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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

APOLLO 6
ANOMALY REPORT NO. 6

ABNORMAL STRUCTURAL PERFORMANCE DURING LAUNCH PHASE

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MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

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ABNORMAL STRUCTURAL PERFORMANCE DURING LAUNCH PHASE

SUMMARY

Approximately 2 minutes 13 seconds after lift-off of the Apollo 6 mission, abrupt changes of strain, vibration, and acceleration measurements were indicated in the S-IVB, instrument unit, adapter, lunar module, and command and service modules; photographs showed objects coming from the area of the adapter. The adapter, however, continued to sustain the required loads with no impairment of the mission.

The investigation was first focused upon the understanding of the coupled vibration modes and characteristics of the launch vehicle and spacecraft. Extensive test programs were conducted. It was eventually concluded that the adapter failure was not caused by vibration.

Extensive study of the airborne photography and other evidence indicated that a large area of the adapter had lost inner facesheet from the honeycomb sandwich panels. Loads and stresses resulting from vibration were determined to be insufficient to initiate such a failure. The investigation was then directed toward determining the range of pressures that could have been trapped in the Apollo 6 adapter sandwich panels, and toward determining the tolerance of the panels to withstand pressure with various degrees of flaws such as adhesive voids and facesheet dents. The degradation effects of moisture and heat exposure on the adhesive strength were also studied and tested. These tests and analyses led to the conclusion that pressure internal to the sandwich panels could have caused the failure, if a large flaw existed. The pressure buildup would have been caused by aerodynamic heating effects on air and moisture trapped in the panel.

The probable cause of the failure was found in the original ultrasonic inspection scan record of the affected adapter panel. In the center of the region where the adapter failed, horizontally along the station 709 panel splice, the record contained two thick anomalous lines extending several feet. Without an X-ray record of this region, the significance of this particular scan record cannot be fully understood. However, since all other evidence had indicated that the adhesive had to be weakened in a rather large area to initiate the failure, the investigation was focused intently upon the station 709 splices of other adapters. Sufficient information was developed to verify that deficient assembly techniques have consistently resulted in abnormalities in the structure at this station. These abnormalities were identified in adapters 12, 13, 14, 15, and 16.

Before the splice abnormalities were pinpointed, corrective action was taken to reduce pressure buildup in the honeycomb panels and to reduce heat degrading effects on the adhesive. This was done by drilling vent holes in the inner facesheet and covering the outer facesheet with cork. The adapters having identified abnormalities in the station 709 splice are being repaired, and the contractor is investigating ways of avoiding these abnormalities in panels yet to be bonded.

INTRODUCTION

A preliminary review copy of this Anomaly Report was first distributed in July 1968 to summarize the analyses performed by a team of NASA and contractor personnel. Since that time, the flight data have been extensively reevaluated and test programs have been conducted. An additional analytical tool, an isodensitracer, was used for quantitative evaluation of the airborne photography.

DISCUSSION

FLIGHT CONDITIONS AND OBSERVATIONS

Photographs taken by an airborne camera show dark areas appearing on the adapter at about 2:13 and pieces separating shortly thereafter. The flight conditions at that time were:

Altitude, ft	152 000
Mach number	5.47
Dynamic pressure, psf	60.23
Angle of attack, deg	2.0

Longitudinal loading on the adapter (including that contributed by bending moments) at 2:13.27, just prior to the anomaly, was 727 lb/in. at the top (station 838) and 578 lb/in. at the bottom (station 502). Of the top load, 33 percent was oscillatory at 5.5 Hz in a plane 45 degrees to the pitch plane and through the -Z/+Y panel intersection. Seventeen percent of the load on the bottom was oscillatory at 5.5 Hz in the pitch plane. The adapter structure was qualified by static testing to 1273 lb/in. at the top and 1230 lb/in. at the bottom under ambient environmental conditions.

LONGITUDINAL OSCILLATIONS

Because the spacecraft was experiencing an unusually high level of low frequency (5.5 Hz) oscillations at the time of the anomaly, numerous tests and analyses were performed to determine whether these oscillations caused or contributed to the failure. All evidence from the investigations has led to the conclusion that the anomaly was not caused by the oscillations.

A modal survey was performed on the adapter shell structure following the Apollo 6 flight, and a total of eleven modes of vibration were identified. Seven were in the 4.90 to 7.24 Hz band, and significant motion of the lunar module was noted. These modes can be characterized as the lunar module acting as a spring-mass system and the adapter providing elastic constraint. Four modes where the motions of the shell were significant were identified in the 17.88 to 27.73 Hz band; these may be characterized as "classical" shell modes.

A review of the flight accelerometer data indicates only 5.5 Hz response just prior to the anomaly, and a maximum deflection of 0.15 inch at the lunar module attachment was deduced. This deflection is an order of magnitude less than that required to overstress the shell significantly.

Although no accelerometers were mounted on the adapter panel for the Apollo 6 flight, excitation of the modes in the 17.88 to 27.73 Hz band would have been detected by accelerometers on the lunar module/adapter attachment fitting, since node lines of these modes do not pass through the attachment points. Response of the higher frequency modes was observed during the lift-off and maximum dynamic pressure regions, where acoustic and aerodynamic buffet, respectively, provide excitation.

In addition to the testing done at MSC, Langley Research Center performed tests on a 1/10-scale model of the full stack configuration, wherein the Apollo 6 static and dynamic loading was simulated. No failure mechanism applicable to the Apollo 6 anomaly was identified during those tests, which are reported in Langley Working Paper LWP-689.

On the basis of the ground and flight test data, it is concluded that the forcing phenomena experienced during flight did not result in sufficient response to precipitate structural failure of the shell.

VISUAL EVIDENCE

Details of the photographs taken by the airborne camera were made more quantitative by scanning with an isodensitracer, which could discriminate 48 incremental changes in density between black and white.

Figure 1 shows the results from 3 of the 39 frames processed. The anomalous area suddenly appeared on the frame taken at 2:13.287, the preceding frames having shown nothing unusual. In subsequent frames, the density pattern changed from frame to frame and returned to the original color in some areas; these data have been interpreted as inward deflection of the surface and subsequent return to the original curvature. It has been concluded from the terminator line of the right side of the adapter that these deflections were quite large, on the order of 6 to 12 inches. An undamaged panel (1.7-inch-thick honeycomb sandwich) cannot deflect to these magnitudes and subsequently return to the original shape. Therefore, the data have been further interpreted as indication that the deflecting area is outer facesheet only, possibly with some fragments of core attached but with no inner facesheet.

The isodensitracer was also used to determine orientation and size of the fragments seen in the photographs. Out-of-plane (shutter plane) orientation of a particle was determined by the grouping of the constant-density contour lines across the face of the particle. Closely spaced lines on one side and broadly spaced lines opposite indicated the direction of out-of-plane tilt; the degree of contour compaction showed the amount of tilt. The frame at 2:13.587 (fig. 2) captured an in-plane view of the two large pieces that came from the adapter at 2:13.420. These pieces total about 35 square feet in area.

TIMING OF ANOMALY

The photographic frame at 2:13.287 captured the first visual evidence; however, accelerometers and microphones provided evidence that the failure was several milliseconds earlier. Timing of pertinent instrumentation changes during the anomaly is shown in figure 3.

The lunar module +Z microphone registered sound beginning at 2:13.296 (fig. 4). This is consistent with sound having been generated on the -Z panel, approximately 16 feet away, at about 2:13.281. The command module pitch and tangential accelerometers tended to confirm this time, showing what might be interpreted as the beginning of a change at 2:13.280 (fig. 4).

The lunar module -Z microphone and +Y apex radial accelerometer, both near the -Z panel, show pronounced changes at 2:13.283 (fig. 4). The disturbance saturated the amplifier of the microphone and allowed the +Y apex fitting to accelerate radially outward at a rate about six times that experienced one-half cycle earlier. The -Z microphone was about 2 feet from the -Z panel surface; this location is consistent with sound originating at the panel surface at 2:13.282.

Because the -Z microphone change can be interpreted relatively well and because the microphone was close to the anomalous area, the time of the failure must have been very near 2:13.282.

ADAPTER STRAIN MEASUREMENTS

Ten of the 14 adapter strain gages were rendered inoperative by the anomaly. The four remaining measurements, located at station 775, θ = 214 degrees (fig. 5), indicated longitudinal and circumferential strains for the outer and inner facesheets of the -Y panel. Power for the gages that failed was received through a wire harness routed up the inside wall of the -Z panel. The four gages which remained operative received power through a separate wire harness.

Prior to the anomaly, all the gages were measuring strains similar to those experienced on the Apollo 4 mission. At the time of the anomaly, the longitudinal compression stress in the -Y panel increased in both facesheets; the circumferential stress increased in compression on the inner facesheet but remained essentially unchanged on the outer facesheet (fig. 6). One possible cause is that the -Z panel lost effectiveness for carrying longitudinal loading and imposed high circumferential loading upon the upper half of the -Y panel.

The increase in longitudinal stress on the -Y panel can be approximated by complete removal of the -Z panel (station 838 to station 584), with a resulting shift of neutral axis toward the +Z side for the remaining structure. However, removal of the panel does not explain the high increase in circumferential stress on the -Y panel; this shift would have necessitated a circumferential loading of 525 lb/in. compression near station 775. Thus, the nature of damage in the upper half of the -Z panel may have been such that longitudinal stiffness was drastically reduced while circumferential rigidity was unaffected, and since the circumferential loading on the -Y panel increased sharply, the -Z panel must have been locally deformed. The foregoing suggests that the facesheets on the upper half of the -Z panel were intact, but the panel may have sustained longitudinal failure and some deformation along the -Y/-Z edge member.

PRESSURE DROP OF ADAPTER CAVITY

At approximately 2:13, two independent pressure measurements indicated a change of about 0.2 psi in the adapter/instrument unit/S-IVB stage cavity pressure. The changes were detected by a differential pressure sensor in the environmental control system of the instrument unit and by a pressure transducer in the S-IVB forward skirt. Both measurements were commutated, but the change in pressure occurred in less than 1 second. The instrument unit sensor measured a drop of 0.1 to 0.15 psi in 0.6 second, and the S-IVB sensor measured a drop of 0.18 psi in 0.8 second.

The hole size necessary to cause the measured pressure changes is 16 to 30 square feet based on instrument unit sensor data or 35 square feet based on S-IVB sensor data. These computations represent a range of interpretation of time and pressure changes.

TRAJECTORIES OF FRAGMENTS

The trajectories of the falling pieces were analyzed to determine whether the pieces were aluminum facesheet, honeycomb core, paint, cork, or sandwich panel. Ballistic coefficients developed for each type material were based on a drag coefficient of 0.85.

The trajectories of the two largest pieces were determined to require a reciprocal ballistic coefficient of between 30 and 70. The only material found to fall within this range was the 0.029-inch outer facesheet, either alone or with core attached.

TELEMETRY INTERRUPTION

The two lunar module test article antennas, which were located below the adapter panels (+Z/+Y quadrant and -Z/-Y quadrant), showed momentary drops of more than 50 dB from 2:13.344 to 2:13.360. About 13 milliseconds later, RF drops of 10 to 15 dB and 8 dB were also noted from certain instrument unit and S-IVB antennas, respectively. The geometry of the vehicle position with respect to the ground stations was such that the line of sight could have been interrupted by falling metallic material.

PITCH TRANSIENT AT SEPARATION

When the command and service module was pyrotechnically separated from the adapter, acceleration transients were experienced in both the spacecraft and launch vehicle. The spacecraft was given a maximum pitch-down rate of 1.6 deg/sec, and the launch vehicle was given a maximum longitudinal deceleration of 0.21g. These transients can be explained by a short-duration forward thrust of the -Z adapter panel.

Each of the adapter panels is normally deployed outward by two thrusters aligned axially with the vertical edge members at station 584. The panel is hinged at station 584, and the cross sectional curvature of the panel provides the required moment arm for torquing the panel outward. The thrusters stroke for 1.5 inches. The combined force of both thrusters is initially about 9500 pounds, and the force decreases linearly to zero in the 0.2 second normally required to stroke the 1.5 inches.

To produce the vehicle transients experienced would have required approximately the total energy of both thrusters; that is, rather than rotating the -Z panel, the deployment thrusters translated it forward about 1.5 inches. Also, the panel must have offered little, if any, deflection resistance, which would detract from the ability of the thrusters to produce the vehicle transients. The foregoing is consistent with the strain data in that it indicates that almost all shear rigidity was lost between the panel and its edge members.

ORBITAL TUMBLING LOADS

Five days after launch, the tumbling S-IVB/adapter was photographed. The quality of the photographs was insufficient for determination of the extent of panel damage; however, they did show all panels of the adapter to be deployed normally. The rotational rate about a lateral axis was determined to be 90 deg/sec. This rate of rotation indicates that in preventing the panels from being closed by the centrifugal forces developed, the outside retention cables were applying substantial loads. At first, this seemed contradictory to the evidence regarding the strain gages and the pitch transient; however, analyses showed that only a small amount of structure between the retention cable attachment to the panel (fig. 5) and the door is required to restrain the panel from closing. The failed panel could have resisted collapsing under this restraint by tension in the outer facesheet, reacted by the hinge.

The assembly tolerances for the retention cable attachment bolts to the panels permitted an undesirable situation. The bolt was tightened on two 3-inch-diameter doublers on each side of the honeycomb panel; a spacer was provided to prevent excessive forces from being applied to the core (fig. 7). However, drawing tolerances permitted the spacer to be as much as 0.030 inch undersize; thus, of the 105 in-lb torque normally anticipated with a 7/16-inch-diameter bolt, only 25 percent would have been sufficient to crush the core. This is not especially serious but is undesirable and has been corrected on the drawing.

PRESSURE DIFFERENTIAL IN PANELS DURING FLIGHT

The honeycomb core of the Apollo 6 adapter panels was vented cell-to-cell but not to the atmosphere. Consequently, a differential bursting pressure would develop during launch. The 14.7-psi atmospheric pressure of air trapped in the core at lift-off would be increased by aerodynamic heating of the adapter surface. The temperatures on Apollo 6 were high enough that any water in the panel would have been converted to steam.

To bracket the range of pressure the Apollo 6 honeycomb core could have experienced, an analysis was performed both with and without water in the cells. The results (fig. 8) indicated that a maximum pressure of approximately 33 psig could have been attained at the time of the anomaly, when the outer and inner facesheets were at temperatures of 297° F and 202° F, respectively.

ABILITY OF PANELS TO CONTAIN PRESSURE

Pressure tests were performed on panels to determine the effects of bond voids, crushed core, heat, water, and load on panel integrity. The results are summarized in tables I through III, figure 9, and the following paragraphs.

Sheet-to-Core Bond Voids

Tests to establish how sheet-to-core bond voids affect pressure containment capability are summarized in figure 9. These tests were performed on 15- by 15-inch panels with 0.029- and 0.015-inch aluminum facesheets and 1/4- by 0.001-inch aluminum honeycomb core. The test specimens were sealed by edge frame members so that high pressures could be applied to the core without leakage. The test consisted simply of pressurizing the specimen until failure, noting the failing pressure. No load or heat was applied.

These specimens failed by the mechanism of the built-in void permitting the facesheet to bulge to a curvature such that the peel strength of the adhesive was exceeded. Once started, the entire facesheet came off explosively. The data from these tests indicate that the relationship between pressure containment capability and void size is fairly predictable.

Effects of Dents

Panel tests performed to determine effects of dents are summarized in table I. The test specimens were identical in size to those used in the sheet-to-core void tests, but they had no bond voids. Indentation was achieved by a pendulum fixed-mass system with which dents of various diameters and depths could be made.

These tests were originated because of the possibility that debonding between facesheet and core might result if the inside surface of the adapter was inadvertently struck and dented during launch preparation work on the lunar module; this work is performed on platforms attached to the adapter inner wall. However, debonding evidently does not occur. The pressure containment capability of the panels with dents was much better than that of the panels with sheet-to-core bond voids. Depth of the dent appeared to be more significant than diameter. Depths up to 0.030 inch did not affect pressure containment capability. The crushed core resulting from dents 0.039- to 0.059-inch deep degraded the pressure containment capability by about 26 percent.

Effects of Moisture and Heat

The adapter panels are bonded with HT-424 adhesive. From handbook type data, obtained from a number of investigators, it is known that the strength of this adhesive is degraded by heat and by moisture. Recent tests on small specimens indicate 47 percent degradation of tensile strength after a 30-day soak in water, followed by a 1/2-hour thermal soak at 300° F.

In order to obtain insight regarding the effects of moisture and heat on pressure tolerance of the adapter panels, tests were performed by the contractor and by MSC, using specimens representative of the adapter panel construction. The contractor used 15- by 15-inch specimens; MSC used 24- by 36-inch specimens. The results of these tests are given in table II.

Basic differences in the manner in which these test programs were conducted may account for some of the inconsistency of the results. In the contractor's tests, the specimens were deliberately heated slowly, requiring from 30 minutes to an hour to achieve test temperatures. This was done to permit good temperature control and to permit the wet specimens to pressurize by conversion of the moisture to steam. At MSC, a flight-representative temperature/time profile was applied to the specimens, which were then failed with an external pressure source, the total test time being about 10 minutes.

These kinds of test are difficult to perform with consistent results because of difficulty in achieving a uniform distribution of the moisture within the panel prior to the start of the test. The optimum amount of water which would have created the maximum pressure of 33 psi at the time of the Apollo 6 adapter failure is between 0.1 and 0.05 percent by volume. A lesser amount of water would not produce enough steam; too much water would create a heat sink and hold temperatures down, with a limited amount of heat applied. In both test series, moisture was introduced into specimens by pulling a vacuum at one port on the panel and introducing water in a port on the opposite side of the panel. X-rays of the MSC test specimens prior to the start of testing indicated random and incomplete distribution of moisture. Inasmuch as the contractor's specimens were heated slowly, the resulting "simmering" effect would tend to produce better distribution. On the other hand, the prolonged exposure to heat and pressure introduces a degrading creep effect which is nonrepresentative of flight conditions.

Consequently, these tests did not yield quantitative data. However, accepting the data as is, it has been concluded that the Apollo 6 flight failure could not have resulted from this failure mode alone.

Effects of Load, Heat, and Voids

Tests for combined effects of load, heat, and voids are summarized in table III. The test specimens had the same core size and facesheet thickness as those used in the previous test programs, but they were only 12 by 12 inches, had no edge framing, and had a doubler bonded to each facesheet at the two loaded ends. The test plan was to achieve a specified load and temperature, then pressurize the panel to failure. However, without edge framing, which would have affected load-carrying capability, the panels leaked so badly that pressures of only 35 to 45 psi could be attained (the compound used to seal the edges of the panels would blow out). Therefore, the tests were conducted by attaining the maximum pressure possible and then increasing the end loading until the panel failed.

Panel 5, with a 1-inch-diameter void, was loaded to design ultimate while a 45-psig core pressure and the Apollo 6 heating conditions were being applied. Subsequent inspection revealed no propagation of the void. All other specimens with 1-inch-diameter voids demonstrated end-loading capability well above the design ultimate load; specimens with 2-inch-diameter voids failed slightly below design ultimate loading.

Thus, from these tests, it is concluded that combined loading with reasonable size voids, alone, could not have caused the flight failure.

PERTINENT INSPECTION HISTORY OF ADAPTERS

The adapter is manufactured in circumferential quarter sections and is inspected at the factory for bond quality. The automated ultrasonic through-transmission technique used for this inspection employs water to couple a probe to the test surface and uses transmitted energy in the 0.5- to 5.0-MHz band. The panel surface is scanned at 0.1-inch intervals, and a permanent record (C-scan) of the response is generated. The scan lines are of uniform density except when the probe traverses bond voids, adhesive-filled core, and edges of facesheets, splice plates, and doublers. The location and extent of any voids can thus be determined from this C-scan. However, in the area of core splices, doublers, etc., a C-scan is inconclusive in that existing voids may be mistaken for normal construction details. Therefore, X-rays are generally taken when a discrepant condition is suspected. All voids are repaired by injecting adhesive; after the adhesive has cured, the area is reinspected, usually by coin tapping, to assure that an adequate bond has been made.

The C-scan from the -Z panel of the Apollo 6 adapter contained an anomalous area (see fig. 10), approximately 2 feet long at the station 709 butt splice near the +Y edge of the panel. However, no X-rays were taken in this area. Subsequently, inspection of C-scan and X-ray records for adapters 12, 13, 14, 15, and 16 revealed that deficient assembly techniques of the adapter at station 709 have consistently resulted in abnormalities in the structure at this station. With the additional knowledge gained by comparison of the C-scan and X-ray records on the same structure, the C-scan record for the adapter of Apollo 6 was reviewed recently, and it was concluded that voids were present in the -Y panel and that very likely the anomalous area in the -Z panel contained intermittent voids.

Figure 11 illustrates the deficient assembly at the 709 splice of adapters 12 through 16. The outside doubler, the outside facesheets, and the internal doubler are assembled in the relative positions shown and are placed on a "glide" sheet which has the curvature of the adapter quarter panel. These four elements cannot move with respect to each other because they are tack-riveted. On the assembly of facesheets and doublers are placed three honeycomb core elements (A, B1, and B2 in the figure). Honeycomb core A is approximately the width of the internal doubler, is placed over the doubler, and is shallower than cores B1 and B2 by an amount equal to the thickness, 0.032 inch, of the internal doubler. Cores B1 and B2 should rest on the facesheets.

The deficiency identified in the adapters is caused by core B1 being misplaced onto the internal doubler, as shown in the lower left of figure 11. The misplacement of core B1, or of core B2, then produces a bump in the internal face sheet, displaces core A, and creates the three voids shown. If adequate adhesive is provided for the core splicing operation, void A and B will be filled by the foaming adhesive. However, void C may not fill because the core overlap on the internal doubler can prevent passage of the adhesive into this void. If the quantity of adhesive supplied for the core splices is inadequate, voids A and B may also exist. Void C was found on adapters 13, 14, and 15 and has been repaired by injection of adhesive.

Prior to the Apollo 6 anomaly, adapters were not further inspected for bond voids after leaving the factory, except by coin tapping at suspected areas of damage. One adapter (SLA 5) was returned to the factory after having been at Kennedy Space Center (KSC) for some time and was given a receiving inspection by portable equipment. Since the anomaly, three adapters (SLA 5, 7A, and 11) have been inspected by the portable eddy sonic technique at KSC; only four debonds have been found: three doubler-to-facesheet debonds and one facesheet-to-core debond under a damaged bracket. One doubler debond was about 3 inches in diameter, the others were less than 1 inch in diameter, and all were either in or near a previously repaired area. The facesheet-to-core debond was 1/2 inch in diameter and was under the attachment rivet of a damaged electrical harness support bracket. The Apollo 6 adapter had 649 of these brackets, most of them on the -Z panel; each bracket was attached to the inner facesheet with four rivets.

In another type of inspection, the porta-pull test, an annular cut is made in the facesheet to form a small-diameter specimen of facesheet bonded to core. A lug is then bonded to the specimen and subsequently pulled to ascertain whether the tensile strength of the adhesive is within specification limits. Adapters have always passed these tests. In one adapter, 7A, some water was found in the panel when the annular cut was made. This particular adapter had been exposed to weather for some time prior to the porta-pull test. The Apollo 6 adapter had been drenched in a rainstorm when its cover blew off during transport to the pad. A recent review indicates that normal panels are thoroughly sealed on all edges and that it is unlikely that a rain shower would cause water to enter the honeycomb core.

SUMMATION OF FINDINGS AND EVALUATION

From the foregoing discussion, the anomaly seems to have all of the characteristics that are consistent with the inner facesheet separating from the panel. The event was sudden, the outside surface had the flimsy characteristic expected of a thin facesheet, the panel lost effectiveness for carrying longitudinal loading, and the parts that came off were not complete sandwich panel but only outer facesheet, possibly with some core attached.

To verify that a large amount of inside sheet can come off without taking the outside sheet with it, a test was performed using a full circular section of an adapter (SLA 2). A pressure of 77 psi applied to the core removed the entire inner facesheet from one panel and split the outer facesheet longitudinally as a result of the excessive hoop tension. The core had been deliberately crushed in a 3-inch-diameter area to precipitate failure. (A bond void would have lowered the failing pressure, but this was impractical to accomplish on the existing test specimen.) All the evidence, in combination, establishes that differential pressure in the honeycomb core was the mechanism that produced the large extent of panel failure of the Apollo 6 adapter. The estimated failed area is shown in figure 12.

Although the nature of the failure is believed to be understood, the weakness or flaw through which the failure might have begun could have been any one or a combination of several possibilities uncovered by the investigation. The exact nature of the 2-foot anomalous area in the ultrasonic C-scan cannot be explained since X-rays were not taken; however, a major anomaly was undoubtedly present. Many electrical harness support brackets were riveted to the inner facesheet of the -Z panel; any one of these brackets, if inadvertently struck or improperly loaded, could have lifted the facesheet from the core and caused a debond. Tolerances for the retention cable attach bolt could have allowed a 3-inch-diameter area of core to be crushed by bolt torque. All of these possible flaws were located in the area of the failure on the Apollo 6 adapter. Finally, moisture may have contributed by reducing the ability of the panel to contain pressure.

In an effort to narrow these possibilities, additional tests were performed. Electrical harness support brackets were pulled off the inner facesheet to determine how much debonding could result. Although all four rivets failed and the bracket was pulled completely off the panel, the only debonding was on the order of 1/2 inch in diameter at the rivet attach points. Test specimens representative of splice-plate-to-facesheet bonds were prepared with built-in bond voids and tested to establish whether the voids would propagate. The bond voids did not propagate; the specimens failed at the expected stress level, consistent with the reduced area of bond. These modes of failure for the anomaly are improbable.

The retention cable attachment bolt is not a strong suspect because the bolt installation had to be intact to permit the panel to withstand the closing forces generated by the orbital tumbling. Photographic evidence substantiates that the panel did resist these forces. This mode of failure is improbable.

Hence, a deficiency associated with the large anomalous area of the C-scan is highly suspected as being the initiator of the failure. The station 709 abnormalities found consistently in later adapters substantiate this suspicion.

CONCLUSIONS

The most probable cause of the Apollo 6 adapter failure was an abnormal splice assembly at station 709, resulting in a facesheet bond too weak for the internal panel pressures achieved.

The anomaly demonstrated the basic integrity of the adapter, in that even with some of the structure ineffective, the adapter sustained the loading at the end of first-stage boost. This structural integrity has been substantiated through extensive analyses and test efforts. Two major tests (a short-stack dynamic test and a short-stack static test), many smaller experimental tests, and many analyses were conducted under the direction of the Structures and Mechanics Division at the Manned Spacecraft Center. These involved effort by the Langley Research Center, the North American Rockwell Corporation, the Grumman Aircraft Engineering Corporation, Philco Ford, The Boeing Company, Bell Aerosystems, and TRW, Incorporated. The large tests, and many of the smaller ones, utilized flight-type hardware. Capability for the dynamic and heating environments was fully explored. All of this effort verified structural integrity for subsequent missions and established that the Apollo 6 adapter failure was not caused by a basic design deficiency.

CORRECTIVE ACTION

Future adapters will have a cork covering over the external surface to reduce temperatures and internal pressures. Also, small holes will be drilled in the inner facesheet to vent the panels. Flight pressures will then be only 50 or less percent of the pressures experienced on Apollo 6 (fig. 13). The effectiveness of corking and venting was assessed, based upon the results of a panel vent test performed by the contractor (fig. 14) and upon the lower temperatures attained with 0.030-inch cork covering (fig. 15). The results are given in figure 16. These pressures are applicable for all Apollo missions having a launch thermal response corresponding to the Apollo 9 baseline trajectory.

Additionally, the portable eddy-sonic technique will be used to inspect for bond quality after the adapter arrives at Kennedy Space Center. After all launch preparation work on the lunar module has been completed inside the adapter, the inside surface will be visually inspected for inadvertent damage, zone by zone, with specific approval required for each zoned area.

Special precaution will be taken to assure that the panels are free of moisture.

The above actions were taken prior to the recently flown missions. Since the splice abnormalities have been identified, the affected regions have been repaired by adhesive injection. The Structures and Mechanics Division has determined that the core-splice splice plate (fig. 11) is not required. Consequently, the contractor has been directed to revise the design to not have this internal splice plate and thus avoid abnormal assemblies in the panels yet to be bonded.

TABLE I.- EFFECTS OF DENTS

Dent size, in.		Pressure at failure, psig
Diameter	Depth	
0	0	265
1	0.039	199
1	0.039	195
1	0.039	193
2	0.050	199
2	0.050	179
2	0.059	187
3	0.024	335
3	0.030	268
3	0.038	235
5	0.010	347
5	0.010	234
5	0.026	230

TABLE II.- EFFECTS OF MOISTURE AND TEMPERATURE

(a) Tests Performed By Contractor

Panel number	Temperature, °F	Moisture content (by volume), percent	Pressure, psig	
			No failure	Failure
1, 2, 3	272 to 361	1	253	40 to 50
4	335	0		54
5	Ambient	0		152
6	Ambient	0	253	
	325	0		162
7	Ambient	0	252	
	325	0		118
8	Ambient	0	194	
	295	1		37
9, 10, 11, 12, 13*	Elevated	1		43 to 52

*Two of these had 1-inch-diameter bond voids but failed on the facesheet opposite the one with the void.

(b) Tests Performed By MSC

Panel number	Temperature, °F		Burst pressure, psig
	Outer facesheet	Inner facesheet	
1	239	224	112
2	240	221	112
3	244	236	104
4	247	233	78
5	243	229	125
6	245	232	115

TABLE III.- EFFECTS OF LOAD, ELEVATED TEMPERATURE, AND VOIDS

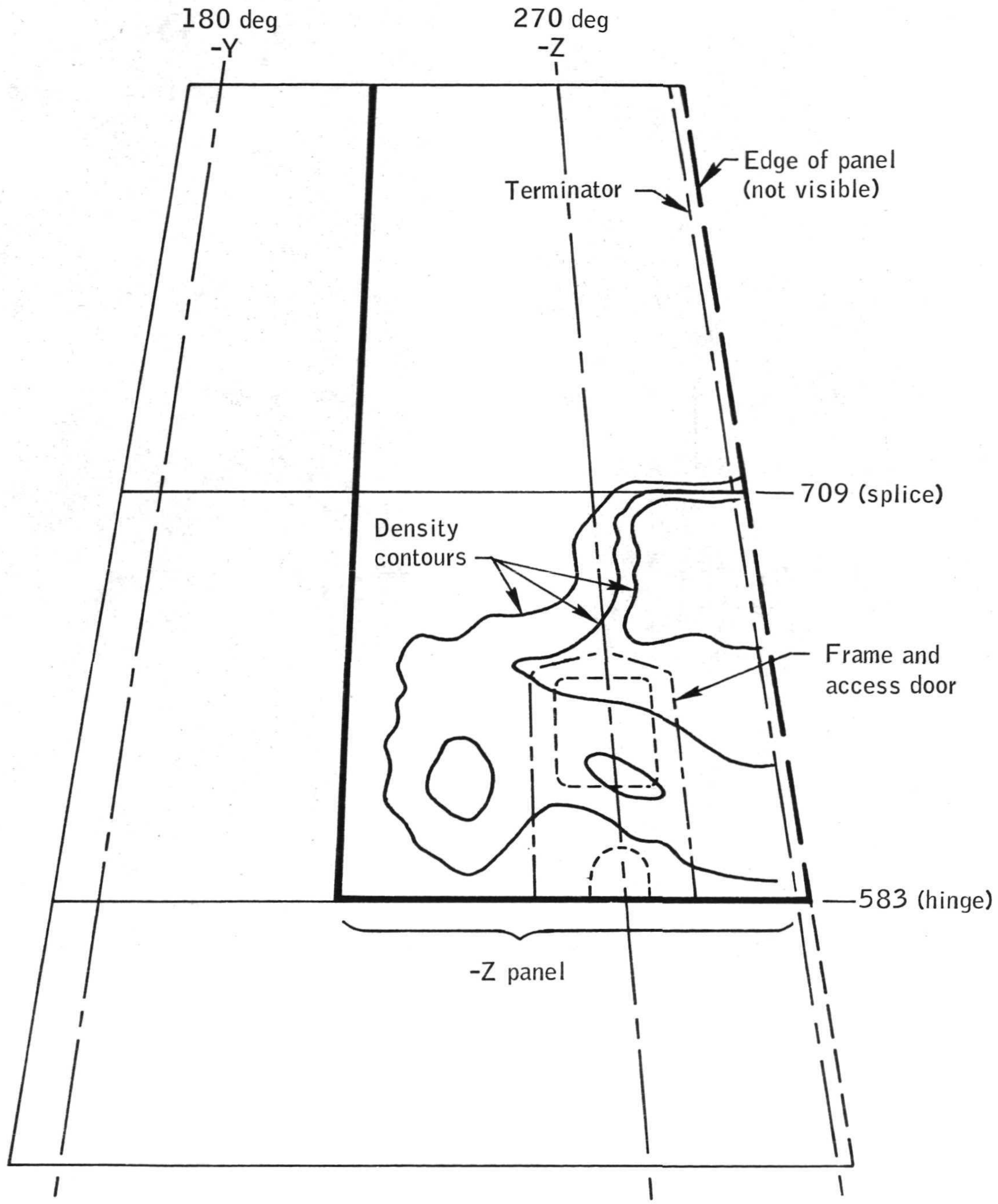
Panel no.	Temperature, °F		Load, lb/in		Pressure, psig	Void diameter, in.
	Inner facesheet	Outer facesheet	No failure	Failure		
1		275	1500		[a]40	0
2		320	1500		[a]30	0
3		295		1775	[a]30	0
4	150	295		1465	0	[b]1
5	150	295	1240		45	[c]1
6	150	295		1900	35	[b]1
7	145	295		1210	40	2
8	140	295		1120	40	2
[d]9		295		1150	2.5	2

[a]Higher pressure could not be attained because panel leaked badly.

[b]Failure not in void area. Doubler added for load input rolled over and cut into facesheet.

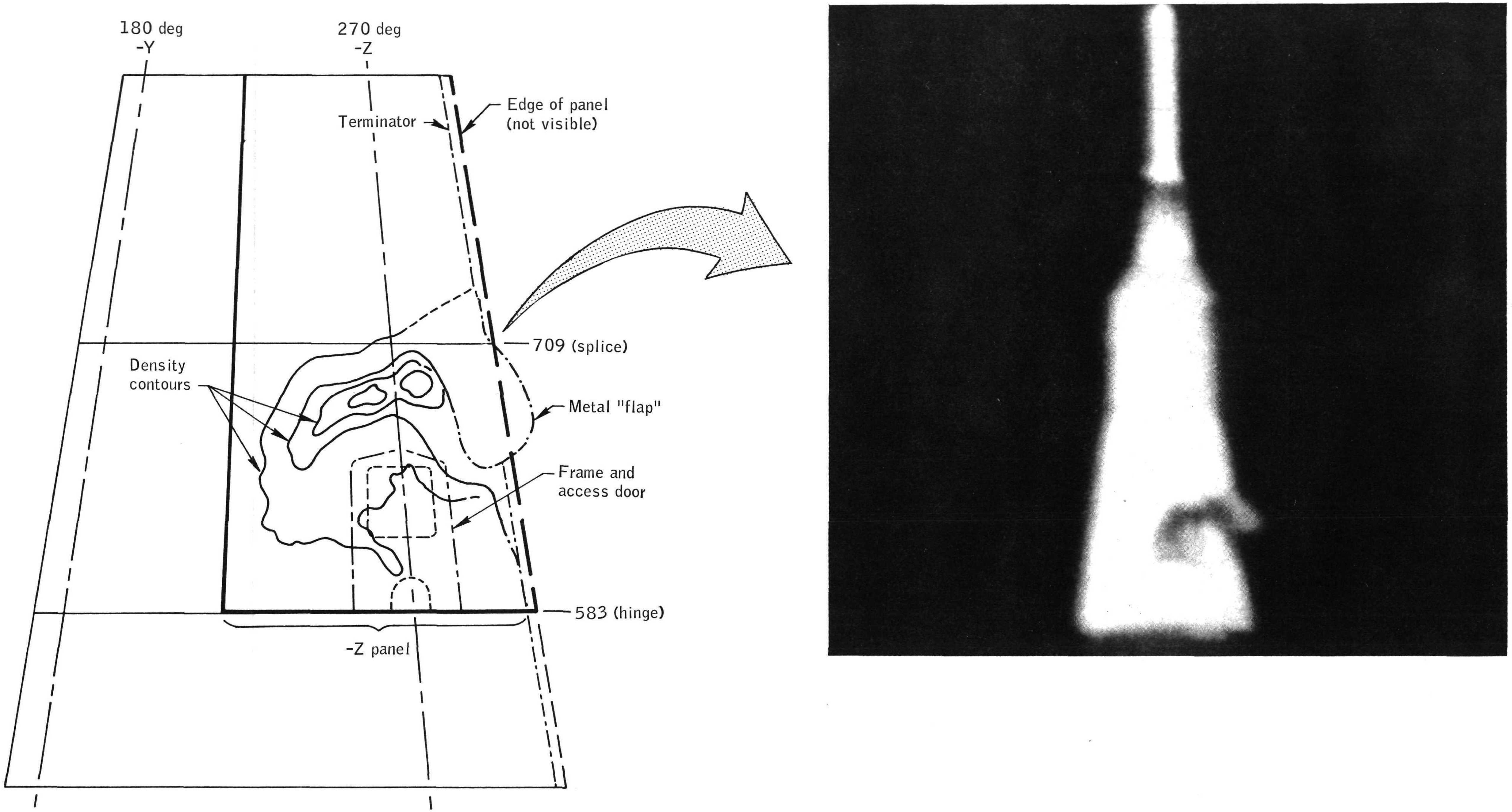
[c]Void did not propagate. Ultimate design load is 1240 lb/in.

[d]One percent moisture (by volume) injected into panel. Failed through void.



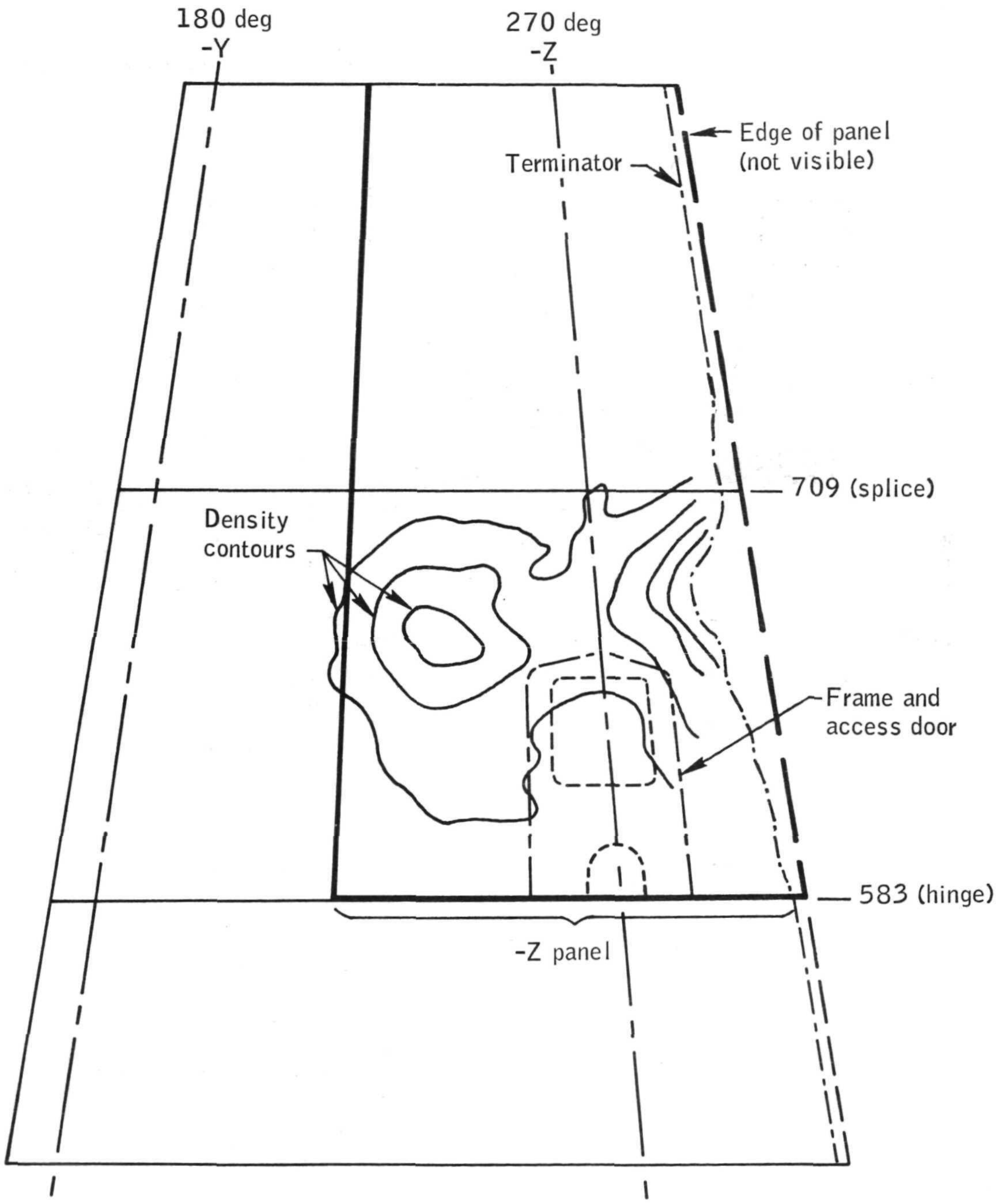
(a) 2:13.287.

Figure 1.- Densitometer traces at time of anomaly.



(b) 2:13.320.

Figure 1.- Continued.



(c) 2:14.054.

Figure 1.- Concluded.

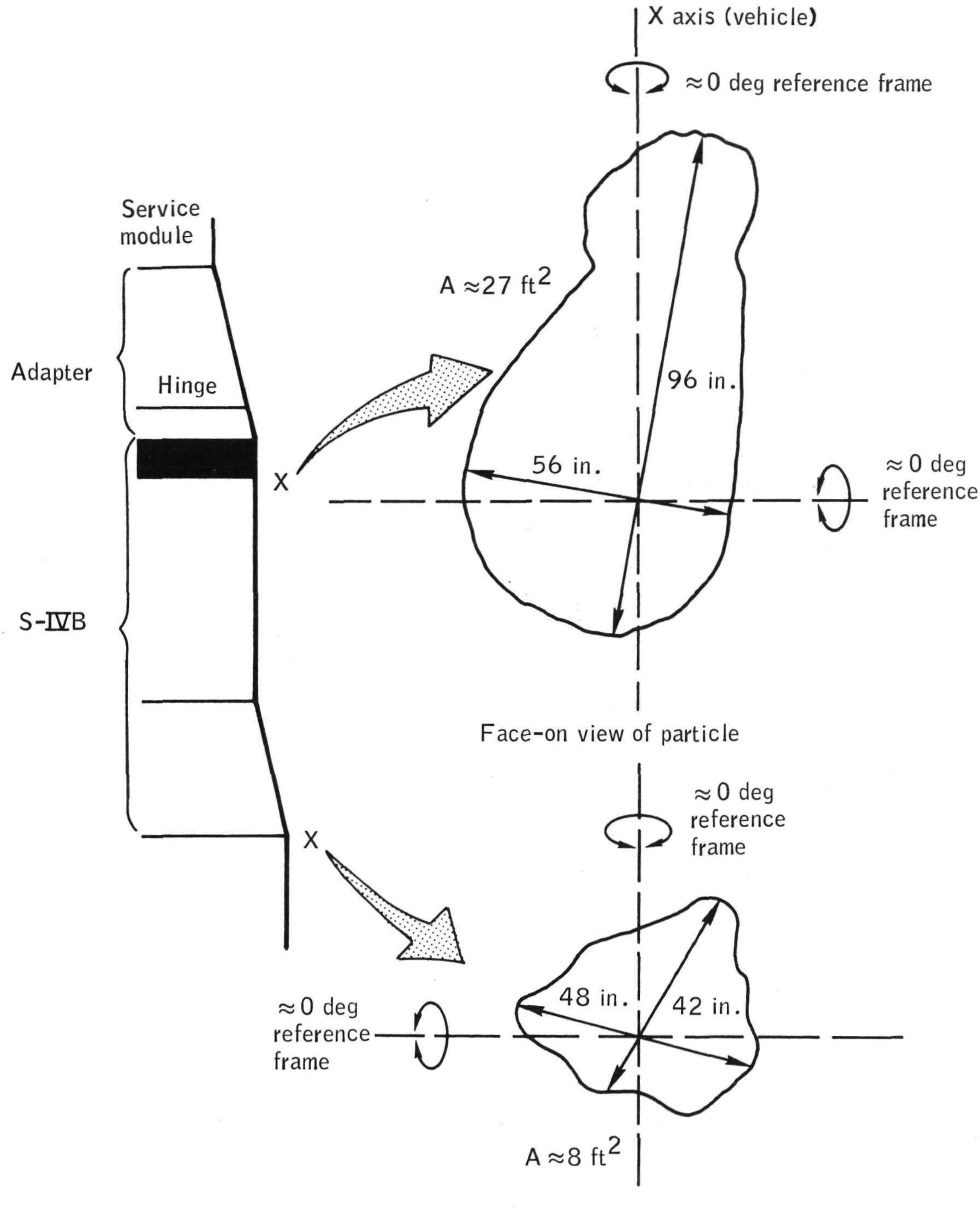


Figure 2.- Pieces observed at 2:13.587.

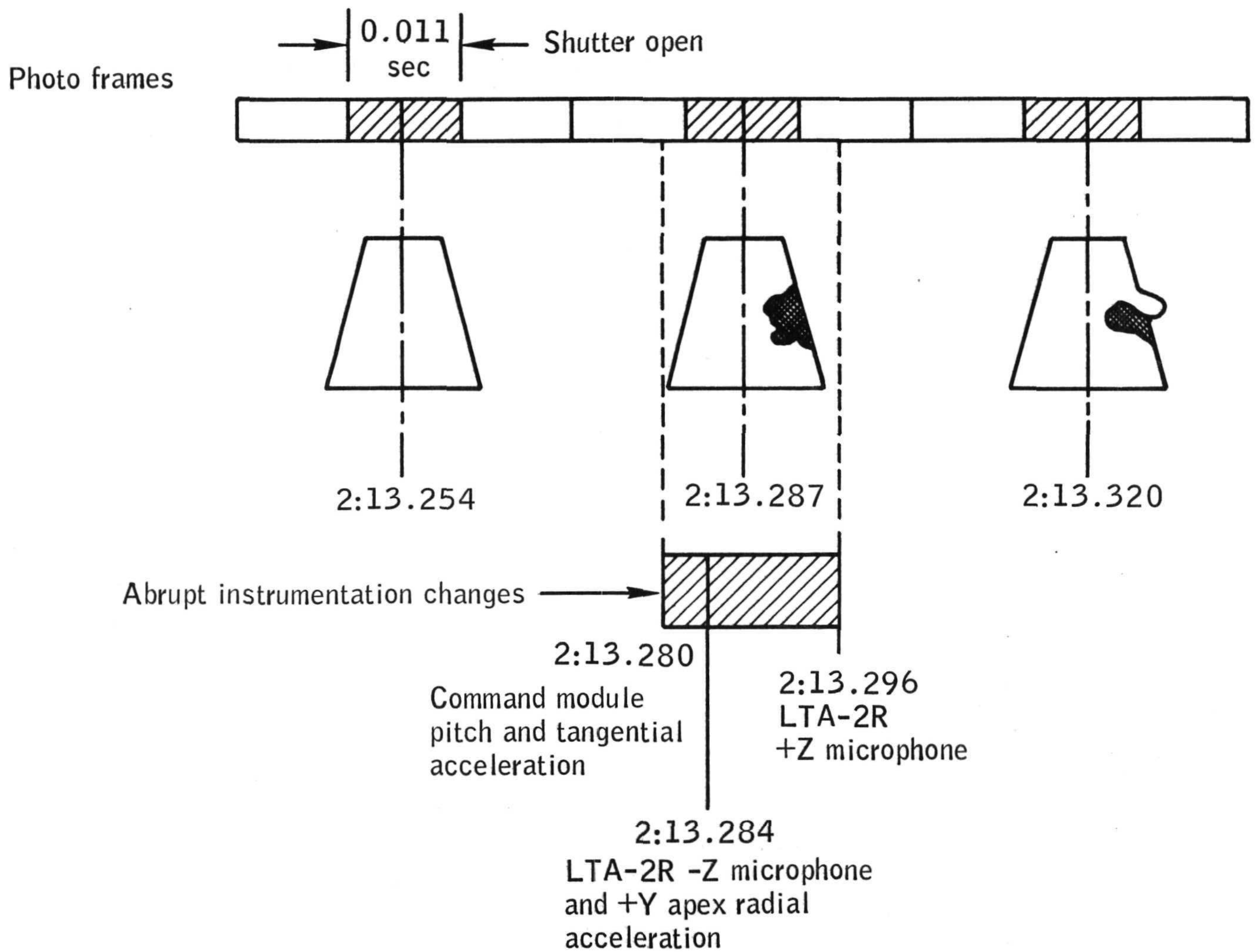


Figure 3.- Timeline.

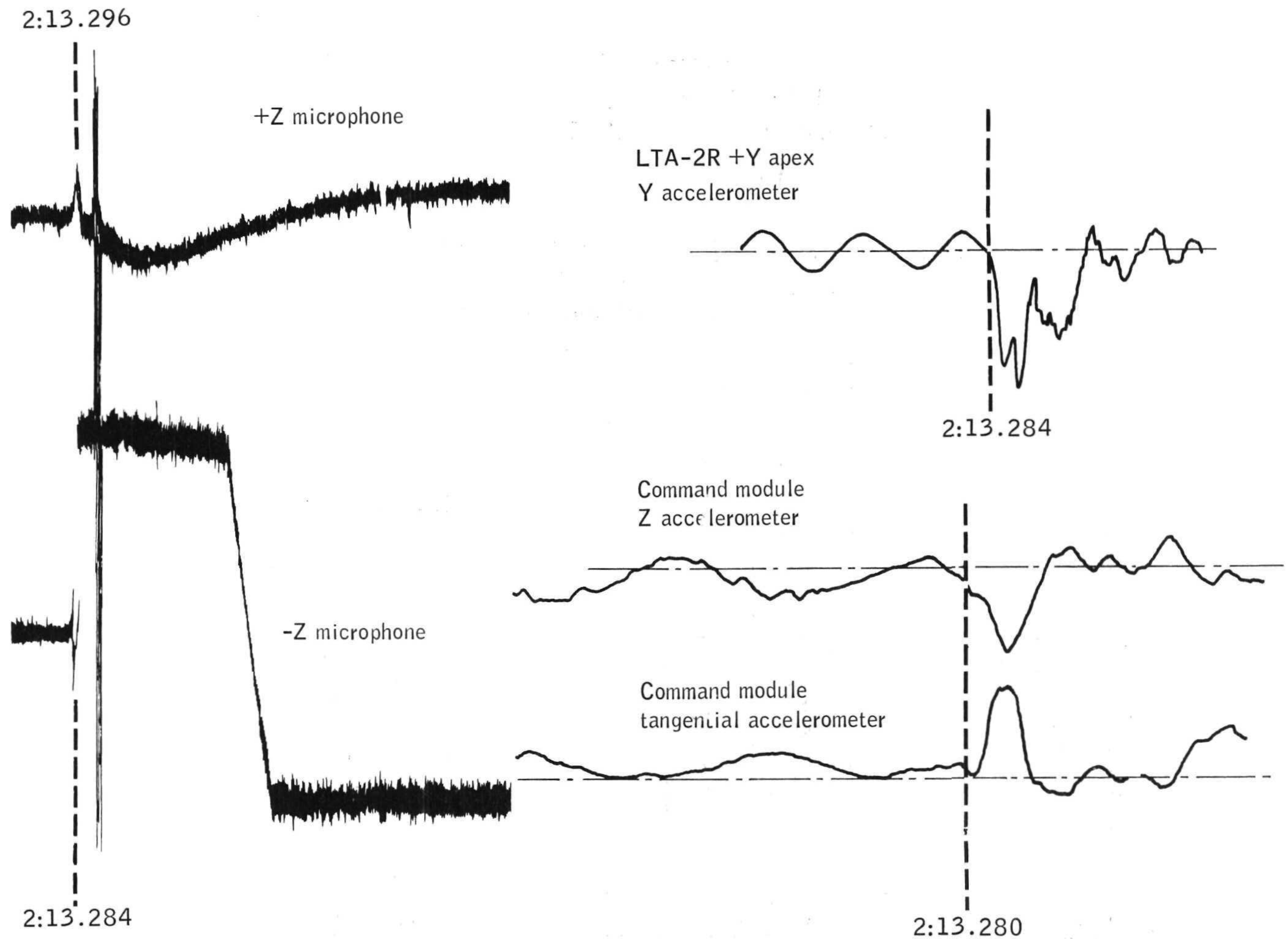


Figure 4.- Instrumentation changes at time of anomaly.

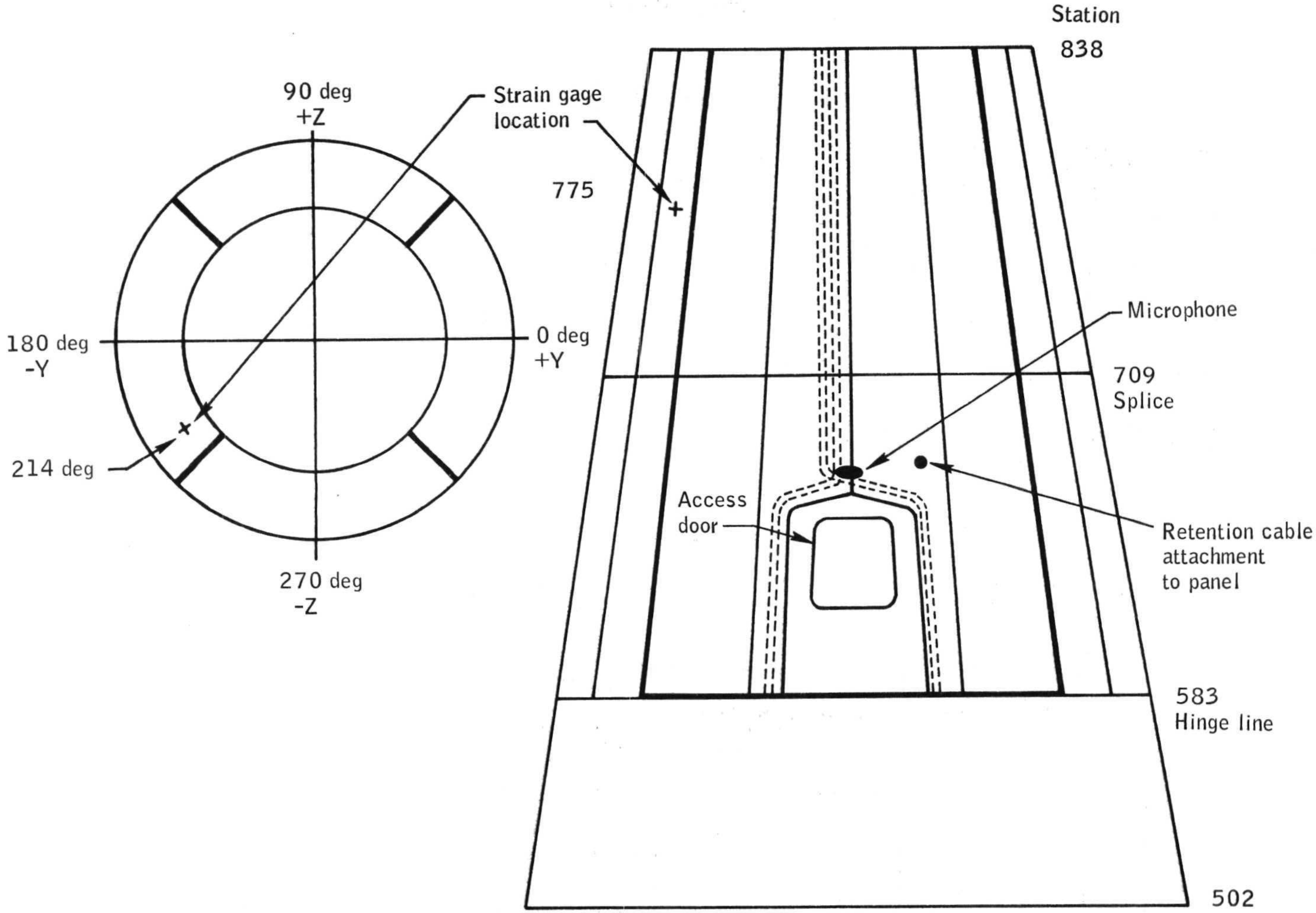
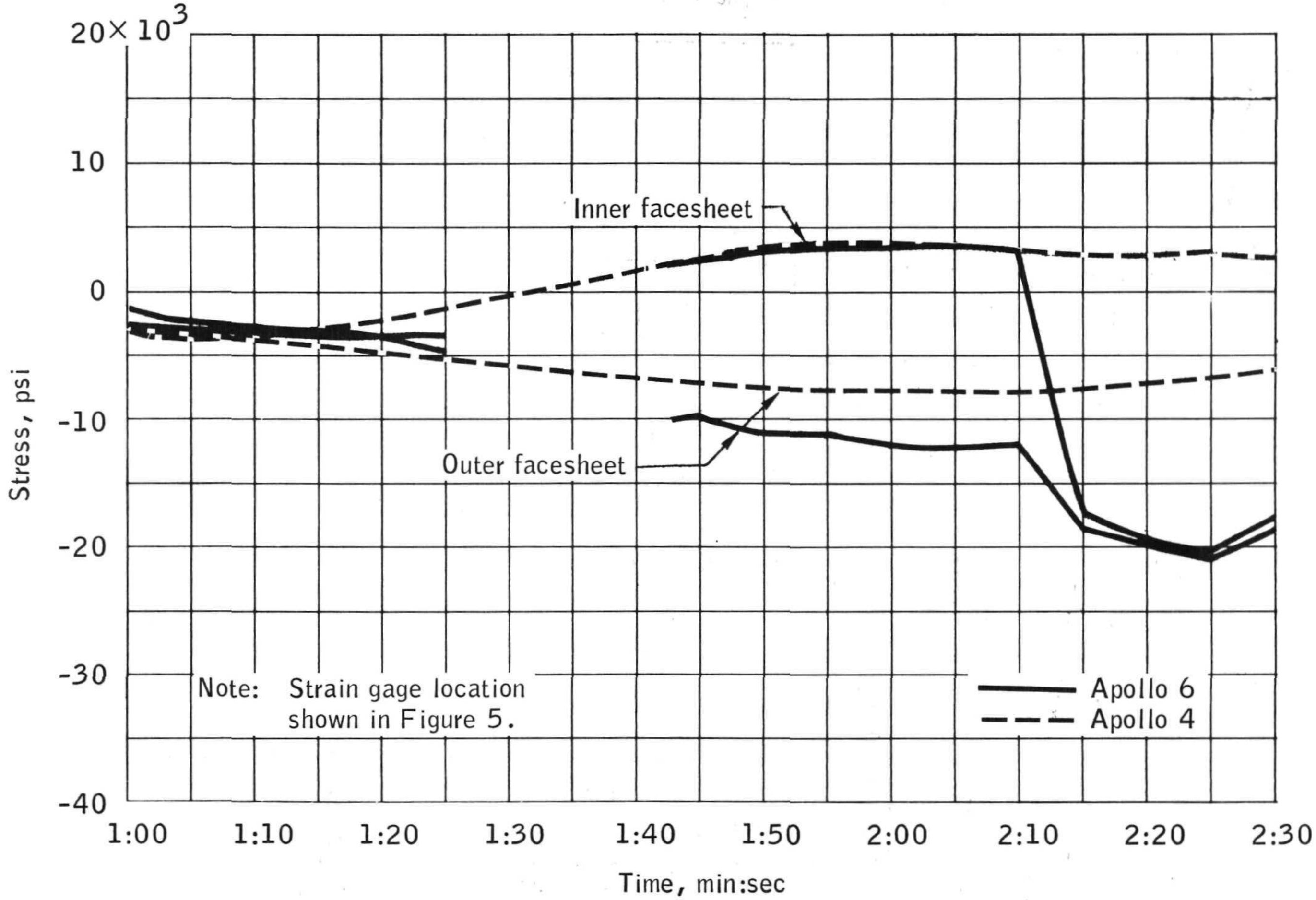
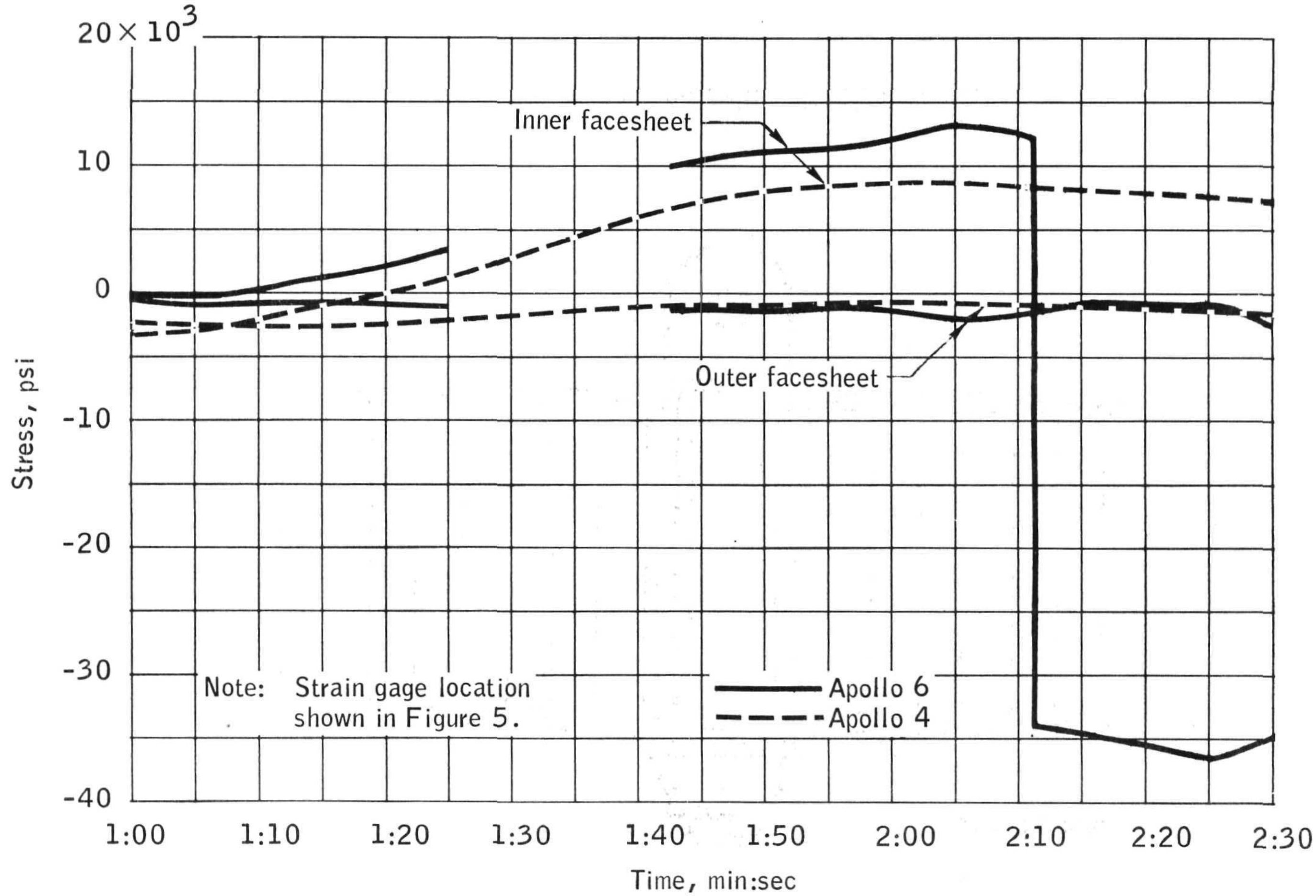


Figure 5.- Adapter general arrangement and strain gage location.



(a) Longitudinal.

Figure 6.- Stresses at time of anomaly.



(b) Circumferential.

Figure 6.- Concluded.

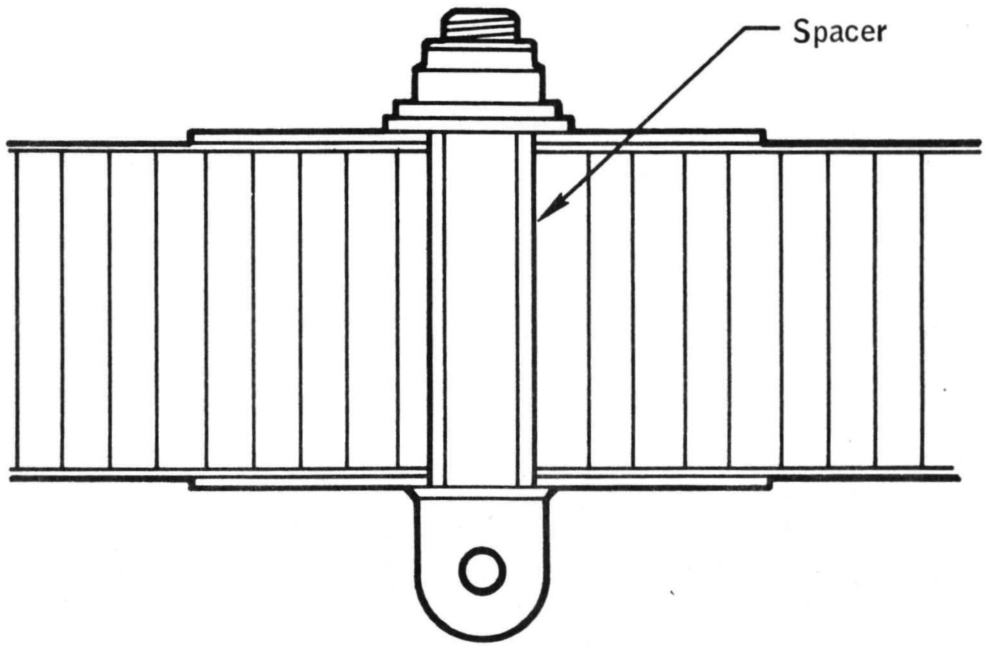


Figure 7.- Retention cable attachment bolt.

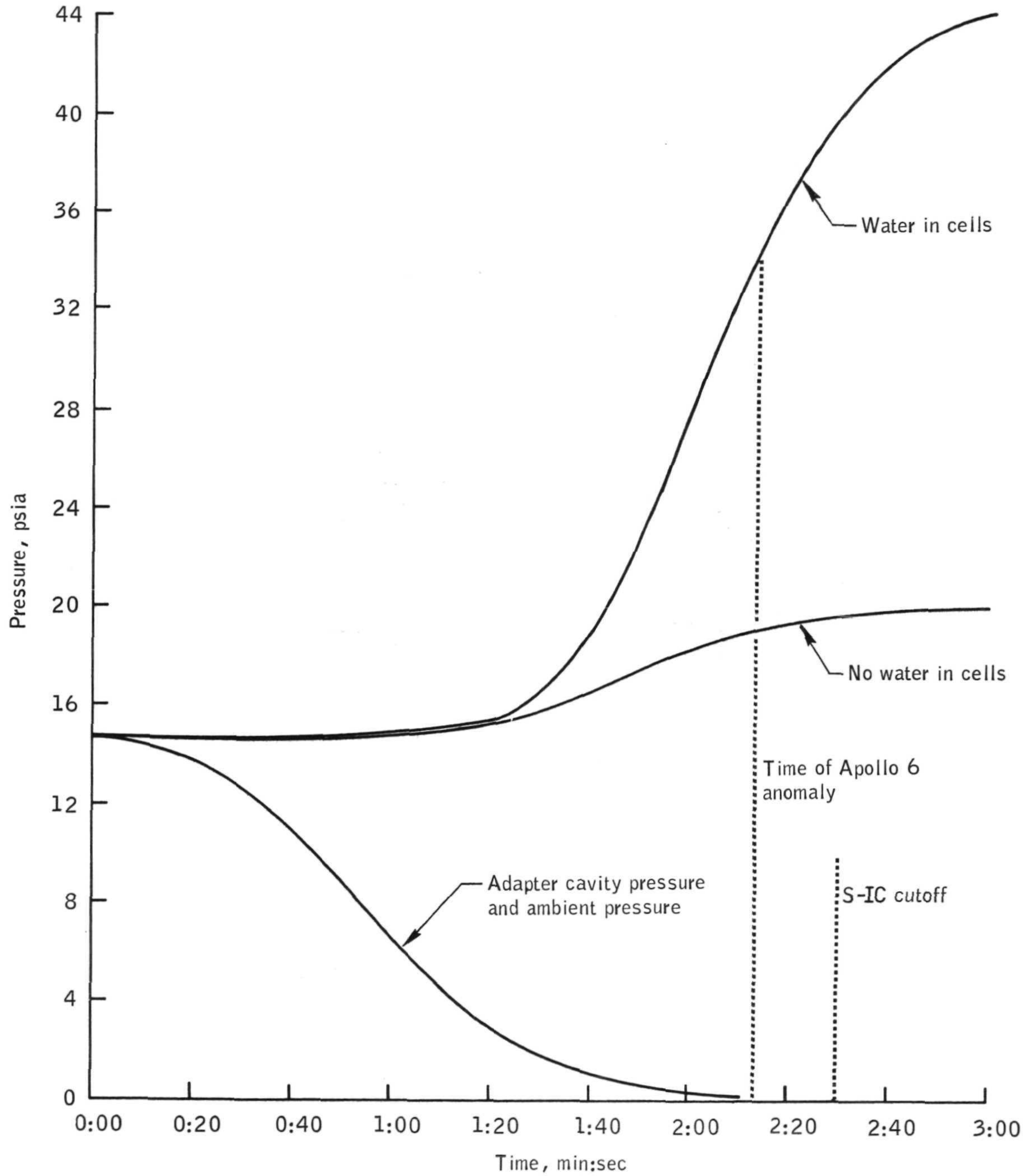


Figure 8.- Innercell pressure on Apollo 6 during launch.

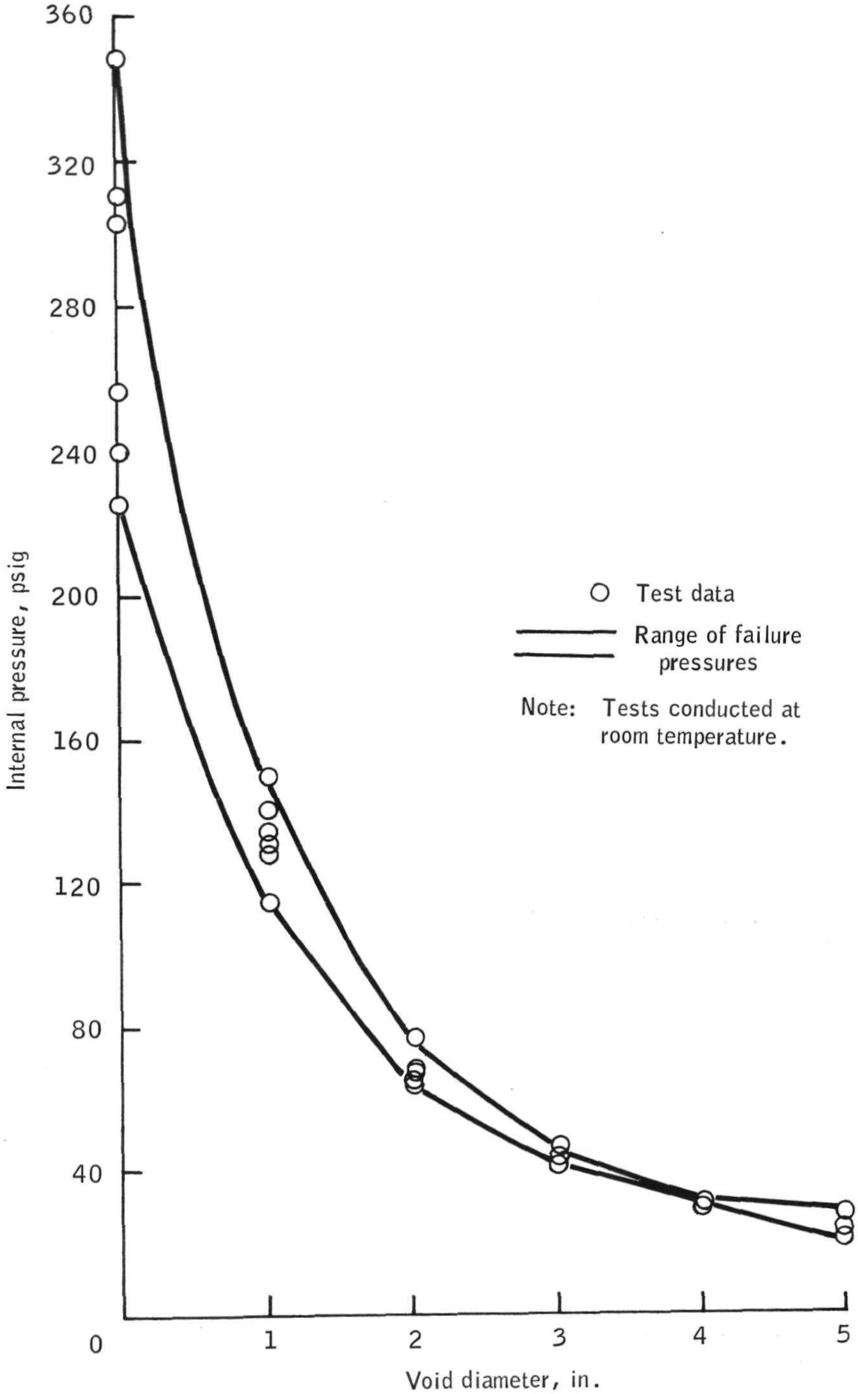


Figure 9.- Effects of sheet-to-core bond voids.

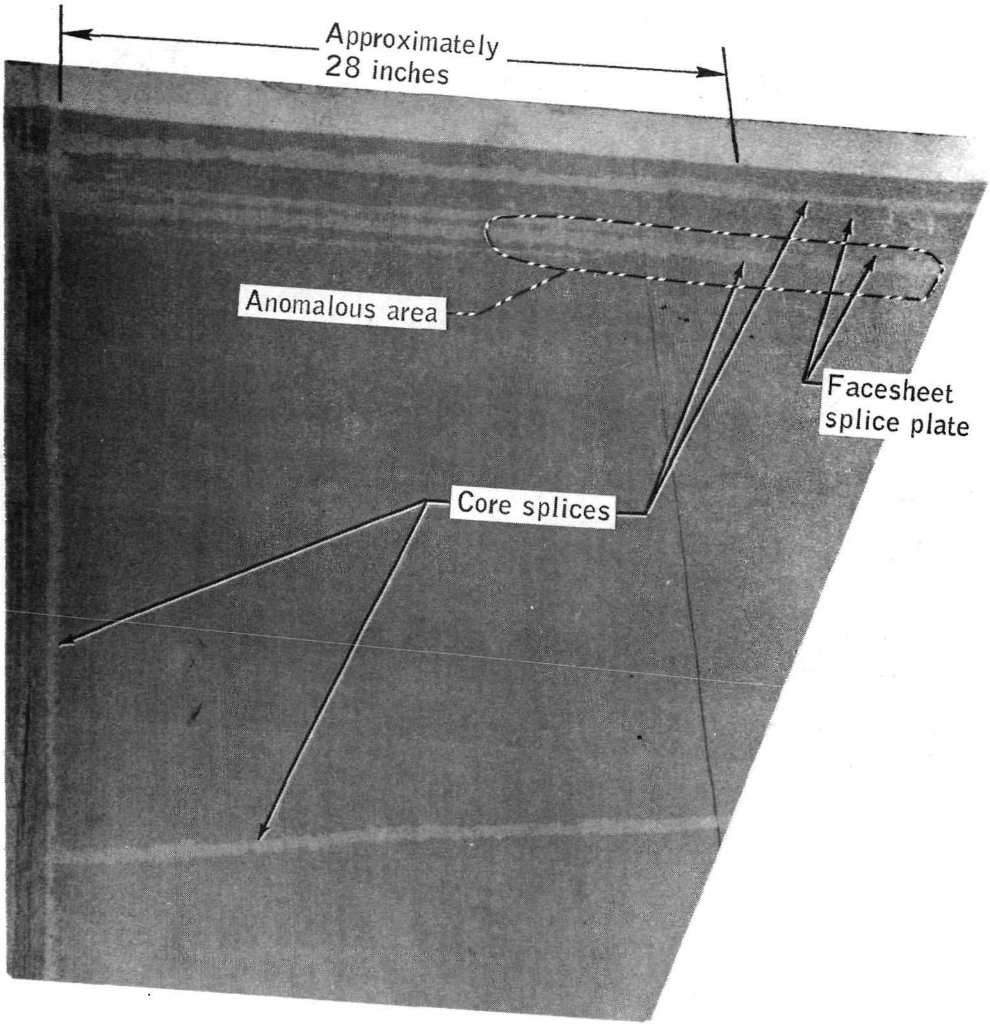
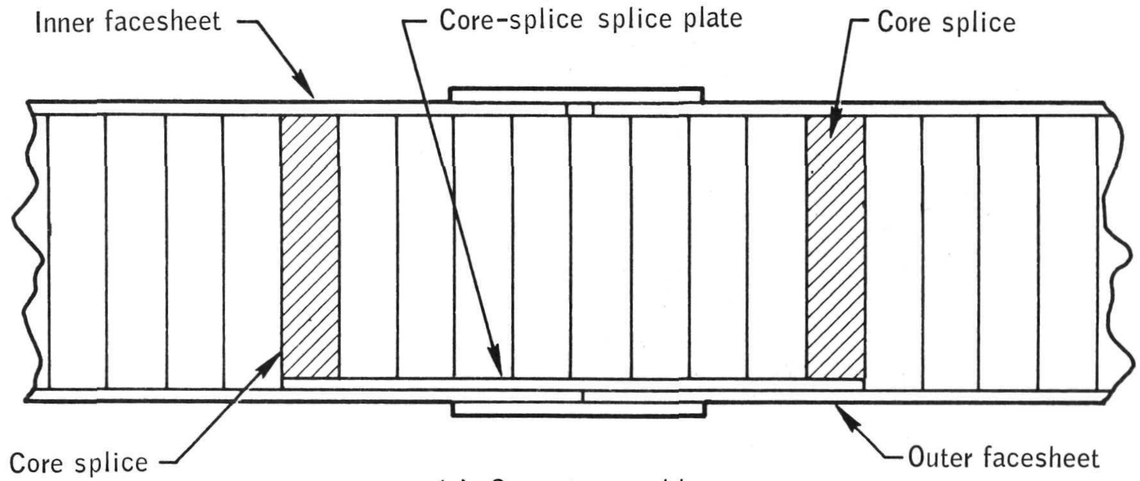
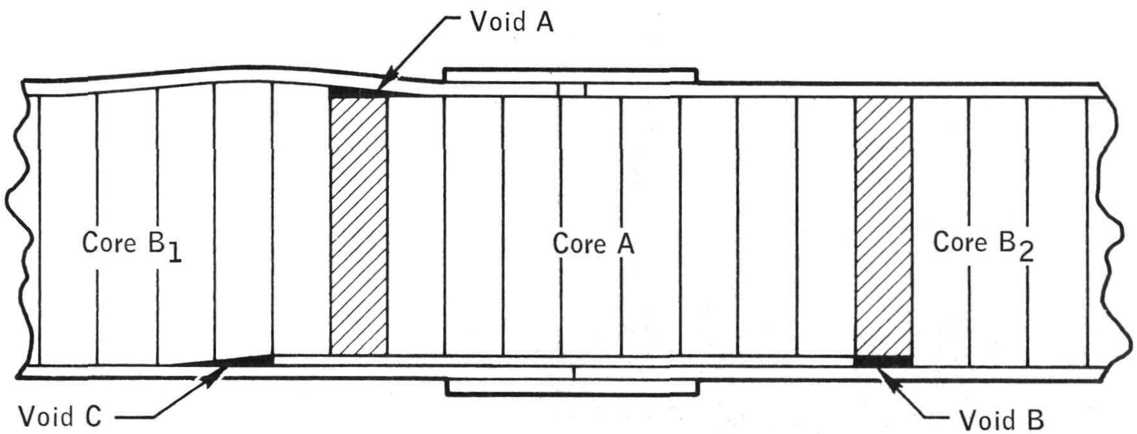


Figure 10.- Anomalous area of C-scan.



(a) Correct assembly.



(b) Incorrect assembly.

Figure 11.- Splice abnormality found in adapters 12, 13, 14, 15, and 16.

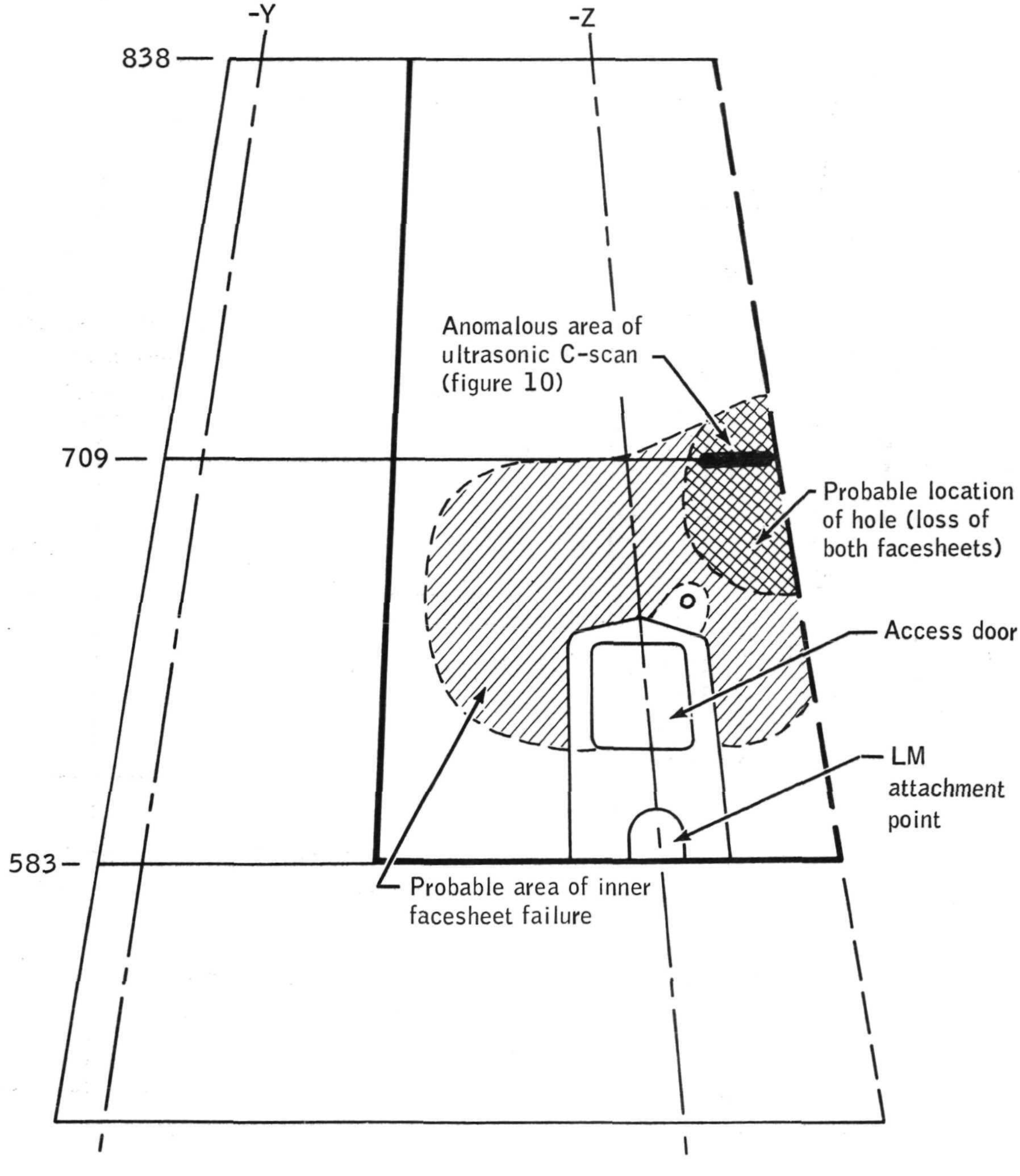


Figure 12.- Probable areas of inner face sheet failure.

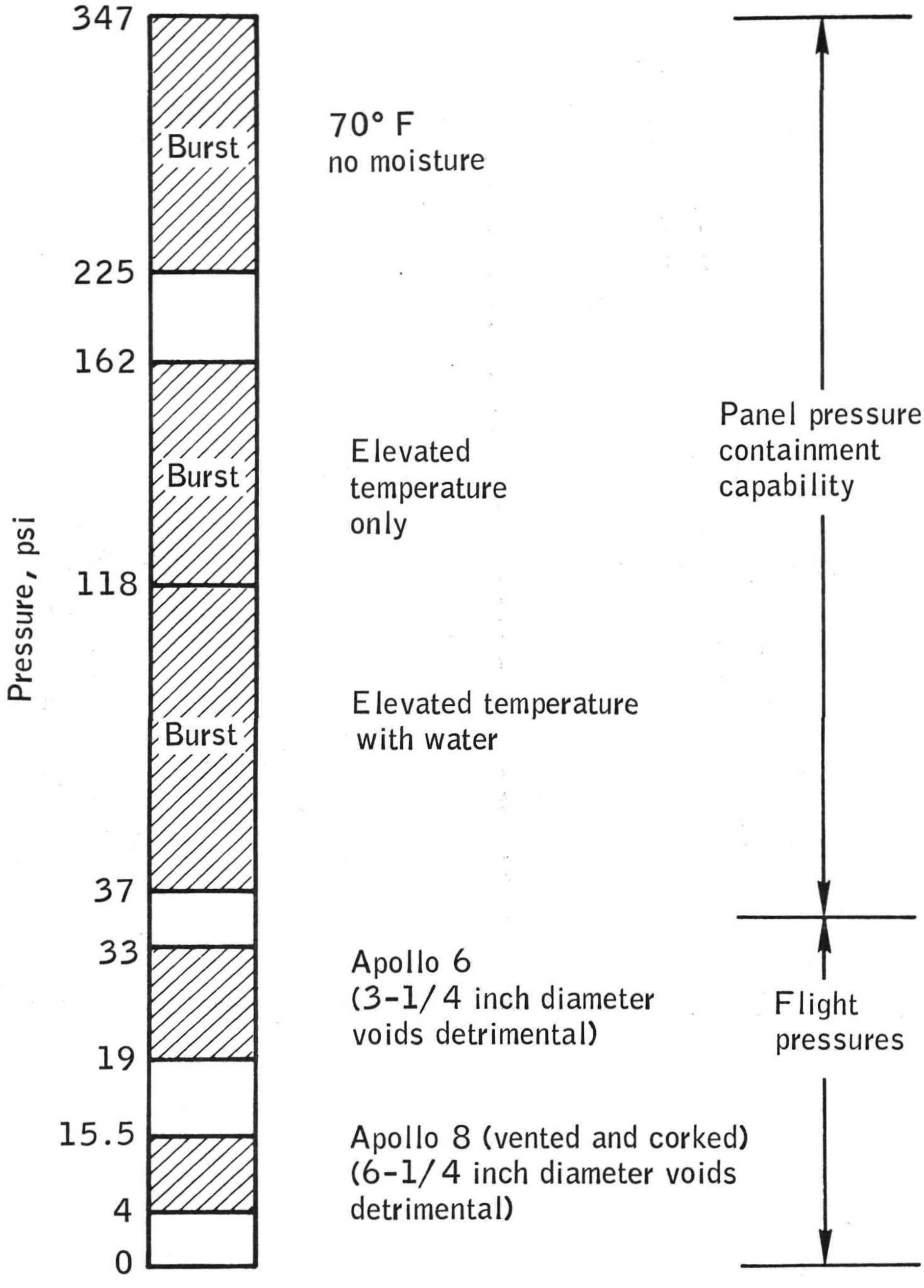


Figure 13.- Honeycomb core differential pressure.

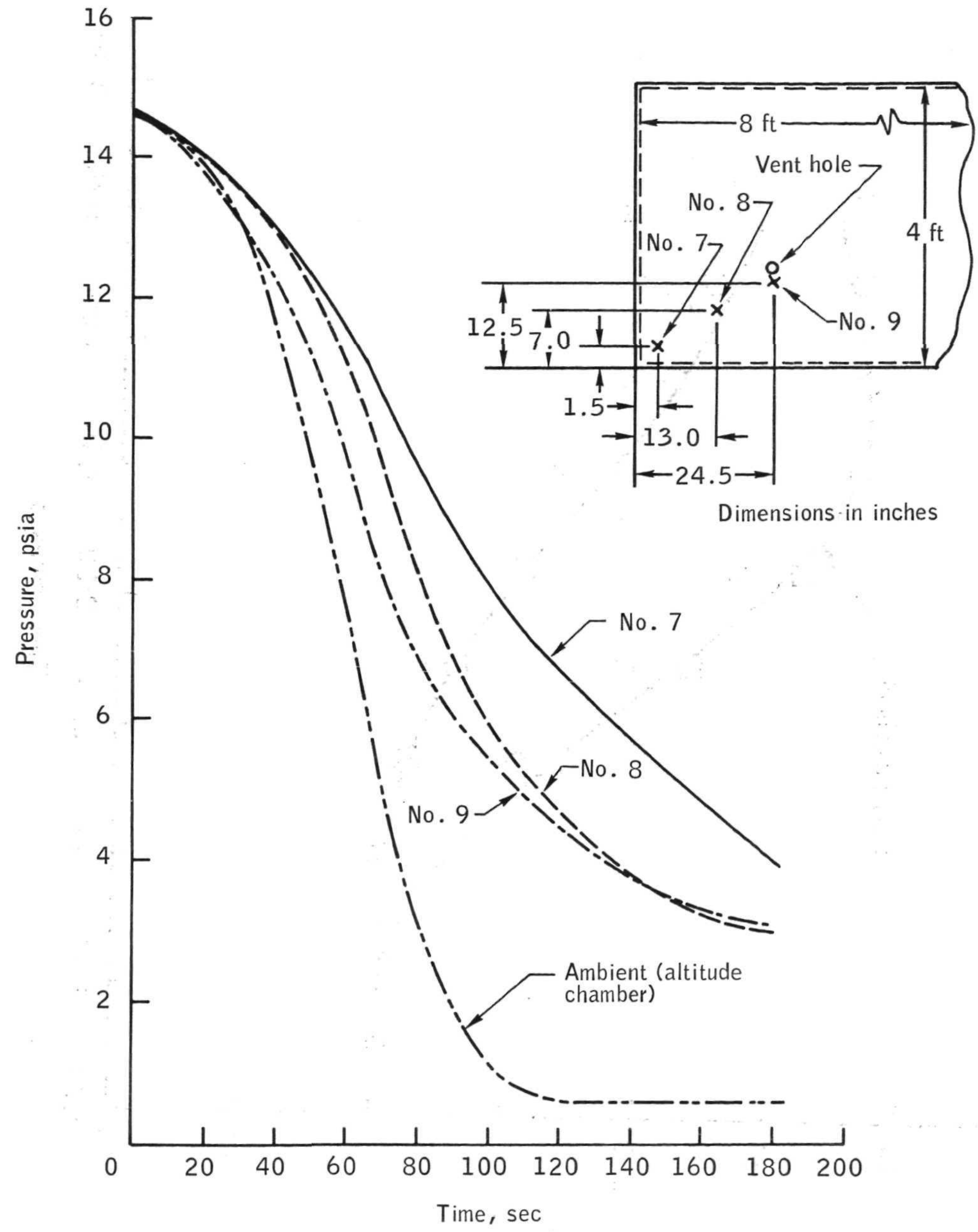


Figure 14.- Test results with vented panel.

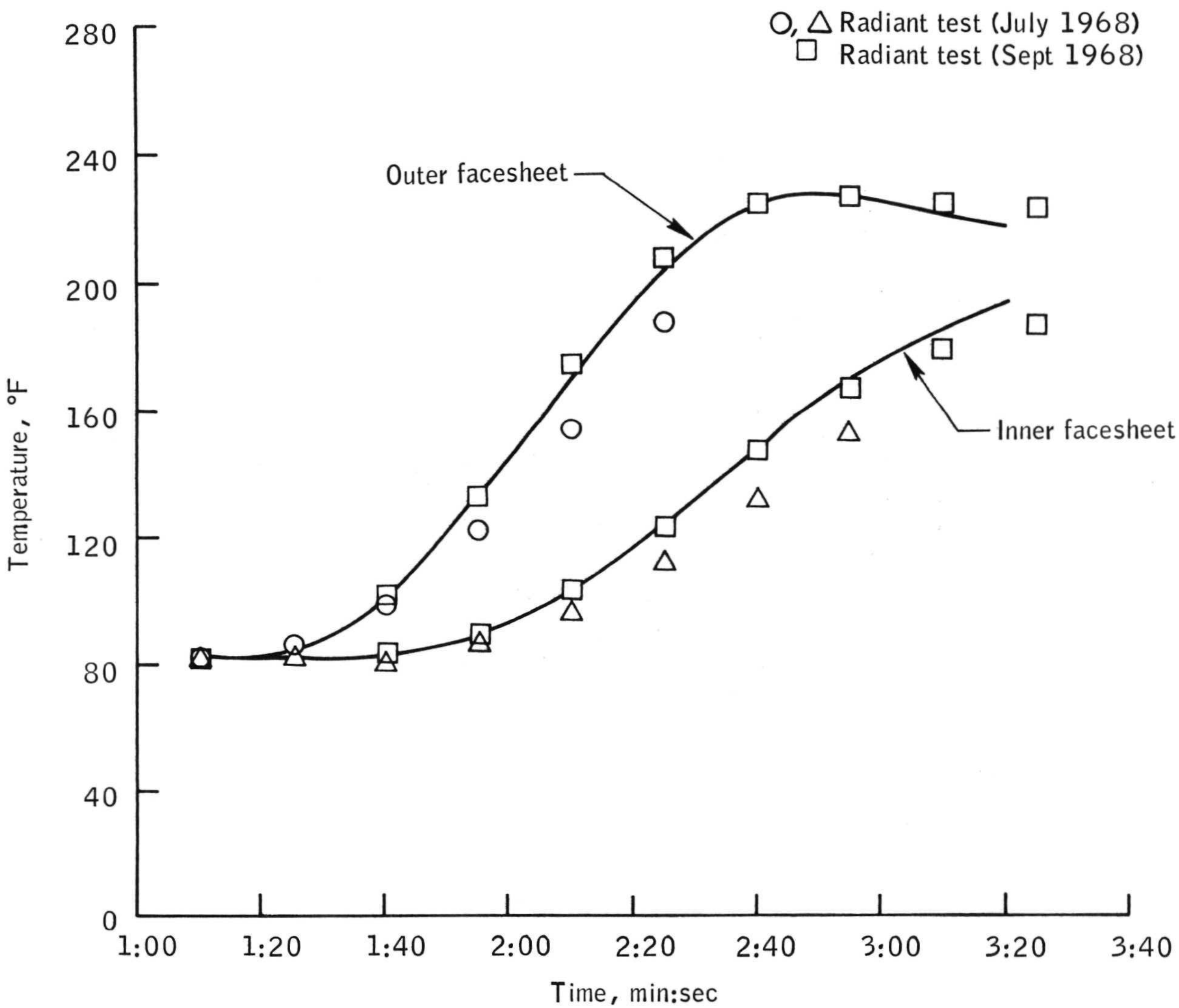


Figure 15.- Thermal response of honeycomb panel covered with 0.030-inch cork.

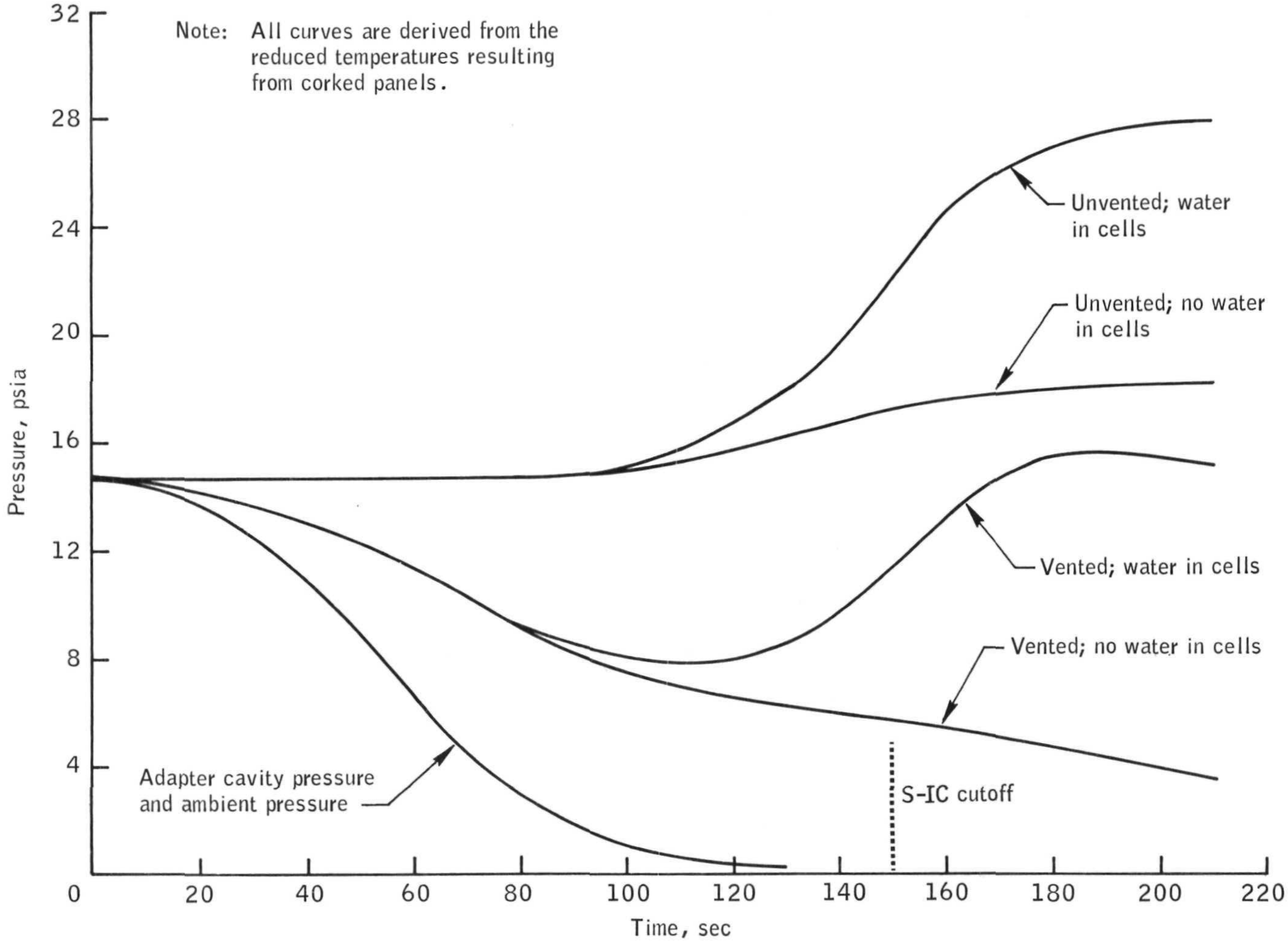


Figure 16.- Honeycomb core pressure reduction for corked and vented panels.