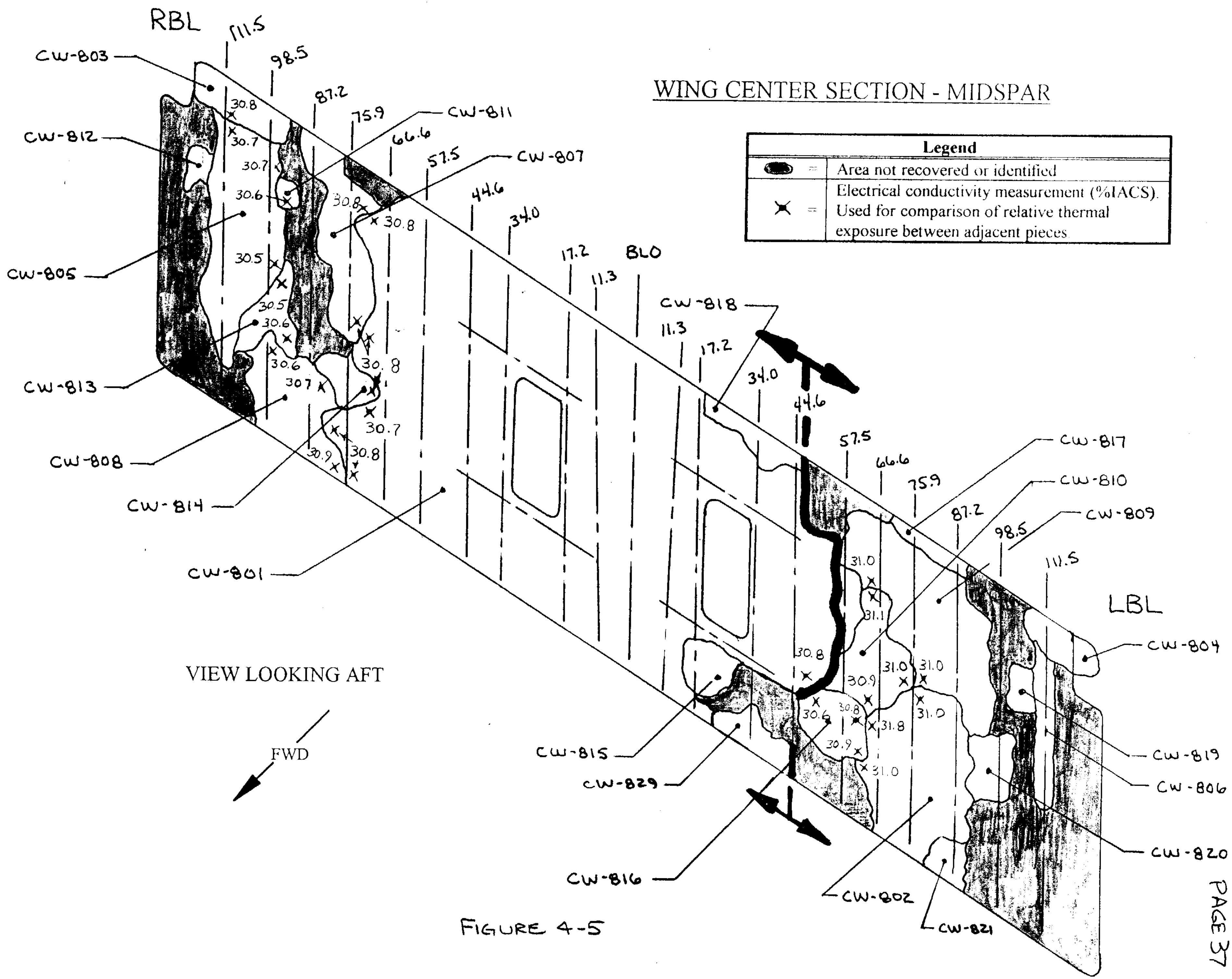
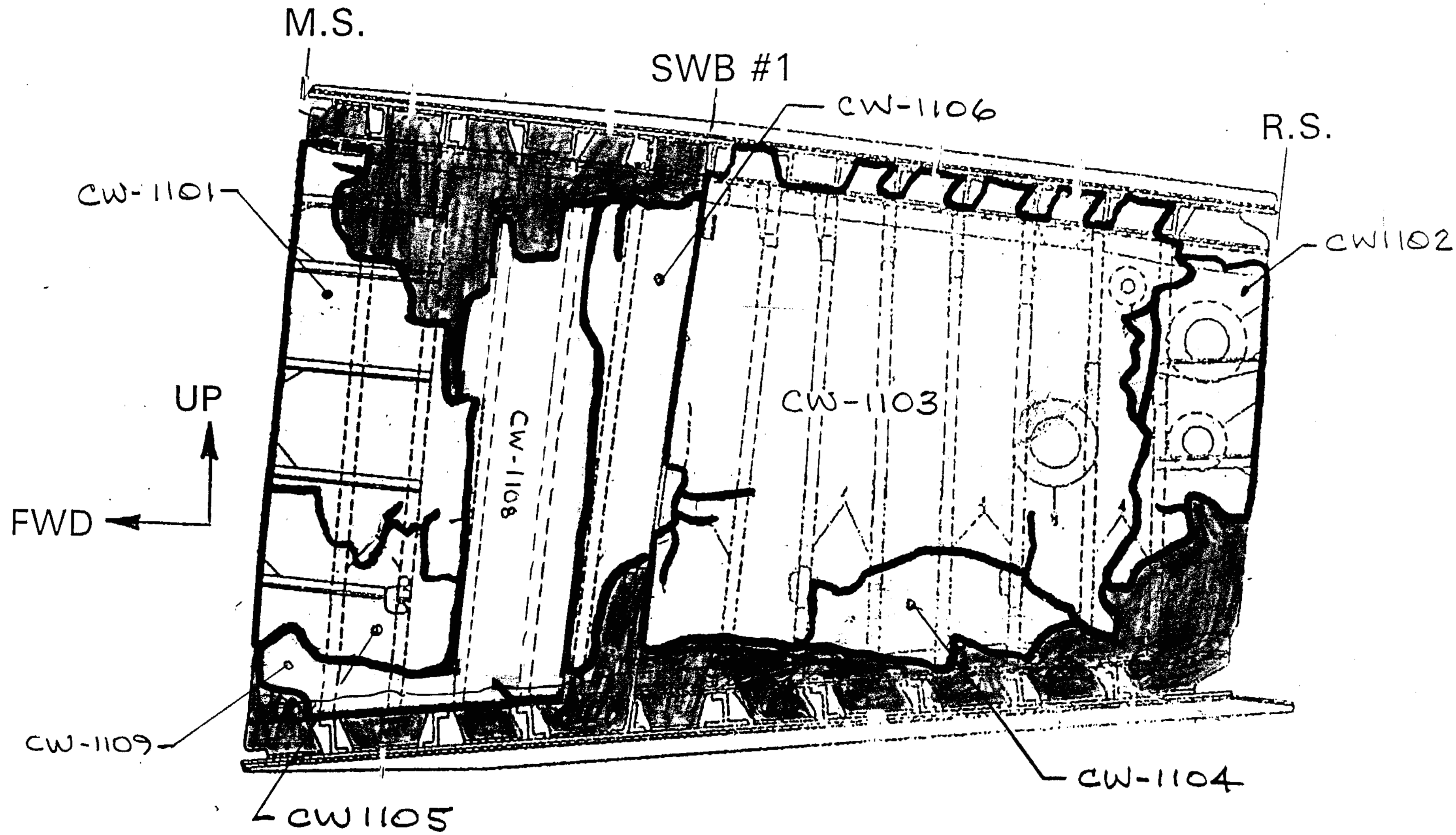


FIGURE 4-5

WING CENTER SECTION - BL 0.00 RIB



Legend		
(dark shading)	=	Area not recovered or identified
X	=	Electrical conductivity measurement (%IACS). Used for comparison of relative thermal exposure between adjacent pieces.

LEFT SIDE (VIEW LOOKING RIGHT)

FIGURE 4-6

WING CENTER SECTION - SPANWISE BEAM #2

Legend		
(dark shaded area)	=	Area not recovered or identified
X	=	Electrical conductivity measurement (%IACS). Used for comparison of relative thermal exposure between adjacent pieces.

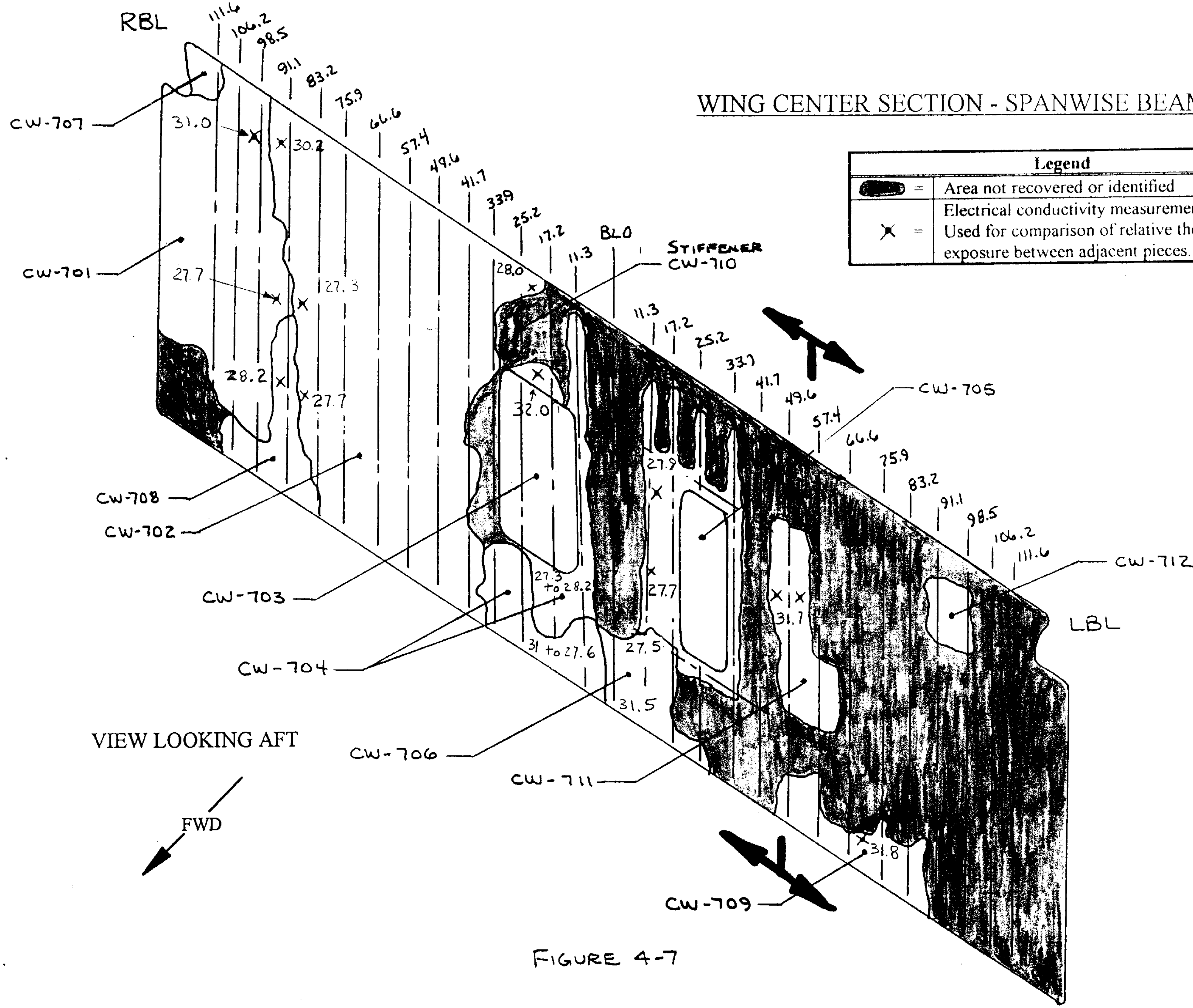


FIGURE 4-7

WING CENTER SECTION - SPANWISE BEAM #3

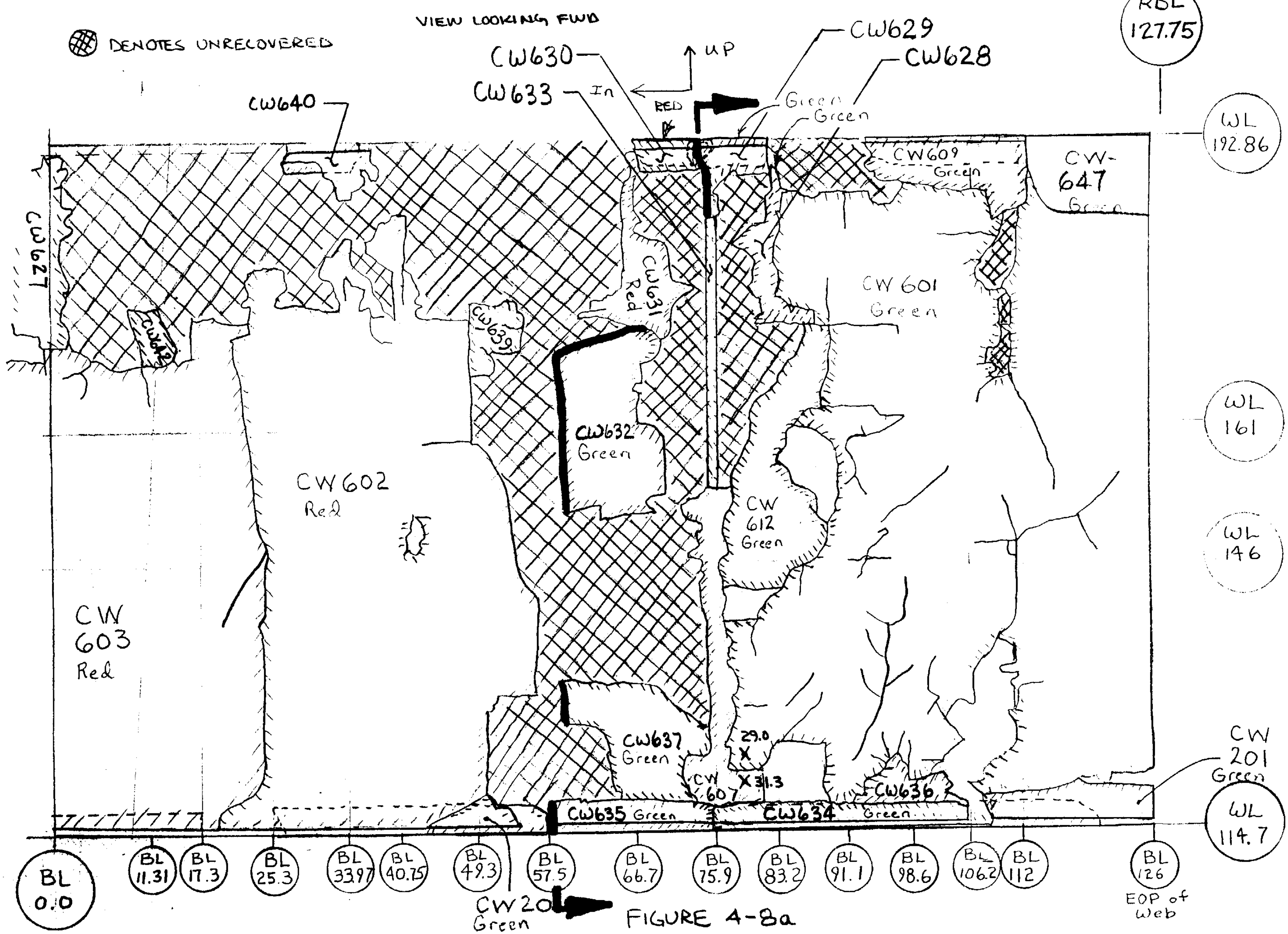


FIGURE 4-8a

WING CENTER SECTION - SPANWISE BEAM #3

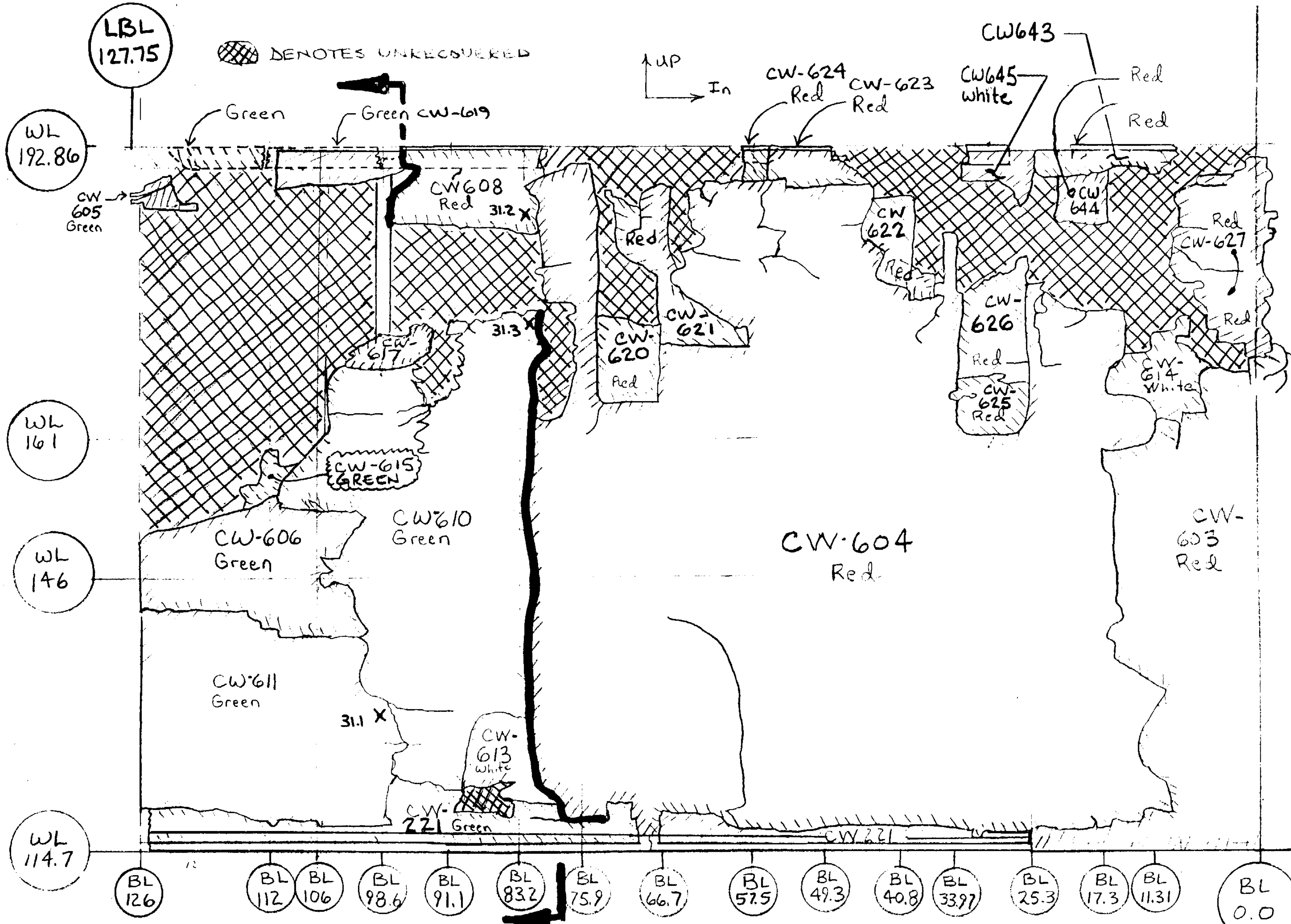


FIGURE 4-8b

WING CENTER SECTION - FRONT SPAR

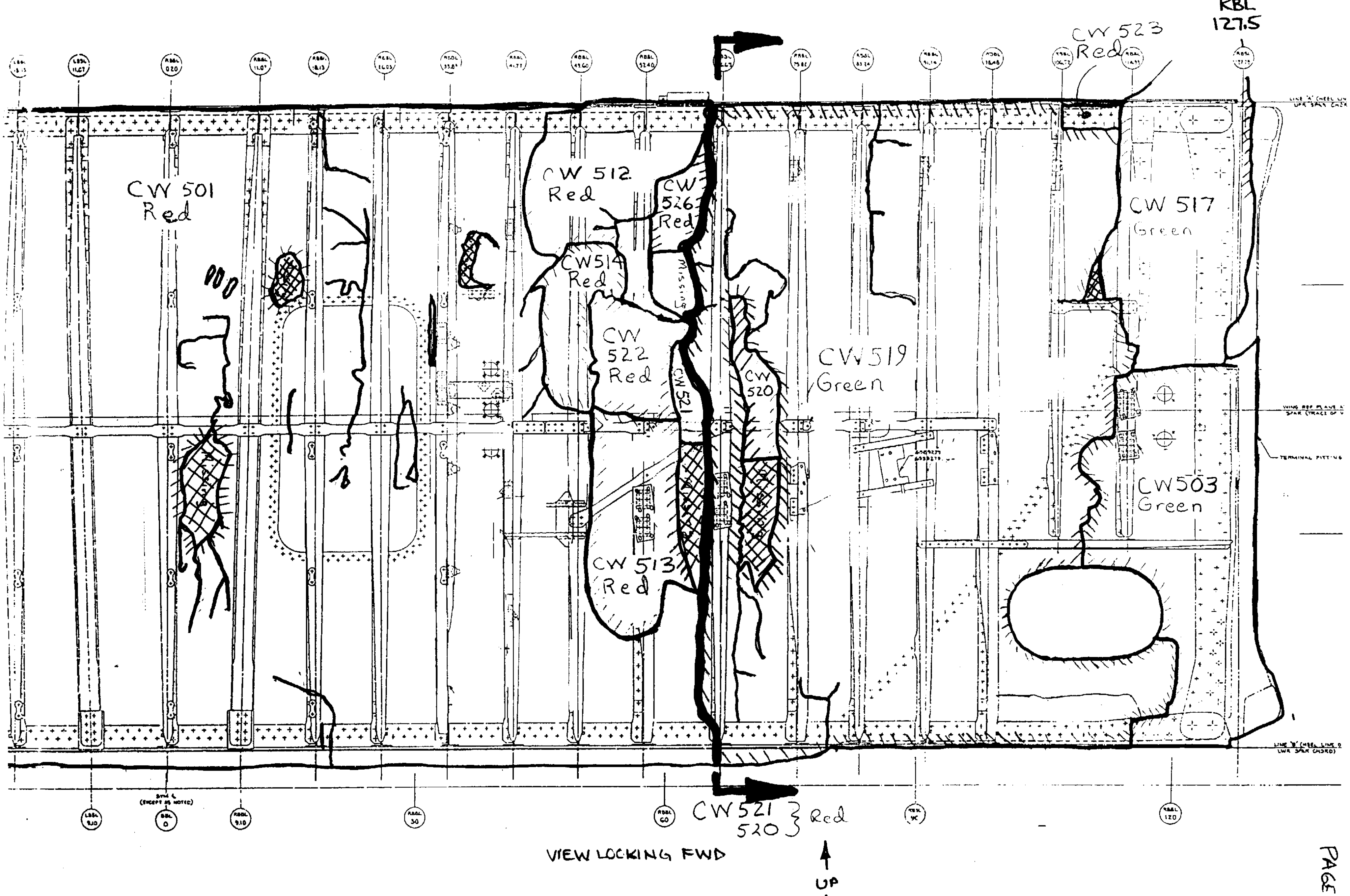


FIGURE 4-9a

WING CENTER SECTION - FRONT SPAR

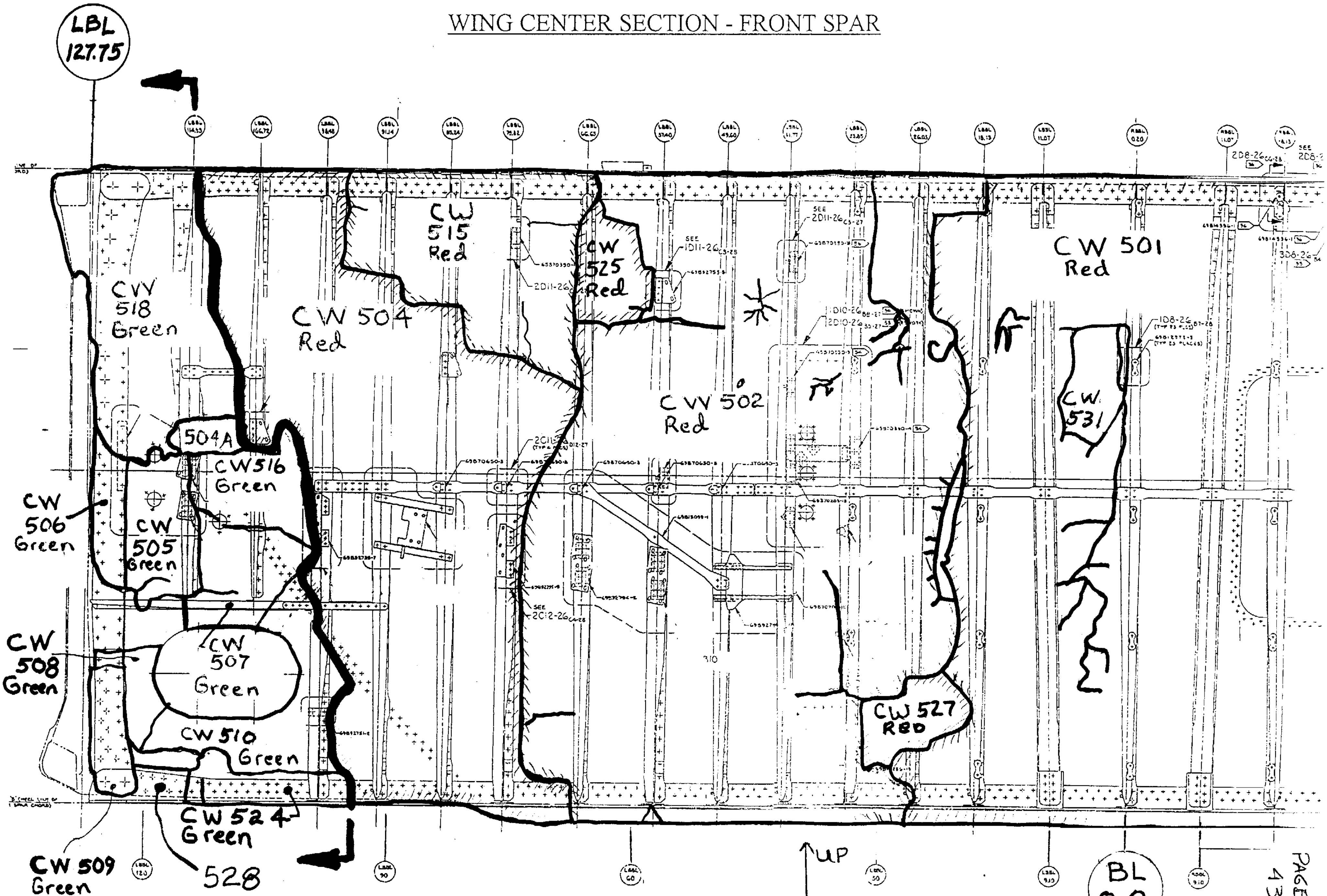
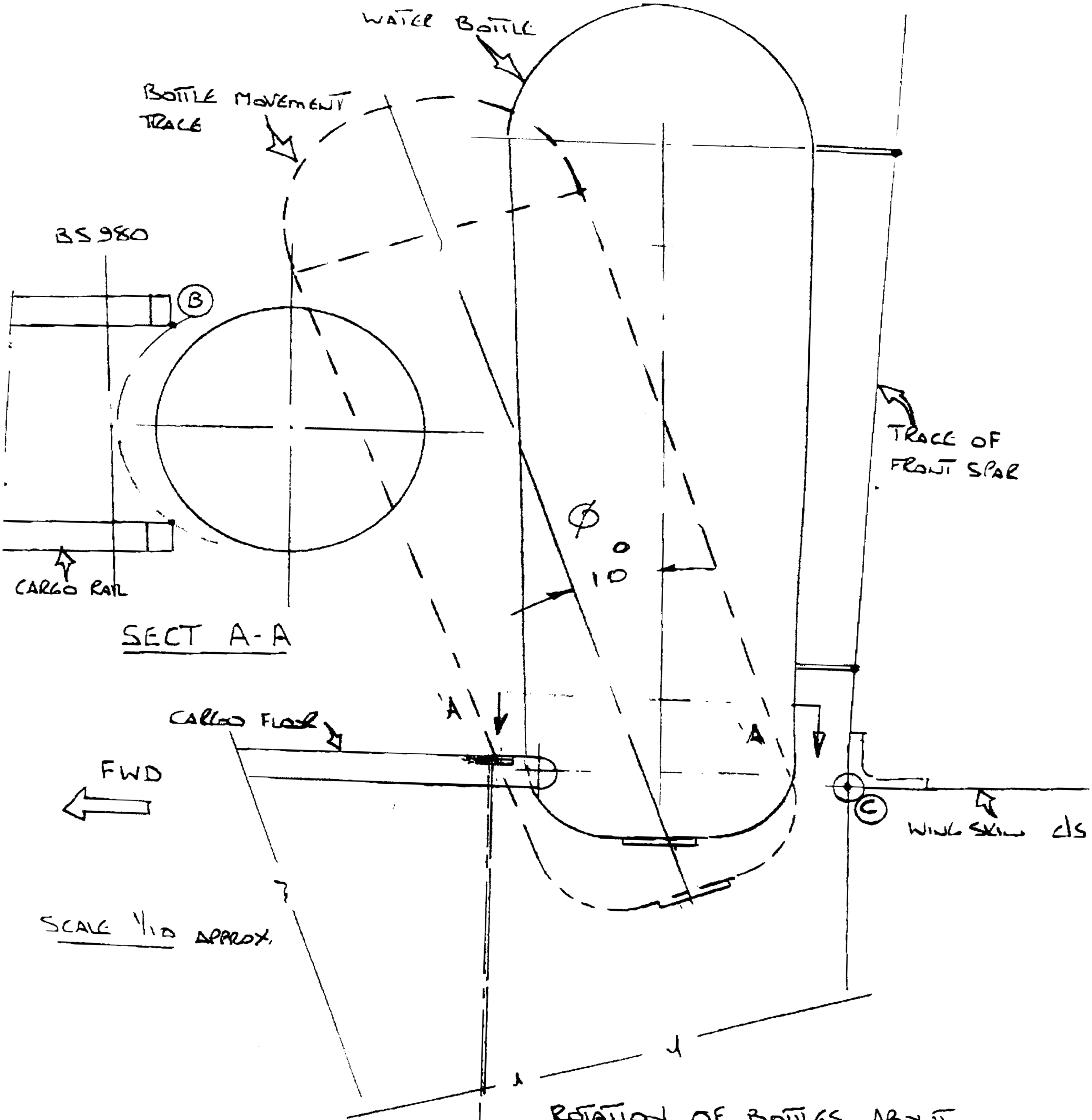


FIGURE 4-9b

SIDE VIEW OF WATER BOTTLE INSTALLATION



ROTATION OF BOTTLES ABOUT POINT (C) TO CONTACT (B) IS APPROX 10°

FIGURE 4-10

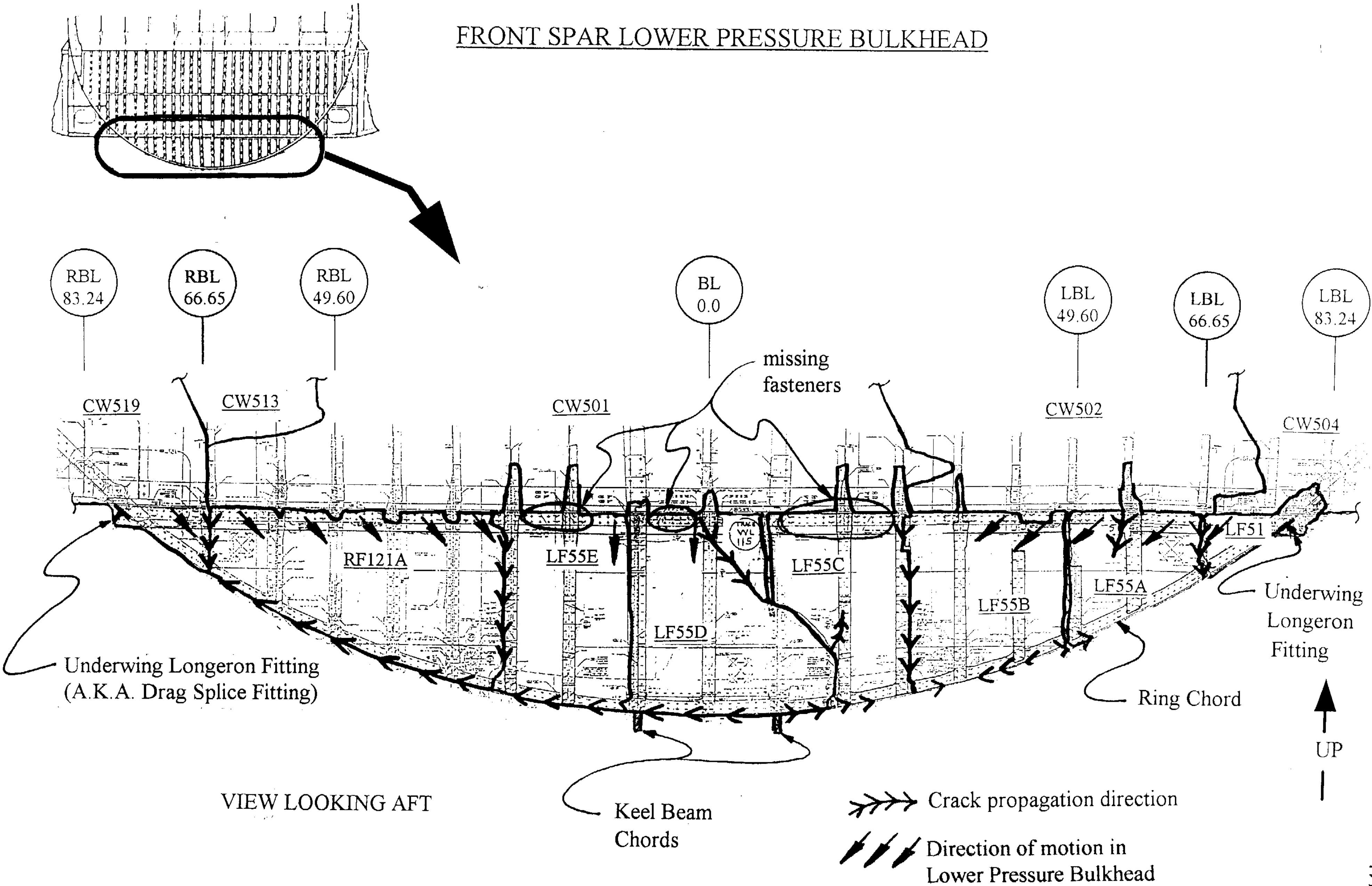

FRONT SPAR LOWER PRESSURE BULKHEAD
RBL 83.24
RBL 66.65
RBL 49.60
BL 0.0
LBL 49.60
LBL 66.65
LBL 83.24
CW519
CW513
CW501
CW502
CW504
missing fasteners
RF121A
LF55E
LF55D
LF55C
LF55B
LF55A
LF51
Underwing Longeron Fitting
Underwing Longeron Fitting (A.K.A. Drag Splice Fitting)
Ring Chord
UP
VIEW LOOKING AFT
Keel Beam Chords
Crack propagation direction
Direction of motion in Lower Pressure Bulkhead

FIGURE 4-11

KEEL BEAM AND WING CENTER SECTION INTERFACE

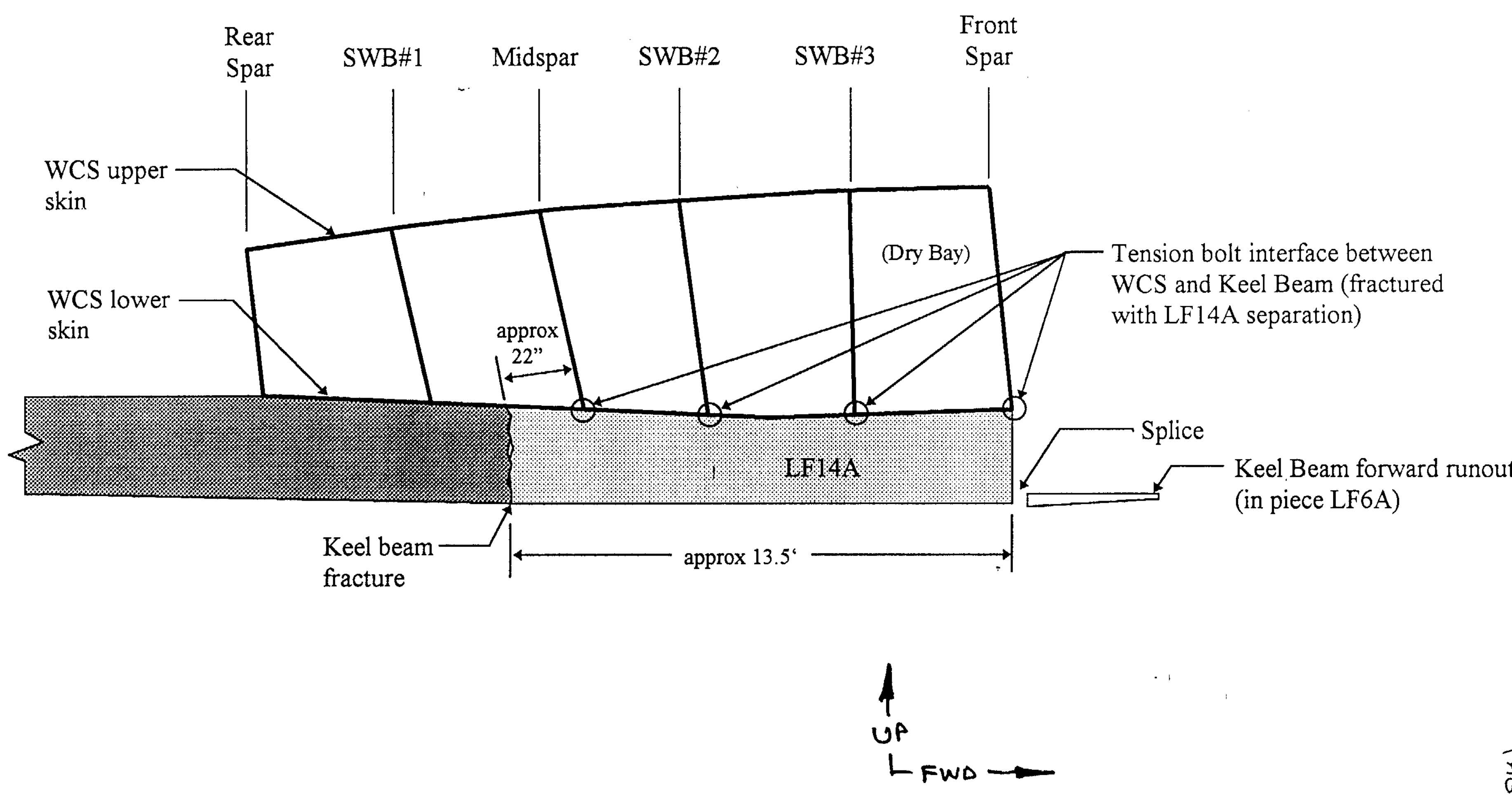


Figure 5-1

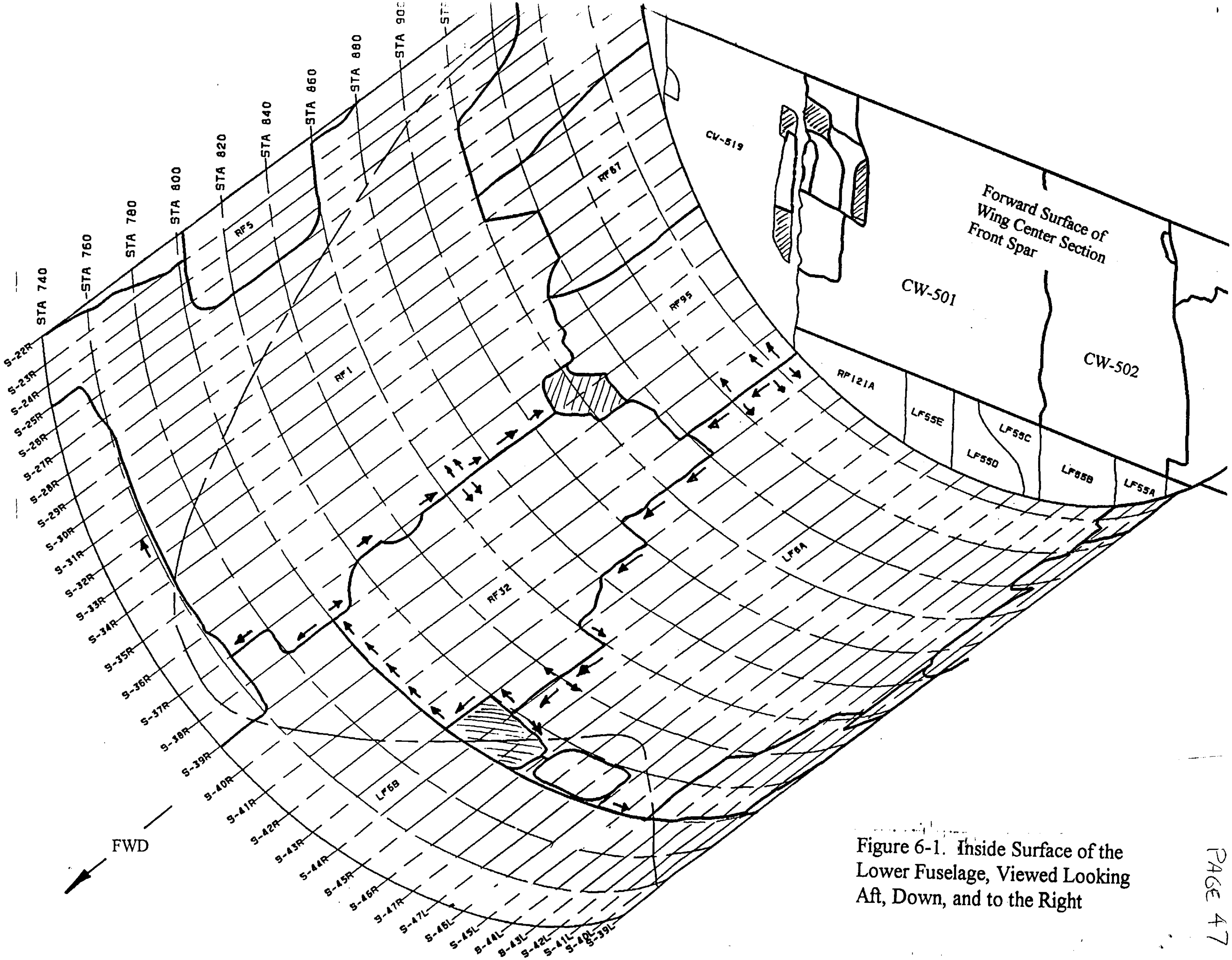


Figure 6-1. Inside Surface of the Lower Fuselage, Viewed Looking Aft, Down, and to the Right

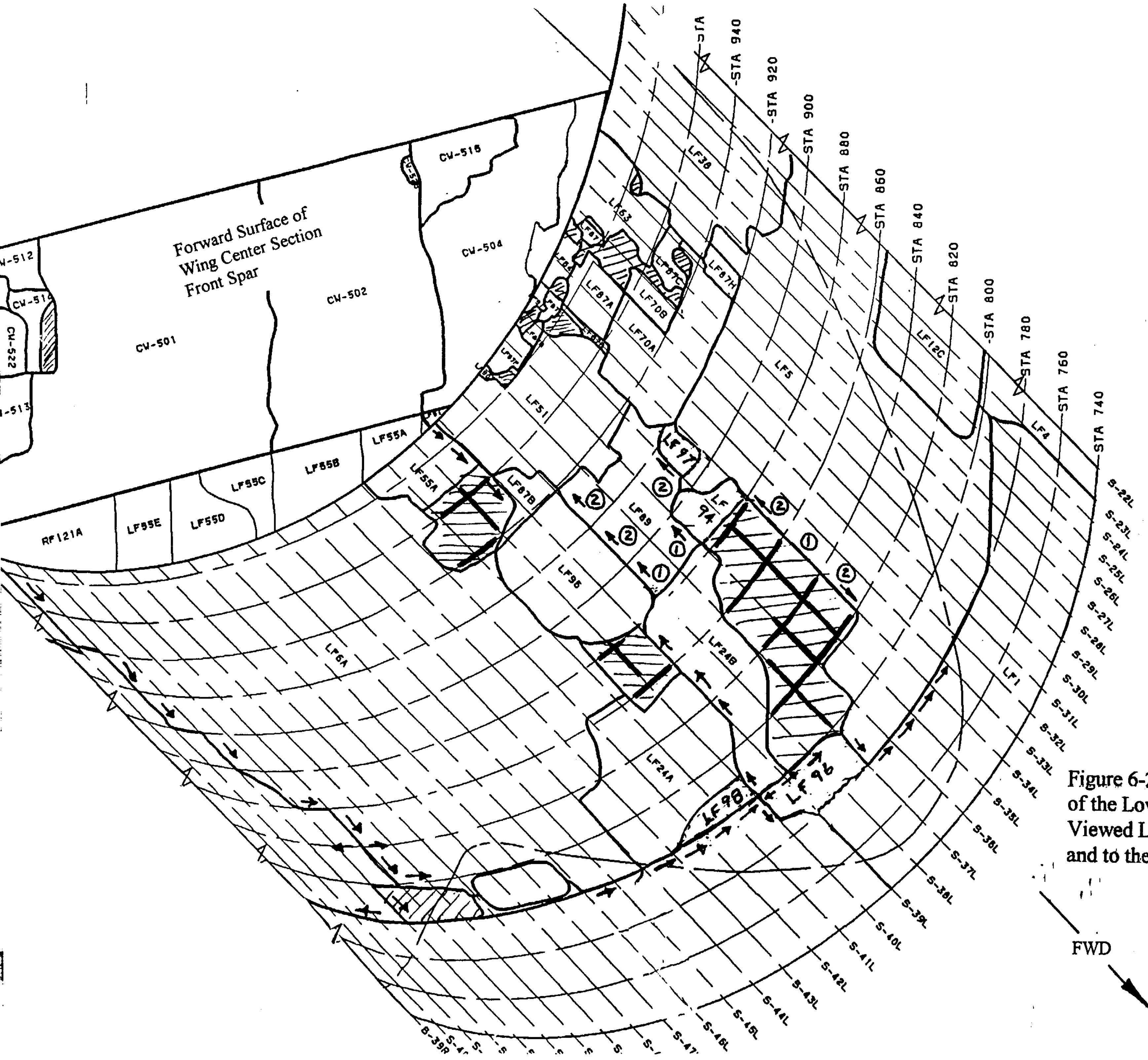


Figure 6-2. Inside Surface of the Lower Fuselage, Viewed Looking Aft, Down, and to the Left

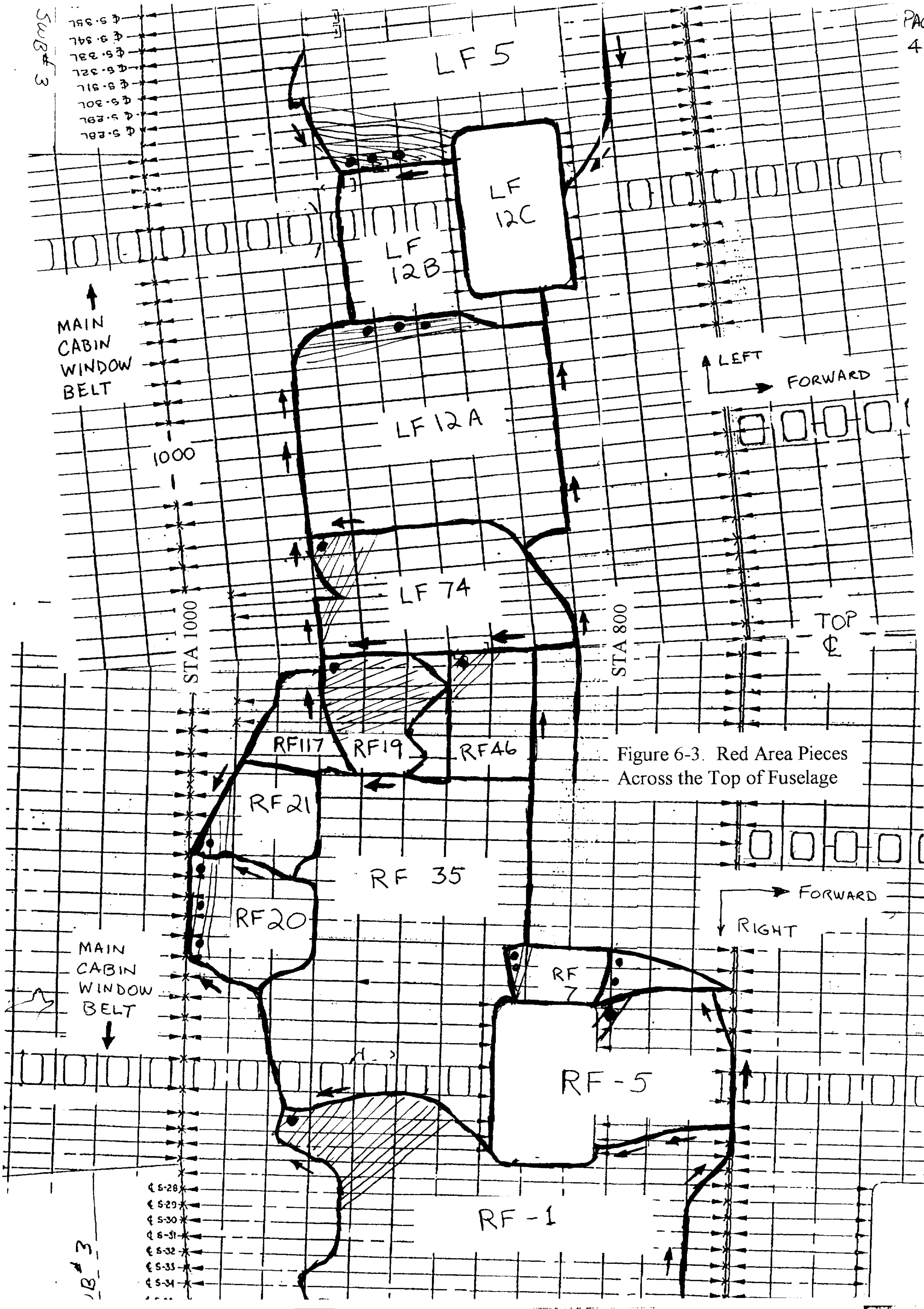
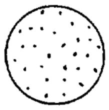


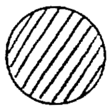
Figure 6-3. Red Area Pieces Across the Top of Fuselage

Fuselage sooting diagrams

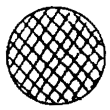
No sooting evident



Light sooting

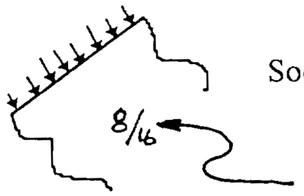


Moderate sooting



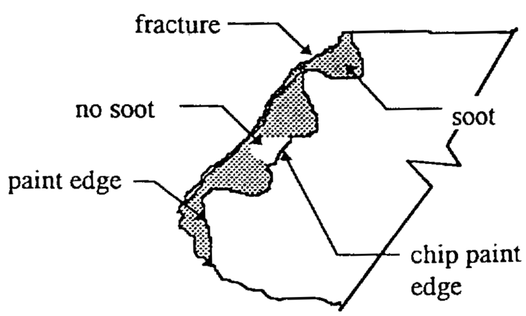
Heavy sooting

Surveyed panels are all recovered from the Green debris field and are located from approximately STA 910 to STA 1600.
Aft of STA 1600, no sooting is evident internally. On the exterior, there is light to moderate sooting extending aft along the entire length of the fuselage from approximately the main deck window belt on the RHS to approximately S-8 on the LHS



Sooting deposits evident on edges with arrows.

Panel recovery date

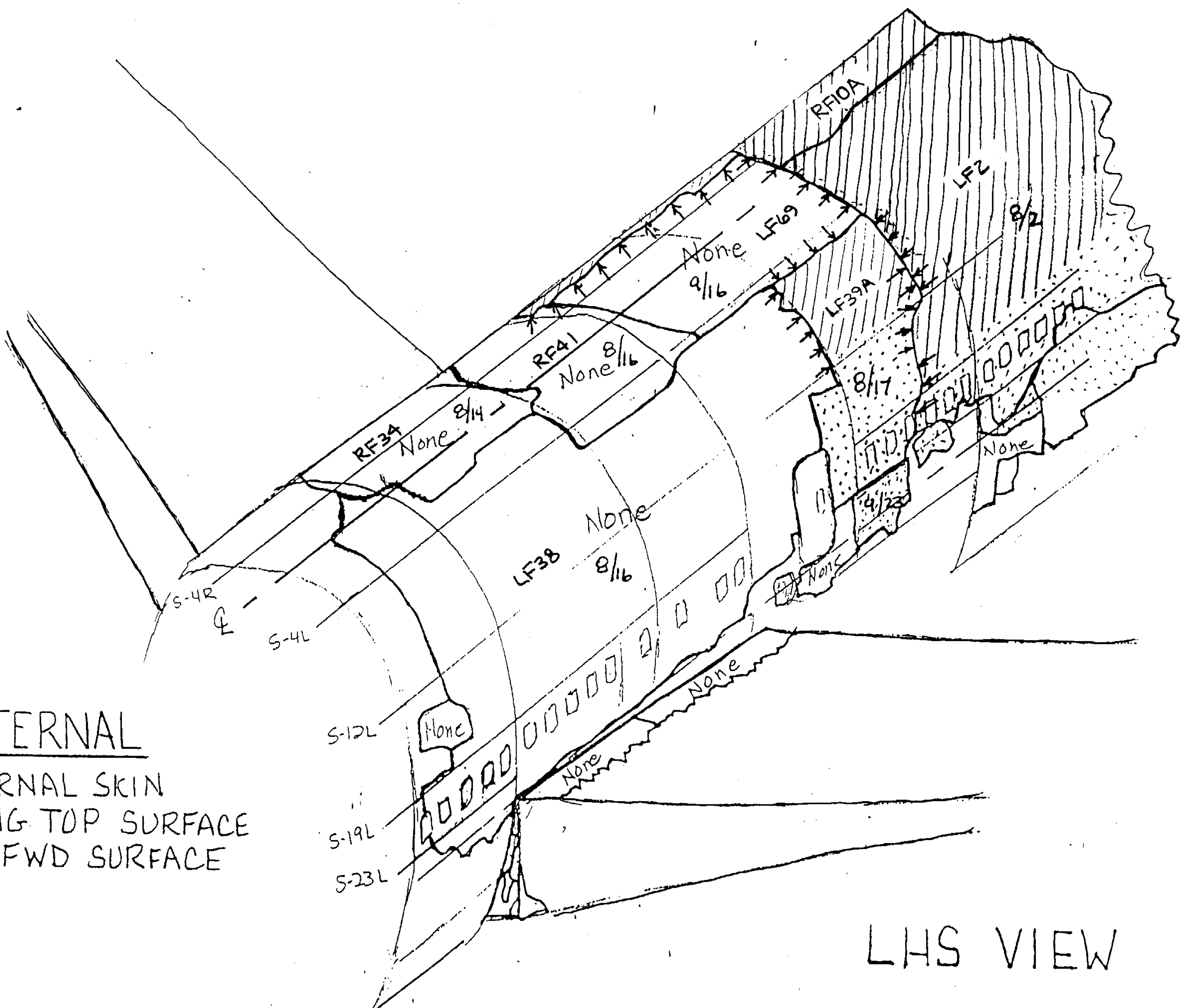


Determination primarily made by examining external paint failures near the fracture edge. Soot deposits remain on underlying paint when the top layer peels near fracture.

FIGURE 10-1

EXTERNAL

EXTERNAL SKIN
WING TOP SURFACE
F/S FWD SURFACE



LHS VIEW

FIGURE 10-2

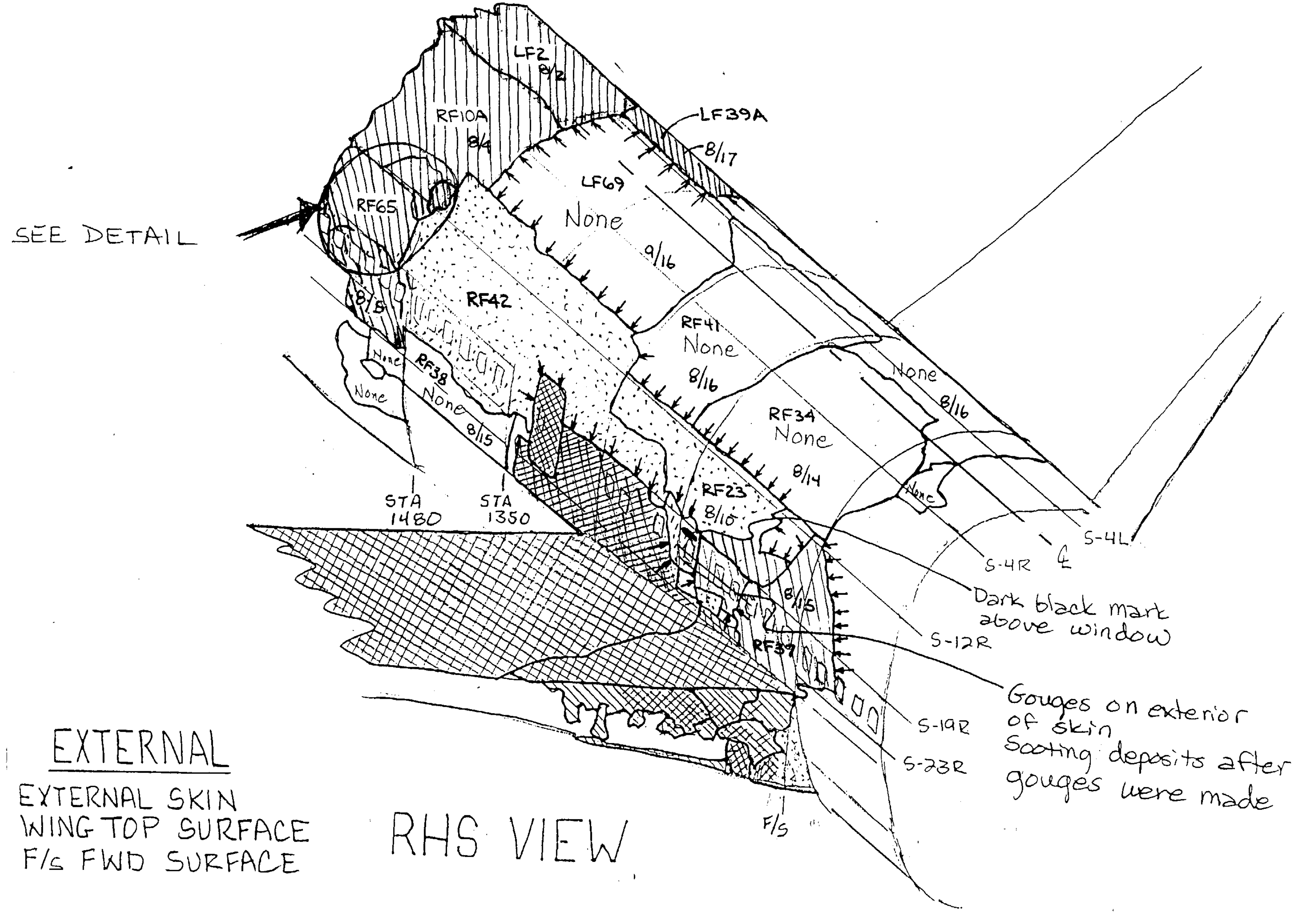

SEE DETAIL
LF2
8/2
RF10A
8/4
LF39A
8/17
RF65
LF69
None
9/16
RF42
8/15
RF41
None
8/16
None
8/16
RF34
None
8/14
None
RF38
None
8/15
None
None
STA 1480
STA 1350
RF23
8/10
8/15
RF37
S-4L
S-4R
℄
Dark black mark above window
S-12R
Gouges on exterior of skin
Sooting deposits after gouges were made
S-19R
S-23R
F/S
EXTERNAL
EXTERNAL SKIN
WING TOP SURFACE
F/S FWD SURFACE
RHS VIEW

FIGURE 10-3

INTENTIONALLY BLANK

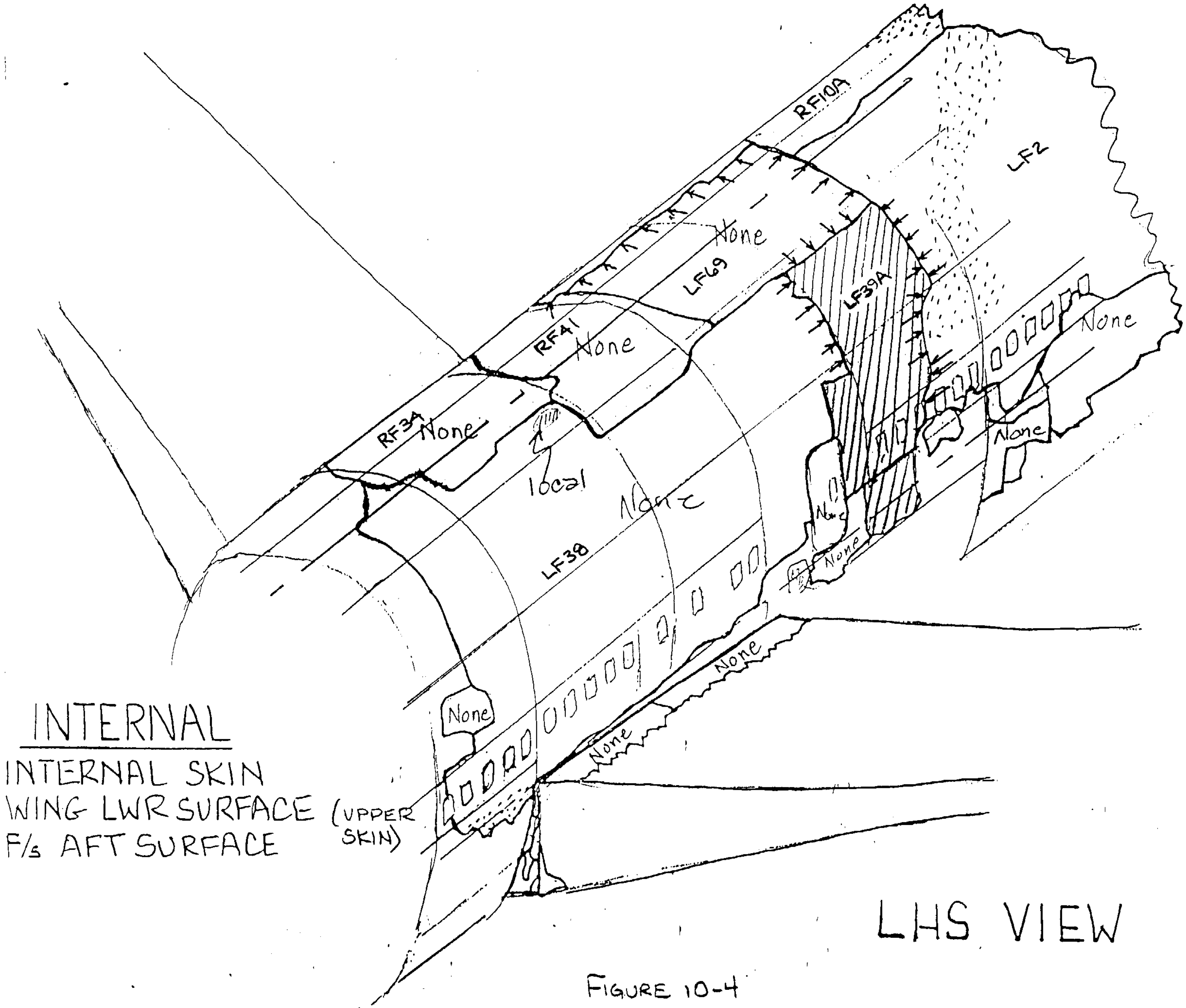

RF10A
LF2
None
LF69
LF39A
RF41
None
None
RF3A
None
local
None
LF38
None
None
None
None
None
INTERNAL
INTERNAL SKIN
WING LWR SURFACE (UPPER SKIN)
F/S AFT SURFACE
LHS VIEW

FIGURE 10-4

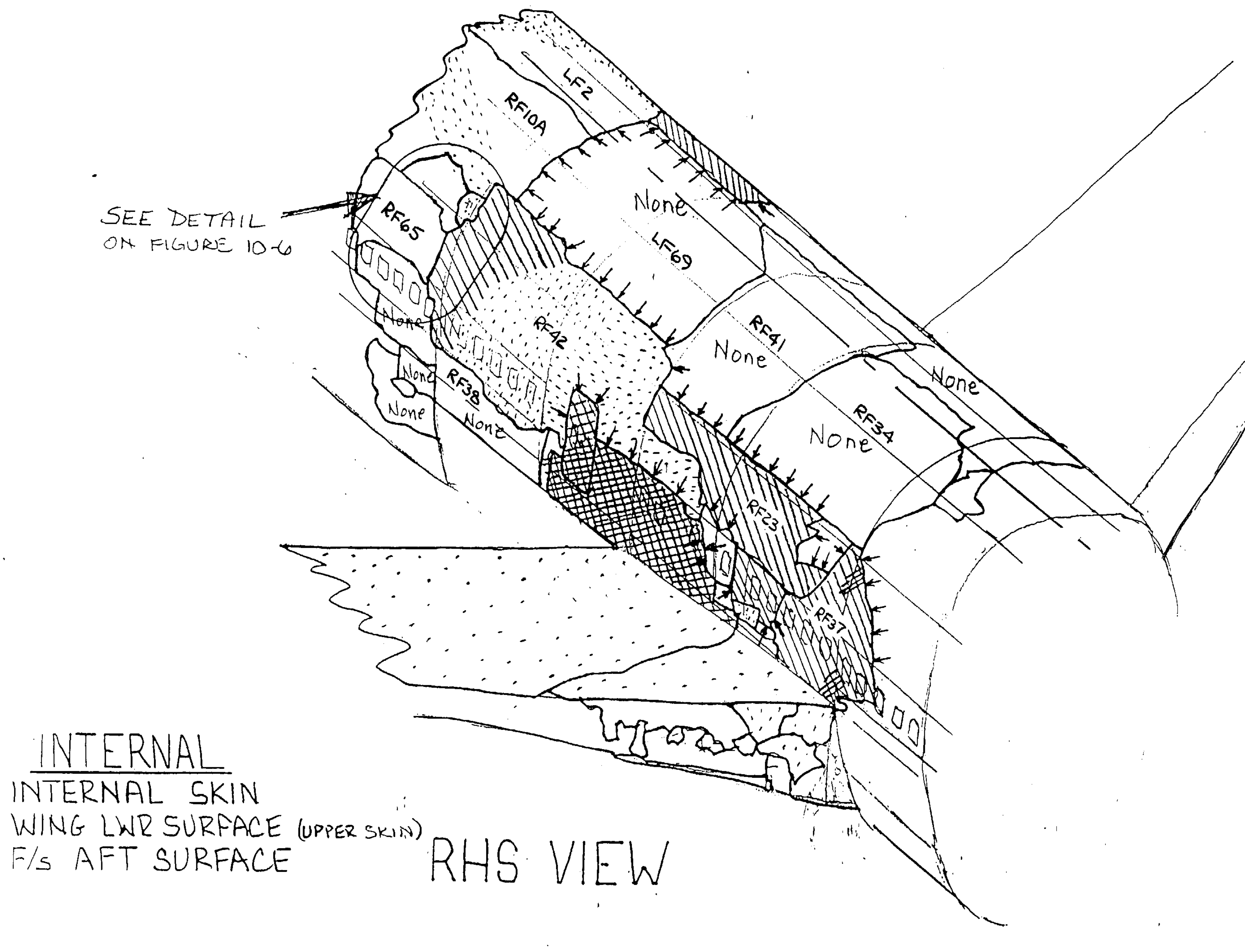

SEE DETAIL
ON FIGURE 10-6
LF2
RF10A
RF65
None
LF69
RF42
RF41
None
None
RF38
None
None
None
RF34
None
None
RF23
RF37
INTERNAL
INTERNAL SKIN
WING LWR SURFACE (UPPER SKIN)
F/S AFT SURFACE
RHS VIEW

FIGURE 10-5

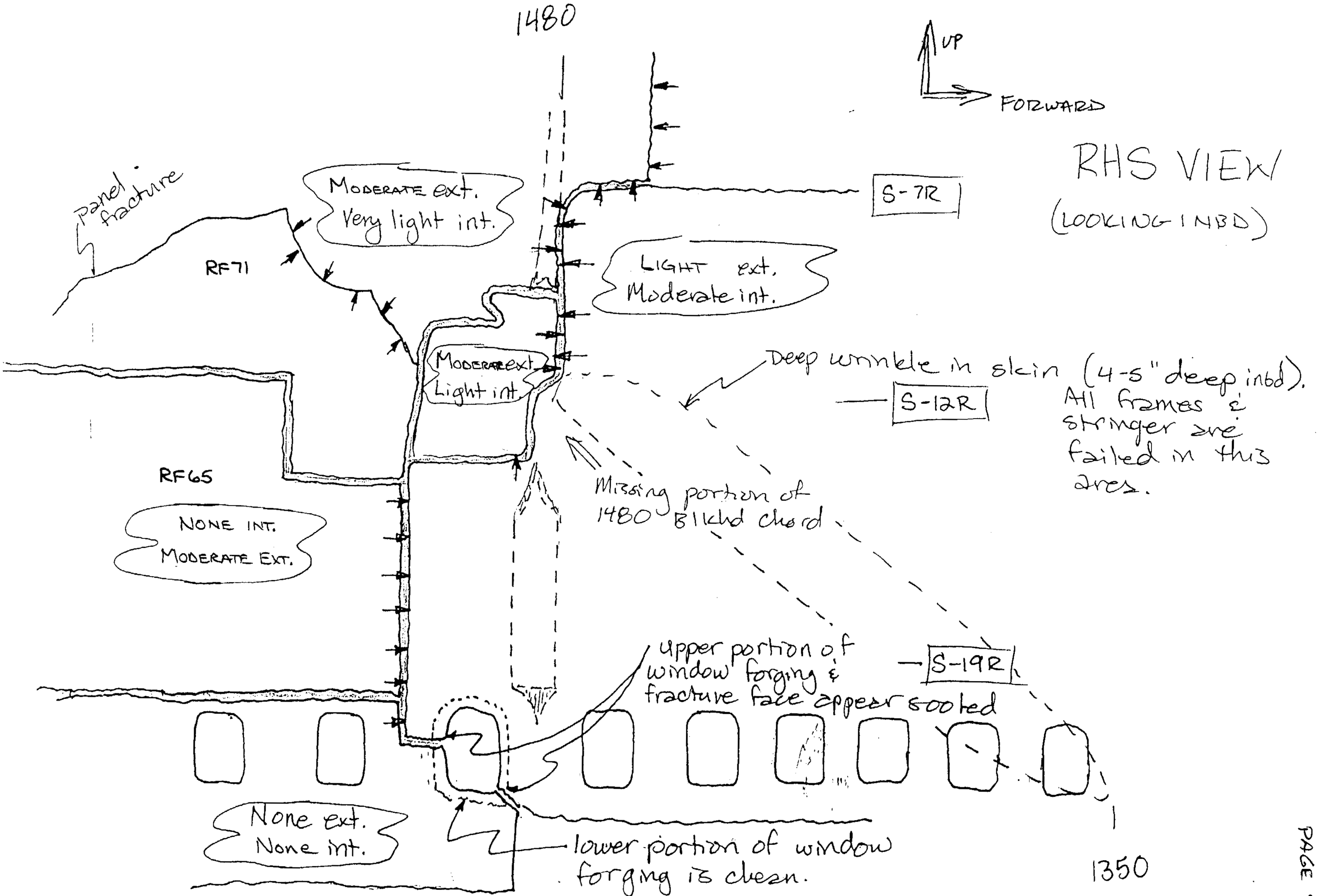

1480
UP
FORWARD
RHS VIEW
(LOOKING INBD)
panel fracture
MODERATE ext.
Very light int.
RF71
LIGHT ext.
Moderate int.
S-7R
MODERATE ext.
Light int.
Deep wrinkle in skin (4-5" deep inbd).
All frames & stringer are failed in this area.
S-12R
RF65
NONE INT.
MODERATE EXT.
Missing portion of 1480 Blkhd chord
upper portion of window forging & fracture face appear sooted
S-19R
None ext.
None int.
lower portion of window forging is clean.
1350

FIGURE 10-6

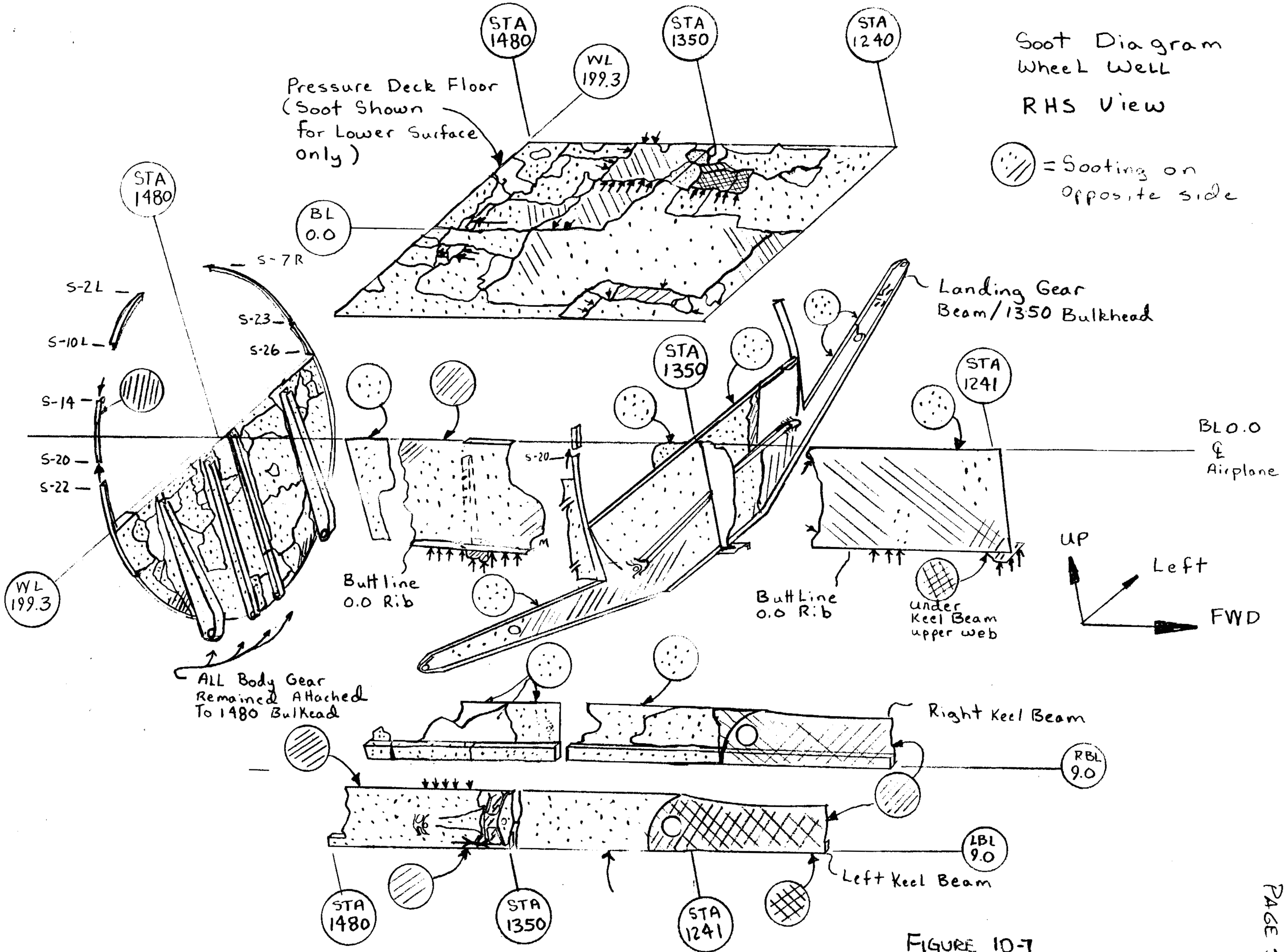

Soot Diagram
Wheel Well
RHS View
= Sooting on Opposite side
STA 1480
STA 1350
STA 1240
WL 199.3
Pressure Deck Floor (Soot Shown for Lower Surface only)
BL 0.0
STA 1480
S-7R
S-2L
S-23
S-10L
S-26
S-14
S-20
S-22
WL 199.3
Landing Gear Beam/1350 Bulkhead
STA 1350
STA 1241
BL 0.0
℄ Airplane
S-20
Buttline 0.0 Rib
ButtLine 0.0 Rib
Under Keel Beam upper web
UP
Left
FWD
ALL Body Gear Remained Attached To 1480 Bulkead
Right Keel Beam
RBL 9.0
LBL 9.0
Left Keel Beam
STA 1480
STA 1350
STA 1241

FIGURE 10-7