NATIONAL TRANSPORTATION SAFETY BOARD
Investigative Hearing
Alaska Airlines Flight 1282
Boeing 737-9, N704AL
Left Mid Exit Door Plug Separation in Portland, OR
January 5, 2024

Docket No.	**SA-543**
EXHIBIT	
15A	

Materials Group Chair's Factual Report

(55 Pages)

National Transportation Safety Board

Office of Research and Engineering

Washington, DC 20594

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MATERIALS LABORATORY

Factual Report 24-007

March 31, 2024

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A. ACCIDENT INFORMATION

Location: Portland, Oregon
Date: January 5, 2024
Vehicle: Boeing 737-9, N704AL
Investigator: John Lovell, AS-10/Clint Crookshanks, AS-40

B. SUMMARY

On January 5, 2024, about 1714 Pacific standard time, Alaska Airlines flight 1282, a Boeing 737-9, N704AL, returned to Portland International Airport (PDX), Portland, Oregon, after the left mid exit door (MED) plug departed the airplane leading to a rapid decompression. The airplane landed on runway 28L at PDX without further incident, and all occupants (2 flight crewmembers, 4 cabin crewmembers, and 171 passengers) deplaned at the gate. Seven passengers and one flight attendant received minor injuries. The flight was operated under Title 14 Code of Federal Regulations (CFR) Part 121 as a scheduled domestic passenger flight from PDX to Ontario, California (ONT).

C. COMPONENTS EXAMINED

Left mid exit door (MED) plug with associated frame stop fittings, upper guide rollers, upper guide roller serrated plates and shims, hinge assembly components with attached lower brackets, and strap assemblies.
Exemplar vertical movement arrestor bolts and upper guide track bolts with associated washers, nuts, and pins removed from the right MED plug.

D. EXAMINATION PARTICIPANTS

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E. DETAILS OF THE EXAMINATION

Overall views of the submitted left mid exit door (MED) plug and associated components are shown in figures 1 to 4. The MED plug assembly and items removed from the frame around the MED plug are shown labeled in the upper left image in figure 1. Examined components included the left MED plug assembly that separated from the airplane and was recovered from the backyard of a private residence. Additionally, the examined parts included the frame stop fittings, upper guide roller fittings with associated serrated plates and shims, and recovered components of the lower hinge assemblies with attached lower hinge brackets that were disassembled from the MED frame on the fuselage after the accident.

The left MED plug and associated components were examined initially on scene January 6 through 11, 2024, and subsequently by a group examination conducted at the NTSB Materials Laboratory in Washington, DC, January 23 through 25, 2024. Exemplar upper guide track bolts, vertical movement arrestor bolts, and associated washers, nuts, and cotter pins that were removed from the right MED plug during inspections of the accident airplane conducted on February 13 and 14, 2024, were examined following the group examination.

Multiple components were missing from the recovered items associated with the left MED plug, including all upper guide track bolts, vertical movement arrestor bolts, and associated washers, nuts, and cotter pins. Additionally, while fractured flange pieces of the hinge guide fitting from the forward lower hinge assembly were recovered, the lift assist spring, spring washers, stop washer and remainder of the hinge guide fitting were not recovered from the forward assembly.

1.0 MED Plug Description

Diagrams identifying various components associated with the MED plug are shown in figures 5 and 6. As designed, the MED plug has 12 stop pins installed in fittings on the forward and aft sides of the plug (6 on each side) that rest against 12 stop pads attached to fittings on the forward and aft door frame elements (6 on each side) as indicated in figure 5. The stop pins, pads, and associated fittings prevent outward motion of the door plug once it is installed in the MED opening in the fuselage.

During installation, the MED plug is guided into the MED opening in the fuselage by means of two upper guide fittings and two lower hinge assemblies (see figures 5 and 6). The two upper guide fittings are located on the forward and aft sides of the plug and engage with two upper guide rollers that are attached to the door frame at the forward and aft sides of the MED opening (see figure 5). Two hinge guide fittings (see figure 6) are attached to the MED plug near its lower end and engage with hinge fittings that are attached to the lower hinge bracket assemblies.

The lower hinge bracket assemblies are attached to the frame at the lower side of the MED opening.

The MED plug is shown in the opened condition in figure 5. To close the MED plug, the upper end swings inboard about the lower hinge bolts until the MED plug is against the seal around the door frame. As the MED plug rotates inboard, each plug stop fitting is positioned a couple inches above the corresponding frame stop fitting as shown in the right diagram in figure 6. The MED plug is then positioned so that openings at the lower ends of the upper guide fittings engage with the upper guide rollers on the frame to guide the movement of the MED plug inboard and down from the open to closed position as indicated with dashed lines in figure 6. Positioning at the lower end of the plug is maintained by the hinge guide fitting, which slides vertically on the upper shaft portion of the hinge fitting. The lower hinge assembly is shown in the closed position on the left side of figure 6. In the closed position, the plug stop fittings are located inboard of the frame stop fittings with little or no gap between each stop pin face and the adjacent stop pad face as shown at the upper right in figure 6.

Once the MED plug is in place, it is secured from moving vertically by two upper guide track bolts that extend through the upper guide fittings below the upper guide rollers and two vertical movement arrestor bolts that extend through the hinge guides and hinge fittings. These four bolts are secured using castle nuts and cotter pins. Once the door is closed and adjusted to specification, gaps should be present between the upper guide rollers and the adjacent upper guide fittings and track bolts as shown in figure 6.

The MED plug is only intended to be opened for maintenance and inspection, which requires removing the vertical movement arrestor bolts and upper guide track bolts to move the plug up off the stops. Two lift assist springs, each providing about 50 pounds of force when fully compressed, assist in keeping the plug raised while clearing the stops and engaging the upper guide fittings with the upper guide rollers during the opening and closing process. Cables at the forward and aft sides of the MED plug restrict the plug from opening further than 15°, suitable for maintenance and inspection purposes.

2.0 Right MED Plug

The accident airplane had an MED plug on each side of the airplane. While the left MED plug separated from the airplane, the right MED plug remained intact and in place. After the accident, the cabin liner and nearby seats were removed from the interior around the right MED plug to reveal the inboard side of the plug as shown in figure 7. The upper guide track bolts and vertical movement arrestor bolts were found in place, and all four bolts were secured with castle nuts and cotter pins. All 12 stop pins were present and secured with locking wires, and the pin heads appeared to be positioned on or near the stop pads as shown in the upper left image in figure 7.

Inspection of the right MED plug was completed on February 13 and 14, 2024. During the inspections, the upper guide track bolts and vertical movement arrestor bolts and associated washers, nuts, and cotter pins were retained for examination as exemplar hardware, and the removed hardware is shown at the lower left side of figure 7. The heads of the upper guide track bolts from the right MED plug were marked with “B30NM4D” around a central dimple, consistent with head markings for the specified bolt. The heads of the vertical movement arrestor bolts from the right MED plug were marked “B30LM3D” around a central dimple, also consistent with head markings for the specified bolt.

On the upper guide track bolts shown in figure 7, the shank appeared slightly darker in areas adjacent to the washers, consistent with witness marks from contact with the upper guide fitting hole bores. The witness marks were relatively uniform around the circumference of the bolts. On the vertical movement arrestor bolts, witness marks were more pronounced with darker features relative to the surrounding areas of the shanks, especially for the bolt from the aft hinge assembly. The locations of the witness marks corresponded to contact with the inboard and outboard ends of the vertical movement arrestor bolt hole through the hinge fitting, and the dark features appeared consistent with transfer of black dry film lubricant applied to the hinge fittings. On the arrestor bolt from the aft hinge fitting, the witness marks were aligned in the same quadrant around the circumference as shown in figure 7. On the arrestor bolt from the forward hinge fitting, the inboard and outboard witness marks were observed in different quadrants around the circumference, and only the mark closer to the bolt head is visible in figure 7.

The nuts and washers on all four exemplar bolts from the right MED plug were removed from the assembly to check for any deformation of the shank. The bolts were placed on a flat surface with the bolt head off the edge to place the grip flush against the surface. Each bolt was rolled about its axis on the surface with low-angle backlighting to look for light penetration through any gaps between the shank and the flat surface. No evidence of grip deformation or wear was detected.

3.0 Left MED Stop Fittings

Overall views of the left MED opening as viewed during the on-scene phase of the investigation are shown in figure 8. When the photographs in figure 8 were taken, the seats in the area around the MED opening had been removed to facilitate examination of the opening. The frame stop fittings for the left MED opening remained intact and attached to the forward and aft sides of the opening after the left MED plug had departed. For reference, the frame stop fittings were labeled as shown in figure 8 with a number indicating the sequential position from top to bottom and a letter to indicate aft (A) or forward (F) side of the MED opening. The same method was used to label the corresponding plug stop fittings.

Overall views of the frame stop fittings as received at the NTSB Materials Laboratory are shown in figure 9. The stop pads on the frame stop fittings had mostly faint linear, vertically oriented scratches on the surfaces, mostly on the upper portions of the pads. The 6A stop pad also had two circumferential marks corresponding to the diameter of the stop pin head that were vertically displaced relative to each other (see the lower left image in figure 10).

The frame stop fittings generally showed sliding contact damage at the upper sides of the fittings as indicated with unlabeled arrows in the right image in figure 9. Closer views of the damage on frame stop fittings 1A, 1F, 6A, and 6F are shown in figure 10. The damage included missing enamel and primer with deformed metal from sliding contact mostly at the upper inboard corners of the fittings. Additional images of each of the frame stop fittings are presented in Appendix A to this report. The damage was generally more extensive on the upper 6 stops (1A to 3A and 1F to 3F) and was more limited on the remaining stops from the lower portion of the MED opening with stops 4A and 4F showing the least extent of damage. As shown in the left image in figure 9, the size of the fitting around the stop pad was larger on the upper 6 fittings compared to the lower 6 fittings.

Representative images of plug stop fitting damage on the left MED plug are shown in figures 11 and 12, and additional views of each of the plug stop fittings are shown in Appendix A. The stop pin shafts were present and secured with lock wire in all 12 plug stop fittings. The pins were similarly positioned within the fitting, and each pin had 5 to 6 threads exposed on the inboard side of the fittings. The stop pin head was missing at locations 3F, 4F, 5F, 6F, 5A, and 6A, and the flared outboard ends of the pin shafts with the missing heads were deformed. The o-rings associated with the missing pin heads remained on the pin shafts as shown at locations 6F and 6A in figures 11 and 12, respectively. At location 3A, the o-ring was partially displaced out of its groove in the pin head, and at location 4A, the o-ring was displaced completely out of its groove in the pin head. Each of the intact pins had a flat deformed area on one side of the pin on the outer edge of the face. The intact pin heads swiveled normally when manipulated by hand.

The plug stop fittings were mostly damaged from sliding contact at the lower sides of the fittings as shown in figures 11 and 12. Additional views showing the damage on all 12 plug fittings are presented in Appendix A. The damage included missing enamel and primer with deformed metal from sliding contact that was heaviest at the lower outboard corners of the fittings. The extent of damage was greatest on plug stop fittings 1F, 2F, and 1A. The damage was least on plug stop fitting 4F, where only a small area of metal on the lower inboard corner was exposed on the fitting, and plug stop fitting 4A, which had intact enamel on the entire lower side and outboard corner of the fitting.

Most of the sliding contact marks had linear features that were oriented parallel to the stop pin axis, consistent with the plug moving outboard relative to the contacted feature. However, angled sliding contact marks were observed overlaying the marks parallel to the pin axis on plug stop fittings 1F and 2F. Unlabeled arrows in the upper left and middle left images in figure 11 indicate sliding contact marks that were oriented parallel to the stop pin axis and those oriented at an angle. The angled marks were consistent with the plug displacing outboard and aft relative to the contacted feature.

The orientation and geometry of the sliding contact marks and damage on the frame stop fittings and plug stop fittings mostly had features consistent with the plug being displaced upward and then outboard. The images in figure 13 show the frame stop fittings positioned next to the mating plug stop fittings at stop positions 1A, 1F, 6A, and 6F. The fittings were positioned so that corresponding areas of sliding contact damage were next to each other with the plug fittings positioned at the upper inboard side of the corresponding frame fitting. Additional images with similar relative positioning at each of the stop positions are included in Appendix A.

The angled sliding contact marks that overlayed the marks parallel to the stop pin axis at plug stop fittings 1F and 2F (see figure 11) were consistent with the plug displacing aft after it had displaced outboard while contacting the frame stop fittings. As shown in the upper left image in figure 13, plug stop fitting 1A had marks on the aft side of the fitting that corresponded to contact with parts of the frame fitting aft of the stop pad. At location 1F, the damage to frame stop fitting from contact with the plug stop fitting was also skewed aft of the stop pad as shown in the upper right image in figure 13.

Angled sliding contact marks were also observed on the forward side of the frame stop fitting next to the outboard edge of the fitting as shown in figure 14. Corresponding contact marks were observed on a damaged area on the plug below plug stop fitting 1A. The frame stop fitting is shown next to the plug with the corresponding contact marks placed next to each other in figure 15 where the plug is displaced upward, outboard, and aft relative to the frame at the point of contact. The direction of the sliding contact and the change in depth associated with the marks are also consistent with the plug moving upward, outboard, and aft relative to the frame at the point of contact when the marks were made.

4.0 Left MED Plug Upper Guide Fittings and Rollers

The forward and aft upper guide fittings on the left MED plug are shown viewed from various angles in figures 16 and 17. Each fitting had a vertical fracture through the inboard wall of the guide track that intersected the inboard upper guide track bolt hole. In each fitting, the fractured wall piece on the side closer to the frame opening (forward side in the forward fitting and aft side in the aft fitting) remained attached to the rest of the fitting at the upper end of the piece where it was bent inboard and upward. On the aft upper guide fitting, the fractured piece was also bent forward at the upper end of the piece.

On the forward upper guide fitting, the fractured and bent piece had a curved deformation near the lower end of the piece. Deformation with a similar geometry was located at a similar location on the aft upper guide fitting. Arrows in the upper left images in figures 16 and 17 indicate this area of curved deformation in each fitting with a radius of curvature that was consistent with the geometry of the bearing outer races on the upper guide rollers attached to the MED opening frame. The apex of the curved deformation relative to the original inboard wall plane was located below the centerlines of the upper guide track bolt holes in each fitting.

The upper guide fittings had deformed areas at the upper sides of the inboard upper guide track bolt holes with smooth reflective surfaces. The deformation extended onto the fracture surface and was not continuous to the mating side of the fracture, indicating that it occurred after the fracture. The smooth deformed areas had features consistent with roller contact on the upper side of the bearing outer race. These areas of roller contact at the upper side of the upper guide track bolt hole are indicated in the lower left images in figures 16 and 17. In the left image in figure 18, the roller is shown positioned against the contact damage at the upper side of the upper guide track bolt hole on the aft upper guide fitting. Similar roller contact marks were also observed at the lower end of the fracture on the forward upper guide fitting corresponding to contact with the lower side of the roller, and the roller is shown positioned near the lower contact area on the forward upper guide fitting in the right image in figure 18.

Close views of the upper guide rollers as received are shown in figures 19 and 20. The serrated plates and shims associated with the rollers were also received but are not shown. Two shims were installed at the forward roller attachment location, and four shims were installed at the aft roller attachment location, consistent with the nominal installation of three shims and maximum of five shims at either location as described in rigging procedures for the MED plug installation.

The bearing outer races on both upper guide rollers rotated freely and smoothly by hand. An area on the forward roller bearing outer race shown circled at the right in figure 19 had material with a dull appearance that appeared deposited on the surface. The area was analyzed using an Olympus Vanta x-ray fluorescence alloy analyzer and was compared to another area of the bearing outer race that appeared free of deposits. The area with the deposit showed a significantly higher level of aluminum compared to the area free of deposits, and the level of titanium was below the limit of detection. The upper guide track bolts are made of a titanium alloy, and as discussed in more detail later in this report, the upper guide fittings are made of an aluminum alloy.

Sliding contact marks were observed on the forward face of the aft upper guide roller bearing as shown in the left image in figure 20. Enamel on the fitting face next to the bearing was also disturbed at the upper and outboard sides. The bearing outer race had green deposits on multiple areas around the circumference appearing consistent with deposits of primer. Most of the primer was located in a thin line near the aft side of the outer race next to the fitting. However, one area of green deposits appeared to have a mashed appearance across the outer race extending toward the forward face of the bearing as shown circled at the right in figure 20.

As shown in figures 16 and 17, the upper guide fittings had intact enamel with no evidence of contact damage around the inboard sides of the inboard upper guide track bolt holes and the outboard sides of the outboard upper guide track bolt holes, including much of the surface around the holes on the fractured and bent pieces as indicated in the upper right images in figures 16 and 17. Areas with missing enamel had tension cracks corresponding to the outside of the bend from the curved roller contact deformation. Faint circular marks consistent with prior contact with washers associated with the upper guide track bolt were visible on the forward upper guide fitting during preliminary examinations. However, both upper guide track bolts were missing from the intact and undeformed outboard holes of the upper guide fittings, and all damage and deformation to the inboard holes appeared to be associated with contact with the upper guide rollers.

Next, the upper guide fittings were disassembled from the left MED plug and cleaned using an ultrasonic cleaner while submerged in ethanol. A view of the upper guide fittings after disassembly and cleaning are shown in figure 21. The upper guide track bolt hole bores and surrounding areas were examined using a stereo optical microscope, and magnified views of the holes on the forward and aft upper guide fittings are shown in figures 22 and 23, respectively. On each fitting, faint marks with darker features were observed on the enamel on the inboard surface around the inboard holes as indicated with unlabeled arrows in figures 22 and 23, markings consistent with prior contact with washers associated with the upper guide track bolt. The hole bores on the lower sides of the inboard and outboard upper guide track bolt holes are also shown in figures 22 and 23. The hole bores had intact enamel and appeared free of any contact damage or wear patterns.

The fracture surfaces on the forward and aft upper guide fittings were examined using a scanning electron microscope (SEM), and representative images are shown in figures 24 and 25. The fracture surfaces showed dimple features consistent with ductile overstress fracture as shown in the middle images in figures 24 and 25. Smooth areas with curving features were observed in areas below the upper guide track bolt holes on each surface as shown in the lower images in figures 24 and 25. The curving features were deformation marks associated with sliding contact damage consistent with post-fracture contact with the upper guide roller outer race.

No indication of any preexisting crack or progressive fracture mechanism was observed on the examined fracture surfaces.

5.0 Left MED Plug Lower End and Lower Hinge Assemblies

Openings for the lower hinge assemblies in the left MED plug lower beam structure are shown in figure 26. At the forward hinge opening, contact marks were observed at the lower side of the opening on the inboard, forward, and outboard sides as indicated with unlabeled arrows in the right image in figure 26. The lower end of the inboard flange on the lower beam was also deformed inboard. At the aft hinge opening, contact marks, deformation, and missing material were observed at the lower side of the opening on the inboard, forward, and aft sides as indicated with unlabeled arrows in the left image in figure 26. The lower end of the inboard flange of the lower beam was deformed inboard similar to deformation at the forward hinge location, but the extent of deformation was greater.

The forward and aft hinge guide fittings were fractured from the plug as shown in figure 27. Where each fitting had been attached, the two lower attachment bolts were fractured, and the two upper attachment bolts remained intact. The threaded ends of the fractured attachment bolts were retained in the nut plates that were attached to the MED plug. As shown in figure 28, all attachment bolts at both the forward and aft hinge guide fitting attachments had similar extents of the threaded end extending beyond the nut plate with approximately 2 to 3 threads exposed. The head end of the fractured bolt at the lower inboard location for the aft hinge guide fitting remained within its hole in the fitting's flange, and head ends of the other three fractured bolts were missing. The heads on each of the intact bolts and the bolt head piece that remained in the aft hinge guide fitting all were marked "B30NM3" around a central dimple, consistent with the specified bolts.

A fractured piece of the aft hinge guide fitting flange was retained at the upper forward attachment bolt location, and fractured pieces of the forward hinge guide fitting flange remained attached at both upper attachment bolts. The serrated plate installed between the hinge guide fitting flange and the plug remained in place at both locations as shown. To facilitate further examination of the fractured hinge guide fitting pieces and associated hardware, the upper attachment bolts were unscrewed from the nut plates, and the lower nut plates were detached from the MED plug. An overall view of the disassembled pieces is shown in figure 29. The holes on the serrated plates were deformed, and serrations were damaged as shown. The upper outboard attachment bolt for the aft hinge guide fitting was bent.

The hinge guide fitting attachment holes in the left MED plug are shown in figure 30 after removing the serrated plates. The edges of the holes showed deformation consistent with bearing contact damage from the attachment bolts, and unlabeled arrows in figure 30 point to the location of the bearing contact damage. The bearing damage had a circular contact pattern consistent with both hinge guide fittings rotating counterclockwise, as viewed looking forward, relative to the underlying plug structure. (Note the view of the forward attachment location shown at the right in figure 30 is a view looking aft.)

The hinge guide fitting flange pieces shown in figure 29 were further examined using an optical stereo microscope and an SEM. The pieces at the upper inboard locations on the forward and aft hinge guide fittings had similar features, and the piece from the forward hinge guide fitting is shown in figure 31 as representative of both pieces. The pieces were fractured from the inboard side of the hinge guide fitting flanges at the upper inboard holes. Evidence of heavy contact with the attachment bolt was observed with missing primer and slight deformation in the contact area. The fracture surfaces had a smeared appearance with elongated dimple features consistent with ductile overstress fracture. Overall SEM images of the fracture surfaces on the piece from the forward hinge guide fitting flange are shown at the right in figure 31. Similar features were observed on the flange piece from the aft hinge guide fitting shown in figure 29.

The forward hinge guide fitting piece from the upper outboard corner of the flange shown in figure 29 was similarly examined. The fracture surface had dimple features consistent with ductile overstress fracture with tensile features on the fracture at the outboard side and bending deformation at the upper side. The aft hinge guide fitting that remained attached to the aft hinge fitting had optically similar fracture features at its upper outboard attachment location, and the upper outboard corner of the flange with the mating sides of the fractures was not recovered.

Fracture surfaces on the lower attachment bolts for the forward and aft hinge guide fittings are shown in figures 32 and 33, respectively. On the fractured lower attachment bolts for the forward hinge guide fitting, the fracture surfaces on the lower inboard bolt shown at the left in figure 32 had uniform rough matte gray features consistent with ductile overstress fracture. The lower outboard attachment bolt shown at the right in figure 32 had smeared features with rough features near the middle, features consistent with ductile overstress fracture under direct shear loads. On the fractured lower attachment bolts for the aft hinge guide fitting, the lower inboard bolt shown at the left in figure 33 had a large shear lip on one side of the fracture consistent with a bending load associated with the fracture. The overall fracture pattern on both lower attachment bolts for the aft fitting shown in figure 33 had uniform rough matte gray features consistent with ductile overstress fracture. No evidence of preexisting cracks or damage was observed on any of the hinge guide fitting attachment bolts.

A close view of the recovered lower hinge assemblies with attached lower brackets disassembled from the left MED frame are shown as received in figure 34. The hinge guide fitting, lift assist spring, lift assist spring washers, stop washer, and vertical movement arrestor bolt hardware were missing from the forward lower hinge assembly as shown in figure 34. On the aft lower hinge assembly, the vertical movement arrestor bolt hardware was missing, and the hinge guide fitting was positioned against the stop washer at the upper end of the hinge fitting. A phenolic washer was also missing from the upper side of the aft hinge guide fitting leaving remnants of adhesive in the area associated with the missing washer.

To facilitate a further examination of the lower hinge assemblies, the hinge fittings were disassembled from the lower hinge bracket assemblies as shown in figures 35 and 36. Upon disassembly, both lower hinge bolt assemblies had one thick and one thin washer under the head and two thick washers and one thin washer under the nut. Additionally, each hinge bolt had thin adjustment washers installed between the hinge fitting and the lower hinge bracket at the forward and aft sides of the fittings. On the forward hinge fitting, the forward assembly had 4 thin adjustment washers at the forward side and 4 more at the aft side of the hinge fitting. The lower hinge bolt from the aft assembly had 5 thin adjustment washers at the forward side and 4 thin adjustment washers at the aft side. According to rigging procedures for the MED plug installation, each lower hinge bolt should have a total of eight thin adjustment washers installed divided evenly between the forward and aft sides of the hinge fitting or moved from one side to the other as needed for plug position adjustments. The rigging procedures state the total count of adjustment washers must remain at eight and adjustments must be made in unison to both fittings.

As assembled, the lower hinge bolt is installed in the lower hinge bracket assembly through bushings with slotted holes that are bonded in place with the long axis of the slot oriented parallel to the horizontal plane. On the aft lower hinge bracket assembly, the aft bushing was rotated as noted in figure 36 such that the long axis of the slot was oriented approximately 55 degrees from the horizontal plane. No evidence of rotation was observed on any of the other slotted bushings in the forward and aft lower hinge bracket assemblies.

The hinge fittings and hinge guide fittings were both made of an aluminum alloy as described in more detail later in this report. The hinge guide fittings were coated with a gold-colored conversion coating followed by green primer. The hinge fittings were also coated with the gold-colored conversion coating, but the exterior was then coated with a black-colored dry film lubricant.

Closer views of the forward hinge fitting shaft including areas around the vertical movement arrestor bolt hole through the shaft are shown in figure 37. The dry film lubricant was rubbed and disturbed on the shaft consistent with contact with the lift assist spring and washers and the hinge guide fitting. Around the vertical movement arrestor bolt holes, the dry film lubricant was disturbed, exposing the underlying conversion coating. Orange-colored deposits were observed on the surface in the lower aft quadrant of the hole at the outboard side of the hinge fitting as indicated in the lower right image in figure 37. When analyzed using energy dispersive x-ray spectroscopy (EDS), the deposits generally had spectra with higher peaks of aluminum, oxygen, and chromium when compared to spectra obtained from adjacent areas of the hinge fitting, which showed a high peak associated with molybdenum and sulfur, consistent with the dry film lubricant. The vertical movement arrestor bolt holes were circular and showed no evidence of damage or deformation from bearing contact with a vertical movement arrestor bolt.

A close examination of the forward hinge fitting shaft revealed the shaft was bent slightly. As described in Materials Laboratory Factual Report 24-010, the upper end of the shaft was bent slightly inboard such that the longitudinal axis at the upper end of the shaft above the vertical movement arrestor bolt hole was angled 0.4 degrees inboard relative to the longitudinal axis of the shaft portion below the hole.

The jam nuts were present and installed on the threaded upper end of the forward hinge fitting as indicated in figure 37. The jam nuts were tight against each other with hand forces applied to the nuts. A gap was observed between the lower jam nut and the upper face of the fitting shaft as noted in figure 37. The size of the gap was consistent with the thickness of the missing stop washer, and damage consistent with contact with the washer was observed on the lower edges of the lower jam nut including extending up the rounded edges at corners between adjacent wrench flats.

The jam nuts on the upper end of the aft lower hinge assembly were also present and tight when tested by hand. The stop washer was deformed with the outer edges dished upward around the lower jam nut. To facilitate further examination of the aft lower hinge assembly, the jam nuts at the upper end of the hinge fitting were disassembled from the fitting, and the remaining components of the assembly were slid off the upper end of the hinge fitting shaft. Figure 36 shows the aft lower hinge assembly after disassembly.

After disassembly, the deformed stop washer from the aft lower hinge assembly was placed with the upper side of the washer on a flat table, and the extent of deformation was measured using a vertical height gage placed at the inside diameter of the washer. The maximum height measured 0.193 inch. The extent of deformation was calculated by subtracting the thickness of the washer (0.078 inch as measured with calipers on the deformed washer) from the height measurement, and the result showed the outer edge of the stop washer was deformed upward approximately 0.115 inch relative to the inner edge.

Close views of the vertical movement arrestor bolt holes through the inboard and outboard walls of the aft hinge guide fitting are shown in figure 38. The vertical movement arrestor bolt holes were circular with mostly intact primer and showed no evidence of damage or deformation from bearing contact with a vertical movement arrestor bolt.

Overall views of the aft hinge fitting shaft are shown in figure 39. The dry film lubricant was rubbed and disturbed on the shaft consistent with contact with the lift assist spring and washers and the hinge guide fitting. The upper end of the shaft was bent inboard relative to the lower end as shown in the middle image in figure 39. Three-dimensional measurements of the shaft as described in Materials Laboratory Factual Report 24-010 showed the longitudinal axis at the upper end of the shaft was angled inboard by 3.7 degrees relative to the lower end of the shaft. The change in angle was from plastic deformation focused primarily at the vertical movement arrestor bolt hole.

Closer views of the vertical movement arrestor bolt hole through the aft hinge fitting are shown in figure 40. On the outboard side of the hinge fitting, the vertical movement arrestor bolt hole was elongated, and small cracks were observed at the forward and aft sides of the hole as noted in the left image in figure 40. The upper and lower sides of the elongated hole each had a radius corresponding closely to the specified hole diameter but with centers offset by 0.039 inch. The cracks intersected the hole at the forward and aft sides, and the area around the cracks was slightly concave consistent with plastic deformation (necking). Upon closer examination of the unopened cracks in the SEM, the fracture plane appeared to intersect the surface at a slant angle consistent with ductile overstress fracture. Although hole elongation was observed, the vertical movement arrestor bolt hole showed no evidence of damage or deformation from bearing contact with a vertical movement arrestor bolt.

The inboard side of the vertical movement arrestor bolt hole through the aft hinge fitting is shown at the right in figure 40. The area below the hole was deformed with heavy sliding contact extending from below the hole and upward past the hole centerline. The dry film lubricant was disturbed in the area of sliding contact, exposing the underlying conversion coating. However, the area at the upper side of the hole appeared relatively undisturbed. The radius at the upper side of the hole was consistent with the specified hole diameter and showed no evidence of bearing damage or deformation from contact with a vertical movement arrestor bolt.

An area below the vertical movement arrestor hole on the inboard side of the aft hinge fitting had black material on the surface that appeared darker than the dry film lubricant as indicated in the right image in figure 40. The black deposit was analyzed using EDS, and the resulting spectrum is shown in figure 41. High peaks of molybdenum and/or sulfur, aluminum, oxygen, and carbon were observed consistent with materials associated with the hinge fitting as shown in the upper two spectra in figure 42. However, significant peaks of silicon, calcium, titanium, and chromium were also observed. As shown in the lower two spectra shown in figure 42, peaks of carbon, oxygen, silicon, calcium, titanium and chromium were observed in a sample of the primer used on the door plug, and peaks of carbon, oxygen, and titanium were included in the enamel. By comparison, the peaks of silicon, calcium, titanium, and chromium were largely absent from other areas of the hinge fitting as shown in the upper two spectra in figure 42 from representative areas where the gold-colored fitting surface was exposed near the hole and another area where the dry film lubricant was intact.

To aid in interpreting contact damage observed at the lower end of the left MED plug, the aft hinge guide fitting was placed back onto the hinge fitting and clamped in place with the upper inboard hole on the hinge guide fitting aligned with the corresponding hole on the MED plug as shown in the upper image in figure 43. The upper hinge guide was also rotated counterclockwise (as viewed looking forward) relative to the plug, which brought the hinge guide fitting close to curved contact marks on the inboard side of the hinge opening in the plug's lower beam and the nearby curved deformation at the lower end of the inboard flange. The location of the contact corresponded to sliding contact marks observed on the inboard side of the hinge fitting at the lower side of the vertical movement arrestor bolt hole. Additional areas of damage with missing material at the forward and upper forward sides of the opening were consistent with contact with the hinge guide fitting flange. Evidence of enamel and primer transfer was also observed on multiple coils on one side of the lift assist spring, and one of those areas is shown in figure 44.

Curved damage consistent with contact with a hinge fitting shaft was also observed on the inboard side of the forward hinge opening in the left MED plug lower beam and on the adjacent lower end of the inboard flange as shown at the right in figure 45. Additional contact marks were observed on the outboard side of the opening as indicated with unlabeled arrows in the right image in figure 45. The spacing between the marks corresponded with the approximate spacing between the hinge guide flange and the hinge shaft centerline. The threads at the upper end of the forward hinge fitting were damaged on the outboard side of the hinge as shown in the left image in figure 45, damage that could be associated with the forward contact mark on the outboard side of the hinge opening shown in the right image in figure 45.

6.0 Left MED Plug Upper End

The upper end of the left MED plug was bent outboard, and the exterior skin had a crease located at the rivet line for the upper beam. The crease, indicated with unlabeled arrows in figure 46, is shown highlighted with low-angle lighting. On the inboard side of the plug shown in figure 47, the three gussets between the upper beam and the adjacent skin were fractured through the outboard flange attached to the skin. The flanges were fractured adjacent to the fillet radius between the outboard and inboard flanges of the gusset. Closer views of the fracture in the aft gusset are shown in figure 48. The fractures on all three gussets showed deformation and fracture features consistent with ductile overstress fracture consistent with the outboard legs of the flanges moving outboard with the bent upper end of the skin. Fractured sealant and enamel were observed at the upper edge of the upper beam outboard flange as noted in figure 47, consistent with tensile overstress fracture associated with the skin bending deformation.

Dark deposits were observed on the inboard surfaces of the left MED plug where it contacted the cylindrical-shaped rubber seal around the door frame. Closer views of deposits at the upper end of the left MED plug near the middle and aft gussets are shown in figure 49. The deposits appeared to be concentrated along multiple horizontal lines, and unlabeled arrows in figure 49 point to the linear concentrations. The positions of the linear features relative to the upper edge were measured with calipers. The positions were approximately 0.50 inch, 0.68 inch, 0.85 inch, 1.03 inch, 1.18 inch, and 1.27 inch averaged from two measurement positions.

7.0 Materials Testing and Analysis

The upper guide fittings, hinge fittings, and hinge guide fittings were all made of aluminum alloy 7050-T7451. In order to analyze composition, hardness, and conductivity of the materials used in these components from the left MED plug and associated hinge assemblies, surface coatings were removed from a flat portion of the flange at the lower ends of the upper guide fittings, a flat side on the curved lower ends of the hinge fittings, and the flat upper and lower surfaces of the aft hinge guide fitting by grinding with silicon carbide-embedded paper up to 600 grit. In order to get access to a stable flat area on the upper guide fittings for hardness testing, the flanges at the lower ends of the upper guide fittings were cut from the remainder of the fittings using a water-cooled abrasive saw before coating removal and testing.

Composition of the five selected components from the left MED plug listed in the previous paragraph was determined using the Olympus Vanta alloy analyzer. In each case, the material was identified as aluminum alloy 7050, consistent with the specified alloy for the selected components.

Conductivity was measured on the five selected components from the left MED plug using a Fischer Sigmascope SMP350 conductivity meter fitted with an FS40 probe set to a frequency of 60kHz. Measured conductivity ranged from 40.4% IACS to 41.2% IACS, all within the specified conductivity range for the specified alloy and temper designation.

Hardness was measured on the five selected components from the left MED plug using a Rockwell indenter. Hardness, averaged from five indentations on each piece, was 86.3 HRBW, 87.9 HRBW, 85.4 HRBW, 86.0 HRBW, and 85.7 HRBW for the forward and aft upper guide fittings, forward and aft hinge fittings, and aft hinge guide fitting, respectively. All hardness measurements were within the specified hardness range for the specified alloy and temper designation.

Samples of the linear dark deposits on the left MED plug seal area were taken at four locations around the plug perimeter by rubbing with a cotton swab wetted with ethanol. The dark deposits lifted easily, and the samples were analyzed using an

Agilent Fourier Transform Infrared (FTIR) Model 610 bench spectrometer with a diamond attenuated total reflectance (ATR) accessory in accordance with ASTM E1252-98 (American Society for Testing Materials E1252-98: *Standard Practice for General Techniques for Obtaining Infrared Spectra for Qualitative Analysis*). The spectrometer was used to collect and process infrared wavelength absorbance spectra of the unknown material.

The spectra for the swabs from the area around the left MED plug seal were all matches to one another. The spectral peaks within those spectra corresponded to particular functional groups found within molecular structure of the unknown material. A doublet peak at ~2920 cm^{-1} and ~2850 cm^{-1} corresponds to a carbon-hydrogen stretching bonds. Peaks at ~1460 cm^{-1} and ~1370 cm^{-1} are indicative of a carbon-hydrogen (C-H) deformation bonds. A peak ~724 cm^{-1} is indicative of a carbon-carbon (C-C) vibrational bond. The spectrum was consistent with a straight-chained aliphatic hydrocarbon. A spectral library search was performed on the unknown spectrum. The spectral search found a strong match to several petroleum-based materials including petrolatum (petroleum jelly). The spectrum of a known sample of petroleum jelly was compared to the accident samples. It was an exact match to the accident spectra. Samples of dark deposits on the right MED plug that were collected from the upper seal area during the right MED plug examination had a similar spectrum when also analyzed by FTIR. As reported by the representative from Spirit AeroSystems that participated in the group examination, Vaseline (petroleum jelly) was applied to the seal during installation to assist in the installation process.

A dark green deposit was observed on the exterior surface of the left MED plug at the upper leading edge as shown in figure 46. A sample of the deposit was collected with a cotton swab wetted with ethanol. The sample was removed with difficulty, and most of the deposit remained intact on the surface after sampling. The sampled material was analyzed by FTIR as described above.

The spectrum for the residue contained spectral peaks that corresponded to particular functional groups found within molecular structure of the unknown material. The presence of a broad peak at ~3440 cm^{-1} is indicative of a nitrogen-hydrogen stretching bond. The presence of a smaller broad peak at ~3180 cm^{-1} is indicative of an oxygen-hydrogen stretching bond. A doublet peak at ~2920 cm^{-1} and ~2850 cm^{-1} corresponds to carbon-hydrogen stretching bonds. A single peak at ~1730 cm^{-1} is indicative of a carbonyl (C=O) stretching bond. A peak at ~1645 cm^{-1} is indicative of a carbon-nitrogen (C=N) double bond. A single peak at ~1580 cm^{-1} is indicative of a nitrogen-hydrogen (N-H) bond. A single peak at ~1470 cm^{-1} is indicative of an oxygen-hydrogen (O-H) deformation bond. A single peak at ~1380 cm^{-1} is indicative of a carbon-carbon (C=C) aromatic double stretching bond. Peaks at ~1270 cm^{-1} and ~1250 cm^{-1} are indicative of carbon-nitrogen (C-N) stretching bonds. Peaks at ~1060 cm^{-1} and ~1025 cm^{-1} are indicative of a carbon-oxygen-carbon (C-O-C) bond. A single peak at ~710 cm^{-1} of a carbon-carbon (C=C) aromatic double bending bond. The spectrum was consistent with presence of an amine and a carbohydrate. A spectral library search was performed on the unknown spectrum. The spectral search found a few spectral similarities to cellulose. Cellulosic material is found in natural plant fibers and leaves. A mixture search was also performed. There were matches to several other natural nitrogen-containing material sources.

Given the combination of spectral patterns and similarities to several natural amino-carbohydrates and other materials, the unknown material was most likely plant material. Plant or leaf material consists of a combination of carbon, nitrogen, carbohydrates, organic acids, mineral substances, and water. Molecular bonds for these materials were all present within the unknown spectrum.

Submitted by:

Matthew R. Fox, Ph.D.
Chief Technical Advisor - Materials

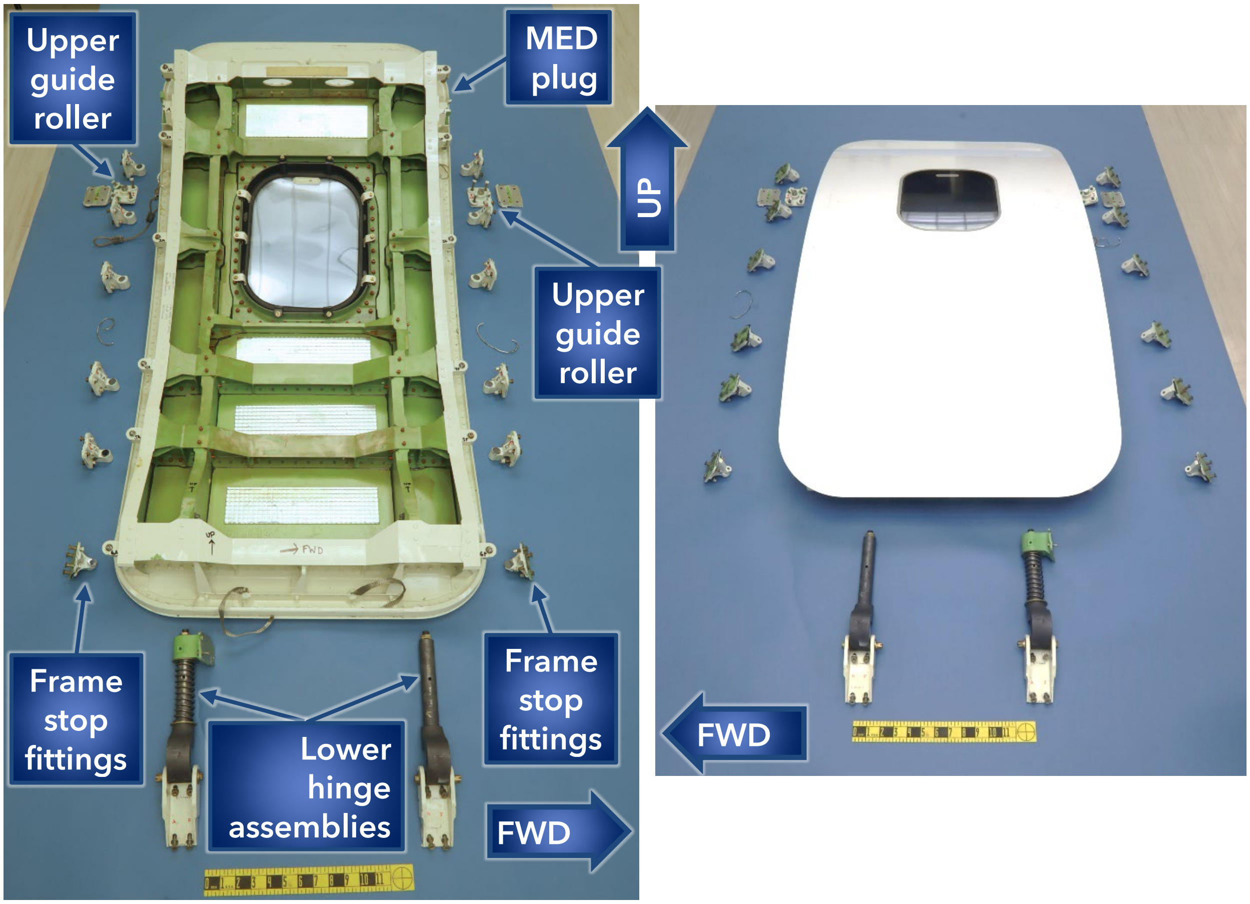


Figure 1. Overall views of the submitted left MED plug and associated components showing an interior view (left image) and exterior view (right image).

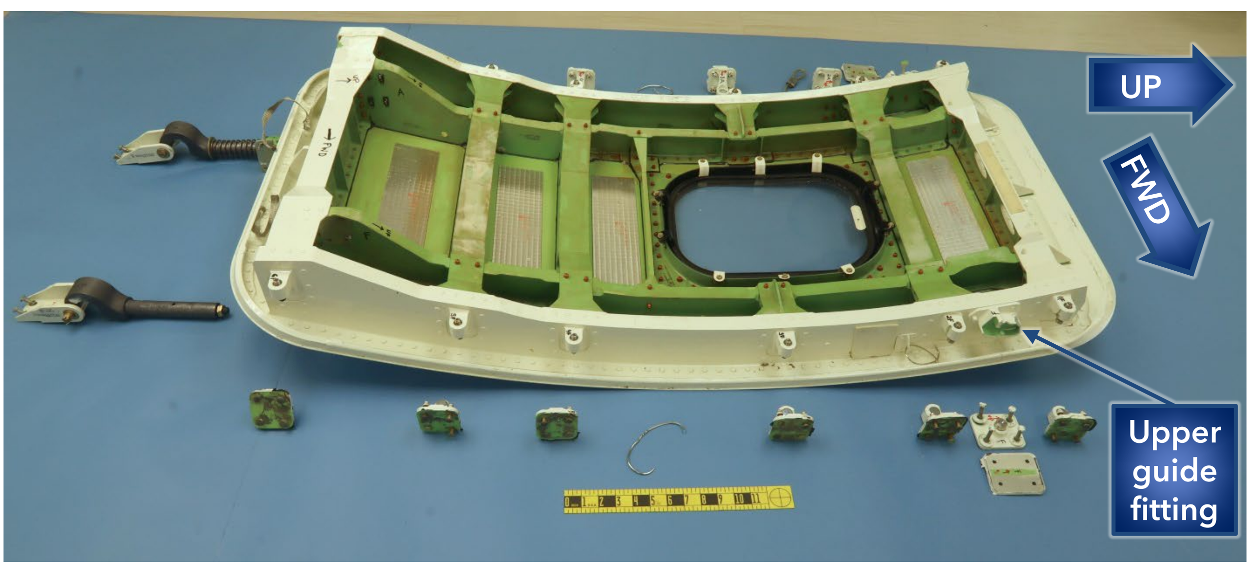


Figure 2. Overall view of the forward side of the submitted left MED plug and associated components.

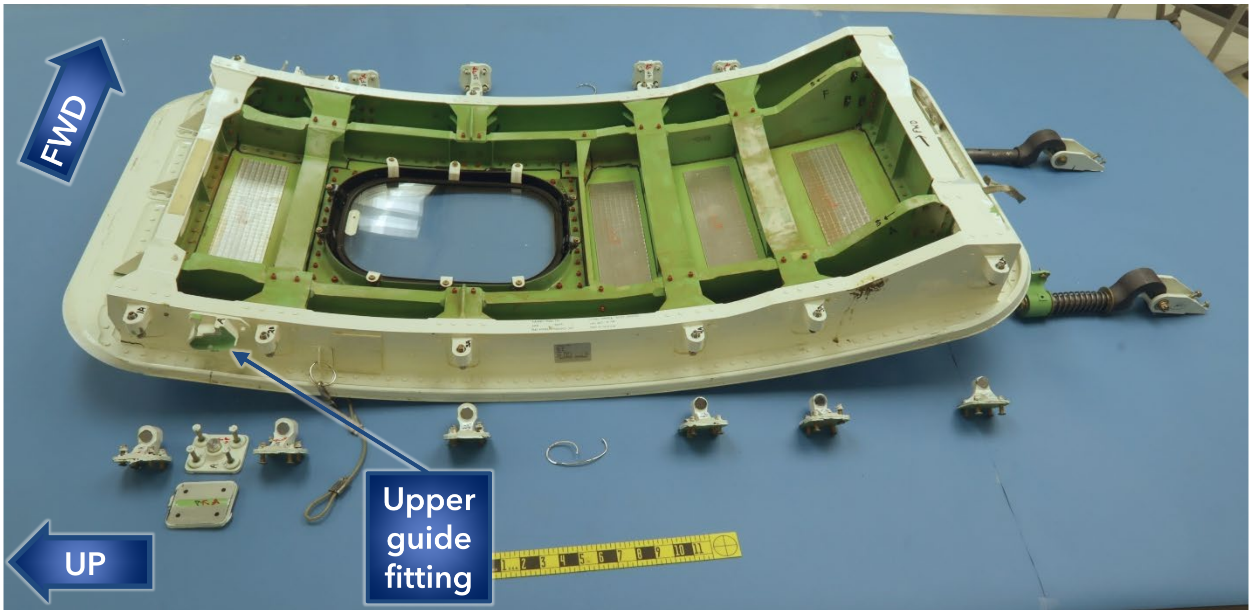


Figure 3. Overall view of the aft side of the submitted left MED plug and associated components.

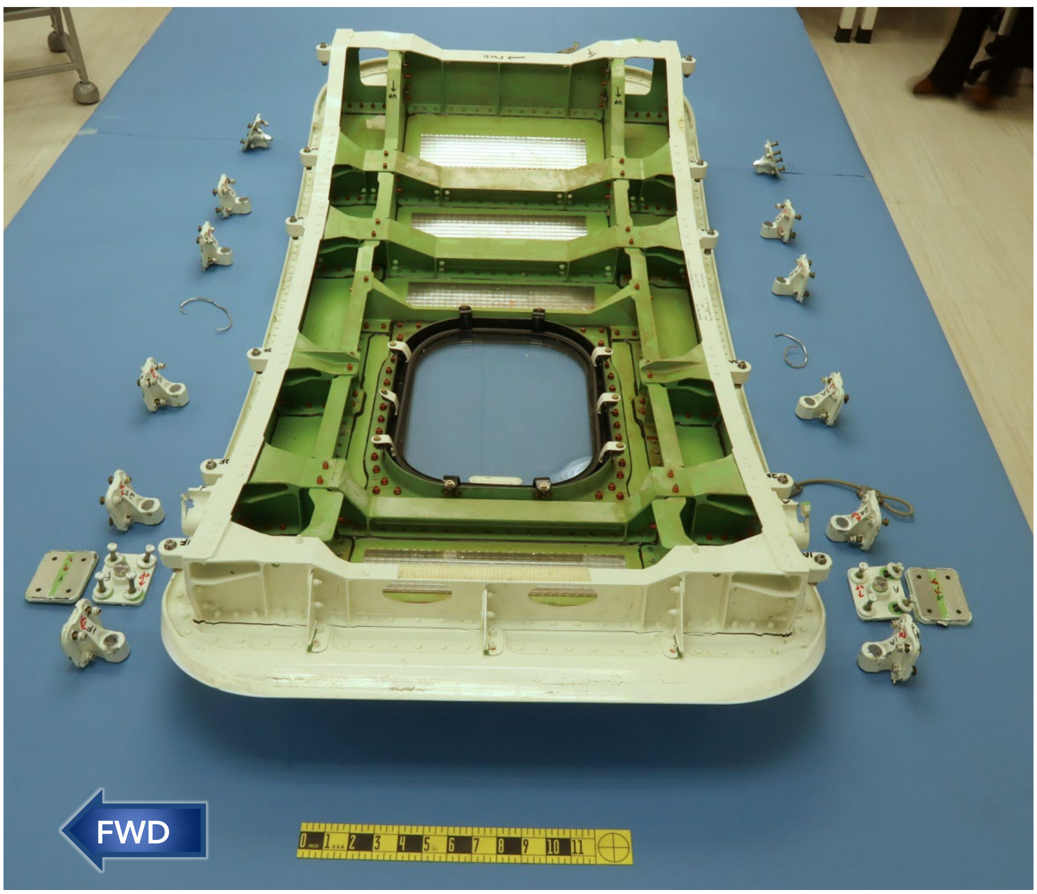


Figure 4. Overall view of the upper side of the submitted left MED plug and associated components.

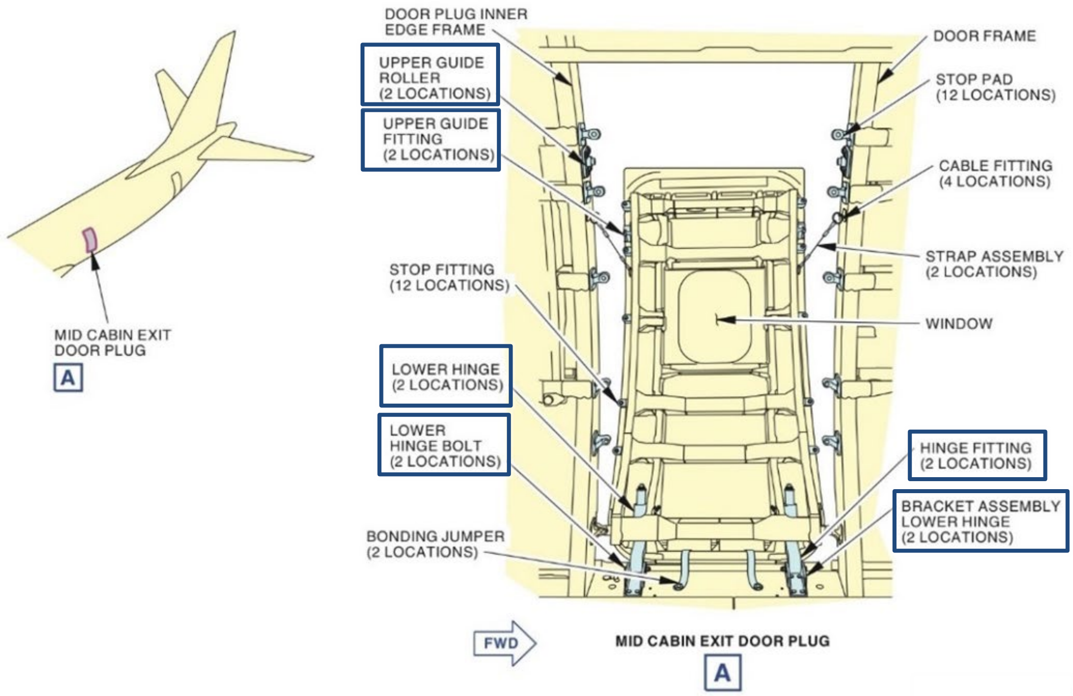


Figure 5. Diagram of a left MED plug in the opened condition. Items highlighted with rectangles are shown in the next figure. (Source: Boeing. Image Copyright © Boeing. Reproduced with permission.)

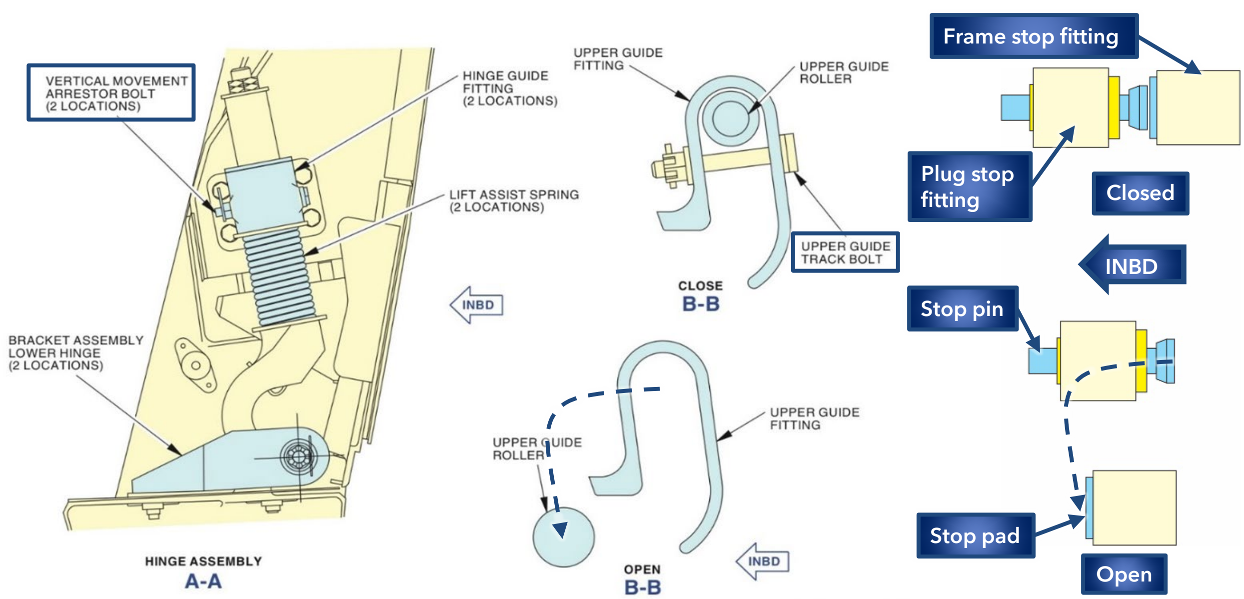


Figure 6. Detail diagram (left and middle) of the hinge assembly, upper guide fitting, and upper guide roller highlighting installation positions of the vertical movement arrestor bolts and upper guide track bolts (Source: Boeing. Image Copyright © Boeing. Reproduced with permission). A diagram illustrating the stop fittings in the open and closed positions is shown at the right. Dashed lines with arrows indicate the plug's displacement path to complete the closing motion from the open position.

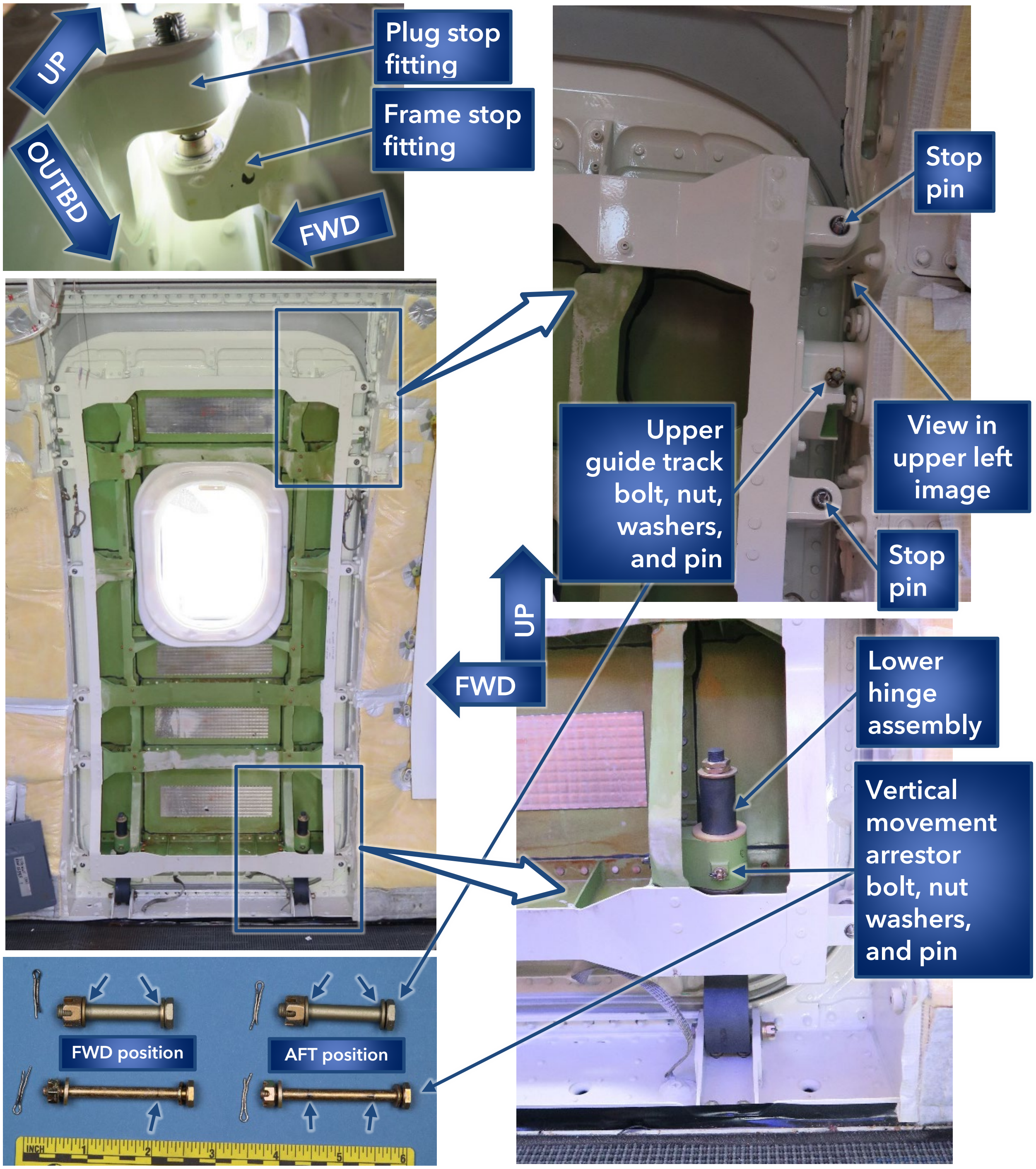


Figure 7. Right MED plug on the accident airplane after the interior cabin liner and passenger seats were removed (middle left image) with closer views of the upper guide fitting (upper right image) and lower hinge assembly (lower right image). The upper left image shows a view of the upper aft stop pin on the stop pad, and the lower left image shows a close view of upper guide track bolt hardware and vertical movement arrestor bolt hardware removed from the forward and aft sides of the right MED plug. Unlabeled arrows in the lower left image point to witness marks from contact with mating components.

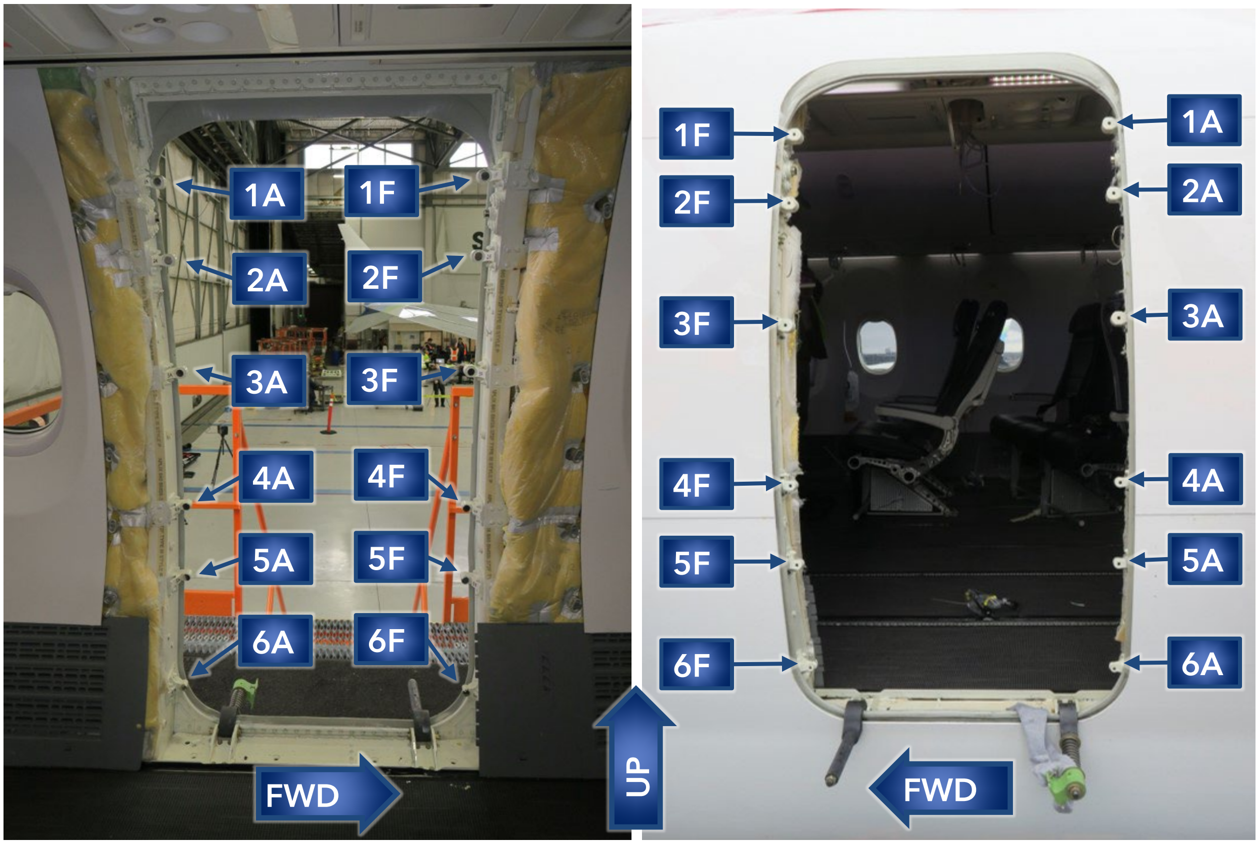


Figure 8. Interior (left image) and exterior (right image) views of the left MED opening in the fuselage after nearby passenger seats were removed. Frame stop fittings are indicated as labeled on scene.

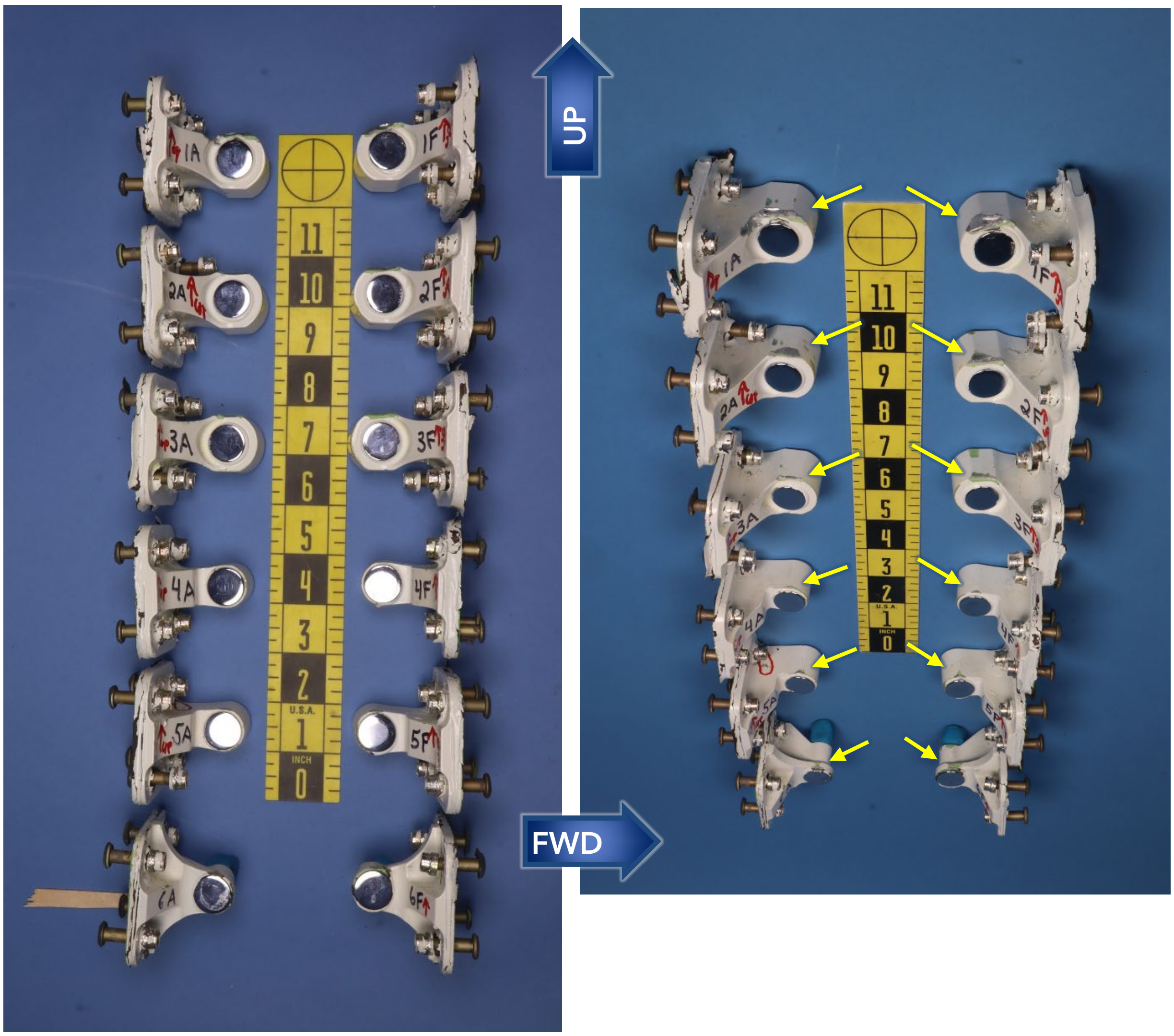


Figure 9. Overall views of the frame stop fittings that had been disassembled from the left MED frame on the fuselage. Unlabeled arrows in the right image point to sliding contact damage on the upper sides of the fittings.

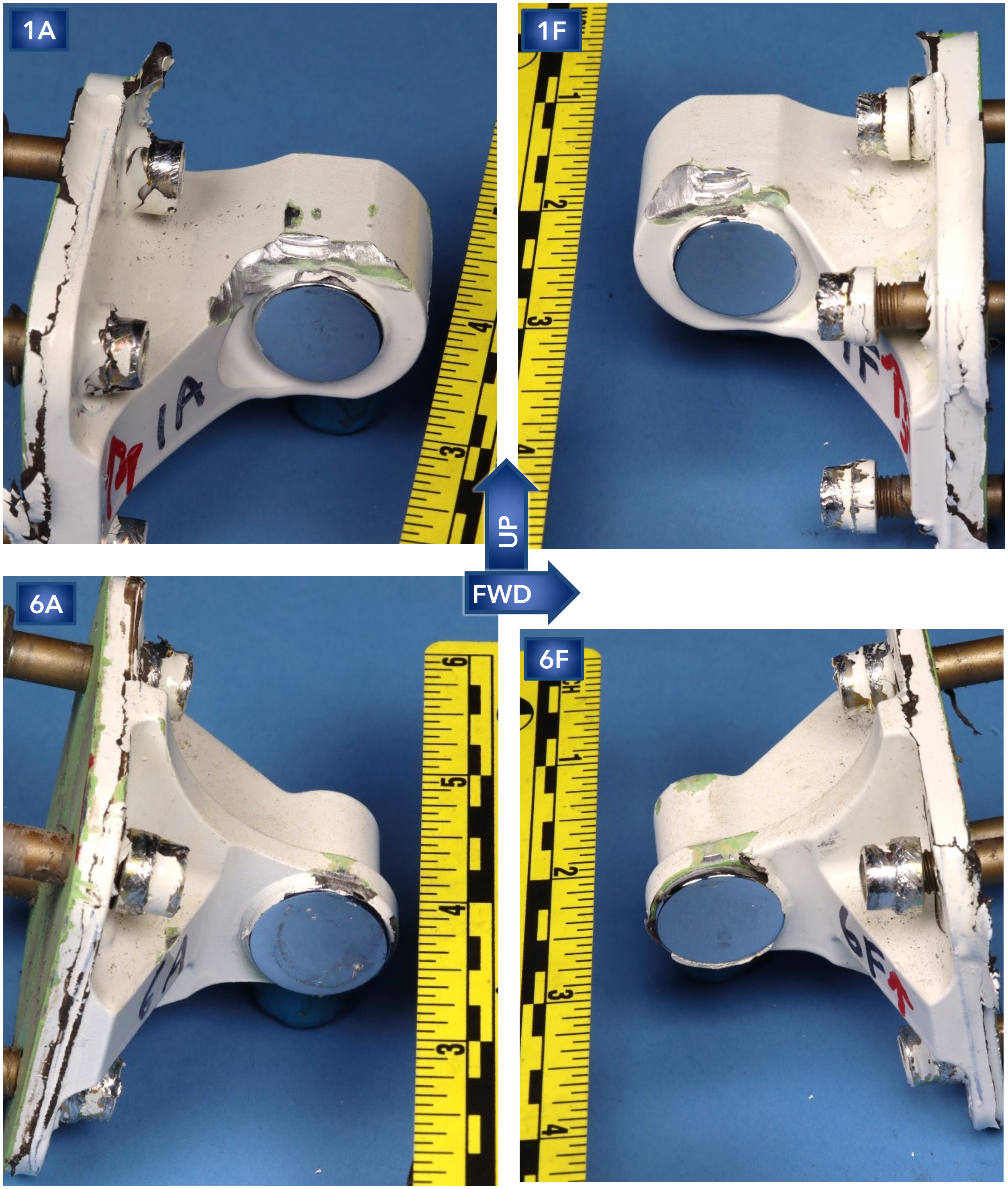


Figure 10. Closer views of damage at the upper sides of frame stop fittings 1F, 1A, 6F, and 6A (as received after disassembly from the left MED frame on the fuselage).

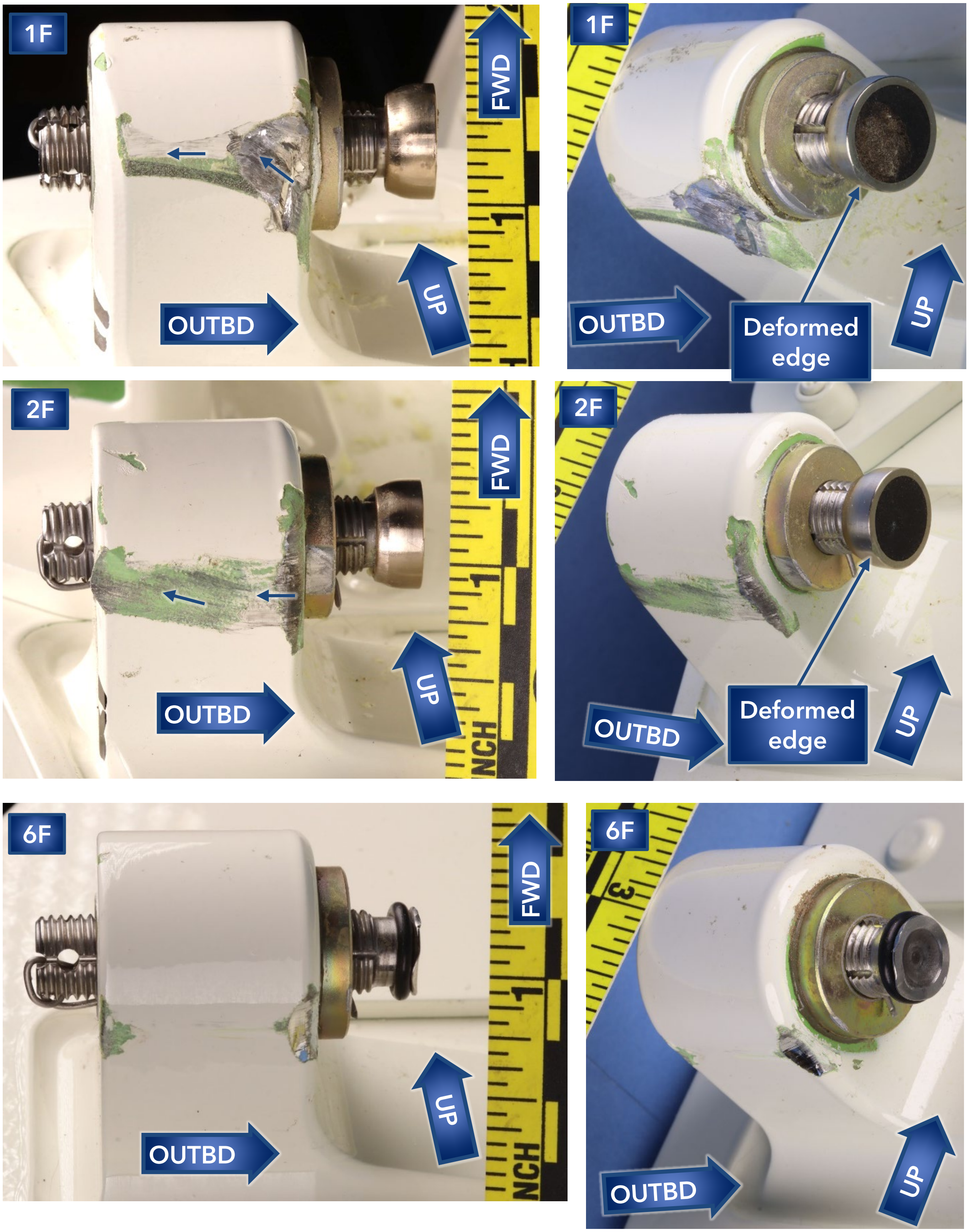


Figure 11. Views of sliding contact and pin head damage on plug stop fittings 1F, 2F, and 6F on the forward side of the left MED plug. Unlabeled arrows in the upper left and middle left images indicate directions of sliding contact.

Figure 12. Views of sliding contact and pin head damage on plug stop fittings 1A and 6A on the aft side of the left MED plug.

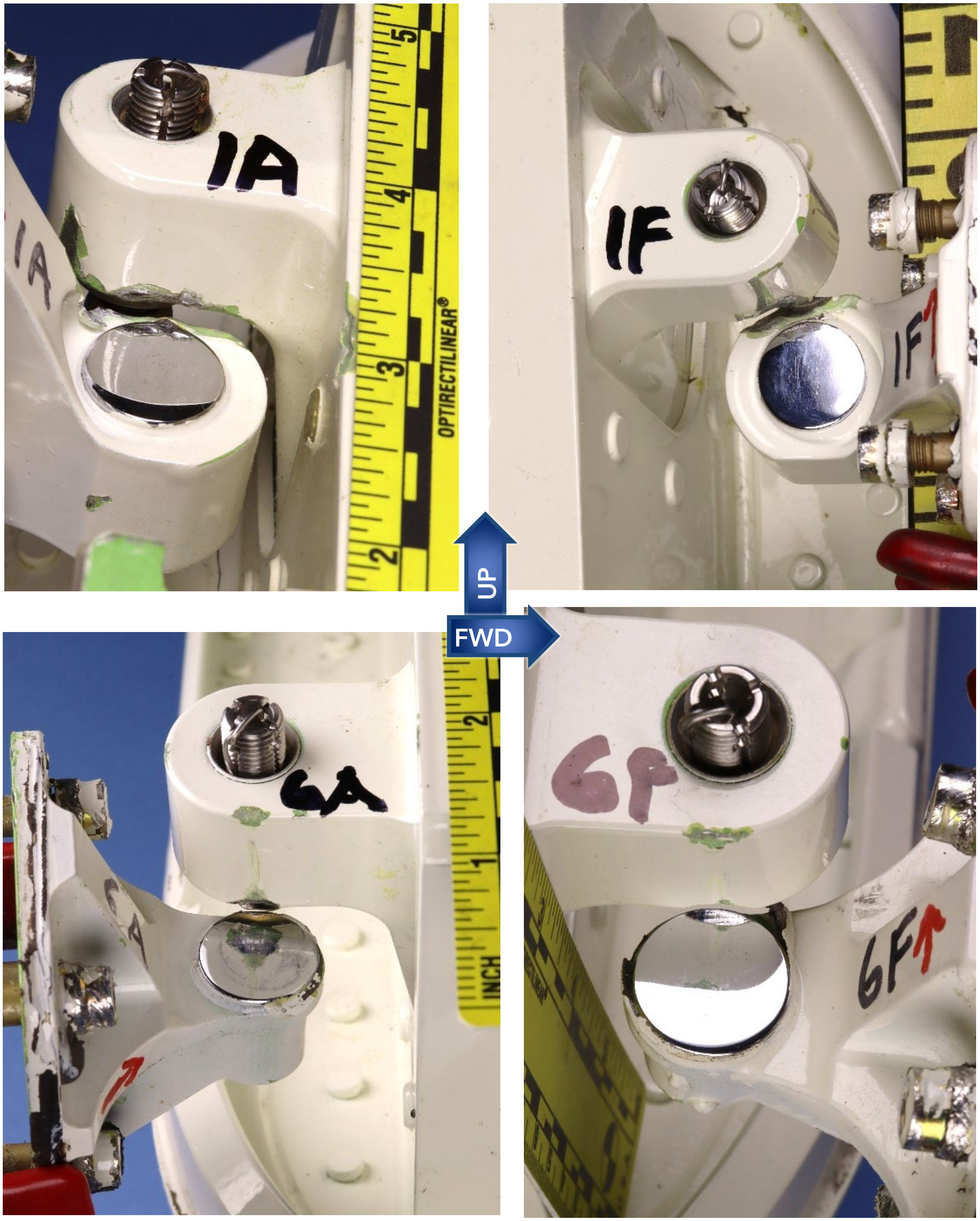


Figure 13. Close views of stop locations 1F, 1A, 6F, and 6A with sliding contact damage on the frame stop fittings placed next to the corresponding sliding contact damage on the plug stop fittings.

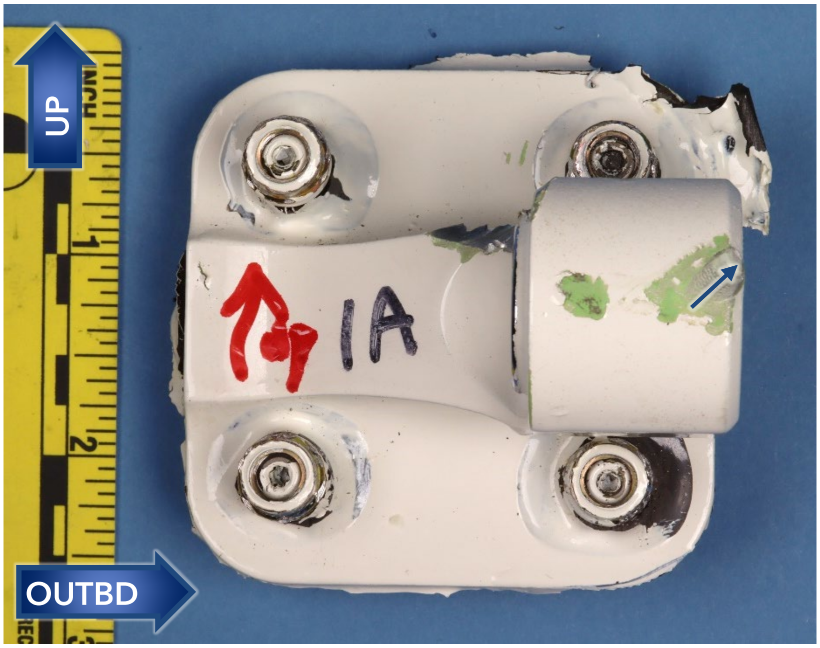


Figure 14. Forward side of frame stop fitting 1A. An arrow indicates the direction of relative motion associated with the sliding contact damage on the forward side of the fitting next to the outboard edge.

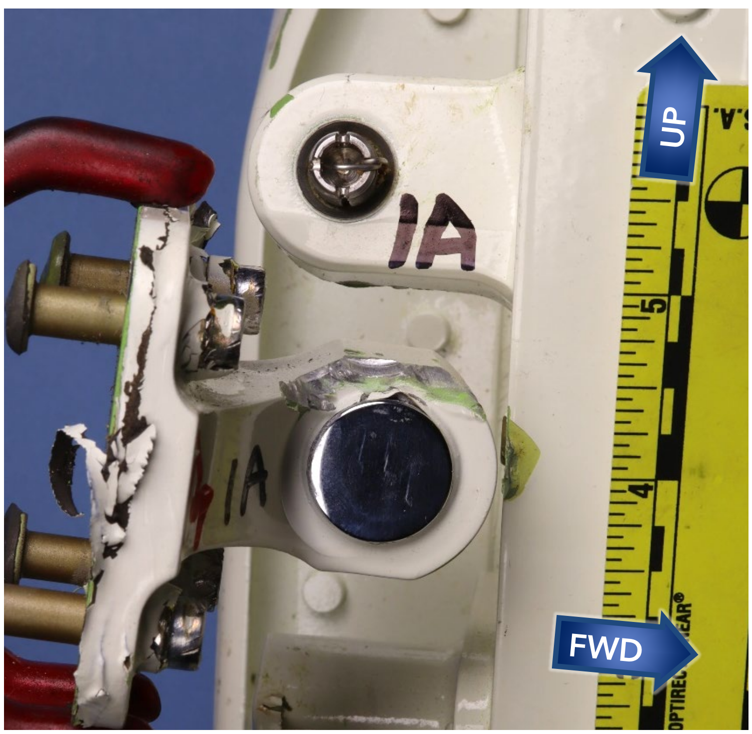


Figure 15. Frame stop fitting 1A with sliding contact damage noted in the previous figure placed next to corresponding damage on the aft side of the plug below plug stop fitting 1A.

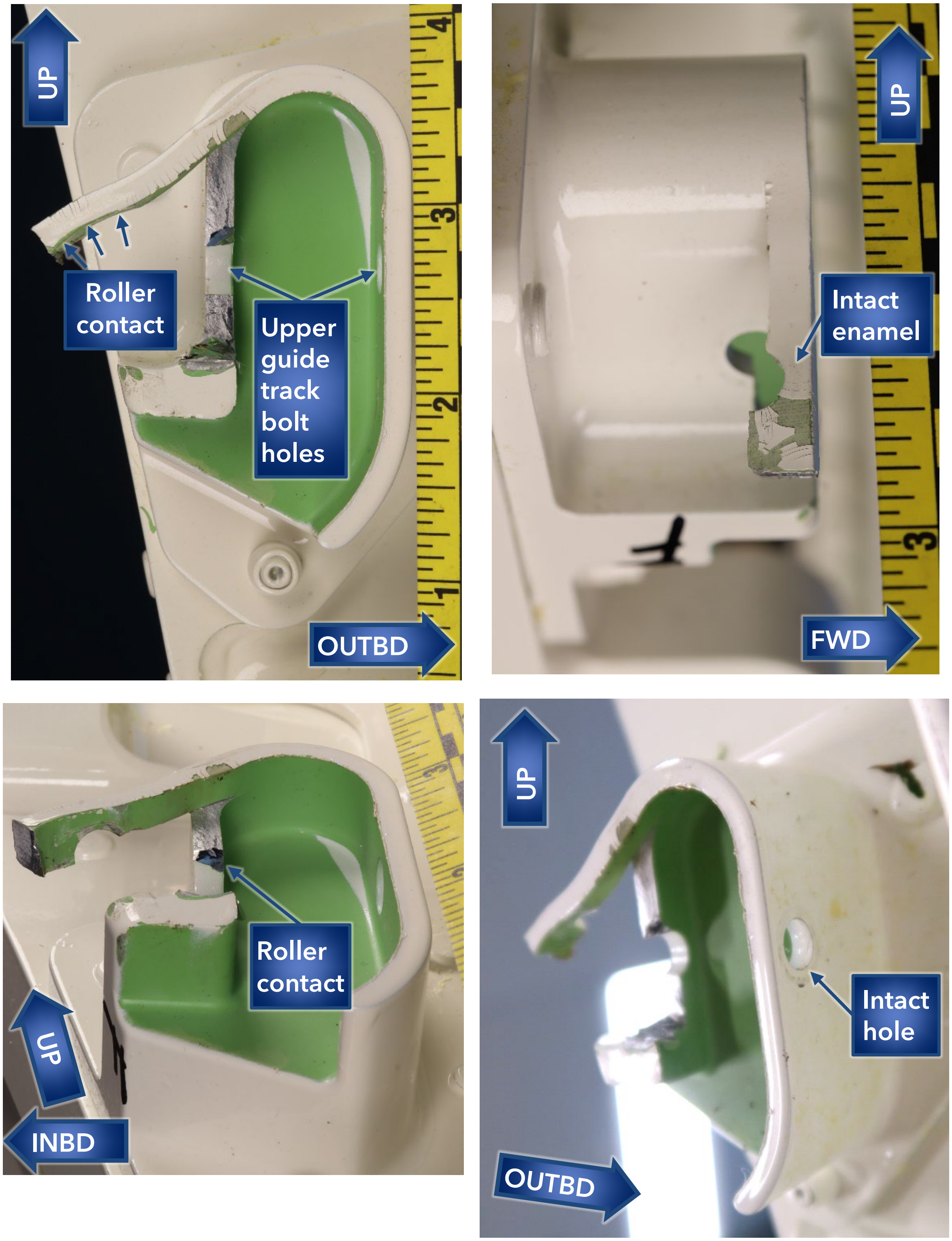


Figure 16. Views of the forward upper guide fitting on the left MED plug. Deformed areas consistent with roller contact are indicated.

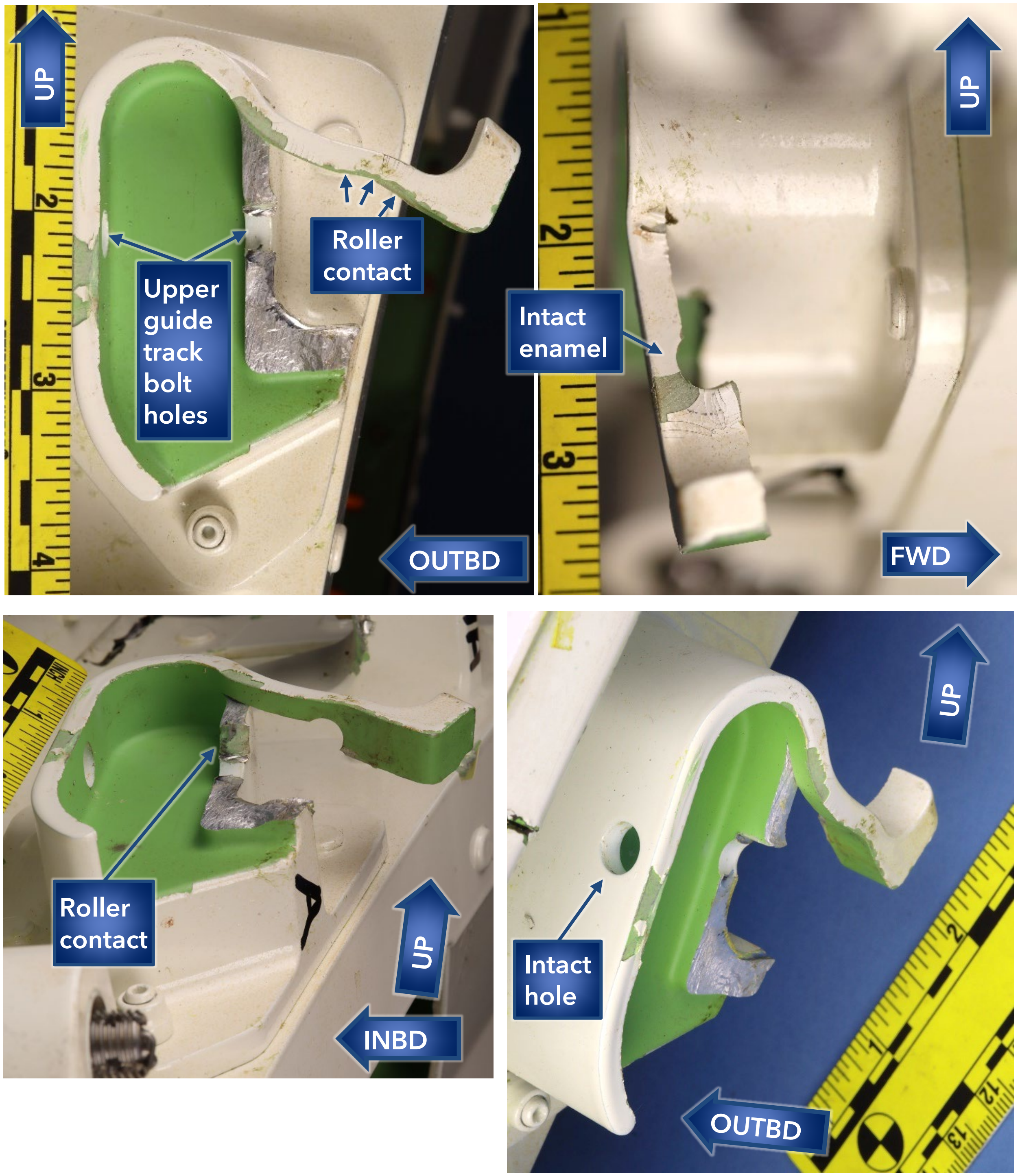


Figure 17. Views of the aft upper guide fitting on the left MED plug. Deformed areas consistent with roller contact are indicated.

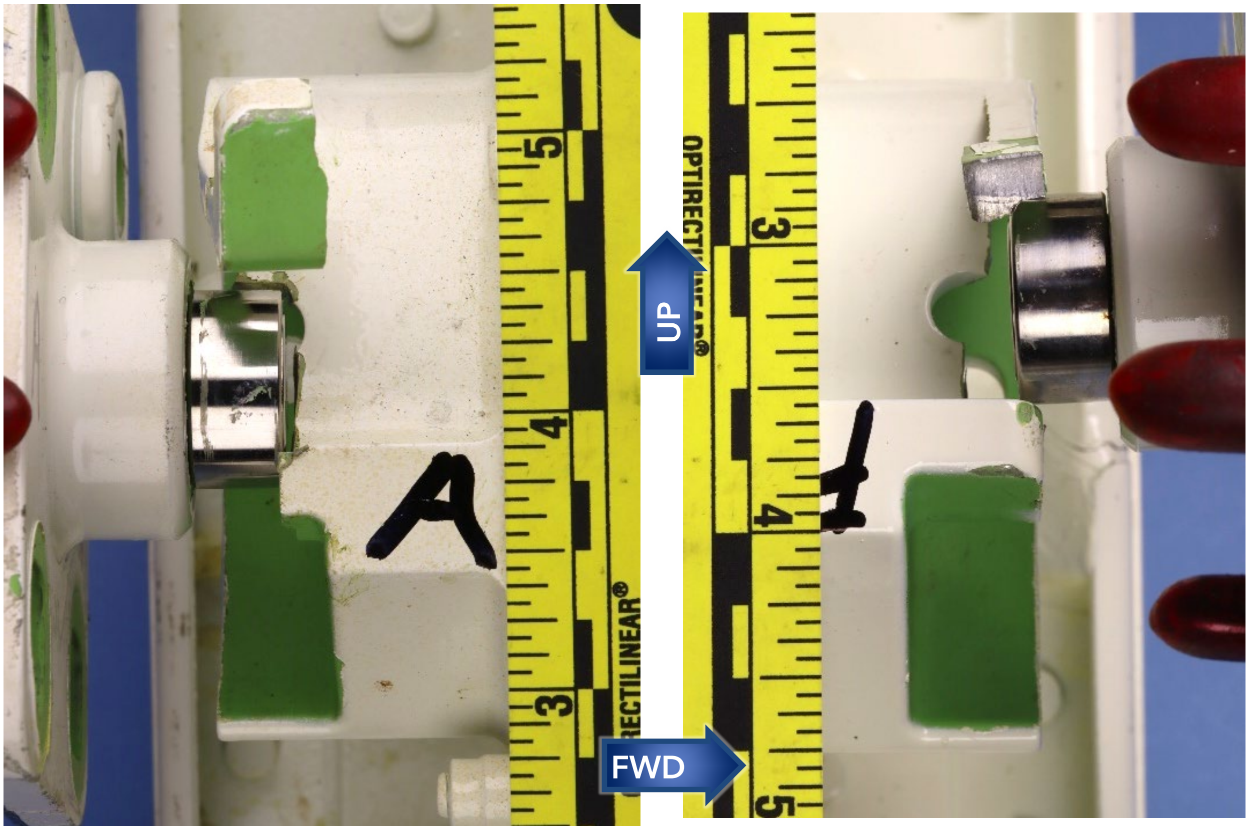


Figure 18. Views of the forward (right image) and aft (left image) left MED plug upper guide fittings with the upper guide rollers positioned close to corresponding contact marks and deformed features on the fittings.

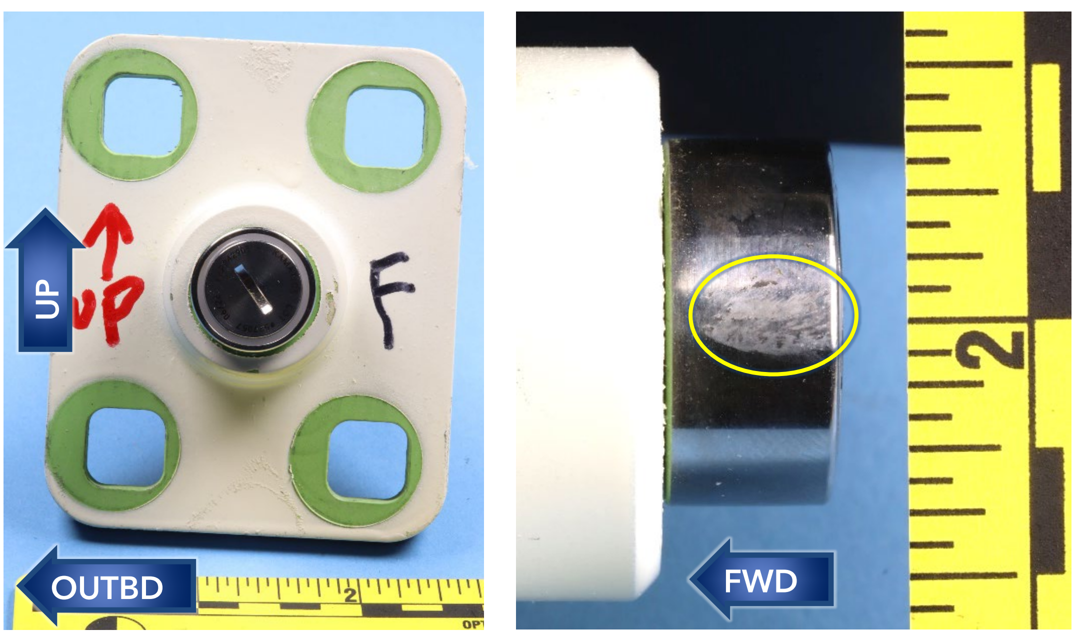


Figure 19. Upper guide roller removed from the forward side of the left MED frame (left image). The right image shows an area of metal transfer on the outer race (circled area).

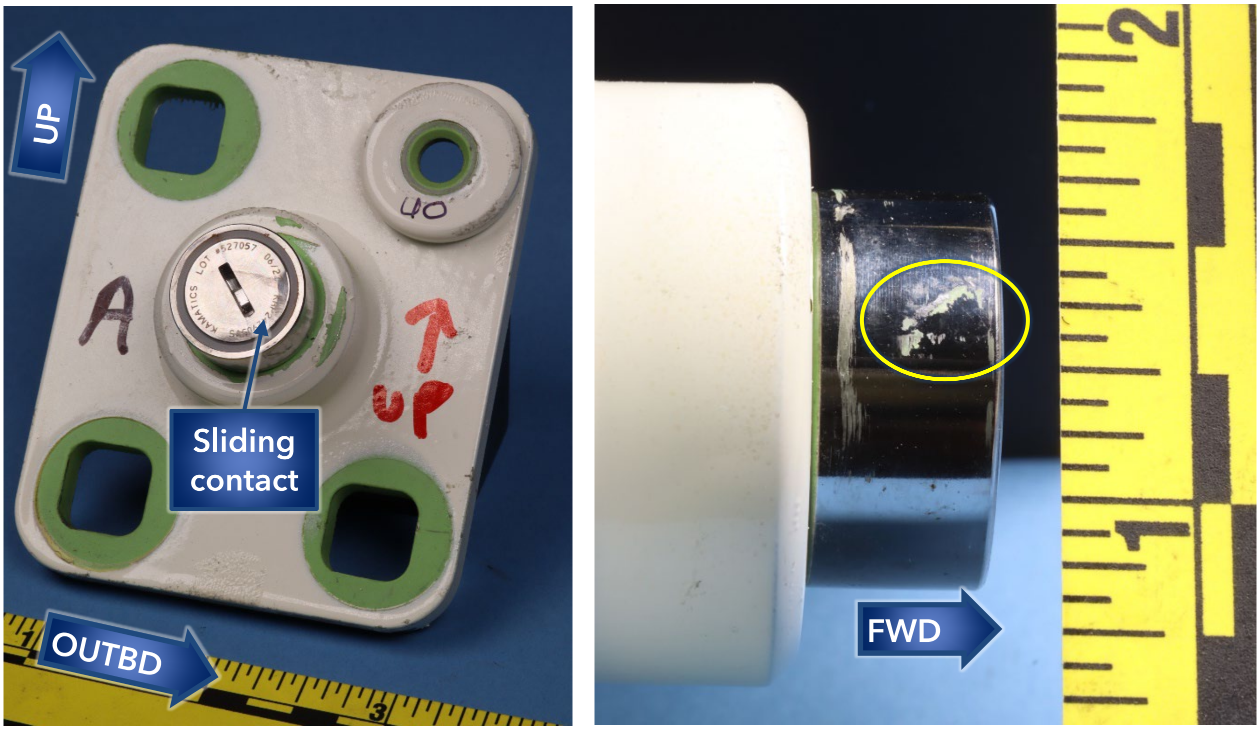


Figure 20. Upper guide roller removed from the aft side of the left MED frame (left image), where sliding contact marks were observed on the forward face. The right image shows an area of enamel and primer transfer on the outer race (circled area).

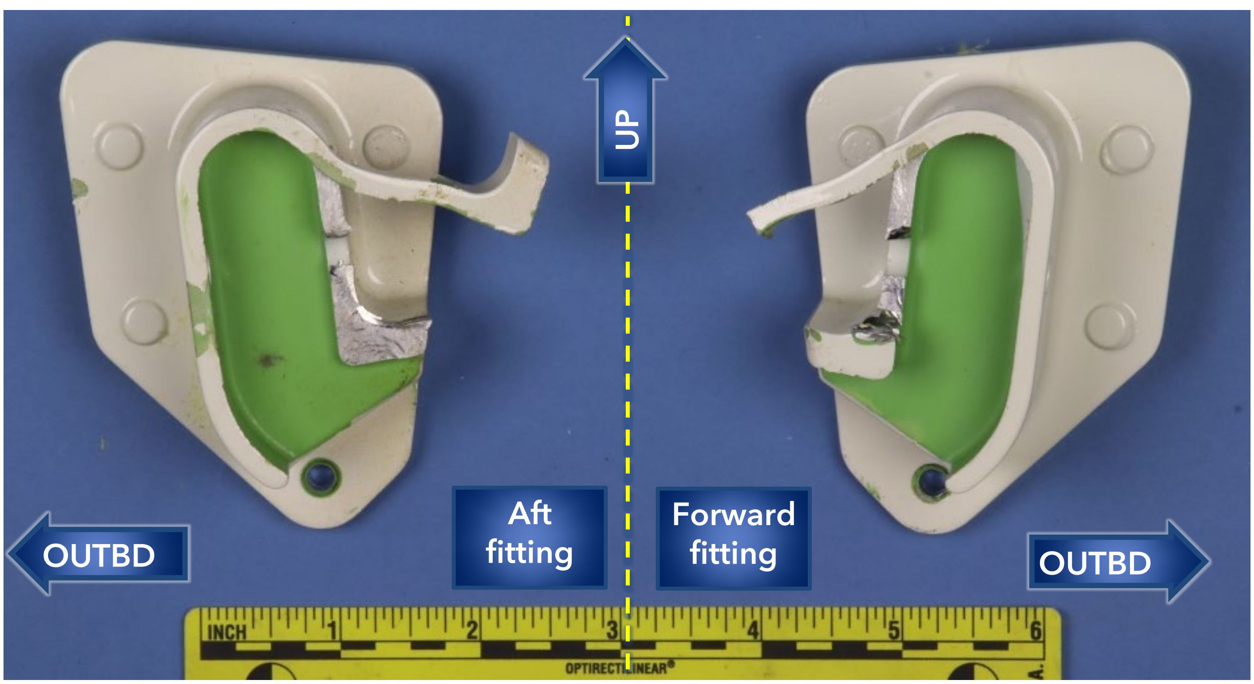


Figure 21. Forward and aft upper guide fittings after disassembly from the left MED plug.

Figure 22. Close views of the upper guide track bolt holes in the forward upper guide fitting from the left MED plug. The forward face of the inboard hole is shown in the upper image, and views of the lower side of the hole bores on the inboard and outboard holes are shown in the lower left and lower right images, respectively. Unlabeled arrows in the upper image indicate faint dark deposits in a circular area around the hole.

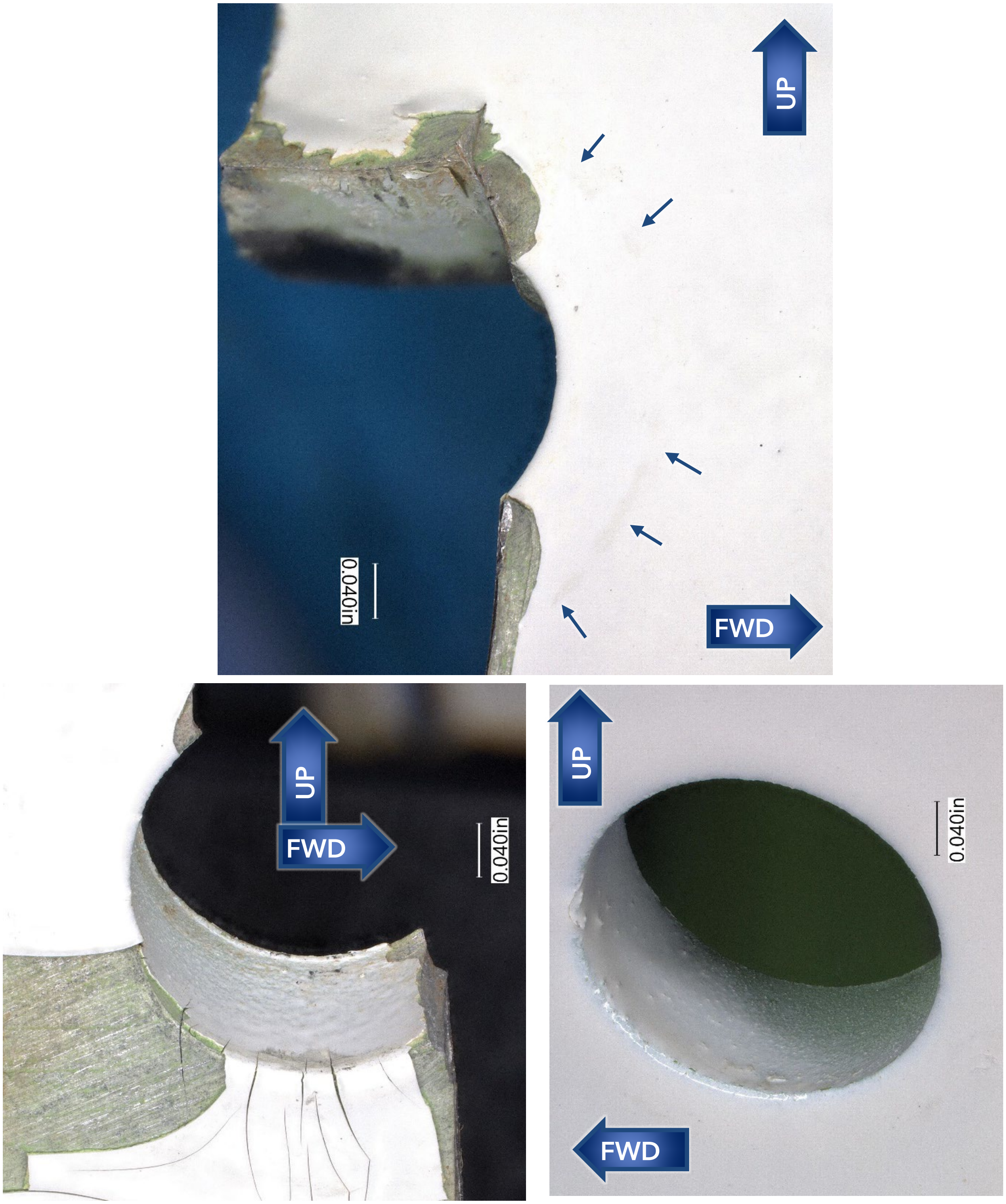


Figure 23. Close views of the upper guide track bolt holes in the aft upper guide fitting from the left MED plug. The forward face of the inboard hole is shown in the upper image, and views of the lower side of the hole bores on the inboard and outboard holes are shown in the lower left and lower right images, respectively. Unlabeled arrows in the upper image indicate faint dark deposits in a circular area around the hole.

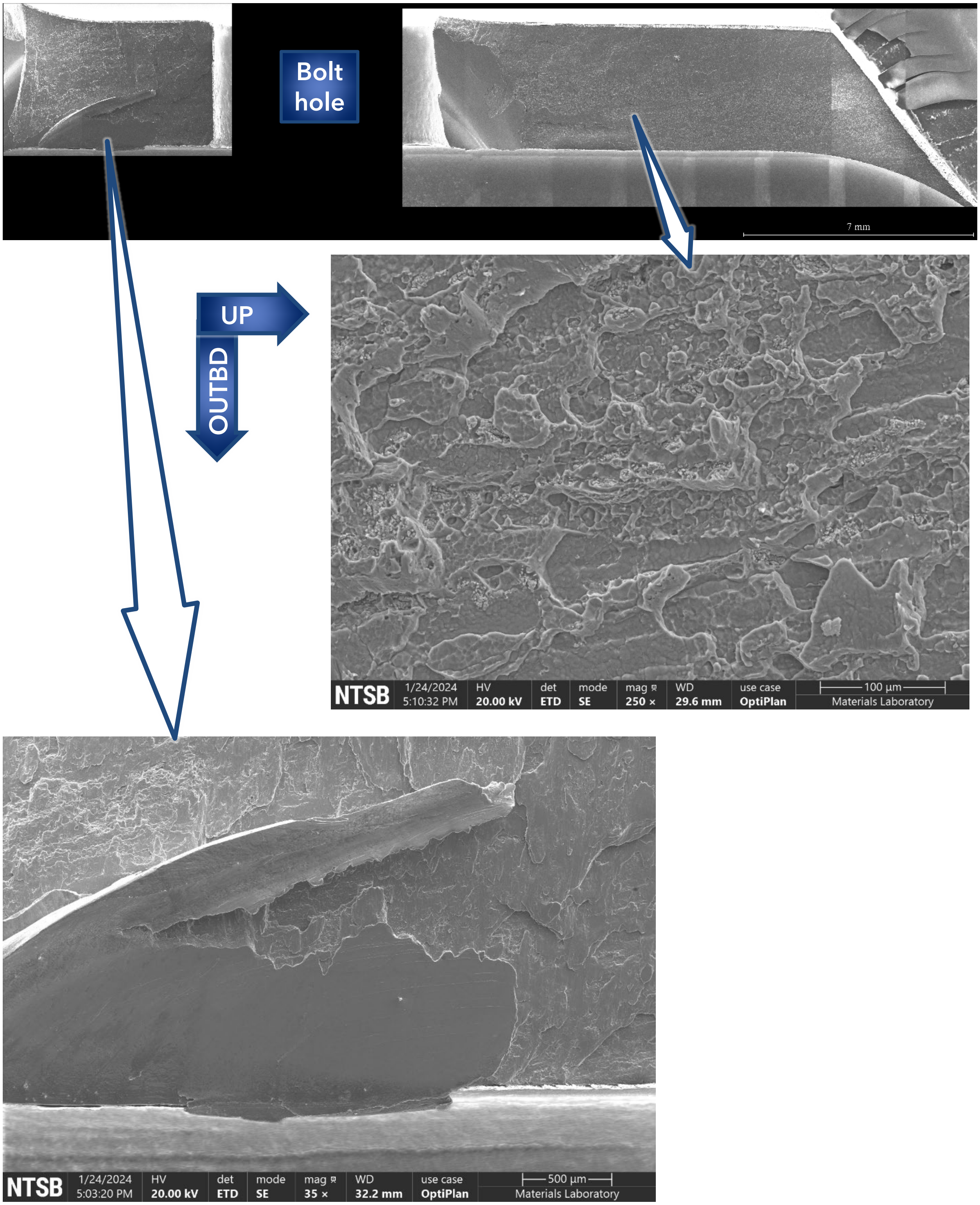


Figure 24. Montage of stitched SEM images of the fracture surface on the forward upper guide fitting from the left MED plug (upper image) with magnified views of typical fracture features (middle image) and an area of smearing damage on the lower outboard side of the fracture (lower image).

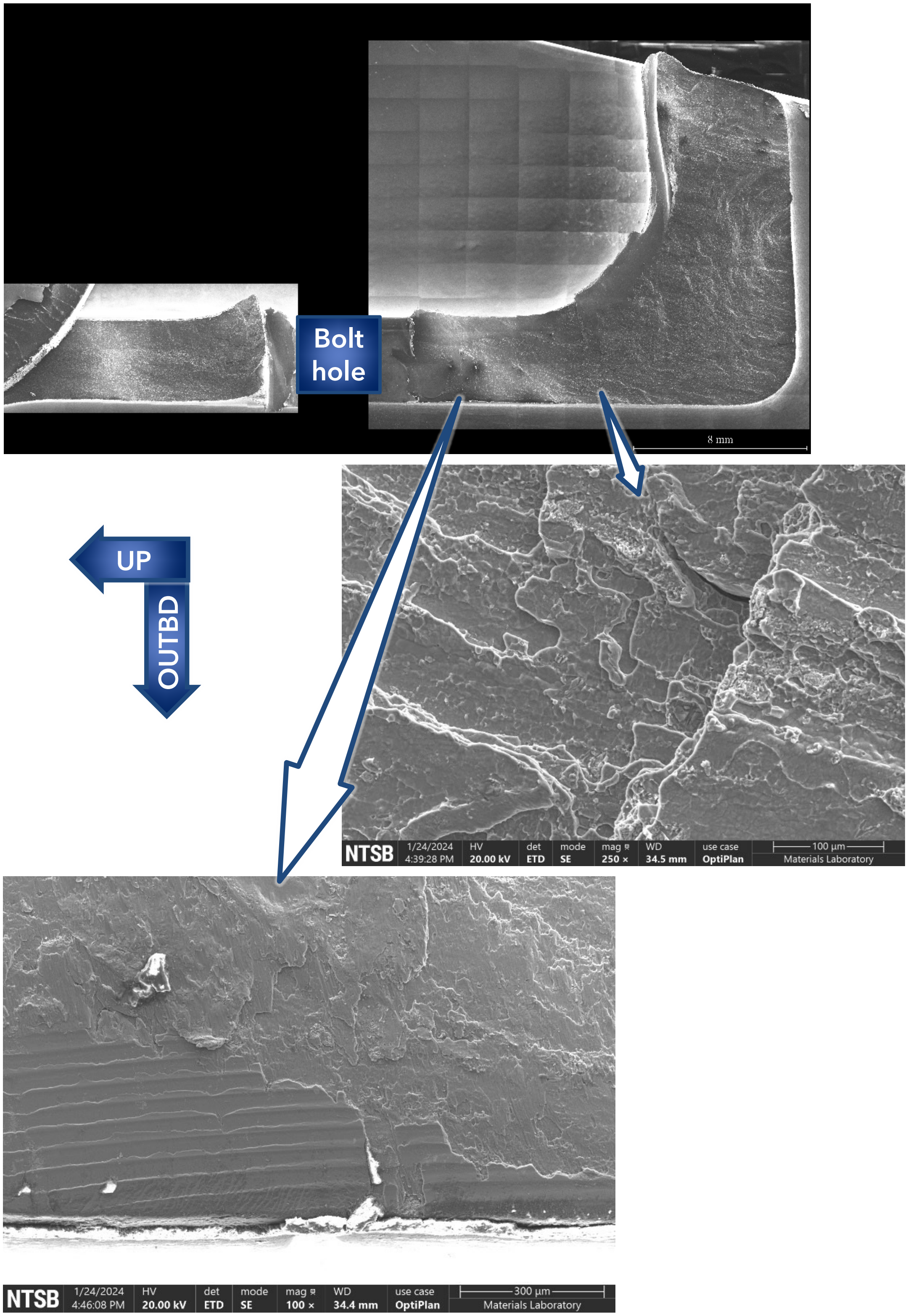


Figure 25. Montage of stitched SEM images of the fracture surface on the forward upper guide fitting from the left MED plug (upper image) with magnified views of typical fracture features (middle image) and an area of smearing damage on the outboard side of the fracture near the bolt hole (lower image).

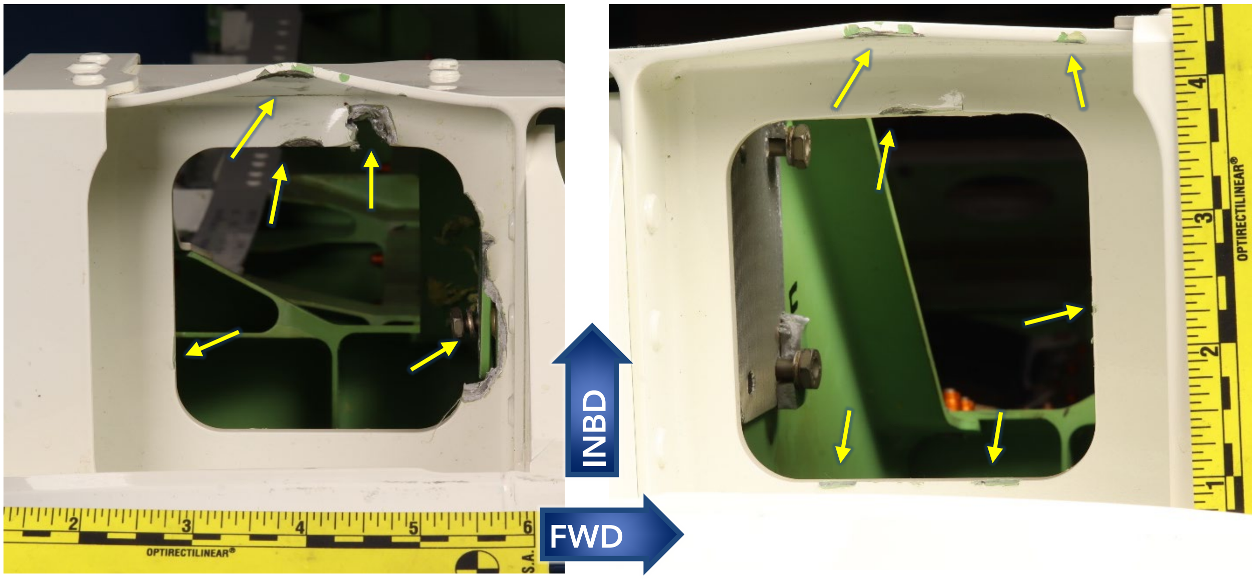


Figure 26. Lower end of the left MED plug showing openings in the lower beam structure for the forward (right image) and aft (left image) lower hinge assemblies. Arrows point to areas of contact damage.

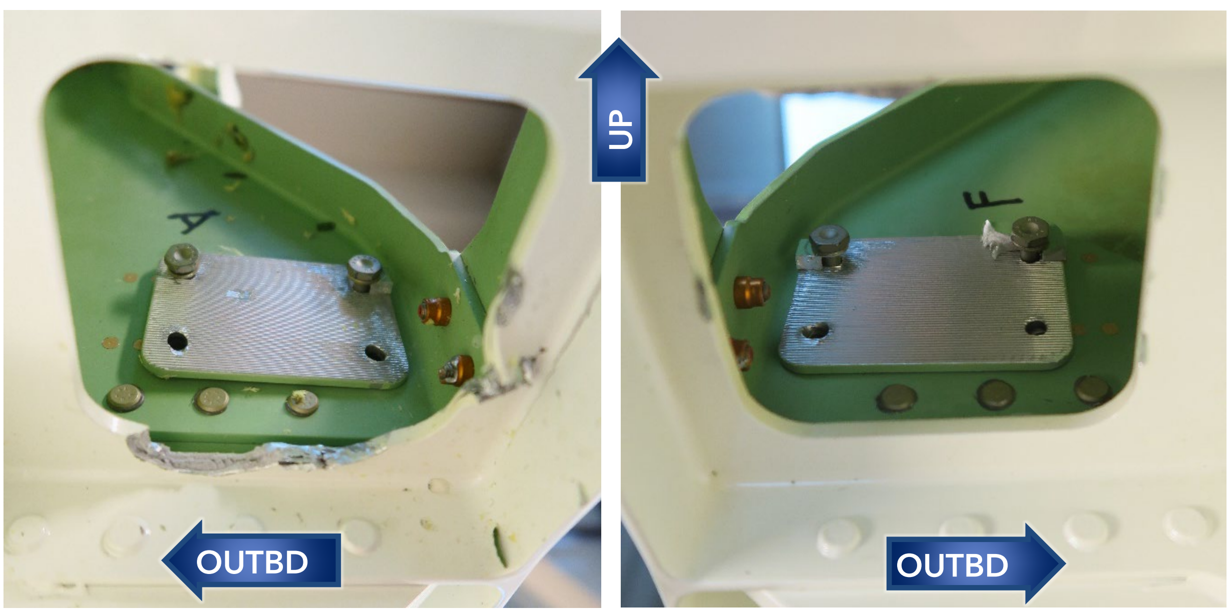


Figure 27. Views of serrated plates at the forward (right image) and aft (left image) hinge guide fitting attachment locations on the left MED plug as viewed through the hinge assembly openings in the lower beam structure.

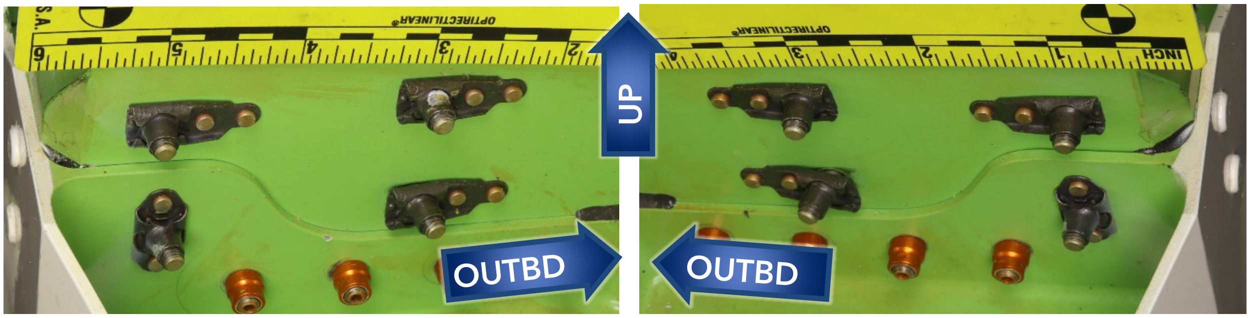


Figure 28. Nut plates and threaded ends of the hinge guide fitting attachment bolts for the forward (right image) and aft (left image) hinge guide fittings on the left MED plug.

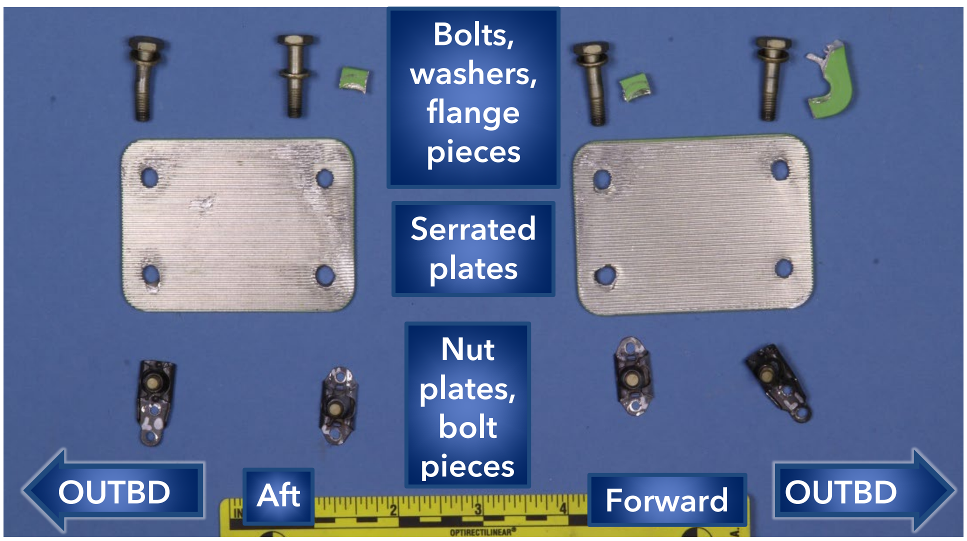


Figure 29. Hinge guide fitting serrated plates, attachment hardware, and flange pieces after disassembly from the left MED plug.

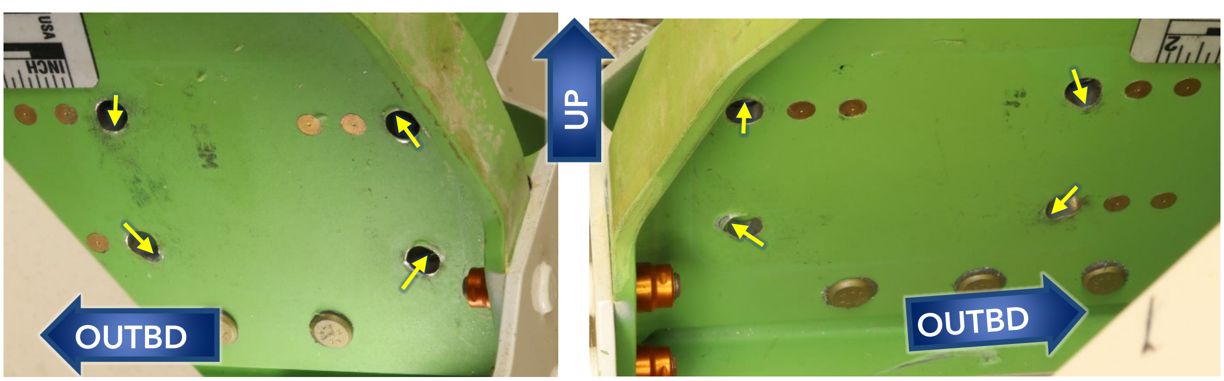


Figure 30. Left MED plug vertical rib surfaces at the hinge guide attachment locations after the serrated plates were removed. Unlabeled arrows point to areas of bearing damage at the edges of the attachment holes.

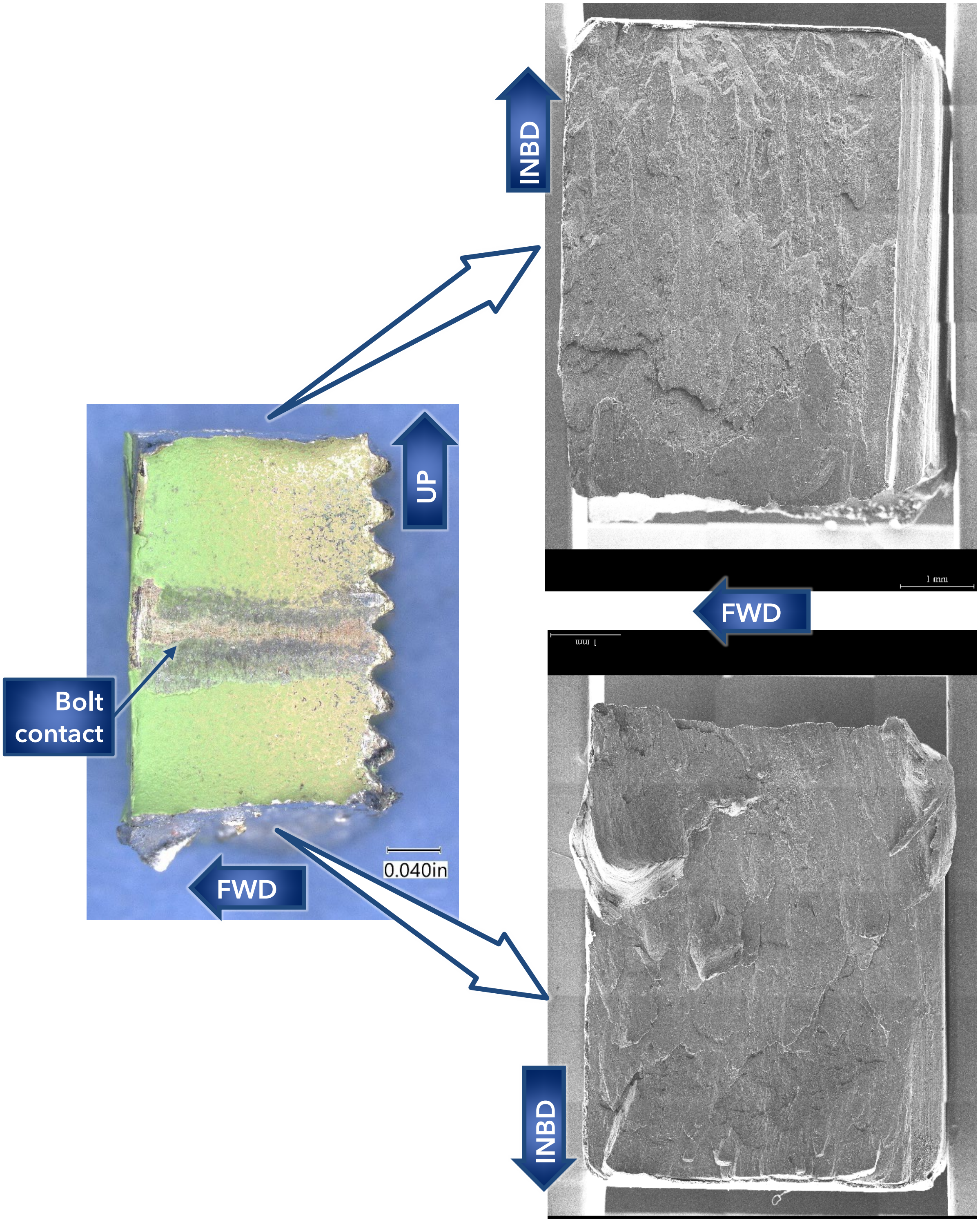


Figure 31. Fractured flange piece at the upper inboard attachment location of the forward hinge guide fitting showing an optical image of the hole bore (left image) and SEM images of the upper (upper right image) and lower (lower right image) fracture surfaces.

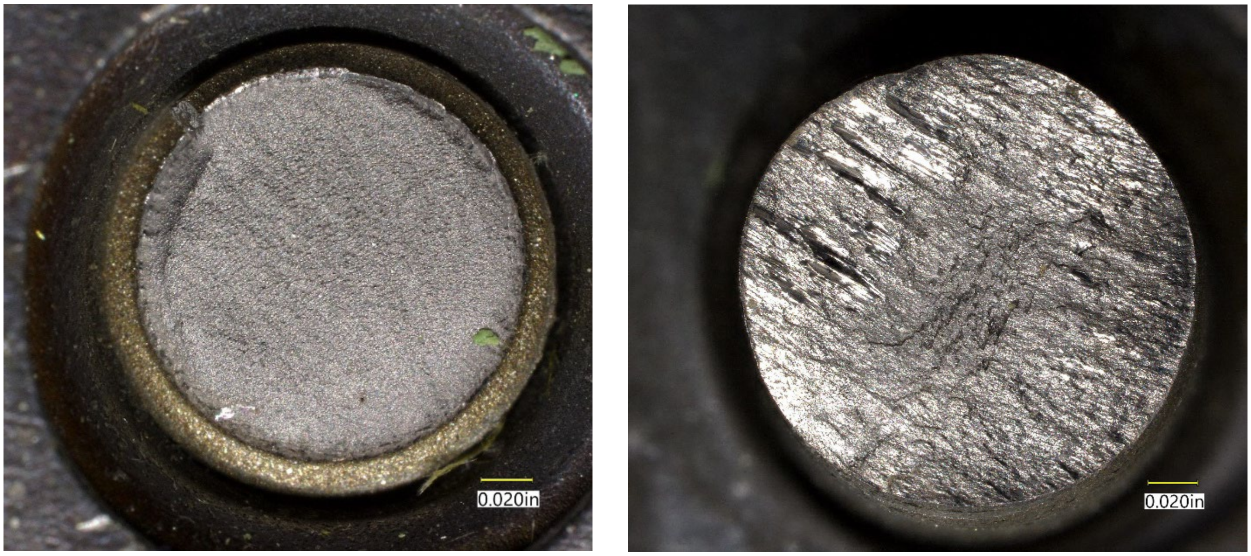


Figure 32. Fracture surfaces of the lower inboard (left image) and lower outboard (right image) attachment bolts for the forward hinge guide fitting from the left MED plug.

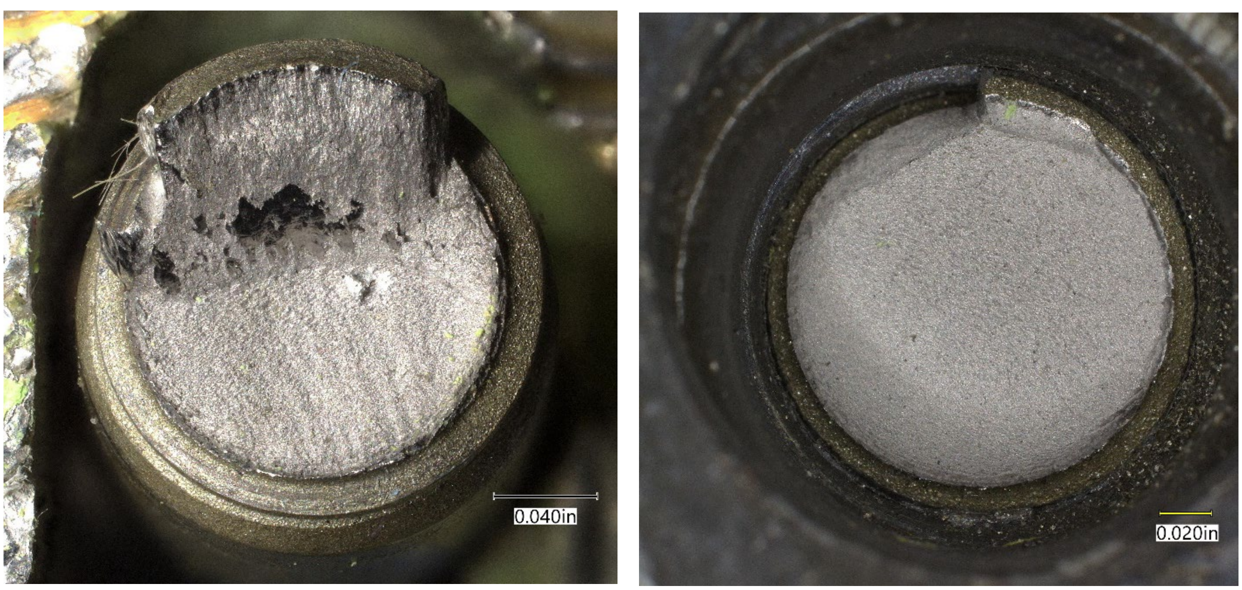


Figure 33. Fracture surfaces of the lower inboard (left image) and lower outboard (right image) attachment bolts for the aft hinge guide fitting from the left MED plug.

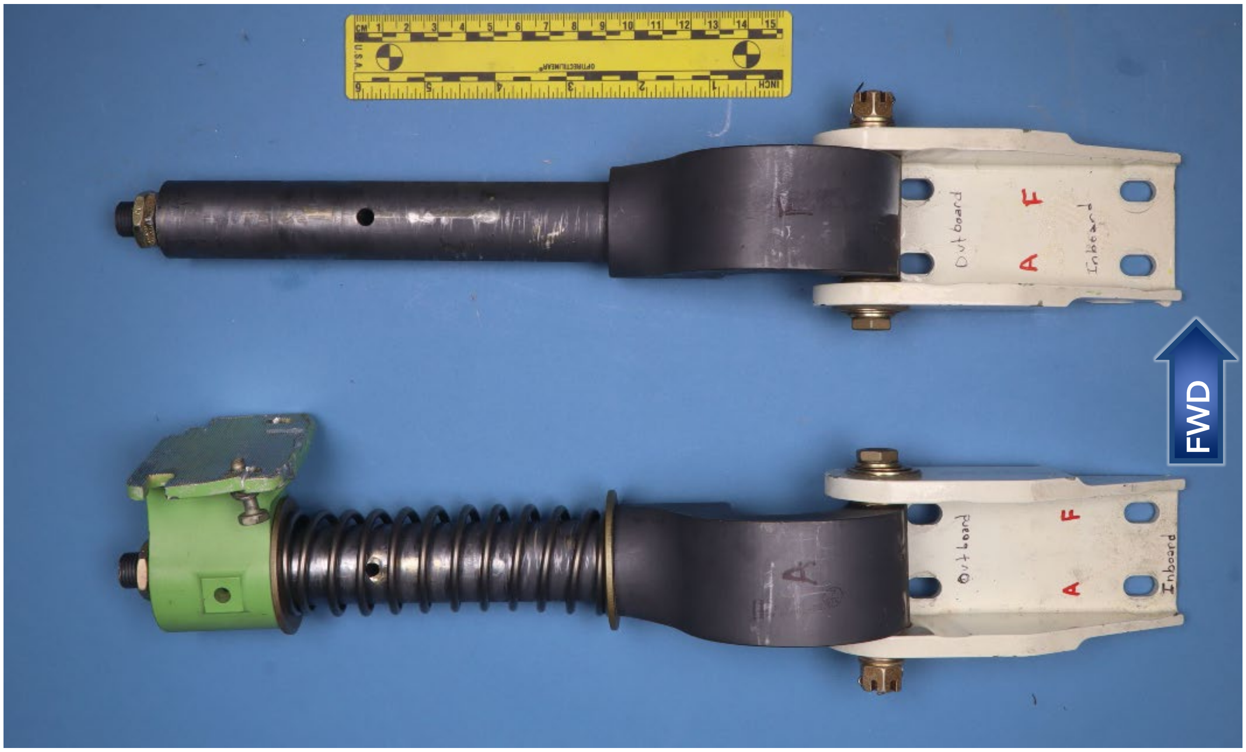


Figure 34. Overall view of the inboard side of the hinge assemblies with attached lower hinge brackets from the left MED plug as received.

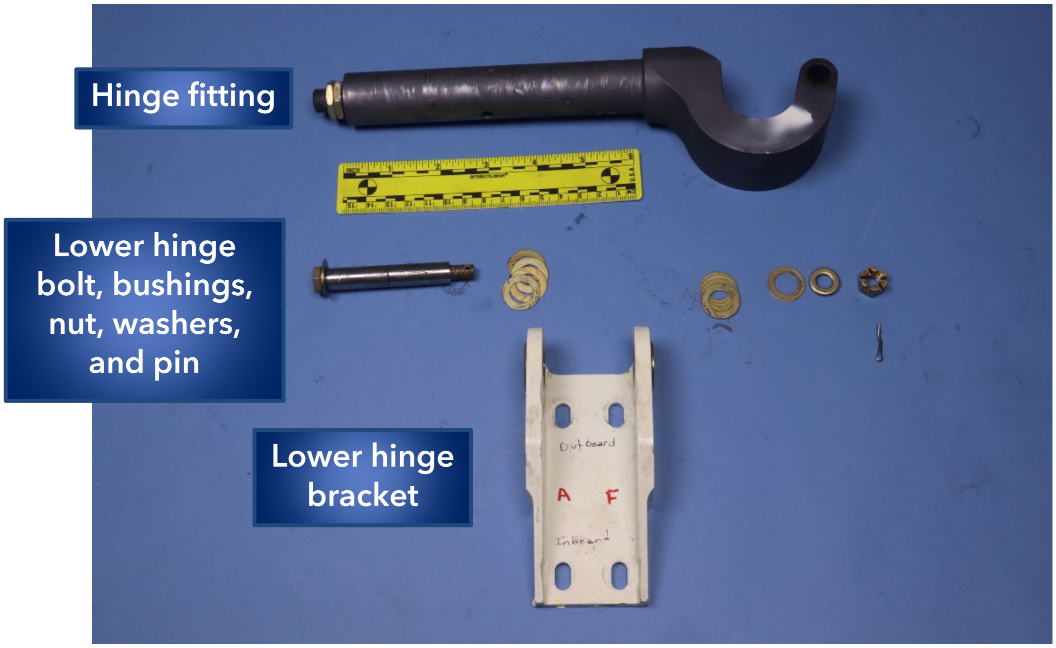


Figure 35. Forward lower hinge assembly components, lower hinge bracket assembly, and associated hinge fitting attachment hardware after disassembling the hinge fitting from the lower hinge bracket assembly.

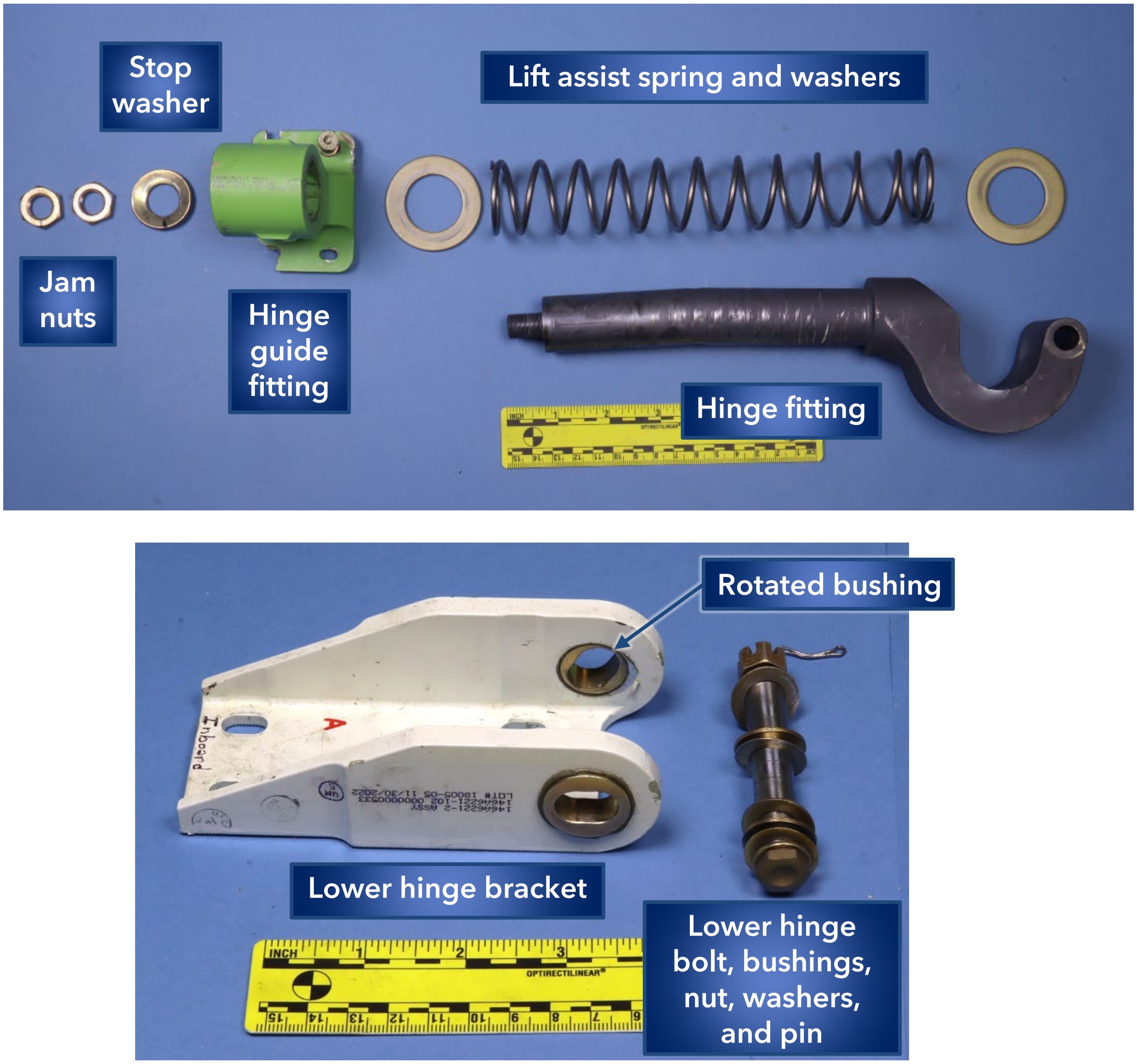


Figure 36. Aft lower hinge bracket assembly and associated hinge fitting attachment hardware after disassembly.

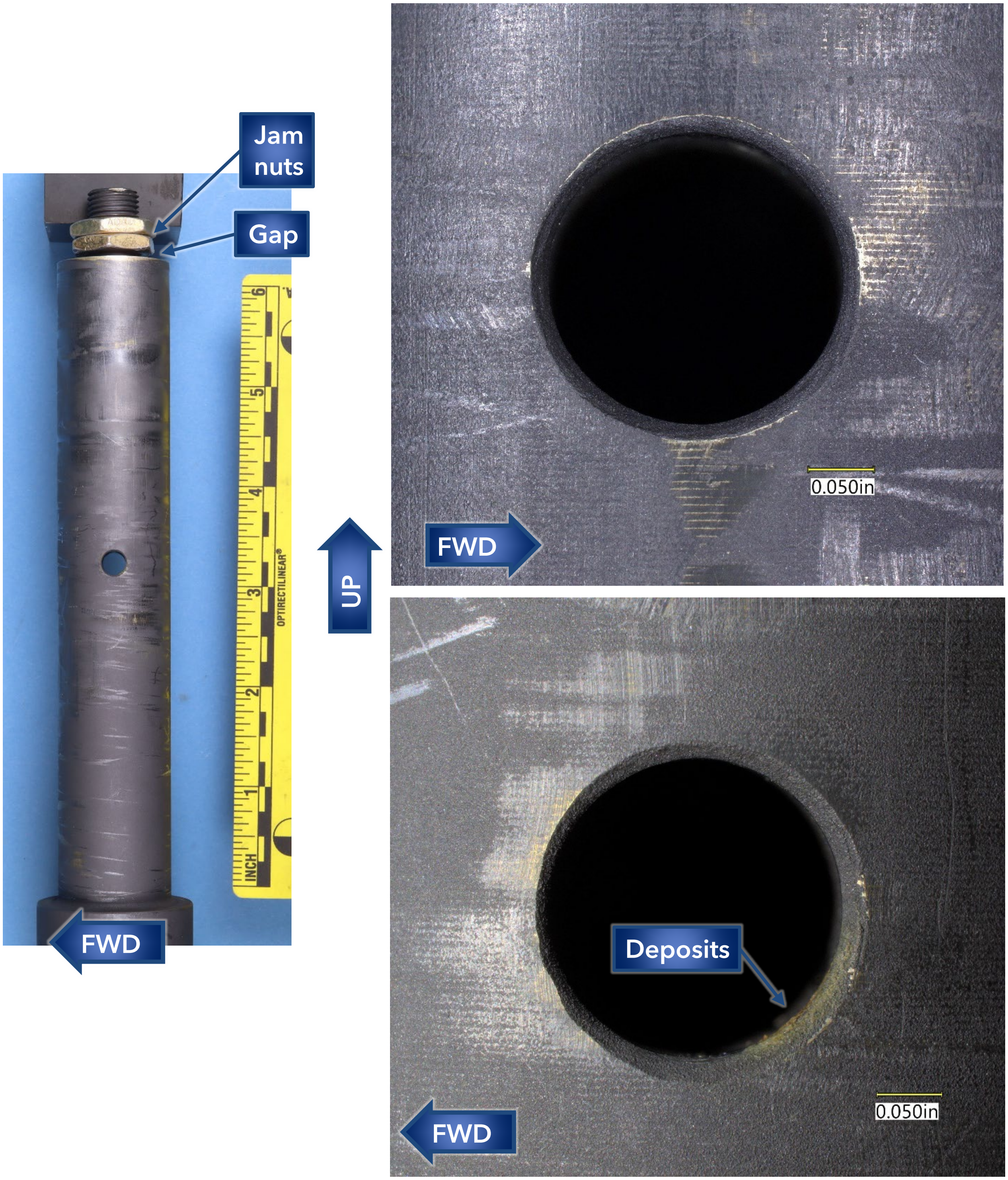


Figure 37. Forward hinge fitting shaft (left image) with closer views of the vertical movement arrestor bolt hole at the inboard (upper right image) and outboard (lower right image) surfaces.

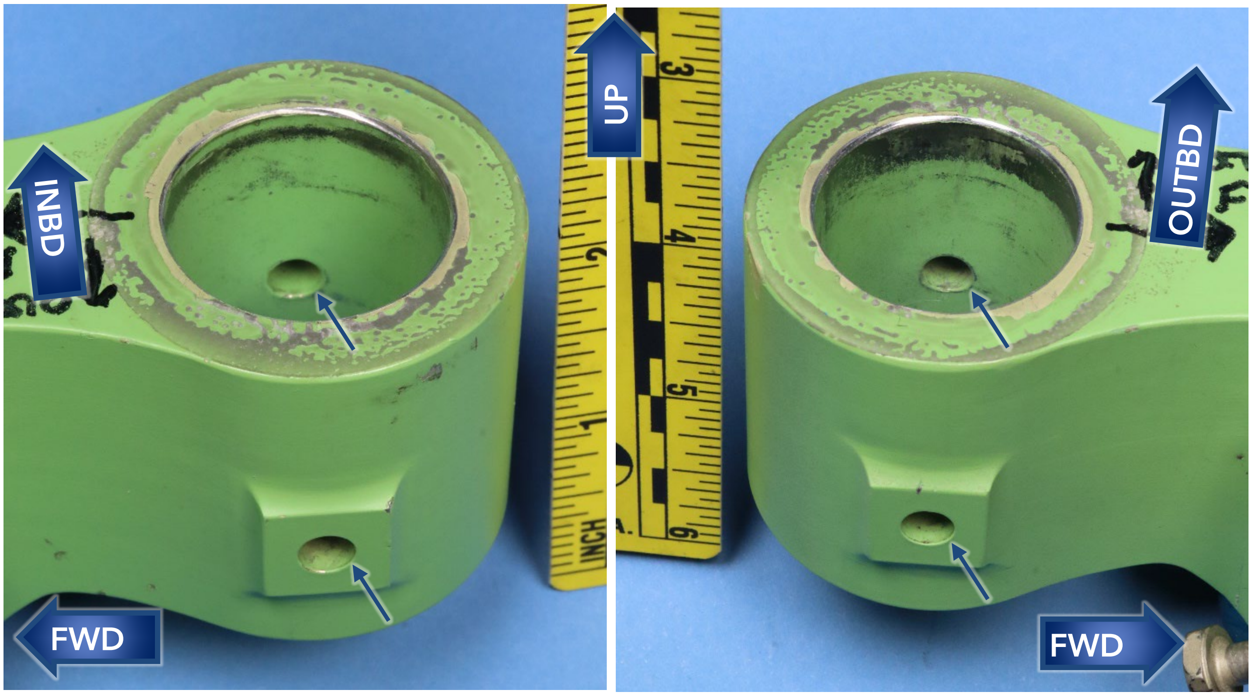


Figure 38. Vertical movement arrestor bolt holes (see unlabeled arrows) at the inboard and outboard sides of the aft hinge guide fitting viewed at angles to show the lower surfaces of the hole bores at the outboard ends (left image) and inboard ends (right image) of the holes.

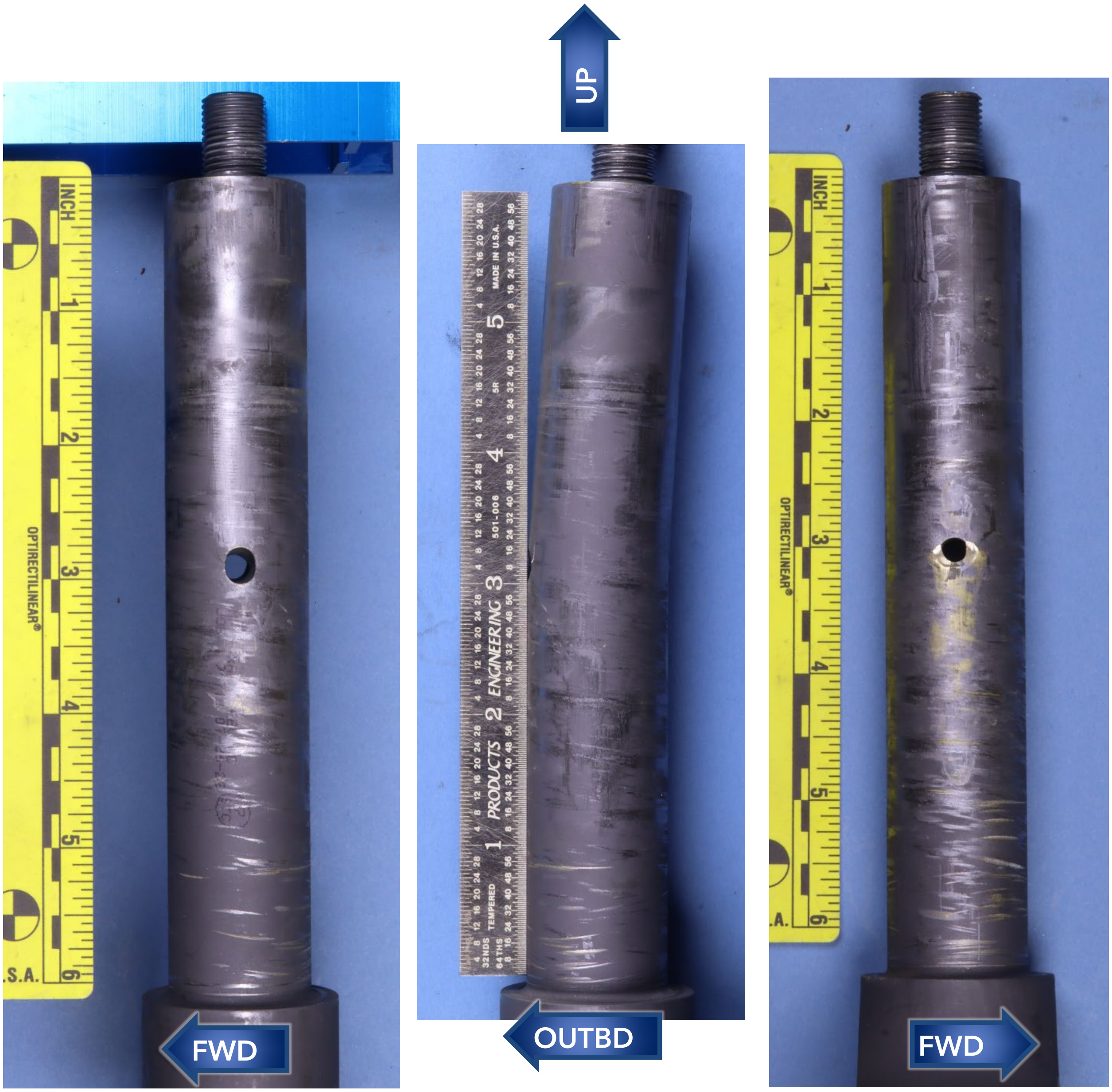


Figure 39. Aft hinge assembly shaft after disassembly showing the inboard (right image) and outboard (left image) sides of the shaft. The middle image shows the bend in the shaft as viewed looking forward.

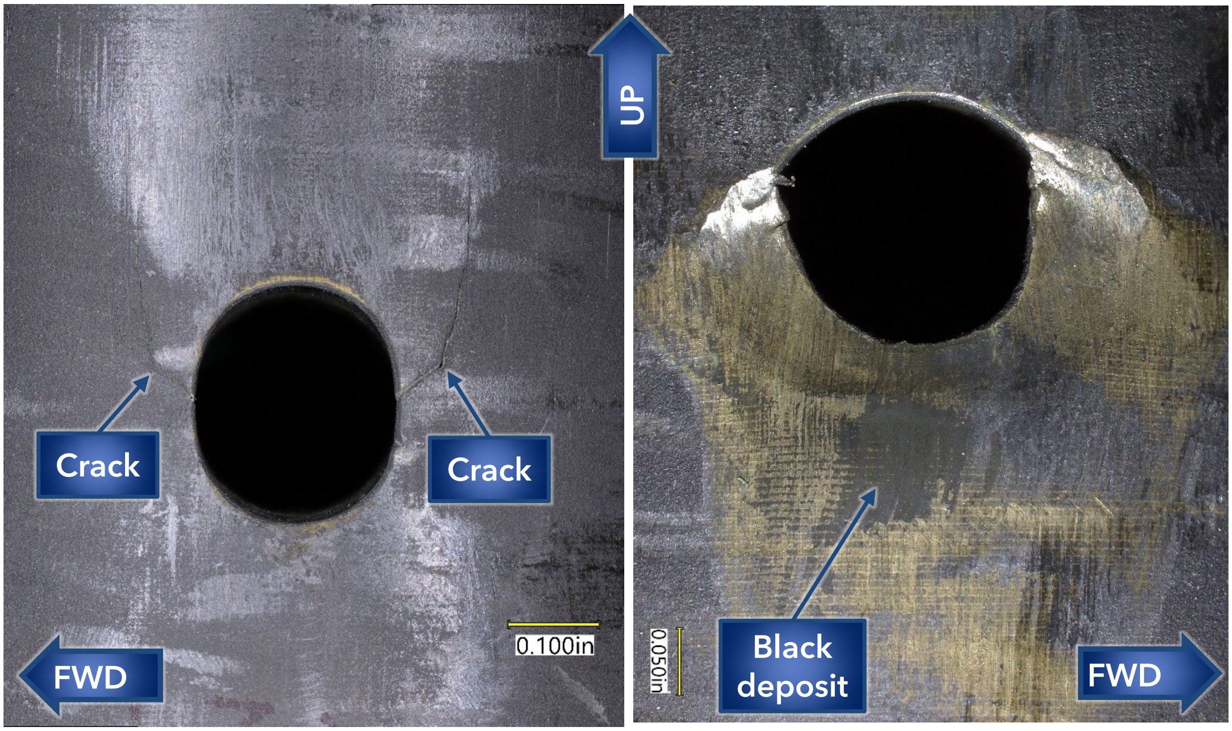


Figure 40. Closer views of the vertical movement arrestor bolt hole through the aft hinge fitting at the inboard (right image) and outboard (left image) surfaces.

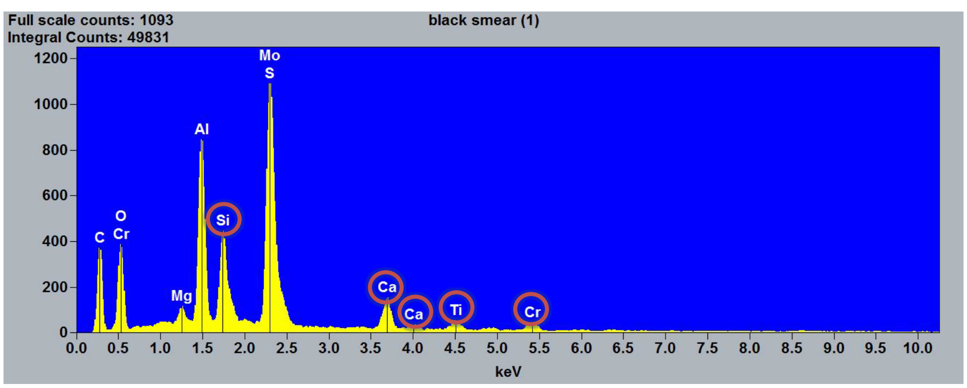


Figure 41. EDS spectrum of a smeared black deposit below the vertical movement arrestor bolt hole shown at the right in figure 40. Circled peaks were also detected in the enamel and/or primer spectra shown in the next figure and were largely absent from other sampled areas of the hinge fitting.

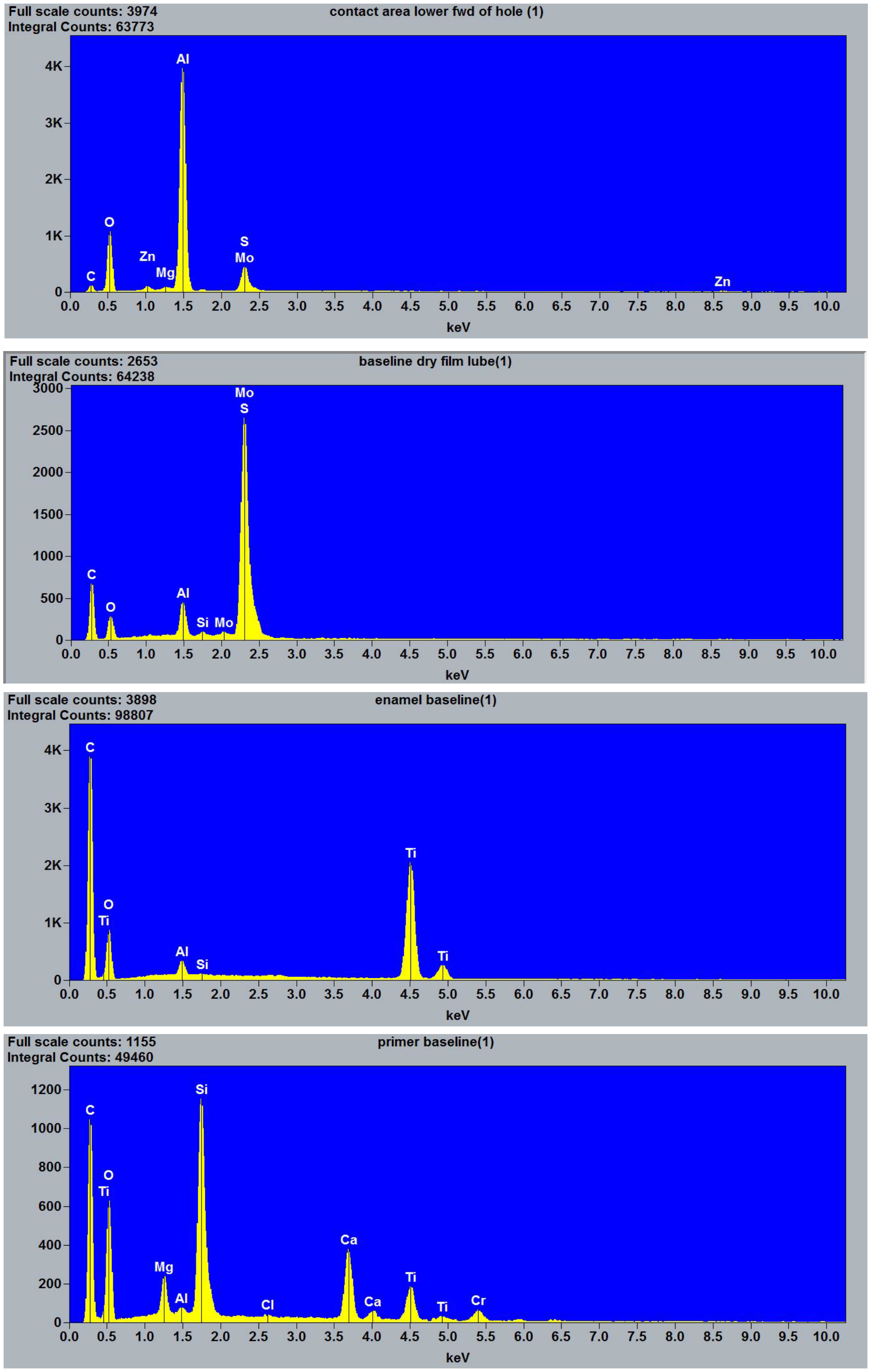


Figure 42. EDS spectra of a gold-colored area at the lower forward side of the hole shown in the right image in figure 40 (upper spectrum), an undisturbed surface on the hinge fitting (upper middle spectrum), a sample of the enamel coating on one of the upper guide fittings (lower middle spectrum) and the primer on the same upper guide fitting (lower spectrum).

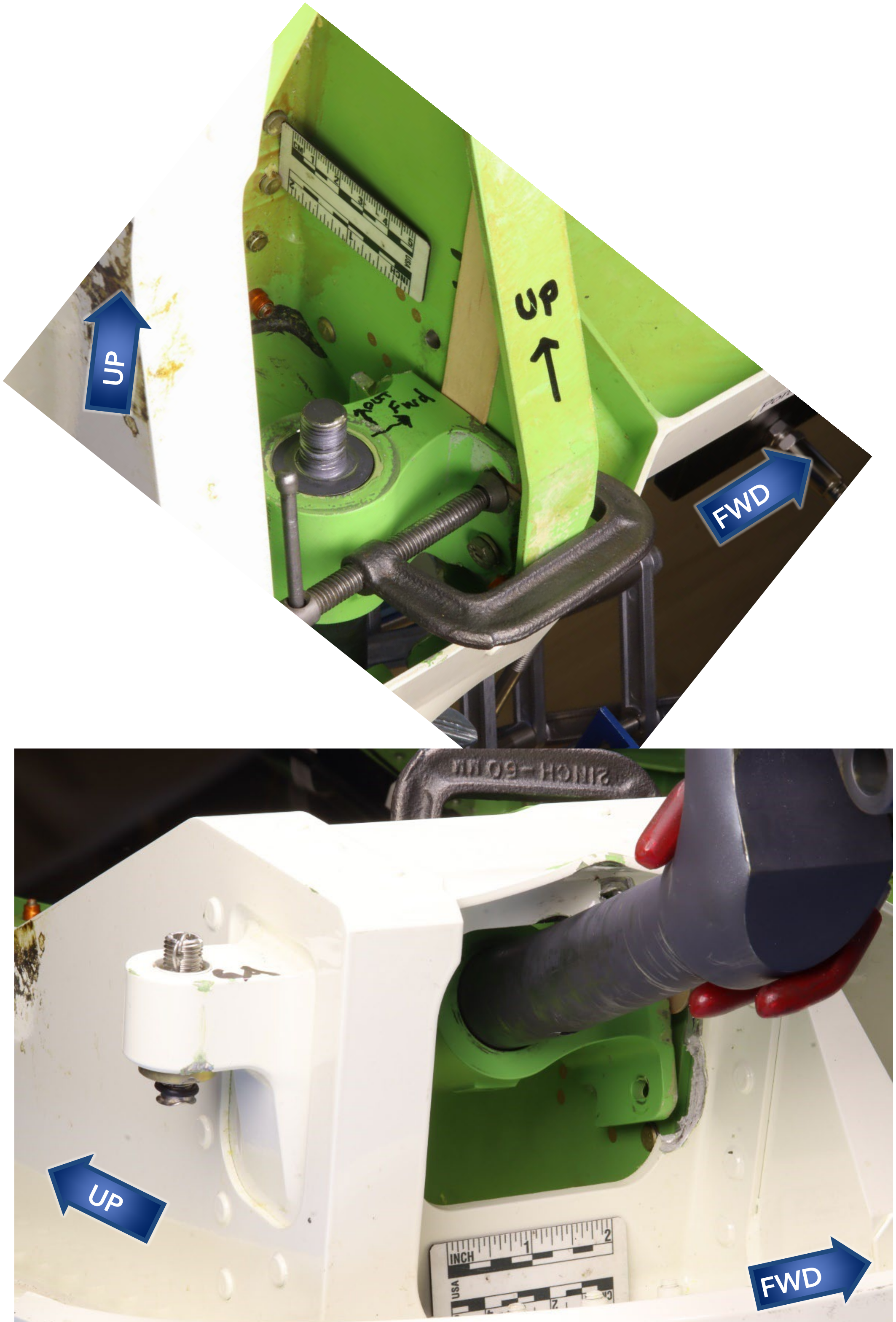


Figure 43. Images of the partially reassembled aft hinge fitting assembly with the hinge shaft positioned next to corresponding contact damage at the lower end of the MED plug as viewed from below (lower image) and from above (upper image).

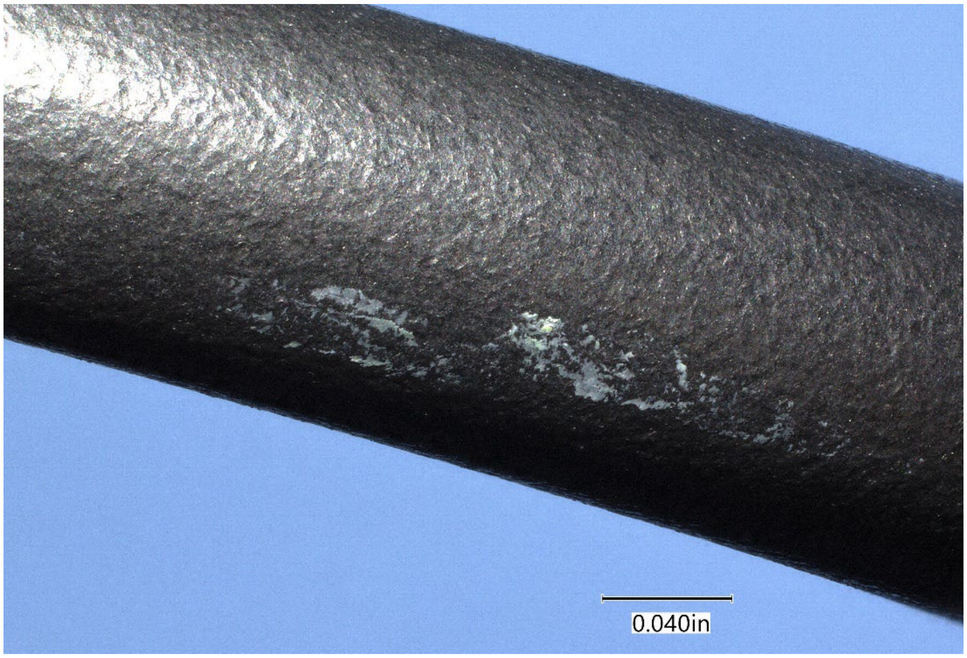
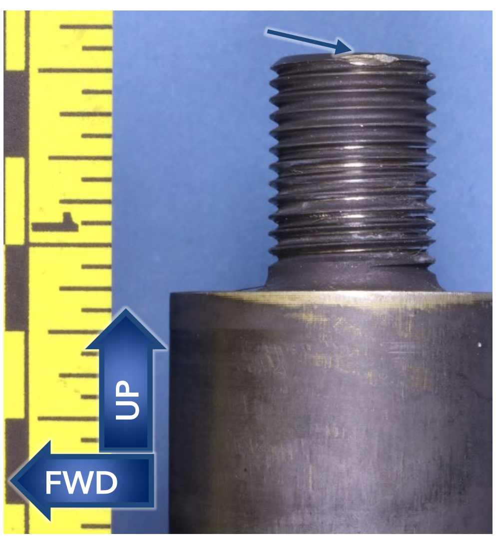


Figure 44. White and green material deposited on the surface of the aft lift assist spring.



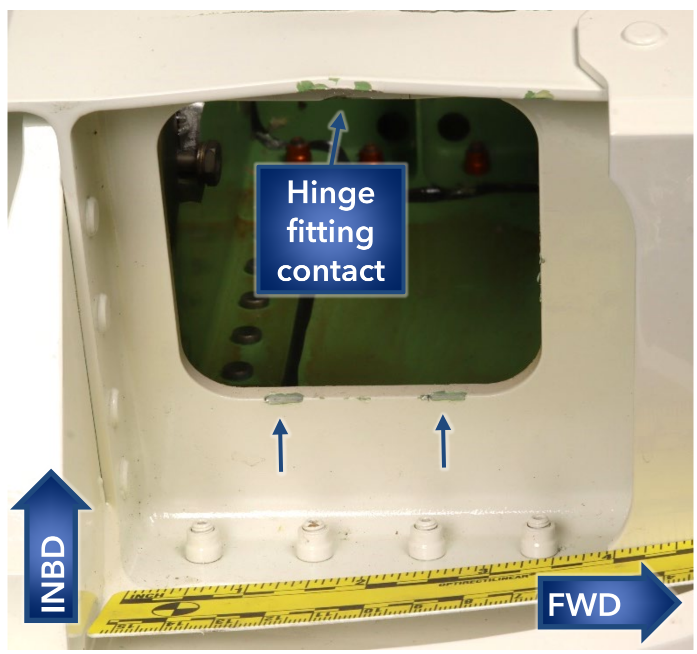


Figure 45. The left image shows a contact mark (unlabeled arrow) observed on the upper end of the forward hinge shaft, outboard side. The right image shows another view of the forward hinge opening in the lower end of the left MED plug where unlabeled arrows point to contact marks on the outboard edge of the opening with a spacing corresponding to the distance between the hinge guide flange and the hinge shaft centerline.

Figure 46. Exterior surface of the left MED plug. Unlabeled arrows point to a crease associated with outward bending at the upper end of the plug. A dark green deposit observed at the upper forward side of the left MED plug exterior surface is shown in the upper image.

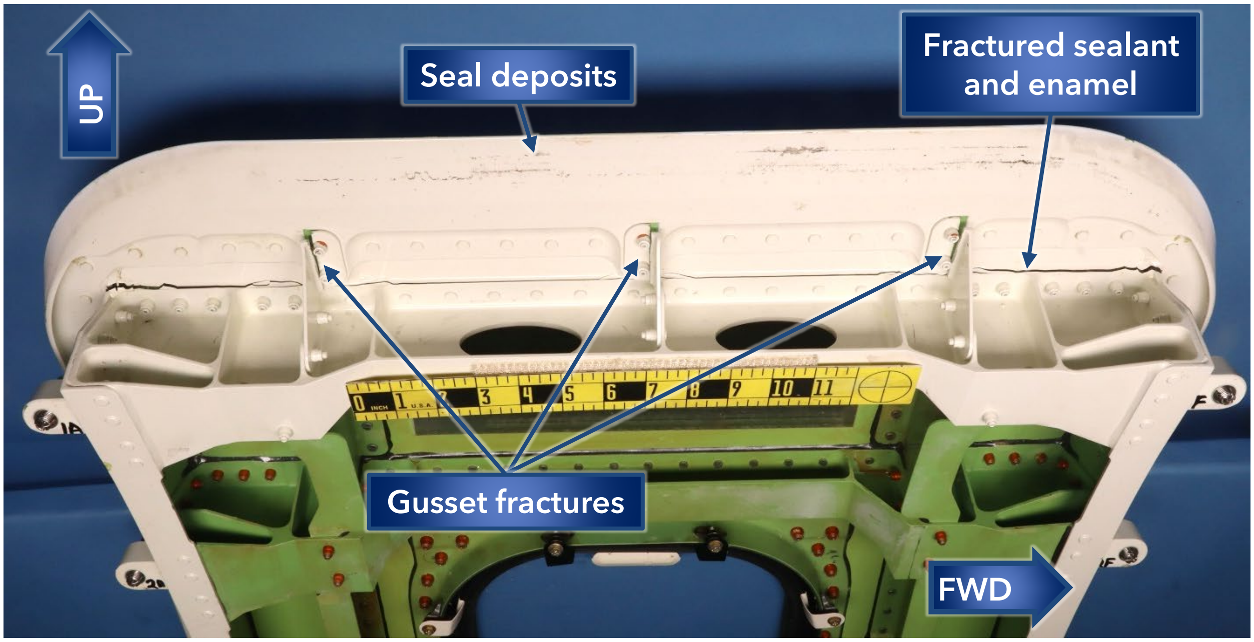


Figure 47. Overall view of the upper end of the left MED plug.

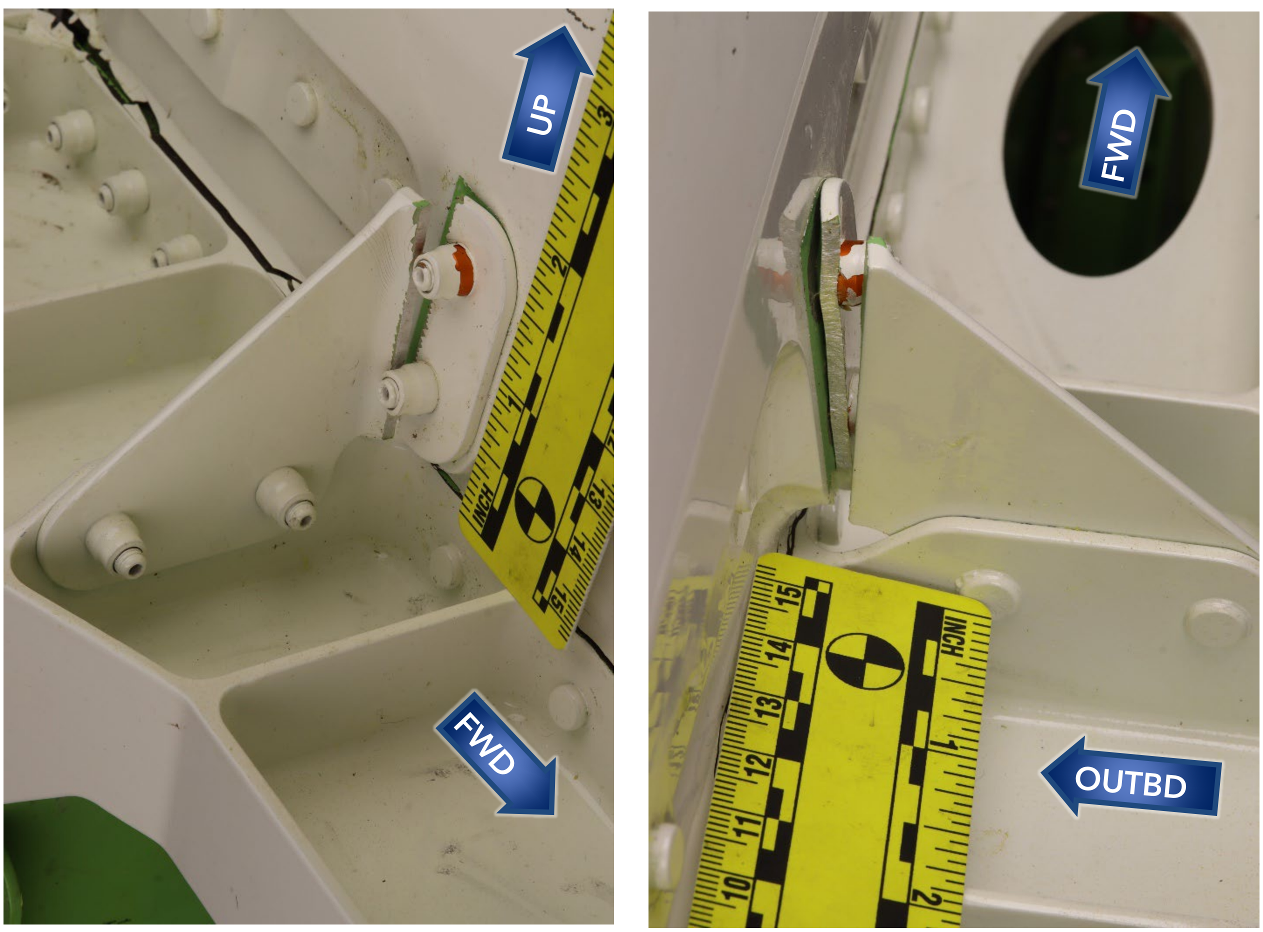


Figure 48. Close views of the aft gusset showing fracture features typical of the three gussets.

Figure 49. Dark deposits at the upper edge of the left MED plug in the seal contact area. Arrows point to deposits that appeared to be concentrated along horizontal lines between the arrows. The left side of the upper image overlaps the right side of the lower image as shown by the ruler that remained stationary when the photographs were taken.