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DC-9 AFT PRESSURE BULKHEAD RESIDUAL STRENGTH TEST

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Presents background, test results and test setup for the DC-9 aft pressure bulkhead residual strength test. The tests were intended to validate the analytic methods of determining widespread fatigue damage (WFD) and multiple site damage (MSD) effects on the residual strength of a complex aft pressure bulkhead structure. Strain data was taken from a variety of locations on the bulkhead pressure web, and from this data, the following information about the aft pressure bulkhead was derived:

- residual strength
- stress distribution around the lead crack
- growth rate of the lead crack
- stress level at link-up of the crack between fastener holes

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1. Introduction

The DC-9 aft pressure bulkhead test is one of several projects in the Federal Aviation Administration's (FAA) WFD evaluation program. The prime contractor to the FAA was the Boeing-Long Beach Company. The Air Force Research Laboratory, Air Vehicles Directorate, Structures Division (AFRL/VAS) was tasked by Boeing to:

a) install all instrumentation per their specifications
b) fabricate a support structure and attach fuselage section
c) design and install pneumatic inlet/exhaust system with associated control systems
d) perform testing and inspections
e) provide test data.

This test report presents the background, test setup and test results for the DC-9 aft pressure bulkhead residual strength test. The purpose of the test was to validate the analytical methods of determining widespread fatigue damage (WFD) and multiple site damage (MSD) effects on the residual strength of a complex aft pressure bulkhead structure. Strain data was taken from a variety of locations on the bulkhead pressure web, and from this data, the following information about the aft pressure bulkhead was derived:

a) residual strength
b) stress distribution around the lead crack
c) growth rate of the lead crack
d) stress level at link-up of crack between fastener holes.

2. Experimental Investigation

The test article was approximately the aft 10 feet of a DC-9 fuselage incorporating the aft pressure bulkhead (Figure 1). This particular aircraft had 57,757 landings and 60,583 flight hours. When mounted on a fixture plate, the enclosed volume was approximately 700 ft^3. The test article preparation by Boeing included a) cutting the fuselage section to a manageable size, b) installing a structure forward of the bulkhead to facilitate mounting the test article and c) creating the MSD and lead crack in the pressure web (Figures 2 and 3). The AFRL/VASV at Building 65, WPAFB received the prepared test article and mounted it to a fixture plate fabricated locally. Government technicians installed all instrumentation and completed the mechanical, electrical and pneumatic systems installations as required (Figures 4 and 5).

In this program, the aforementioned DC-9 fuselage section was fastened to the mounting fixture. This fixture consisted of a 2-inch by 12- by 13-foot American Society for Testing and Materials (ASTM) A-36 steel plate with a 1-inch thick by 11-foot-diameter ASTM A-36 steel ring welded to the side opposite the test article. This ring had four brackets welded onto its periphery to mount the entire assembly to Building 65's existing test support structure using eight 3/4-inch-diameter bolts (AN12-27). Two 12-inch diameter mechanical safety valves, the 6-inch-diameter inlet port, the 8-inch-diameter outlet port, various data and power feed-throughs, and a hinged access hatch were also incorporated into the plate. The test article was mounted via 360 3/8-inch diameter Society of Automotive Engineers (SAE) grade 5 bolts. These fasteners clamped the fuselage transition structure installed by Boeing to the 2-inch-thick steel mounting plate. To minimize air pressure loss, the fasteners passing through to the inside of the test article were installed wet with Dow Corning 733 RTV Sealant. The pilot holes for these fasteners were drilled in the test article transition structure by Boeing-Long Beach. These hole locations were then transferred to the mounting plate and drilled and tapped as necessary.

An epoxy liquid shim (Magnolia Plastics Compound 1039 with 323-C Curing Compound) was used between the test article and the 2-inch-thick plate to ensure that no undesirable loads were introduced into the test article when bolted together. This was necessary because significant warping occurred in the 2-inch-thick plate when the ring was welded to the side opposite the test article. A silicone-based release agent (Mann Formulated Products Ease Release 200) was applied to the fuselage mounting flange to facilitate removal. Prior to final assembly of the steel plate and the test article, Dow Corning 733 RTV sealant was applied to the mating surfaces to ensure an airtight joint. For personnel protection from flying debris when the test article failed, the three open sides around the test article were enclosed with 3/4-inch-thick plywood mounted to steel supports. The area above the test article was left open to allow for pressure relief when test article failure occurred.

The AFRL/VASV technicians performed all instrumentation installation as required by the Boeing test plan. Two remote-control VHS cameras were placed inside the test article, and images were fed to two separate monitors and VCRs at the test control center. These cameras were focused on each end of the lead crack per the Boeing test plan. The remote-control features permitted tilt, pan and focus controls while conducting the test so that the crack tips were continuously being videotaped and monitored by test personnel.

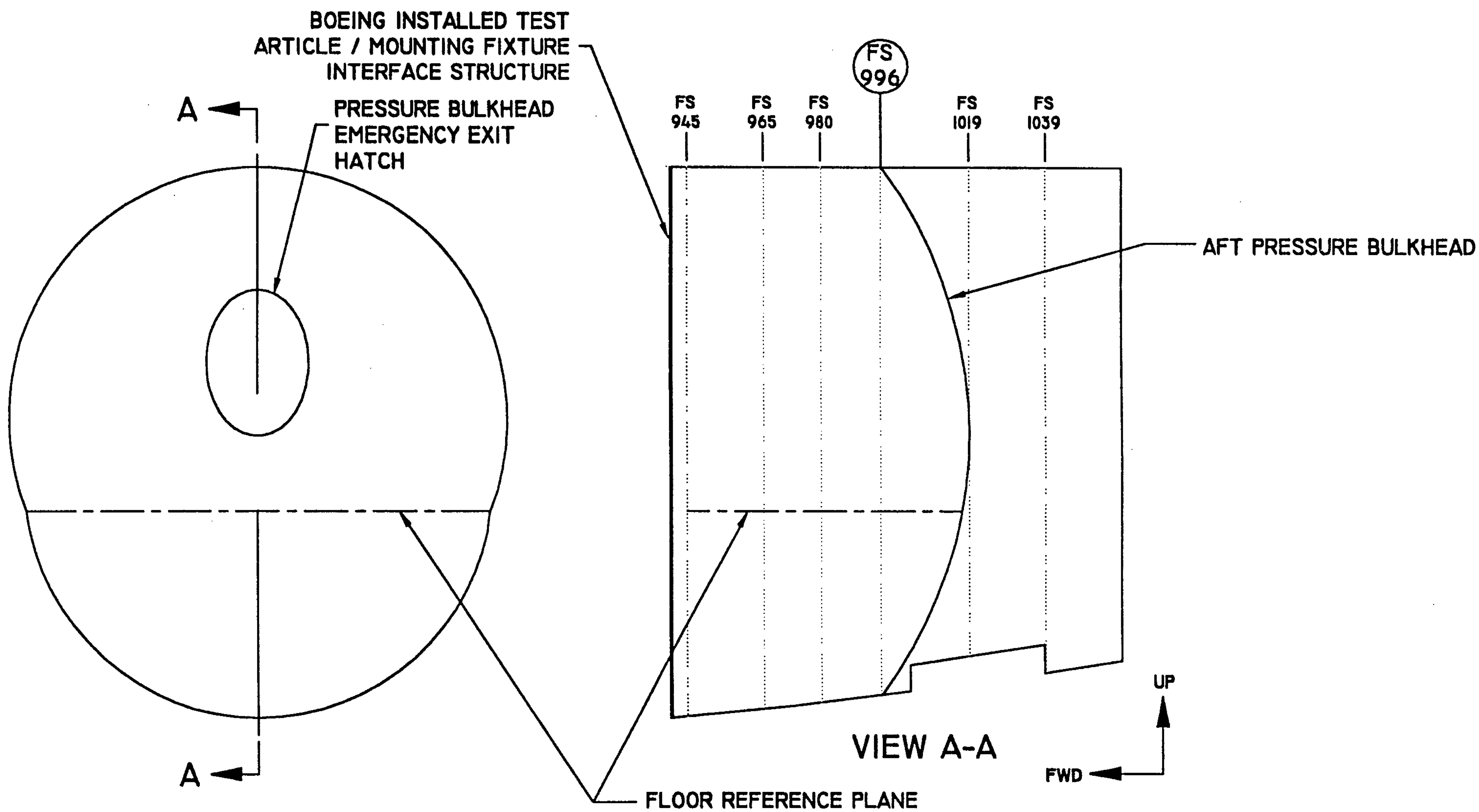

Figure 1. Aft Pressure Bulkhead Test Specimen

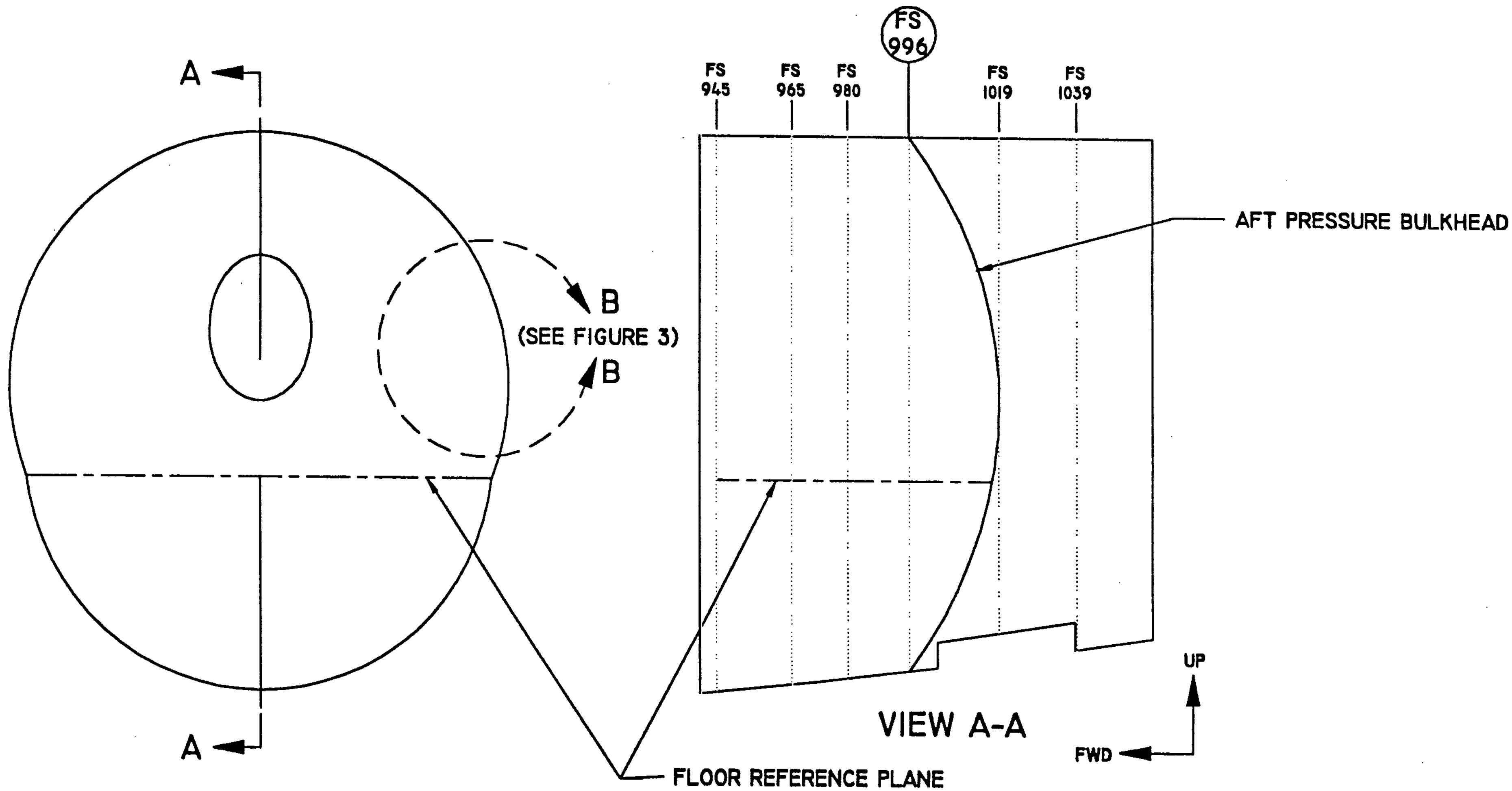

Figure 2. Aft Pressure Bulkhead Initial Damage Locations

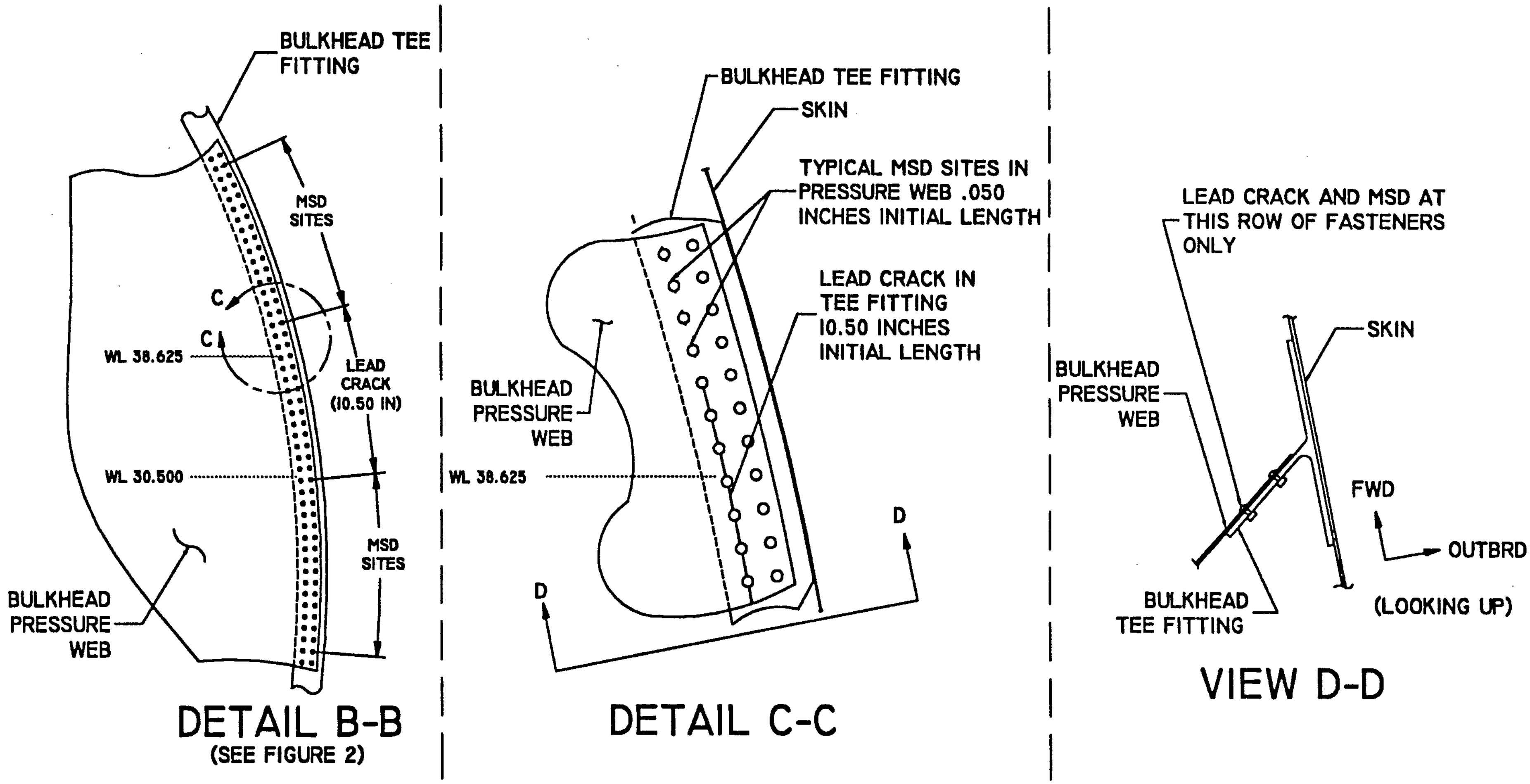

Figure 3. Aft Pressure Bulkhead Initial Damage Detail

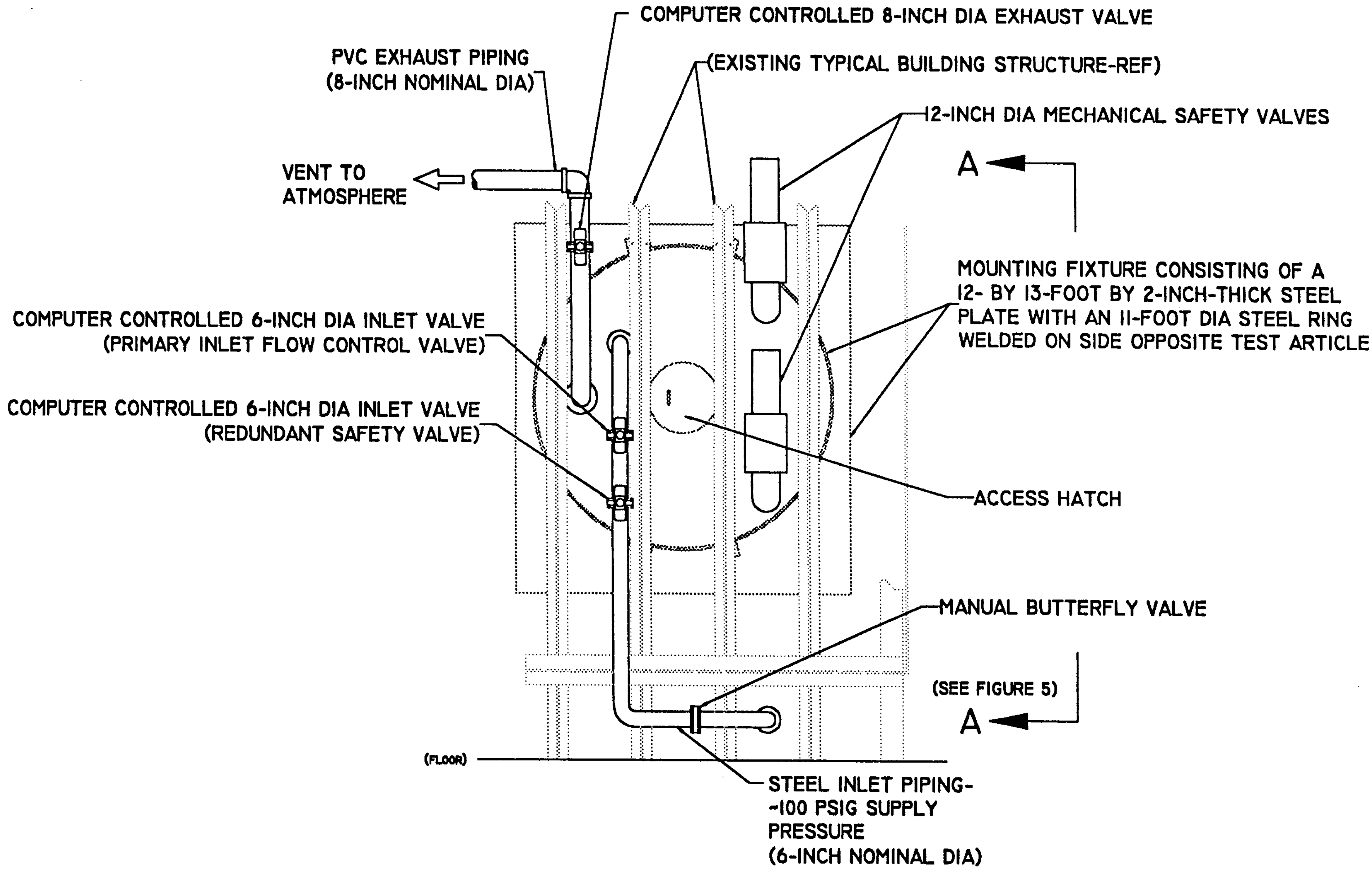

Figure 4. Test Setup, Front View

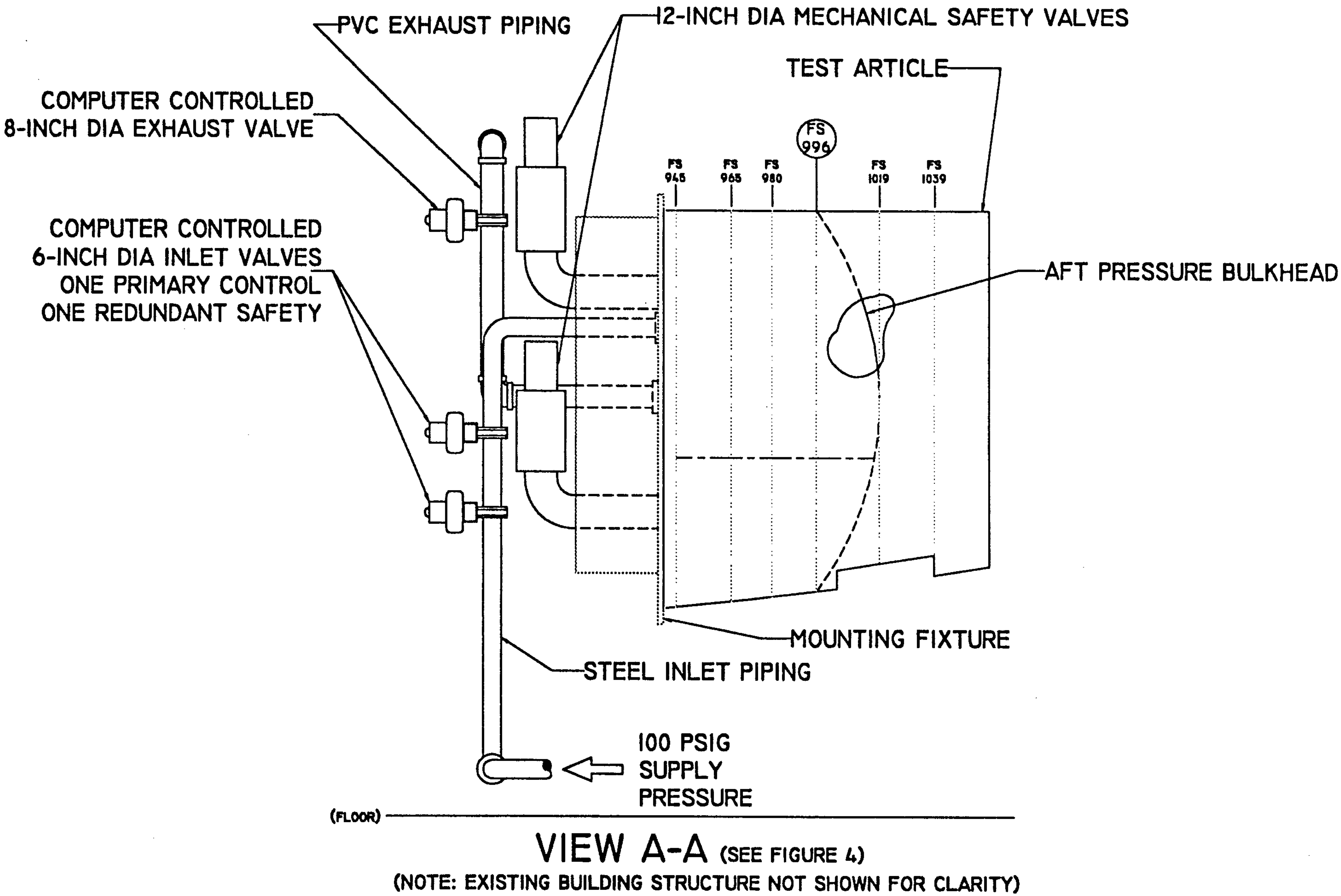

Figure 5. Test Setup, Side View

2.1 Control System

Refer to figure 6. Two Modicon Micro Model 612 programmable logic controllers (one primary, one redundant) were utilized for this test. The primary controller used the feedback from one of the pressure transducers in generating the drive signal to the 6-inch-diameter primary inlet valve. During normal operation, this controller would close the 8-inch-diameter exhaust valve, fully open the redundant 6-inch-diameter inlet valve, and modulate the primary inlet valve to achieve a haversine pressure versus time profile within the test article. Once the specified upper pressure limit was attained, the controller would close both primary and redundant inlet valves and open the exhaust valve until the lower pressure limit was achieved. The cycle would then repeat as necessary.

The second redundant controller was linked in series to the primary controller and sampled the feedback from a different pressure transducer. The primary program signal and step number were sent to the redundant controller over the serial I/O link. The redundant controller used the step number to calculate the expected program signal. The expected and primary program signals were compared (program signal verification). If the two did not match, the test was dumped by the redundant. Bits were toggled between the primary and redundant over the serial I/O link. If the bits stopped toggling for 50 ms, the test would be dumped by either controller.

2.2 Pneumatic System

Refer to figure 7. The shop air system at Building 65 consisted of two Ingersoll-Rand SSR-EP200 (200 HP) air compressors with a nominal output of 892 cubic feet per minute (CFM) @ 125 psi each. These fed a 100 f^3 accumulator via a filter/drier unit. Air inlet to the test article was accomplished by a 6-inch-diameter, schedule 40 steel airline from the accumulator to the 2-inch-thick mounting plate. In this airline, two electronically controlled, pneumatically operated, 6-inch-diameter butterfly valves were placed in series. One of these was the primary inlet flow control valve while the second one was used as a redundant safety valve. These inlet valves were sized based on the preliminary understanding that the test article would have an enclosed volume of approximately 2000 f^3. They were ordered and received prior to the delivery of the test article, which actually had a volume nearer to 700 f^3.

These Flowserve Corp. Automax valves are normally closed. In the event of an electrical power loss or pneumatic control failure, these valves would automatically return to a closed position, thus shutting off the inlet air supply. The electronically controlled, pneumatically operated, 8-inch-diameter butterfly outlet valve was plumbed to exhaust the test article air up and away from the test control center. This Flowserve Corp. Automax valve is normally open. In the event of an electrical power loss or pneumatic control failure, this valve would automatically return to an open position, thus releasing all pressure from the test article. Eight-inch-diameter, schedule 40 polyvinyl chloride (PVC) pipe was used for the exhaust line. Two short, 12-inch-diameter steel lines were used with calibrated weights as mechanical safety valves. These weights were adjustable to permit variable pressures within the test article.

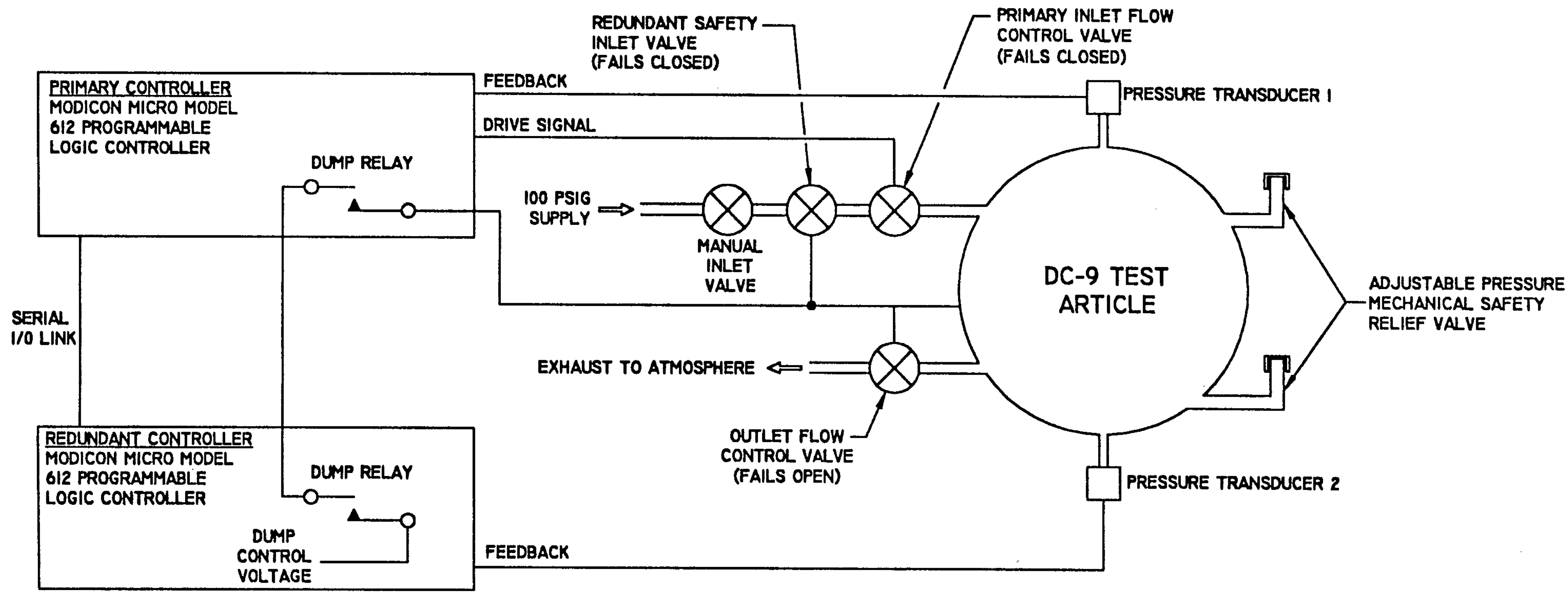

Figure 6. Test Control System Schematic

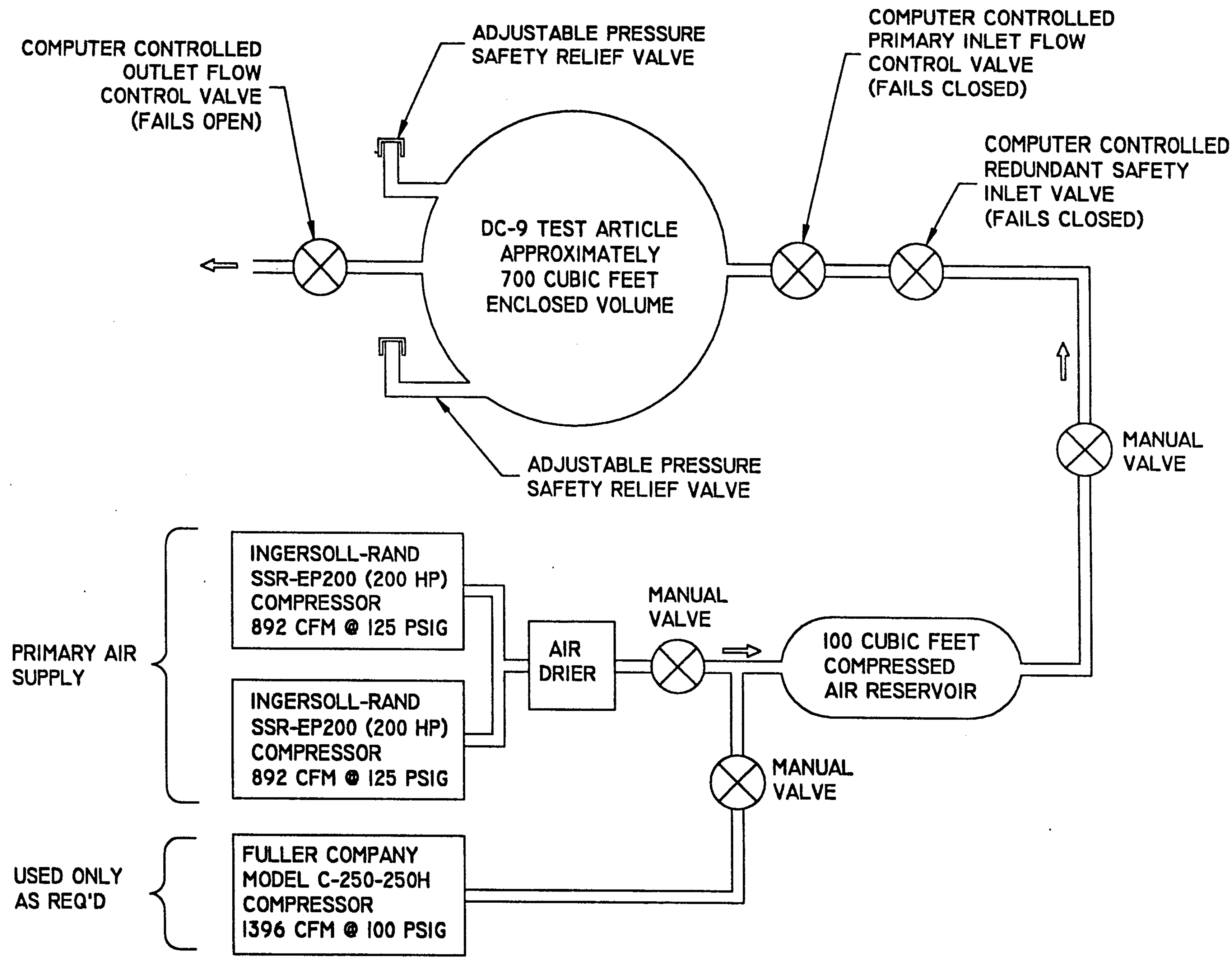

Figure 7. Test Pneumatic System Schematic

2.3 Data System and Instrumentation

The data acquisition system consisted of a Digital Vaxstation, Model 4000-90A computer running VAX/VMS. This system interfaced via an Institute of Electrical and Electronics Engineers (IEEE) bus to a Neff Model 470 multiplexer which was fed by signal conditioning modules designed and fabricated in-house. These modules received their signals from a variety of transducers located at the test article. Two Hydronics Inc. Type TH-1, 0-10 psig pressure transducers were installed in the 2-inch-thick steel mounting plate to sample the test article pressure. The signals from these transducers were recorded by the data system and also used by the control system to regulate the pressure inside the test article. Twenty-two axial (P/N: EA-13-062AQ-350 Opt. W) and twenty-four rosette strain gages (P/N: EA-13-120WR-350 Opt. W) were installed by government personnel at the locations required by the Boeing test plan, Douglas Aircraft Company task assignment drawing ZA151635, Appendix B. The data system sampled, stored, converted and displayed the test data from these sensors at a rate up to 20 samples per second. This system manipulated 98 channels of data and presented it in both tabular and graphical formats in real time at the test operator's station. A 1,000-point history file was also recorded at test article failure. This yielded 800 points before and 200 points after test article failure.

2.4 Video System

The video system consisted of two JVC HR-S7000U VHS VCRs, two JVC monitors, two Panasonic WV-CL324 cameras with Computar TV zoom lenses and Pelco pan/tilt units and a Pelco PT506-24DT pan/tilt remote controller. These VCRs recorded images at 30 frames/sec.

3. Test Procedure

The sequence of testing procedures was to be as follows:

1. Initial strain survey.
2. Critical crack length test prior to crack growth operation.
3. Normal crack growth operation.
4. Final strain survey.
5. Residual strength test operation.
6. If no failure occurs, repeat steps 3 and 5 with modified loading parameters.

3.1 Initial Strain Survey

The procedure for this test was as follows:

1. Set mechanical safety valve weights to vent at 7.8 psig nominal pressure.
2. Visually inspect test article per Boeing test plan, Douglas Aircraft Company task assignment drawing ZA151635, section 9, sheets 5 and 6.
3. Secure test article and fixture hatches.
4. Start data system.
5. Start video system. Use two new VHS tapes.
6. Start Control system.
7. Start pneumatic system.
8. Conduct strain survey at every 10 percent increment of 7.8 psig up to 7.8 psig (.78, 1.56, 2.34, 3.12, 3.90, 4.68, 5.46, 6.24, 7.02, 7.80 psig), allowing sufficient time at each step to allow pressure to stabilize.
9. Purge test article by reducing pressure in 10 percent steps.
10. Repeat 10 percent pressure incremental loading as in step 8 up to 3.12 psig (40 percent of 7.8 psig) to determine hysteresis effects.
11. Purge test article incrementally as in step 9.
12. Shut down systems in steps 4 through 7 in reverse order.
13. Visually inspect test article as in step 2.

3.2 Critical Crack Length Test Prior to Crack Growth Operation

The purpose of this portion of the testing was to determine if the initial 10.5-inch-long saw cut was already at a critical length prior to any sharpening by cycling. The procedure for this test was as follows:

1. Set mechanical safety valve weights to vent at 9.5 psig nominal pressure (attach secondary weights).
2. Secure test article and fixture hatches.
3. Perform system start procedures as detailed in section 3.1, steps 4 through 7.
4. Pressurize test article from 1.0 to 9.5 psig in 0.5 psig increments allowing crack to stabilize if growth occurs.
5. Purge test article by incrementally reducing pressure by 0.5 psig steps.
6. Shut systems down as in section 3.1,step 12.
7. Pressurize test article to 3.80 psig (40 percent of 9.5 psig) in 0.5 psig increments to

determine hysteresis effects
8. Purge test article as in step 5.
9. Shut down systems as in section 3.1, step 12.
10. Visually inspect test article per Boeing test plan, Douglas Aircraft Company task assignment drawing ZA151635, Appendix D.
11. If test article remains intact, proceed to section 3.3, Normal Crack Growth Operation.

3.3 Normal Crack Growth Operation

This phase of the test involved pressure cycling the test article to grow the sawcut in the bulkhead from an initial length of 10.5 inches to a final length of 12.5 inches. In doing so, the crack tips would be sharpened, thus representing a more natural crack geometry. The procedure to be used was as follows:

1. Set mechanical safety valve weights to vent at 7.8 psig nominal pressure.
2. Secure test article and fixture hatches.
3. Perform system start procedures as detailed in section 3.1, steps 4 through 7.
4. Perform 500 pressurization/depressurization cycles from 0.8 to 7.8 psig with a tolerance of +/- 0.1 psig.
5. Using video system, monitor the lead crack propagation and immediately stop cycling if crack reaches a length of 12.5 inches. If this occurs, push the "De-energize Dump Valves" switch on the Control Console, perform tasks 6, 7 and 8 below, and proceed to section 3.4, Residual Strength Test Operation. If crack does not grow to 12.5 inches, push the "De-energize Dump Valves" switch on the Control Console during the depressurization portion of every 500th cycle.
6. Shut down systems as in section 3.1, step 12.
7. Visually inspect test article per the Boeing test plan, Douglas Aircraft Company task assignment drawing ZA151635, Appendix D.
8. Monitor and record new cracks and lead crack length in Appendix C of the Boeing test plan, Douglas Aircraft Company task assignment drawing ZA151635, sheet C-2.
9. Repeat steps 3 through 8.
10. Per every 1000 cycles, visually inspect bulkhead lap splice per the Boeing test plan, Douglas Aircraft Company task assignment drawing ZA151635, Appendix D.
11. Repeat steps 3 through 10.
12. Per every 2000 cycles, perform non-destructive testing (NDI) and visual inspections per the Boeing test plan, Douglas Aircraft Company task assignment drawing ZA151635, Appendix D.
13. Repeat steps 3 through 12 until the lead crack grows to 12.5 inches, and then proceed to section 3.4, Residual Strength Test Operation.

3.4 Residual Strength Test Operation

a. Conduct Final Strain Survey:
1. Set mechanical safety valve weights to vent at 7.8 psig nominal pressure.
2. Visually inspect article per the Boeing test plan, Douglas Aircraft Company task assignment drawing ZA151635, Appendix D.
3. Secure test article and fixture hatches.
4. Perform system start procedures as detailed in section 3.1, steps 4 through 7.

5. Conduct strain survey at every10 percent of 7.8 psig (.78, 1.56, 2.34, 3.12, 3.90, 4.68, 5.46, 6.24, 7.02, 7.80 psig), allowing pressure to stabilize at each step.
6. Record all strain readings at each load step in the data sheet from the Boeing test plan, Douglas Aircraft Company task assignment drawing ZA151635, Appendix B, page B-13.
7. Purge test article by incrementally reducing pressure by .78 psig steps
8. Shut down systems as in section 3, step12.

b. Conduct Residual Strength Test:
1. Set mechanical safety valve weights to vent at 9.5 psig nominal pressure (attach secondary weights).
2. Perform system start procedures as detailed in section 3.1, steps 4 through 7.
3. Pressurize the test article from 1.0 psig to 9.5 psig in 0.5 psig steps, allowing sufficient time between steps for crack to stabilize.
4. If fast fracture does not occur before or at 9.5 psig, measure and record the lead crack, contact the Boeing test engineers, and then begin fatigue cycling from 0.8 psig to 9.5 psig until the lead crack reaches the new specified length.
5. Using new test pressures specified by Boeing engineers, repeat steps 3.4.a and 3.4.b, steps 1 through 4 until the bulkhead fails.
6. Shut down systems as in section 3, step 12.

4. Inspection Procedures

The inspection procedures to be performed were outlined in the Boeing test plan, Douglas Aircraft Company task assignment drawing ZA151635, Appendix D. These included various visual and both high and low frequency eddy current inspections at specified intervals and locations. These intervals and methods are also outlined above in sections 3.1 through 3.4. More detailed information can be found in the aforementioned Boeing test plan document.

5. Testing

System check out commenced on April 4, 2000 and was completed April 7, 2000. During this time, a restriction was fitted downstream of the inlet valves, and the manual butterfly valve upstream of the inlet valves was partially closed to permit better control of the pressurization cycle. The inlet restrictor reduced the inlet cross section area from 28.3 in^2 to 3.1 in^2. Strain gages and pressure transducers were also monitored for function during a 3.12 psig (40 percent of 7.80 psig) strain survey. The control system operating parameters were tuned to yield a test article pressure profile closely matching that of the program profile.

Personnel from the FAA and Boeing, Long Beach arrived for observation of the test on April 18, 2000. Two attempts were made to reach 7.80 psig during the initial strain survey as outlined in section 3.1, Initial Strain Survey. However, leakage limited test article pressure to 6.50 psig both times. A third run to 3.12 psig (40 percent of 7.80 psig) was performed to determine hysteresis effects before modifying the test setup to allow higher pressures. After adjustments were made to the control system parameters, the next run achieved 7.20 psig before system leakage became a limiting factor. Again, a run to 3.12 psig (40 percent of 7.80 psig) was also performed before proceeding to system modifications. After more control system adjustments, a final run yielded only 7.30 psig. Further attempts to achieve higher pressures would require addressing the excessive leaks in the system.

Upon analyzing the leakage situation, it was determined that the only areas which could be remedied were those leaks around the mechanical safety exhaust valves. The top valve gasket was replaced and the bottom valve was covered with a blanking plate, rendering it inoperative. This was deemed safe, however, since these valves were sized based on the original inlet cross section area of 28.3 in^2. As noted above, the inlet area had subsequently been restricted to 3.1 in^2, which was a decrease in inlet area of 89 percent. The loss of one safety exhaust valve was a reduction in exhaust area of only 50 percent, so the system was still in a safe configuration. In addition, a 90 degree elbow was added to the inlet on the inside of the test article to reduce the buffeting of the cameras during pressurization.

After performing these system modifications, testing began again on April 19, 2000 with a run to the required 7.80 psig for the Initial Strain Survey. At this point, the data for strain gages SG1 and SG11, at the upper and lower lead crack tips respectively, indicated that the bulkhead web was being loaded to a level approaching its ultimate material properties. This revealed that the structure would probably experience a catastrophic failure as it was run through the next phase as outlined in section 3.2, Critical Crack Length Test Prior to Crack Growth Operation.

The test setup was then modified for what was anticipated to be the final phase of testing. The control system and mechanical safety exhaust valve were recalibrated for the required 9.50 psig test article pressure. During the run up to 9.50 psig, the data and video systems captured the final moments of the test when strain gages SG11 and SG1 failed in succession to be followed by the entire bulkhead structure. This occurred between 8.97 and 8.99 psig as recorded by pressure transducers P-25316 and P-25295, respectively.

6. Test Results/Summary

Clearly, the early failure of the structure indicated that the initial analysis was flawed in that the lead crack was already at a critical length without the need for cycling to sharpen the crack tips. In retrospect, the manufactured initial crack length (sawcut) should have been shorter to enable cycling to sharpen the crack tips and yield a more realistic test. However, prior to the 2nd day of testing, the Boeing personnel present indicated that newer revised analyses had predicted failure at approximately 9.2 psig with a crack length of 10.5 inches. This was within three percent of the actual failure load. For this final run, the elapsed time from the initial pressurization to bulkhead failure was 5:18.60. The sequence of events is summarized in Table 1.

Table 1. Summary of Test Data

TEST TIME (SECONDS)	PROGRAM PRESSURE (PSIG)	P25295 XDUCER PRESSURE (PSIG)	EVENT
31.50	0.02	0.00	PROGRAM PRESSURE START.
91.55	0.57	0.01	INITIAL PRESSURIZATION OF TEST ARTICLE.
122.60	1.20	1.00	TEST ARTICLE AT 1.00 PSIG.
154.20	2.09	2.00	TEST ARTICLE AT 2.00 PSIG.
176.75	3.12	3.01	TEST ARTICLE AT 3.01 PSIG.
201.25	4.19	4.00	TEST ARTICLE AT 4.00 PSIG.
211.75	4.94	5.02	TEST ARTICLE AT 5.02 PSIG.
241.80	6.21	6.01	TEST ARTICLE AT 6.01 PSIG.
267.90	7.11	7.01	TEST ARTICLE AT 7.01 PSIG.
303.40	8.16	8.00	TEST ARTICLE AT 8.00 PSIG.
309.90	8.28	8.11	STRAIN GAGE 11 AT MAX VALUE.
387.45	8.99	8.80	STRAIN GAGE 1 AT MAX VALUE.
407.45	9.20	8.97	STRAIN GAGE 1 FAILED, LEAD CRACK EXTENDED TO NEXT RIVET HOLE.
408.95	9.20	8.99	STRAIN GAGE 12 AT MAX VALUE.
409.45	9.20	8.99	STRAIN GAGE 2 AT MAX VALUE.
409.95	9.20	8.99	STRAIN GAGE 2 FAILED, LEAD CRACK EXTENDED TO NEXT RIVET HOLE.
410.10	9.20	8.99	STRAIN GAGES 3 AND 13 VALUES ROSE RAPIDLY.
410.15	9.20	8.17	TEST ARTICLE PRESSURE DROPPED, STRAIN GAGE 13 ROSE RAPIDLY, STRAIN GAGE 3 FAILED.
410.20	9.20	5.48	RAPID DE-PRESSURIZTION OF TEST ARTICLE. BULKHEAD FAILED.

As evident from Table 1 and by the graphs in Figures 8 and 9, up to a test time of approximately 300 seconds at a pressure of 7.94 psig, strain gages SG1, SG2, SG3, SG11, SG12, and SG13 recorded a strain level mirroring test article pressure. These strain gages are of particular interest since SG1 through SG3 were in sequential order from the top end of the lead crack tip and SG11 through SG13 were in sequential order from the bottom end of the lead crack tip. At a test time of approximately 300 seconds, the output of SG1 indicated a strain level rising much quicker than the test article pressure. Approximately 10 seconds later at a pressure of 8.11 psig, SG11 reached its maximum value and failed. Gage SG1 failed at 407.45. The final bulkhead failure sequence began at time 408.80 at a pressure of 8.99 psig when SG12 began a rapid rise, followed by SG2 at time 408.90. At test time 409.95, SG2 failed and the upper lead crack tip extended to the next rivet hole, followed rapidly by SG3 and SG13 at 410.10. At test time 410.15, the test article pressure began to fall as the crack extended and vented the compressed air faster than the control system could accommodate the loss. Finally, at test time 410.20, the pressure dropped rapidly, indicating total failure of the bulkhead structure.

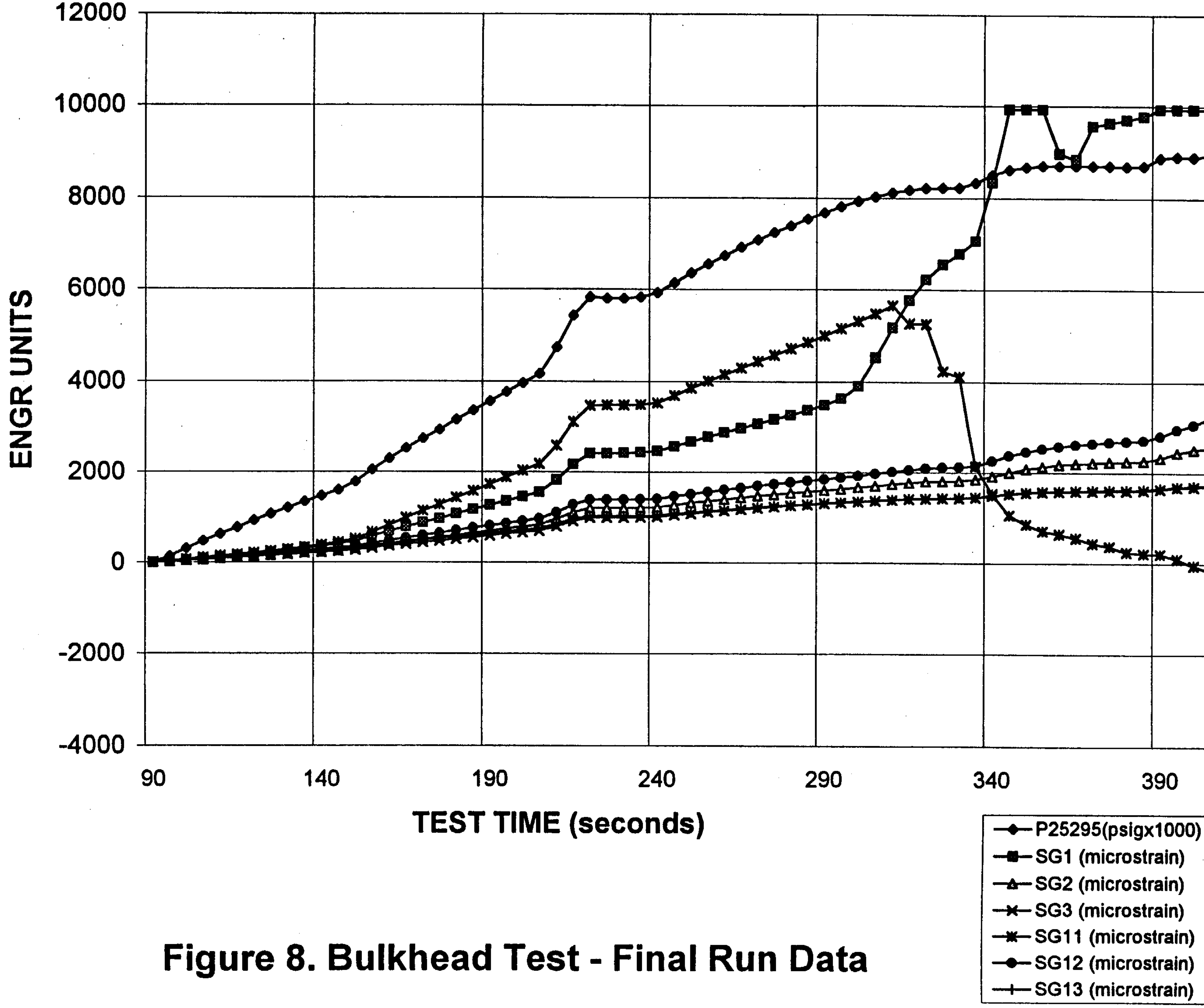

Figure 8. Bulkhead Test - Final Run Data

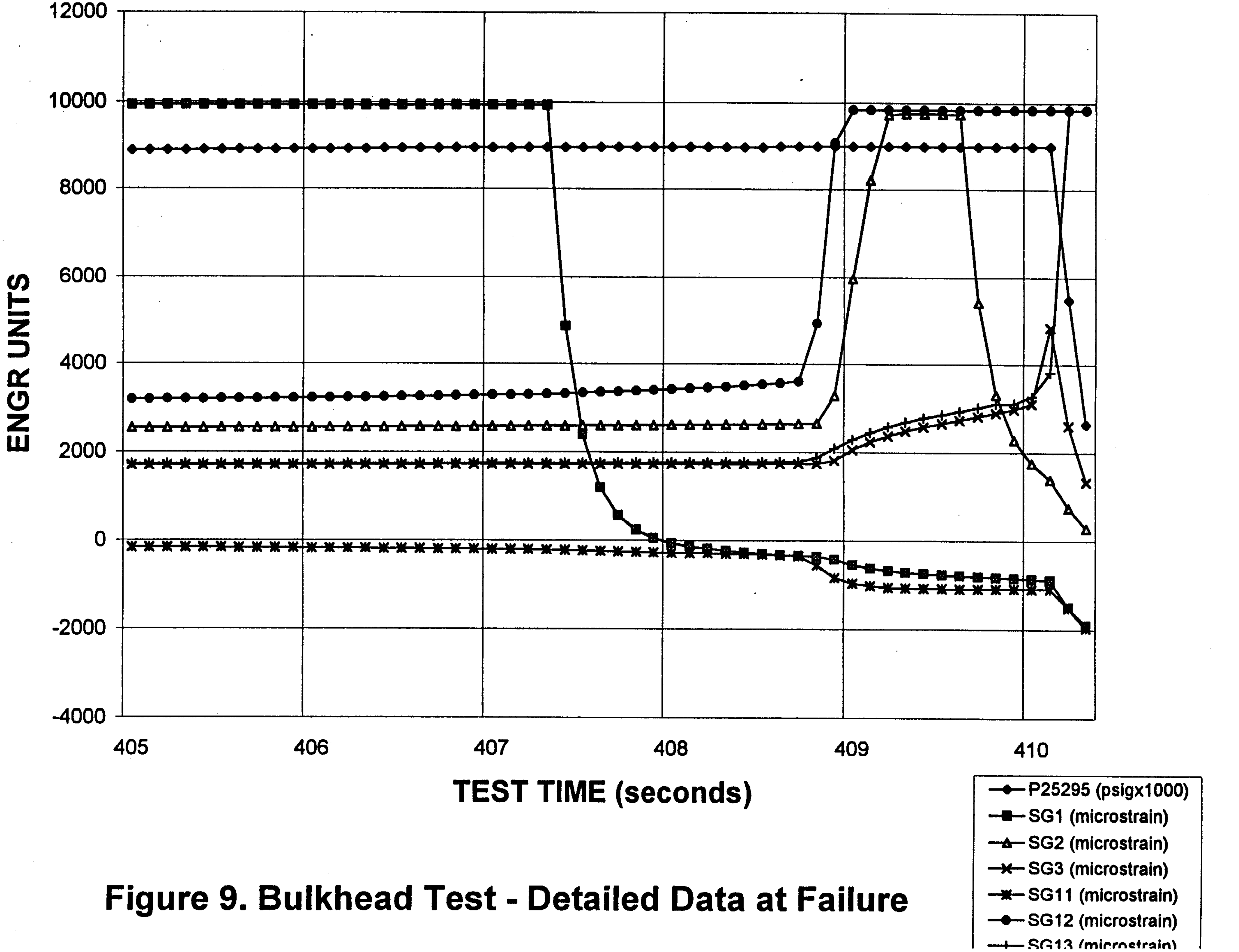

Figure 9. Bulkhead Test - Detailed Data at Failure

7. References

1. Boeing Test Plan, Douglas Aircraft Company Task Assignment Drawing ZA151635, 23 April, 1998.

2. Air Force Research Laboratory, Air Vehicles Directorate, DC-9 Aft Pressure Bulkhead Test Standard Operating Procedures, 14 April, 2000.

List of Acronyms

Acronym	Description
AFRL	Air Force Research Laboratory
ASTM	American Society for Testing and Materials
CFM	Cubic Feet Per Minute
FAA	Federal Aviation Administration
HP	Horsepower
IEEE	Institute of Electrical and Electronics Engineers
MSD	Multiple Site Damage
NDI	Non-destructive Inspection
PVC	Polyvinyl Chloride
SAE	Society of Automotive Engineers
WFD	Widespread Fatigue Damage