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An Investigation of the Causes of Failure of Flexible Thermal Protection Materials in an Aerodynamic Environment

Charles F. Coe

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An Investigation of the Causes of Failure of Flexible Thermal Protection Materials in an Aerodynamic Environment

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TABLE OF CONTENTS

AN INVESTIGATION OF THE CAUSES OF FAILURE
OF FLEXIBLE THERMAL PROTECTION MATERIALS
IN AN AERODYNAMIC ENVIRONMENT

1 INTRODUCTION

Advanced Flexible Reusable Surface Insulation (AFRSI) has been developed as a replacement for the low-temperature (white) tiles on the Space Shuttle Orbiter. AFRSI is a quilted blanket consisting of silica-fiber insulation as the quilt filler, woven quartz-fiber outer fabric and glass-fiber inner fabric. The quilting is done with teflon-coated quartz thread stitched through the three layers of materials. The quilt cells are nominally 1-inch square and there are approximately four (4) quilt stitches per inch. The thickness of the quartz fabric is 0.027 inch and the diameter of the quilting thread is about 0.02 inch. The thickness of AFRSI blankets, which are bonded to the Orbiter surface with RTV-360, varies from about 1/2 inch to 1 inch.

The first application of AFRSI for an Orbiter flight was on the OMS pods for STS-6. Unfortunately, damage of the AFRSI occurred during entry of STS-6. This prompted a post flight wind-tunnel test program to investigate and fix the problem (Refs. 1 - 5); and in fact a successful fix was accomplished. The fix is a ceramic coating of the outer fabric, which bonded the fibers in the fabric and quilt stitches and thus added rigidity to the surface.

Although as mentioned the post STS-6 tests accomplished the desired fix of the AFRSI, they did not reveal the mechanism of failure when AFRSI is exposed to entry temperature and aerodynamic environments. Subsequently, therefore, an assessment of the wind-tunnel test data and some fatigue tests of the quilt-stitching threads were sponsored by Ames Research Center to help pin-point the mechanism of failure (Ref. 6). Reference 6 concentrated on fatigue effects that could be caused by self-abrasion due to dynamic loads from shock waves and separated boundary layers. The static strength of the material had previously been studied (Ref. 7) and was not suspect even though there was an 80-percent reduction in strength of threads after exposure to 1100°F. References 6 and 7 showed that about 5-percent by weight of the teflon coating of the threads was lost due to heat cleaning (650°F for 4 hours plus 850°F for 2 hours) and 100-percent by weight of the teflon was lost due to entry temperatures over 1100°F. The loss of teflon therefore could strongly affect the fatigue of the threads.

For the tests of Reference 6 an apparatus was designed that applied pulsating aerodynamic loads on threads similar to the loads on the quilt stitching caused by oscillating shock waves. The tests showed that there was an extremely large reduction (greater then a factor of 10^6) in the number-of-cycles to failure for threads that had been thermally preconditioned at 1,200°F versus threads that had been heat cleaned. Such a result suggests that AFRSI blanket failures may commence with quilt-stitch thread failures followed by release of quilt cells and loosening of outer fabric which is then free to flutter or to respond to the shock-wave boundary-layer excitation. Previous wind-tunnel tests have not revealed whether the quilt threads or the outer fabric has been first to fail. Because the outer-fabric fibers are not coated with teflon, it is expected that for equal bending radius the fatigue life of the fabric would be less than that of the quilt threads before entry heating and the same after entry heating.

To further study the failure characteristics of AFRSI, additional work has been supported by Ames that included the design of an apparatus to simulate Orbiter entry mean-flow and pulsating aerodynamic loads on small AFRSI blanket panels and tests. The apparatus allowed almost instantaneous starting and stopping of flow and continuous visual inspection of panels so that failure details, including the progression, of blanket damage could be studied. The results of these tests which include the effects of heat cleaning and entry-temperature preconditioning are the subject of this report.

2 TEST APPARATUS

A small wind-tunnel test apparatus with a 1.75- x 3-inch test section has been designed and fabricated to simulate shock-wave boundry-layer air loads on 3- x 5.5-inch AFRSI test articles. The apparatus is located in Ames Building N227D in the northeast corner of room 201. This location was selected to take advantage of a very high volume 140-psi dry air source and an existing outlet valve.

A sketch of the installation is shown in Figure 1 and a photograph is shown in Figure 2. The total apparatus consists of a 2-inch pipe from the air source to a convenient table-top working position, an additional control valve and ball valve, the wind tunnel, a velocity and noise quieting tube and lastly a large sound suppressing box lined with 3-inch thick open-cell foam material. The air source is sufficiently large to allow continuous operation at dynamic pressures (q) greater than 600 psf.

A sketch and photograph of the wind-tunnel part of the apparatus are shown in Figures 3 and 4. The wind tunnel consists of an expansion section that changes the flow cross section from circular to rectangular, the 1.75- x 3-inch test section and a partial butterfly valve with a driven rotating vane that causes pressure oscillations in the tunnel. The rotating vane shown in Figure 5, which spans the bottom wall downstream of the test section, reduces the flow cross section by a maximum of 0.5- x 3-inches. When the vane is parallel to the flow, the stream-side surface is flush with the wall. The rotor is driven by two d.c. motors capable of speeds to 18,000 rpm. The motors are mounted on each end of the rotor shaft.

Most of the wind-tunnel construction material is aluminum; however, hard-wood blocks are used in the test section to contain the AFRSI test articles and an acrylic window is above the test section for monitoring the condition of the AFRSI during tests.

3 AFRSI TEST ARTICLES

Each of the AFRSI test articles, as shown in Figure 6, was installed in a machineable ceramic frame with outside dimensions 7.5-inches long by 6.5-inches wide by 1-inch deep. The test articles were cut from nominally 1-inch thick blankets that had been manufactured for an Orbiter. The blankets were obtained from Rockwell International Corporation after they had been heat cleaned and water proofed. The test articles were first cut to the outside frame dimensions, and then the filler material and inner fabric were carefully trimmed to match the frame inside dimensions. The inner fabric was bonded to an aluminum bottom plate using first a silicone primer (SS4155) then RTV adhesive (560).

Most of the test articles were exposed to entry-temperature conditions (1200°F for 10 minutes) in a radiant heating facility prior to the attachment of the top frame. When the test article cooled to room temperature, the top frame was bonded to the outer fabric layer with Duco cement and attached to the ceramic frame with screws threaded into the bottom plate.

Installation photographs of test articles installed in the test apparatus are shown in Figure 7. It can be noted from Figures 3, 6 and 7 that the inside width of the top frame was 1-inch larger than the 3-inch wide test section, and the ceramic frame was 2-inches wider than the test section. The extra width of the test article was choosen to minimize the effects of the bonded-edge boundary condition in the narrow test channel.

4 TEST SECTION CALIBRATIONS

Prior to AFRSI tests, a calibration panel was installed in the test section to establish that useful mean and fluctuating pressures could be obtained. The primary objective of the design was to simulate entry conditions with dynamic pressure, q, between 250 and 300 psf and with severe shock-wave like pressure oscillations near 1 psi RMS. A secondary objective, but not a requirement, was to determine if launch conditions could be simulated with q near 600 psf. It was also necessary to establish that constant flow conditions could be maintained for at least 5 minutes.

A sketch of the calibration panel is shown in Figure 8. The panel contained 8 orifices to measure the mean values of the surface static pressures and 5 orifices with Kulite transducers to measure the fluctuations. A total pressure probe was installed in the acrylic test-section window extending about 0.5-inch into the stream at x = -2 inches. The pressure mean values were measured with a precision Bourdon type gage and the fluctuations were measured with an RMS meter and recorded with an oscillograph. The frequency bandpass of the fluctuating pressure measurements was from 1 Hz to 5000 Hz.

The results of the calibrations are given in Table 1 and Figures 9 and 10. Table 1 shows data for two total pressure (p_t) settings, 4.0 psi and 12.1 psi, with the rotor turning at 100 revolutions per second (RPS). For these conditions, as shown in Table 1 and Figure 9, the average q in the test section was about 280 psf and 580 psf respectively. The tests showed that continuous flow was possible at q greater than 580 psf, however the rotor tended to autorotate, thus causing a speed control problem. The fluctuating pressures varied from 1.4 psi RMS (173 dB) at $x = -0.5$ inch to 1.1 psi RMS (171 dB) at $x = -4.0$ inches at $p_t = 4.0$ psi. The fluctuating pressures varied from 2.6 psi RMS (179 dB at $x = -0.5$ inch to 1.8 psi RMS (176 dB) at $x = -4.0$ inches. As would be expected, the fluctuating pressures increased slightly, 2 dB to 3dB, in the downstream direction toward the rotor.

The rotor speed selected for the AFRSI tests was based on the time histories of the pressure fluctuations illustrated in Figure 10. These data show the wind-off noise and wall pressure fluctuations at 0 RPS of the rotor and at various rotor speeds to 200 RPS at $p_t = 4.0$ psi (q = 280 psf). A rotor speed of 100 RPS was selected because the pressures had a superior 200 Hz waveform and higher amplitudes than the pressures at other rotor speeds.

5 TEST PROCEDURE

All the AFRSI tests for this investigation were conducted at $p_t = 4.0$ psi to simulate entry conditions with q = 280 psf. In order to achieve the almost instantaneous start-up feature of the test apparatus, the rotor was started first and then the ball valve shown in Figure 4 was fully opened. The adjacent gate valve had been preadjusted for $p_t = 4.0$ psi flow prior to the run. The initial setting of the gate valve was acomplished with the calibration panel in the test section. For subsequent tests of AFRSI the gate valve was not closed at the conclusion of a run, and thus only minor adjustments (usually less than $p_t = 0.2$ psi) were made during each run to maintain the desired flow setting. When the ball valve was opened for each test, a run timer and visual inspection were simultaneously started. A record was made of AFRSI damage as the run progressed. On occasion a run was stopped to record damage and then restarted. Most total run times were from 300 to 500 seconds long. Post-test photographs were taken of each test article.

6 RESULTS AND DISCUSSION

Reference 6 has established that threads used for quilt stitching AFRSI that have been entry-temperature preconditioned self-abrade and disintegrate rapidly when exposed to dynamic loads. This result suggests a possible progression of damage that starts with quilt-stitch failures; but previous investigations have not confirmed that the quilt-stitch failures always precede, and thus cause, fabric failures. Will the fabric fail due to high dynamic loads if the quilt stitching does not fail? (Previous tests have shown that the 1-inch quilted fabric does not fail due to flutter).

There were 11 AFRSI tests conducted for this investigation with some variation of entry-temperature preconditioning and fluctuating-pressure excitation frequency (f_E) as listed below. As can be seen in the listing, most of the tests

No. of Test Articles	Entry-Temp. Preconditioning ?	Dynamic Pressure (q)	Excitation Frequency (f_E)
8	Yes	280 psf	200 Hz
1	No	280 psf	200 Hz
1	Yes	280 psf	0 Hz
1	Yes	280 psf	200 Hz for 2 sec. 0 Hz 2-500 sec.

were of entry-temperature preconditioned AFRSI at $q = 280$ psf and $f_E = 200$ Hz. One test, however, was conducted of an AFRSI sample that had not been temperature preconditioned to illustrate the contrast in performance due to entry heating. Two additional tests were conducted to investigate the effects of large fluctuations of pressure.

6.1 Entry-temperature Preconditioned AFRSI, $q = 280$ psf, $f_E = 200$ Hz

Four examples of the first eight tests of heat-cleaned and entry-temperature preconditioned AFRSI after exposure to $q = 280$ psf and $f_E = 200$ Hz are shown in Figure 11. The end results of all eight tests are not shown because in some cases the fabric-to-outer-frame bond failed, affecting fabric damage, or in some cases the fabric damage started at the frame or test section wall. Nevertheless, the initial quilt-stitch thread failures on all eight tests were valid, and they showed that thread failures started in the rows of thread closest to the rotor within the first 3 to 14 seconds of the test. In all cases threads failed before fabric. There was a large variation in thread failure times and in the progression of failures, probably due to significant differences in the looseness of the quilt-thread loop. For example, Figure 11 (a) shows test results where nearly all of the thread loops failed within 5 seconds, whereas, for the same length of time (5 seconds) Figures 11 (b) and (c) show other test results where loop damage occurred only in the first or second row upstream of the rotor.

The AFRSI failure histories illustrated in Figure 11 show that there was a large variation in run times for initial fabric damage, from 70 seconds to over 400 seconds. Fabric damage always started where quilt stitching had penetrated the fabric. Sections of AFRSI did not always disintegrate before 500 seconds of exposure to the run environment. However, in all cases, the insulating quality of the AFRSI would have diminished shortly after quilt-thread failures due to the movement and relocation of filler material. This resulted in tighter packing of the filler in some locations and voids in other locations.

Observations of the AFRSI test articles during the runs showed that there was a consistent sequence of damage, which was as follows: (1) Quilt threads failed starting where dynamic loads were highest, near the rotor. (2) Outer fabric lifted immediately with the failure of quilt threads. The area and elevation of fabric lifting grew larger with the propagation of quilt-thread failures. (3) As the quilting failed and fabric lifted, filler material moved in the streamwise direction, gradually packing the downstream region so that the fabric was restrained from responding to the dynamic loads. Upstream regions of AFRSI were gradually voided of filler material, which would cause a loss of insulating quality even without outer fabric damage. (4) fabric damage started at a variety of locations along lines where quilt threads had penetrated the fabric. If the initial fabric damage was in a region of tight filler-material packing, the progression of fabric damage was slow. When fabric damage started in a region void of filler material, fabric damage was more rapid, usually resulting in a growing region of disintegration with time (Figures 11 (a) and (b).

6.2 No Entry-Temperature Preconditioning, $q = 280$ psf, $f_E = 200$ Hz

Figure 12 shows the damage to AFRSI after a 500-second run with a test article that had not been entry-temperature preconditioned. Without the entry-temperature preconditioning, it should be remembered that the quilt threads are teflon coated and also that the test article was cut from AFRSI that had been heat cleaned and water proofed. In this case, as would be expected from Reference 6, there were no failures of quilt threads. Some fabric damage started in the lower-right corner of the test article at 14 seconds and also at two locations along the top row of quilt threads at 112 seconds, but the damage did not increase with time. The more extensive damage that started at 200 seconds spread more rapidly. It is of interest that for this case, with quilt threads in tact, the filler material did not move to cause downstream packing. Therefore, the fabric failed where the dynamic loads were maximum - near the rotor.

6.3 Effects of Large Fluctuations of Pressure on Entry-Temperature Preconditioned AFRSI

In order to determine the influence of shockwave-like presssure fluctuations on entry-temperature preconditioned AFRSI, two additional tests were conducted. For one test, the rotor was clamped in a position that did not obstruct the flow. Thus the AFRSI was exposed only to the dynamic loads associated with the test section boundary-layer turbulence at $q = 280$ psf. For the second test, the rotor was turned on only for the first two seconds of the run and then it was clamped for the remainder of the run. The objective of this test was to determine whether the fabric would fail without the high dynamic-load environment after there was initial quilt-thread damage.

Figure 13 shows the AFRSI test article after 500 seconds at $q = 280$ psf and $f_E = 0$ Hz. Except for the single quilt-thread failure at the lower right-hand frame edge, which was probably due to the frame, there was no visible damage. Figure 14 shows the test article that was exposed to $q = 280$ psf at $f_E = 200$ Hz for the first 2 seconds followed by $f_E = 0$ Hz to 500 seconds. In this case, even though there was some quilt-thread failures during the 2-second run, it is significant that there was no further quilt-thread or fabric damage in the absence of the large fluctuations of pressure. The photograph in Figure 14 was made after the initial 2-second run. It can be seen that some lifting of the fabric had taken place within the 2-second run where the quilt threads had failed. A separate photograph after 500 seconds was not made because there was no change in the appearance of the AFRSI.

The results from the final two test articles are important because they clearly confirm that for entry conditions it is the fluctuating pressures in the air-loads that cause AFRSI failures. This result is consistent with Reference 6 which showed the rapid self abrasion of quilt threads. The quilt threads in the AFRSI fail rapidly because the quilt loops tend to be loose and thus they are susceptible to dynamic motion.

7 CONCLUDING REMARKS

Tests of small panels of AFRSI were conducted using a small wind-tunnel that was designed to simulate Orbiter entry mean-flow and pulsating aerodynamic loads. The wind tunnel with a 3-inch wide by 1.75-inch high by 7.5-inch long test section proved to be capable of continuous flow at dynamic pressures (q) near 580 psf with fluctuating pressures over 2-psi RMS at at an excitation frequency (f_E) of 200 Hz. For this investigation, however, the wind tunnel was used to test entry-temperature preconditioned and heat-cleaned AFRSI at q = 280 psf, $p_{rms} \approx 1.2$ psi and $f_E = 200$ Hz. The objective of these tests was to determine the mechanism of failure of AFRSI at entry conditions.

The tests showed that fluctuating pressures were the cause of failures of both entry-temperature preconditioned and heat-cleaned AFRSI at q = 280 psf. Quilt threads on entry-temperature preconditioned AFRSI always failed first, some within 2 seconds of run time, because the quilt loops tend to be loose and are susceptible to dynamic motion that caused rapid fatigue due to self abrasion (Ref. 6). After quilt threads failed, the outer AFRSI fabric lifted and the quilt filler material gradually moved downstream, causing downstream packing and some upstream voids of filler material. Damage to the outer fabric always started where quilt-threads had penetrated the fabric. Fabric disintegrations occurred last in regions void of filler material. Quilt threads did not fail on a sample of heat-cleaned AFRSI that was tested without entry-temperature preconditioning. The outer fabric failed, however, after 200 seconds of exposure to the fluctuating pressures.

8 REFERENCES

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3. IL 712-83-ECK-057, "Appendix Containing Data Results from OS-315 AFRSI Combined Environments Test", Rockwell International Corporation, October 1983.

4. SAS/AERO/84-321, "Results of the Space Shuttle Orbiter Speed Brake AFRSI Integrated Environments Tests OS-316 in the AEDC VKF Tunnel C", Rockwell International Corporation, June 1984.

5. SAS/AERO/84-312, "Results of the Space Shuttle Orbiter AFRSI Integrated Environments Tests 318 in the AEDC VKF Tunnel C", Rockwell International Corporation, May 1984.

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7. Sawko, P. M., "Effect of Processing Treatments on Strength of Silica Thread for Quilted Ceramic Insulation on Space Shuttle", SAMPE Quarterly, July 1985.

9 ACKNOWLEDGMENT

The author wishes to acknowledge the significant contributions of Don Moody for consultation on the design of the test apparatus, its manufacture and assembly, for preparation of the test articles, for conducting the tests and assembling the test results.

TABLE 1. AFRSI APPARATUS CALIBRATION

ROTOR SPEED = 100 RPS; EXCITATION FREQUENCY = 200 Hz

ORIFICE	p(psi)	q(psf)	M	V	p(psi)	q(psf)	M	V
P_t	4.00				12.1			
P1	2.08	274	0.43	480	8.2	562	0.62	687
P2	2.05	279	0.43	484	8.1	576	0.62	696
P3	2.06	277	0.43	483	8.3	547	0.61	679
P4	2.06	277	0.43	483	8.1	576	0.62	696
P5	2.09	273	0.43	479	8.2	562	0.62	687
P6	2.03	282	0.44	487	8.1	576	0.62	696
P7	1.99	287	0.44	492	8.0	590	0.63	705
P8	2.19	258	0.42	466	8.3	547	0.61	679

ORIFICE	RMSpsf	RMSpsi	pk-pk	dB	RMSpsf	RMSpsi	pk-pk	dB
K1	194	1.35	3.77	173	382	2.65	7.43	179
K2	185	1.28	3.60	173	370	2.57	7.19	179
K3	169	1.17	3.29	172	330	2.29	6.42	178
K4	171	1.19	3.33	172	341	2.37	6.63	178
K5	155	1.08	3.01	171	266	1.85	5.17	176

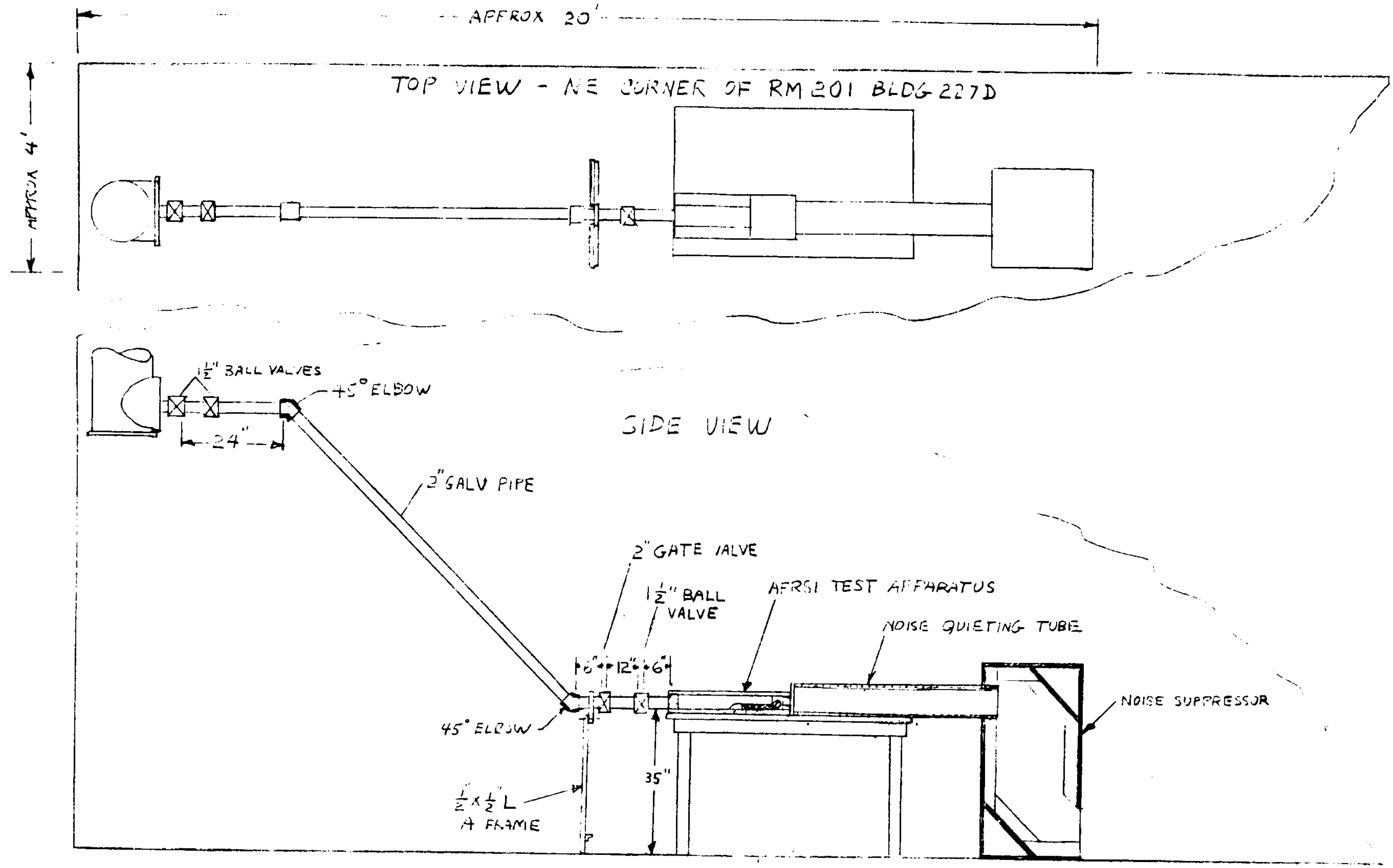

Figure 1. Installation of AFRSI test apparatus in Building 227D.

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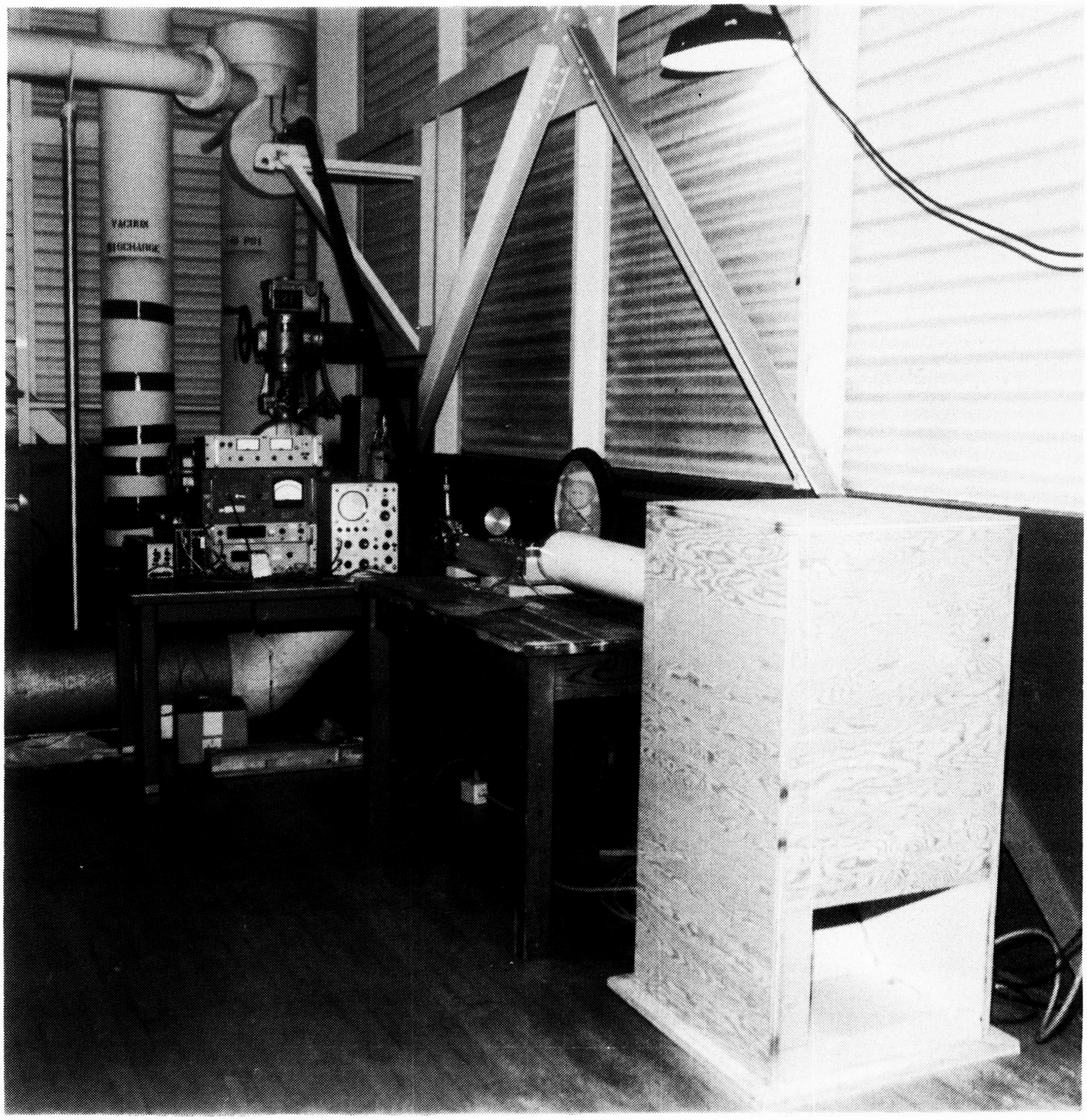

Figure 2. Photograph of AFRSI test apparatus installation.

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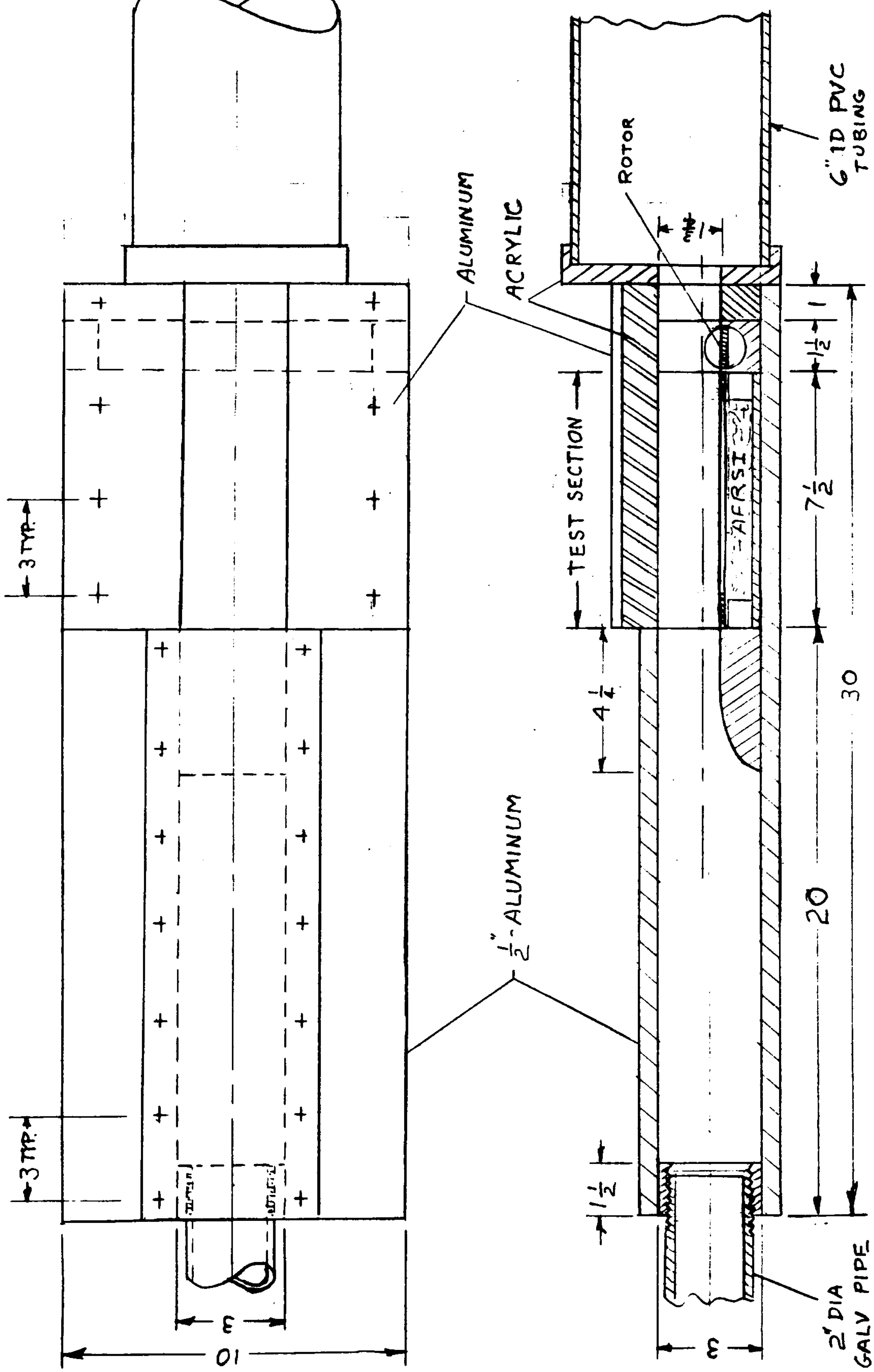


Figure 3. Sketch of AFRSI test apparatus.

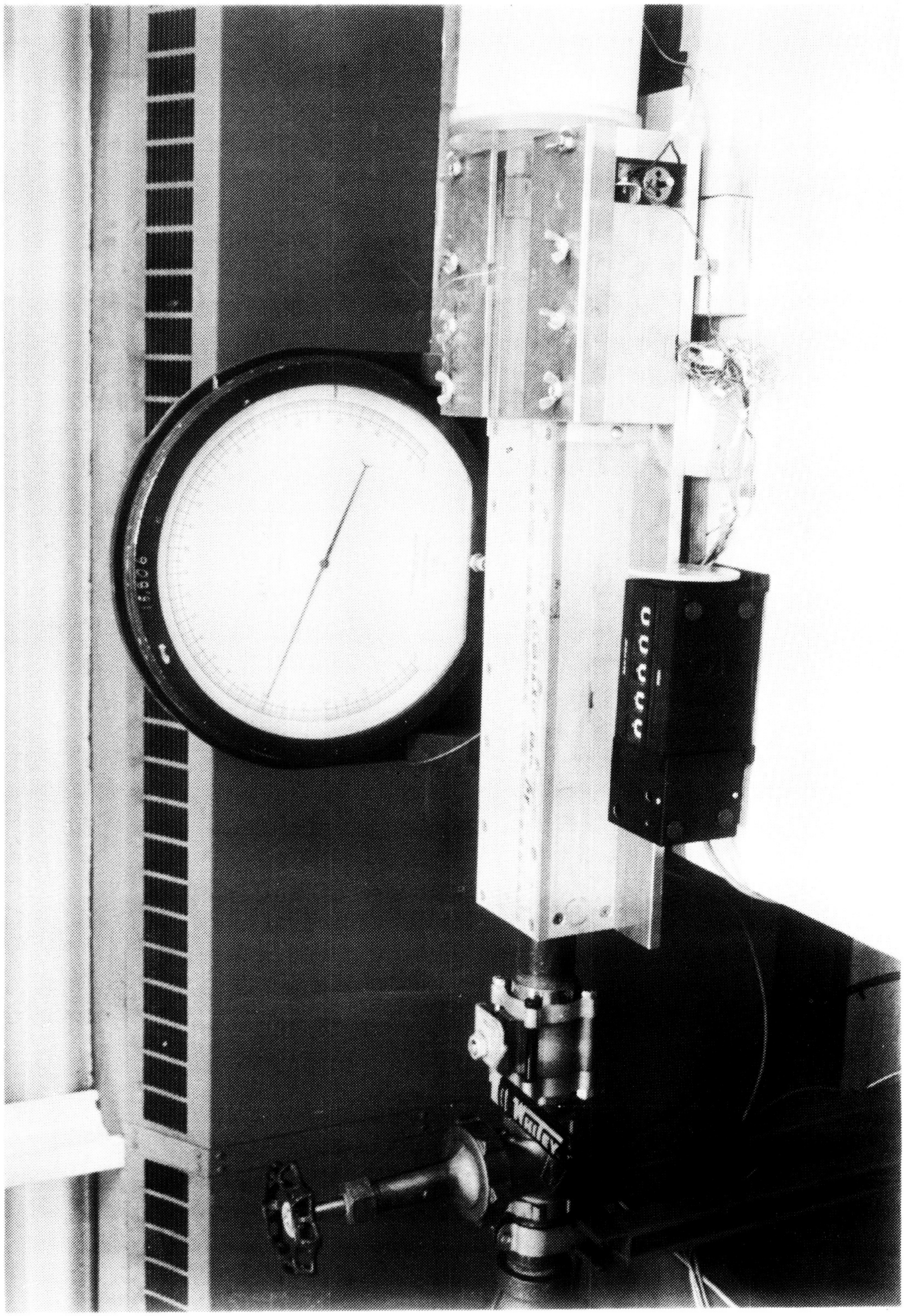
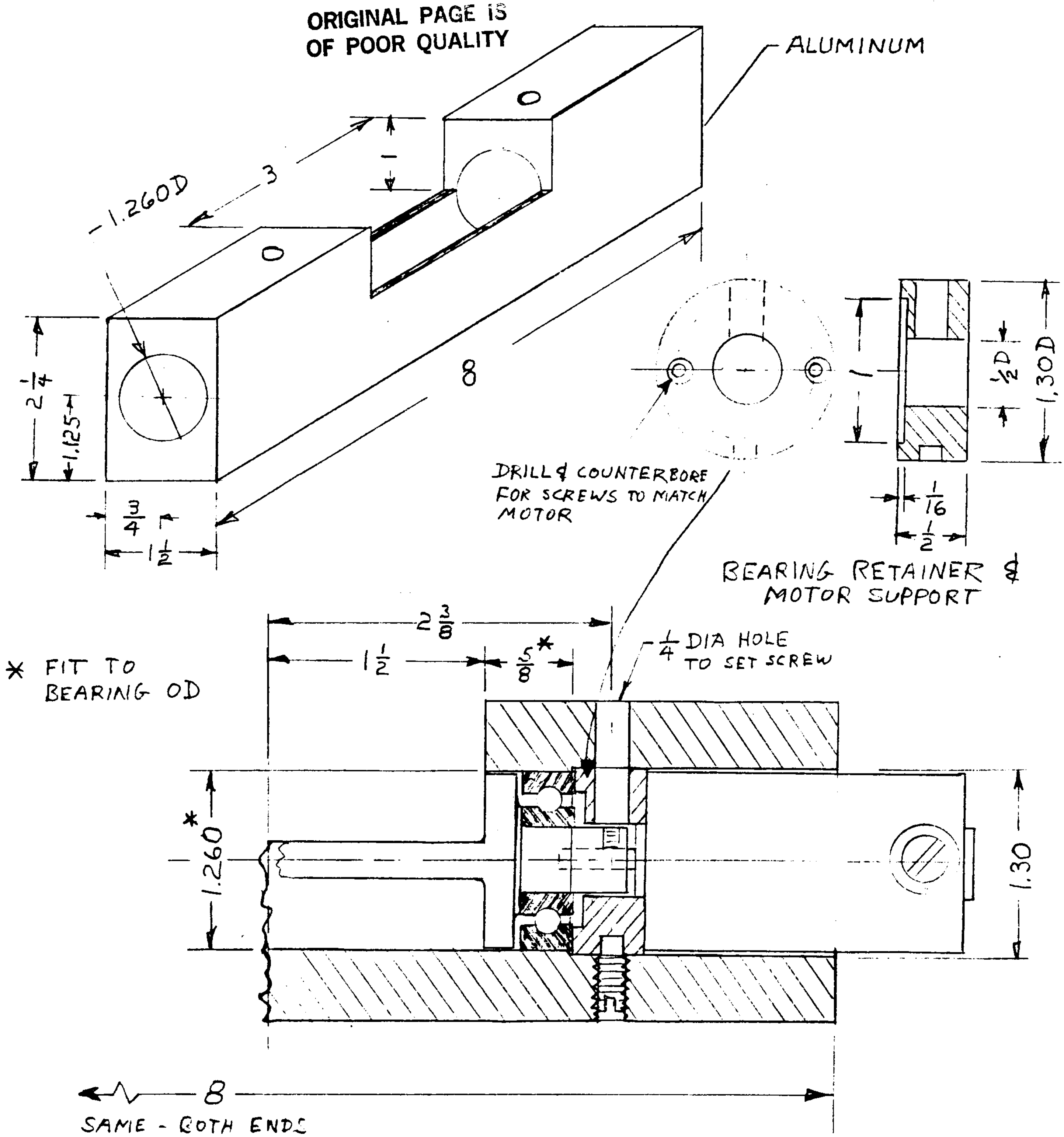


Figure 4. Photograph of the AFRSI test apparatus.



(a) Assembly

Figure 5. Details of the butterfly-valve rotor.

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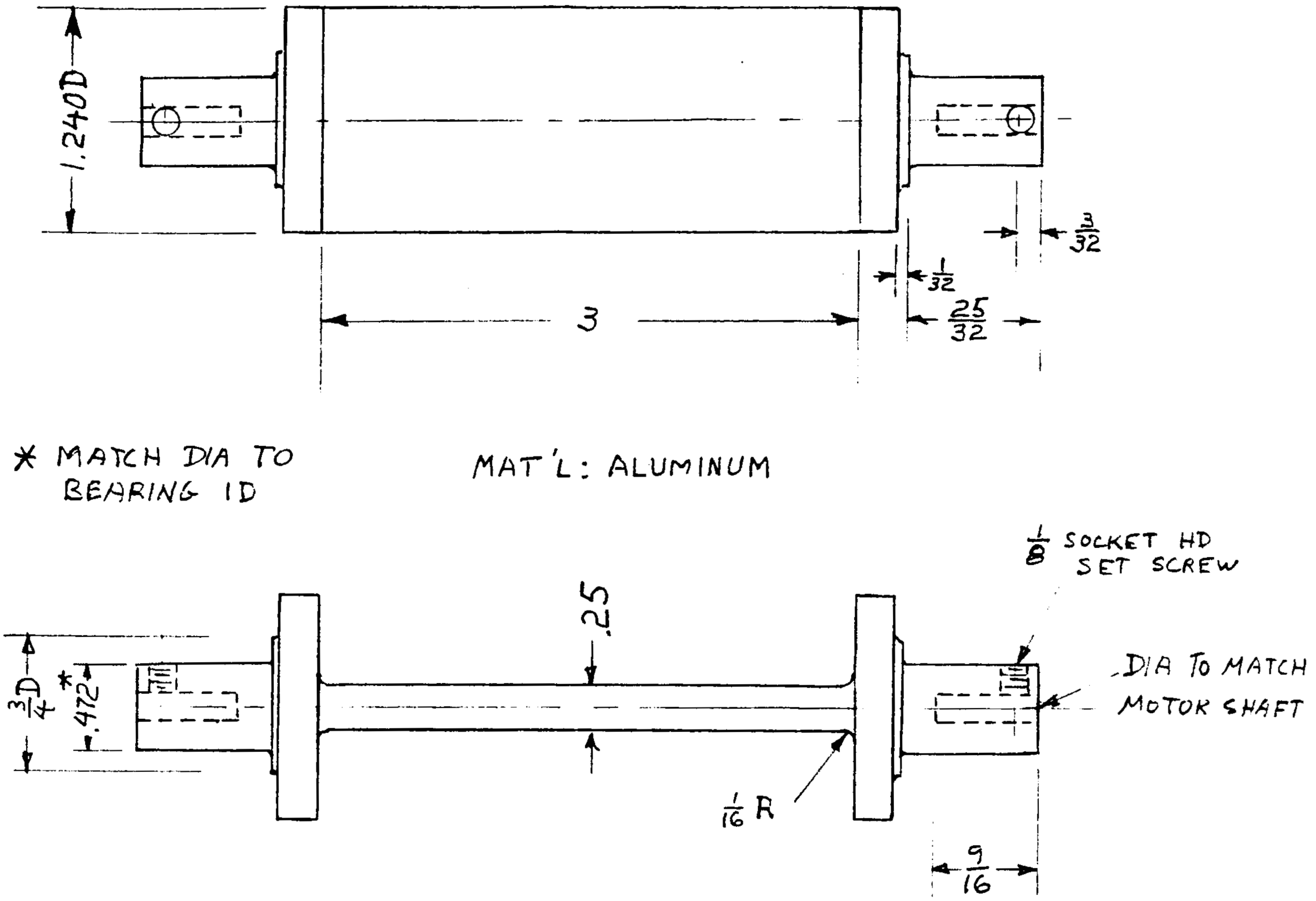

(b) Rotor

Figure 5. Concluded.

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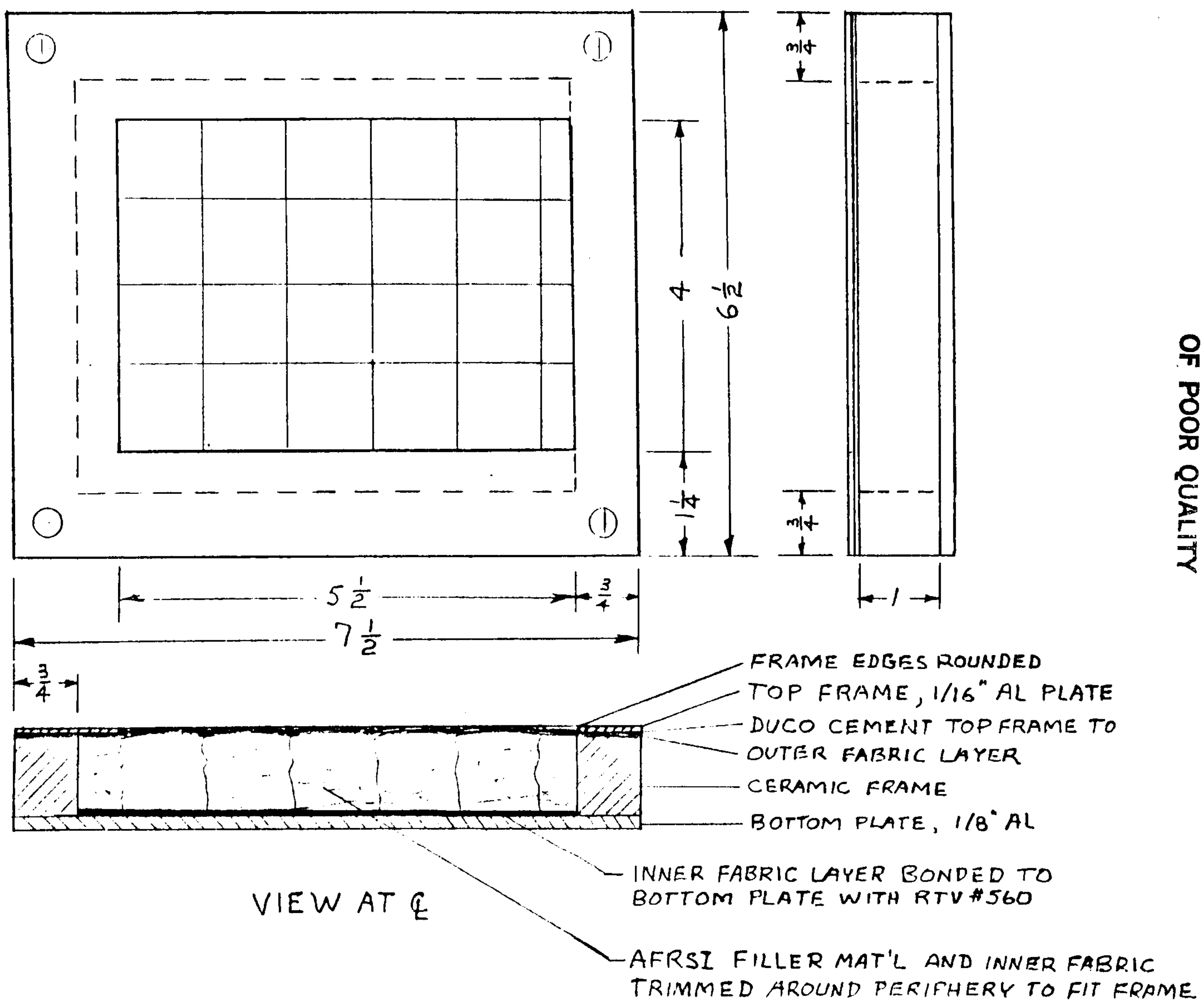
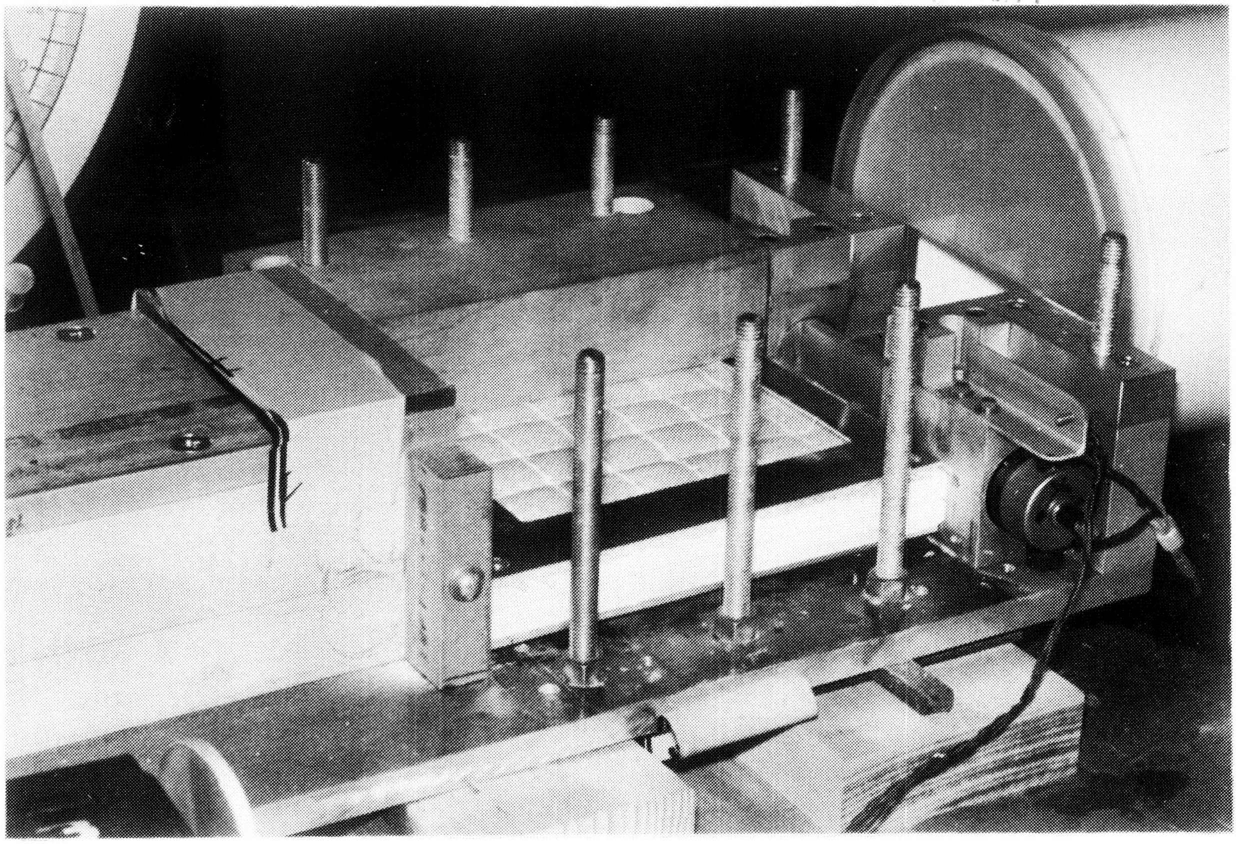
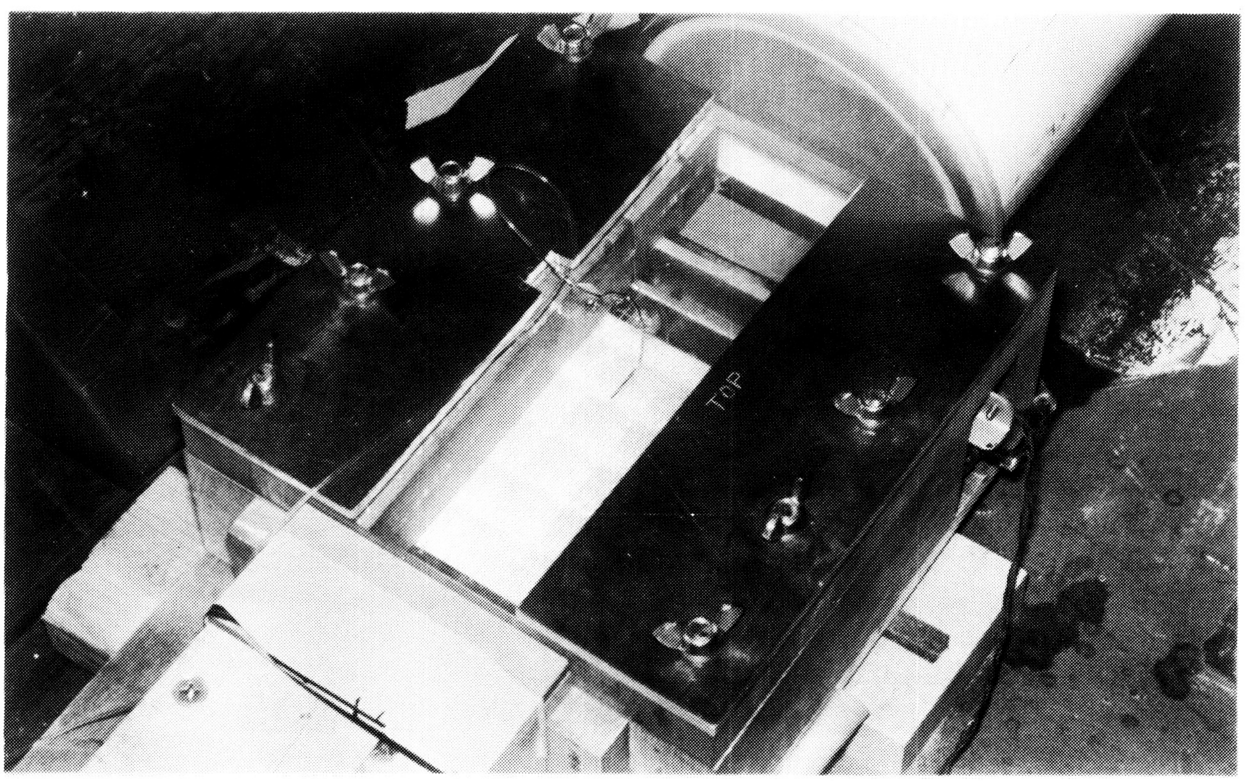


Figure 6. Sketch of AFRSI test article.



Front View



Top View

Figure 7. Photographs of AFRSI test article in the test apparatus.

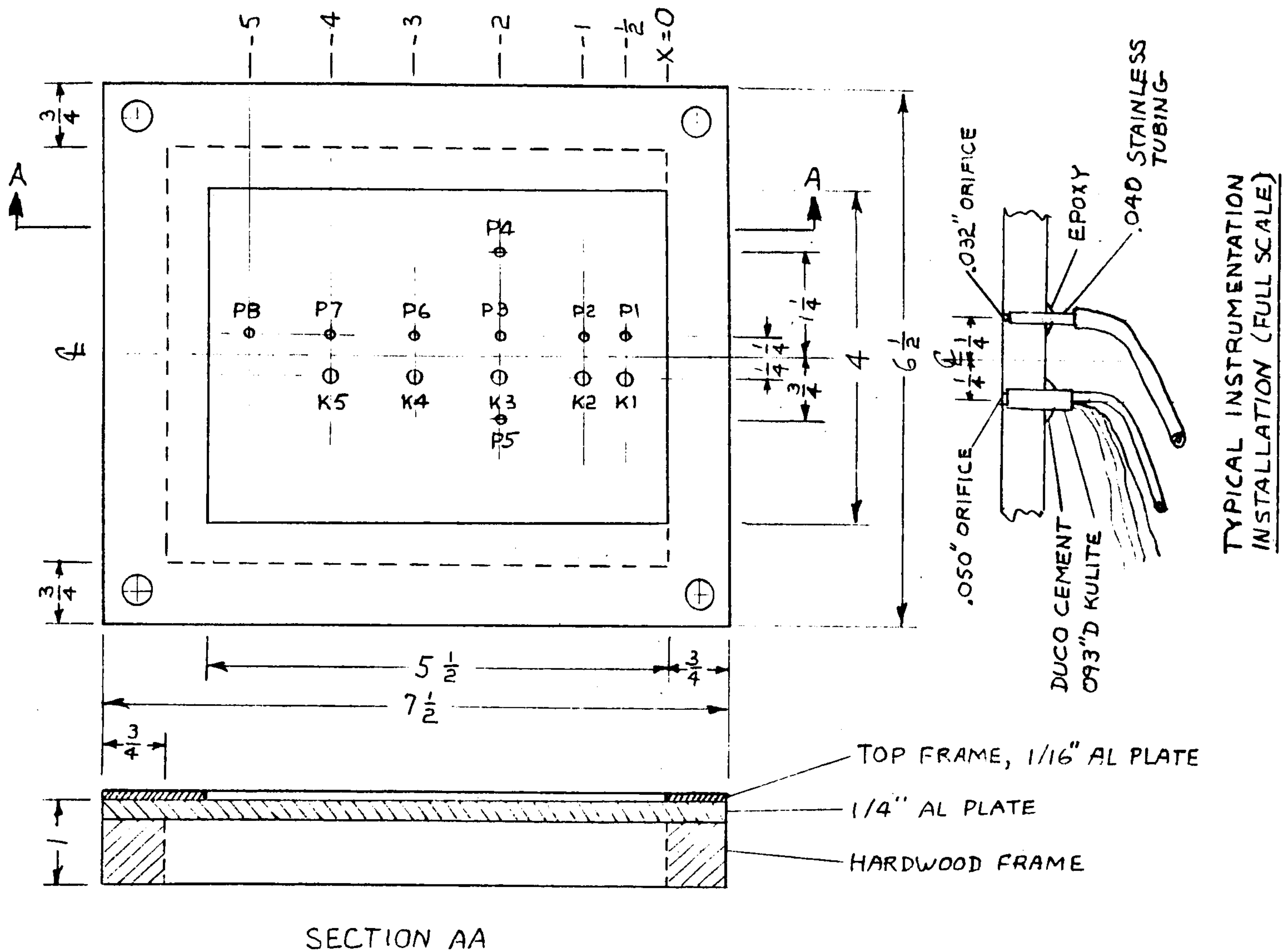


Figure 8. Sketch of calibration panel.

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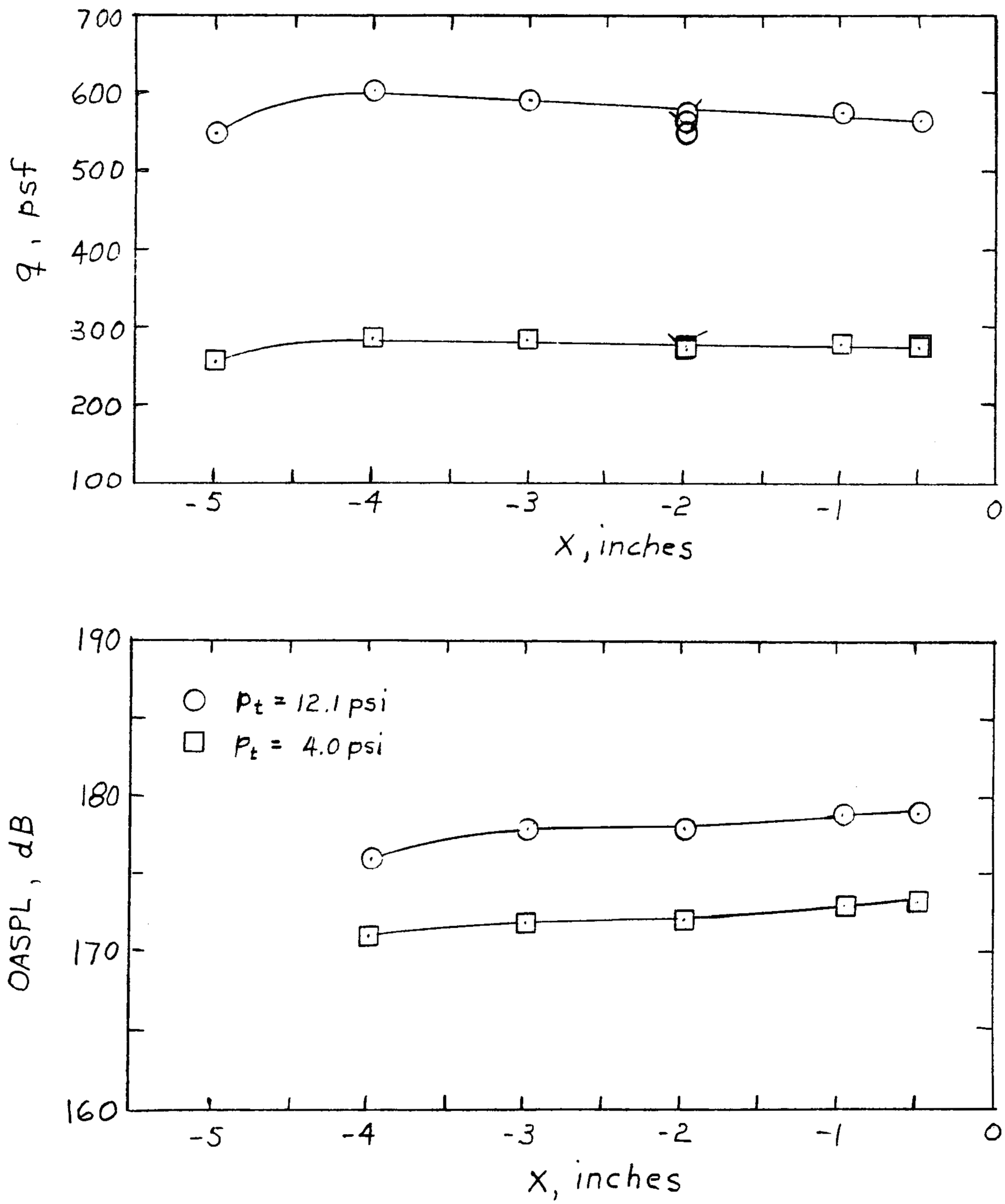


Figure 9. Estimated distributions of dynamic pressure (q) and overall sound pressure level (OASPL) on AFRSI test articles with excitation frequency at 200 Hz.

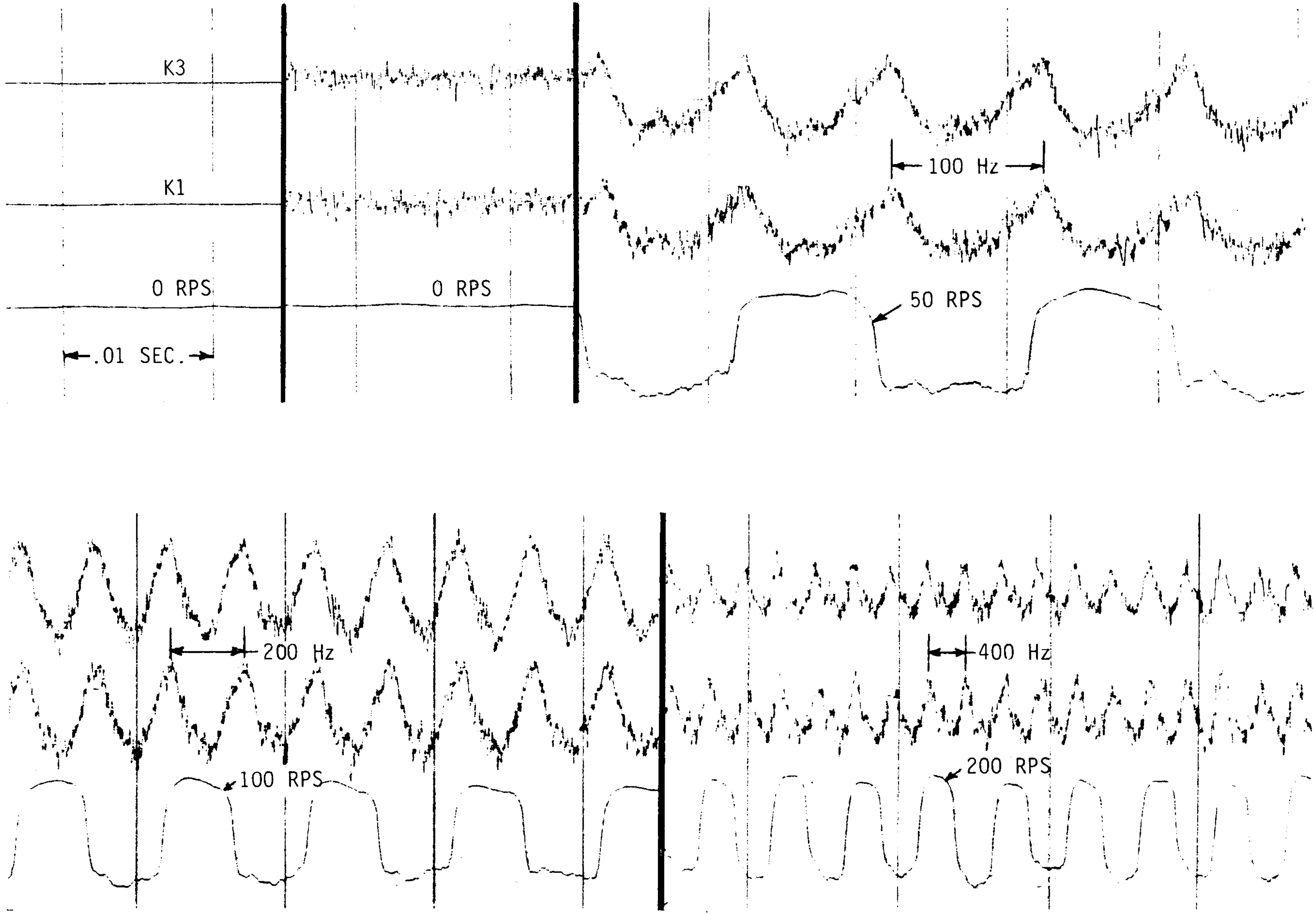
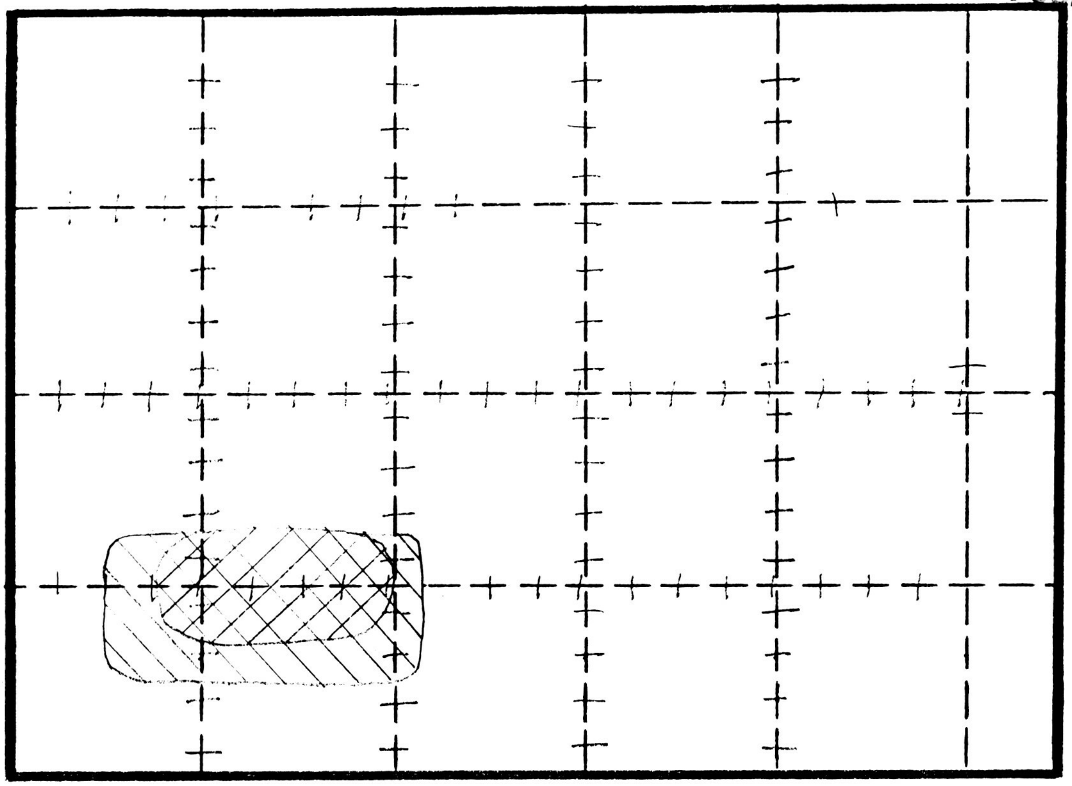
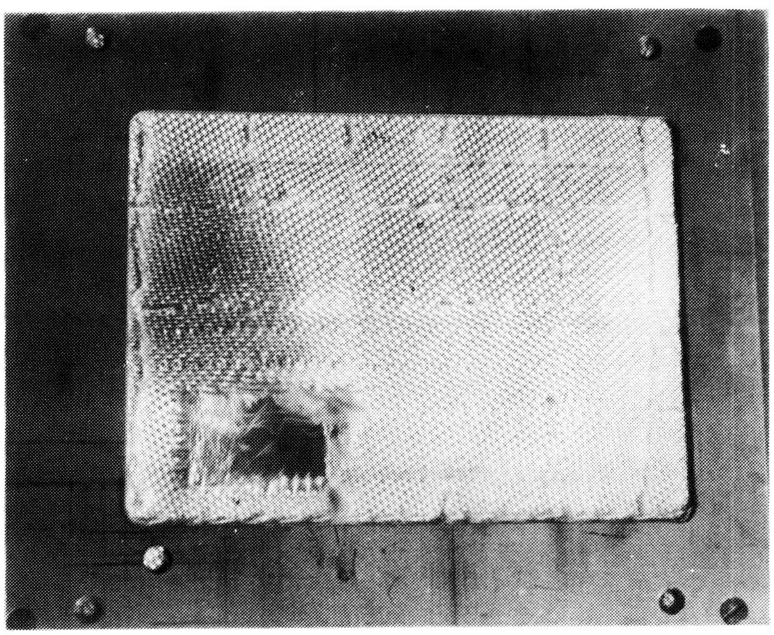


Figure 10. Examples of time histories of fluctuating pressures at $p_t = 4$ psi, $q = 280$ psf, for various rotor speeds.



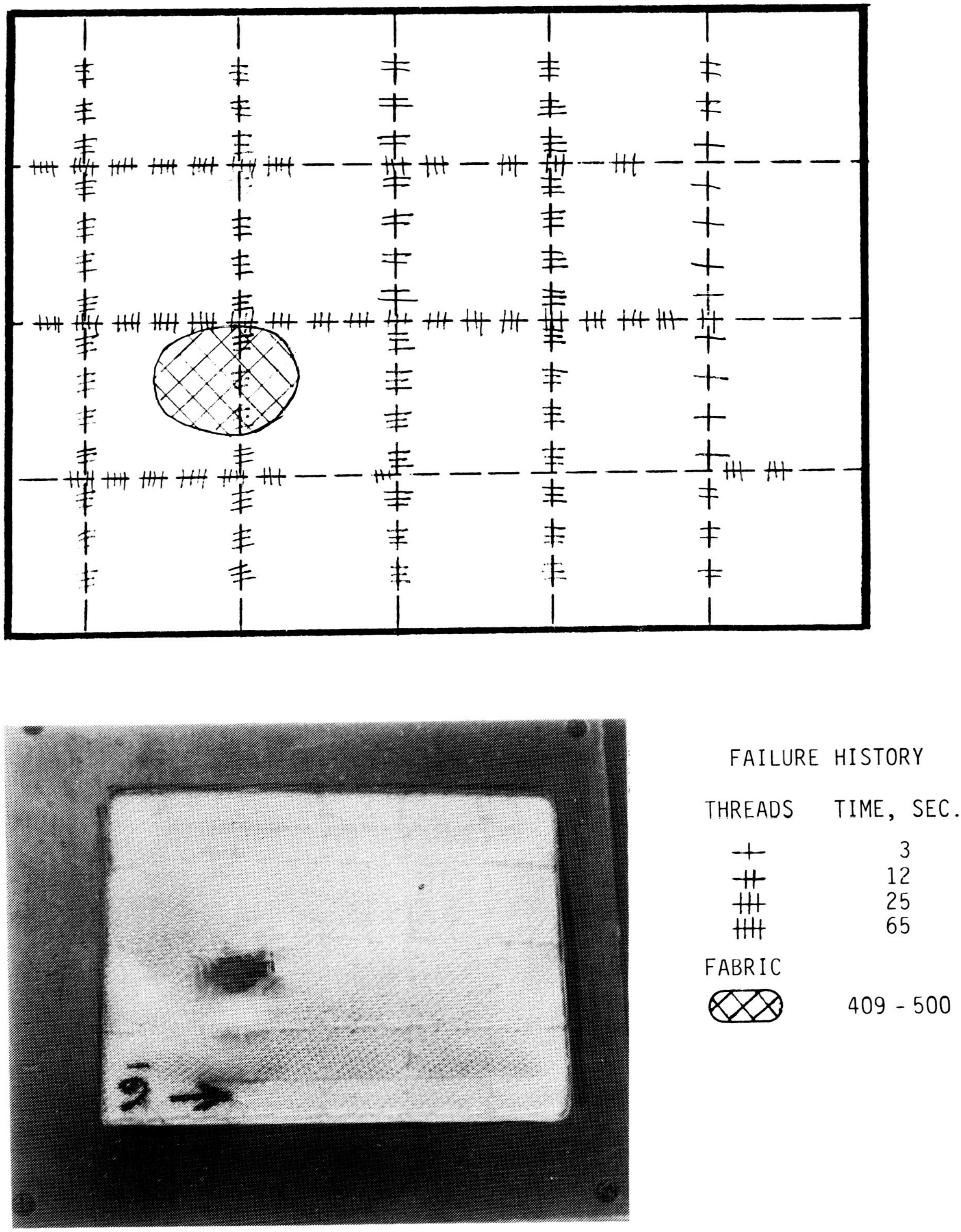


FAILURE HISTORY

THREADS	TIME, SEC.
+	5
FABRIC	
	95 - 120
	150 - 300

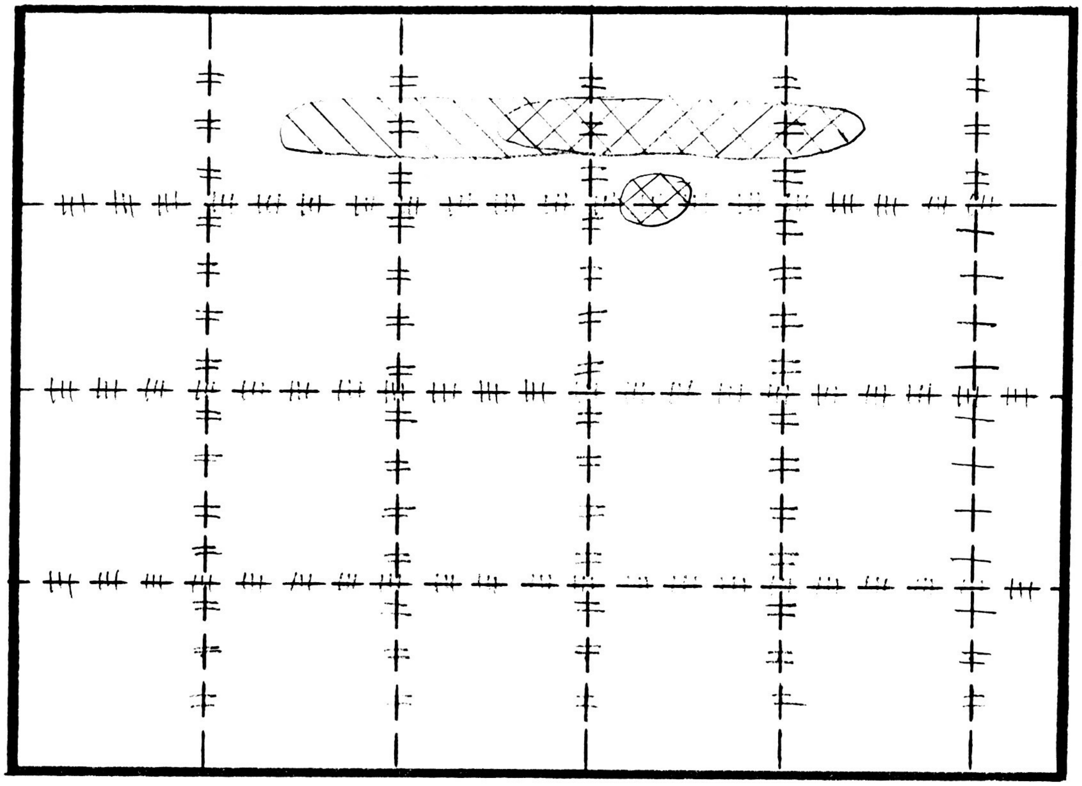
(a) Test article 3

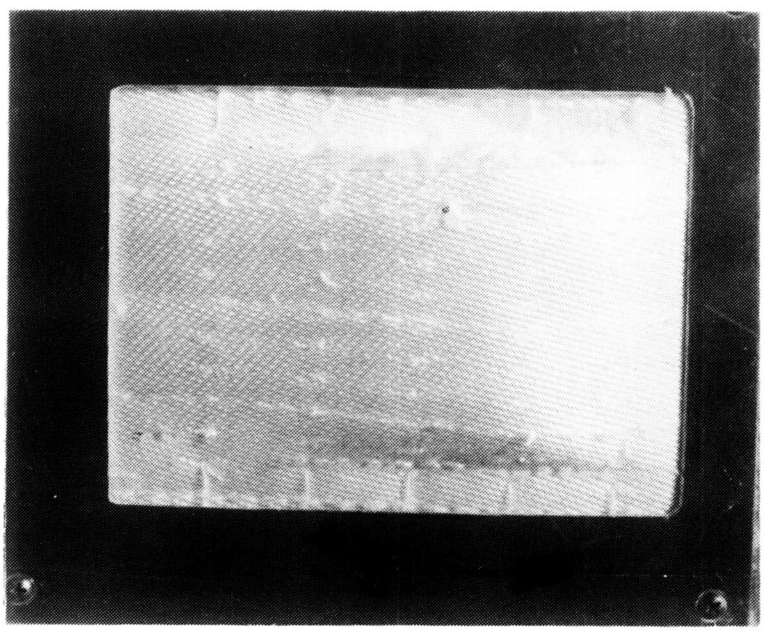
Figure 11. Examples of damage to heat-cleaned and entry-temperature preconditioned AFRSI after exposure to $q = 280$ psf and $f_E = 200$ Hz.



(b) Test article 6

Figure 11. Continued.



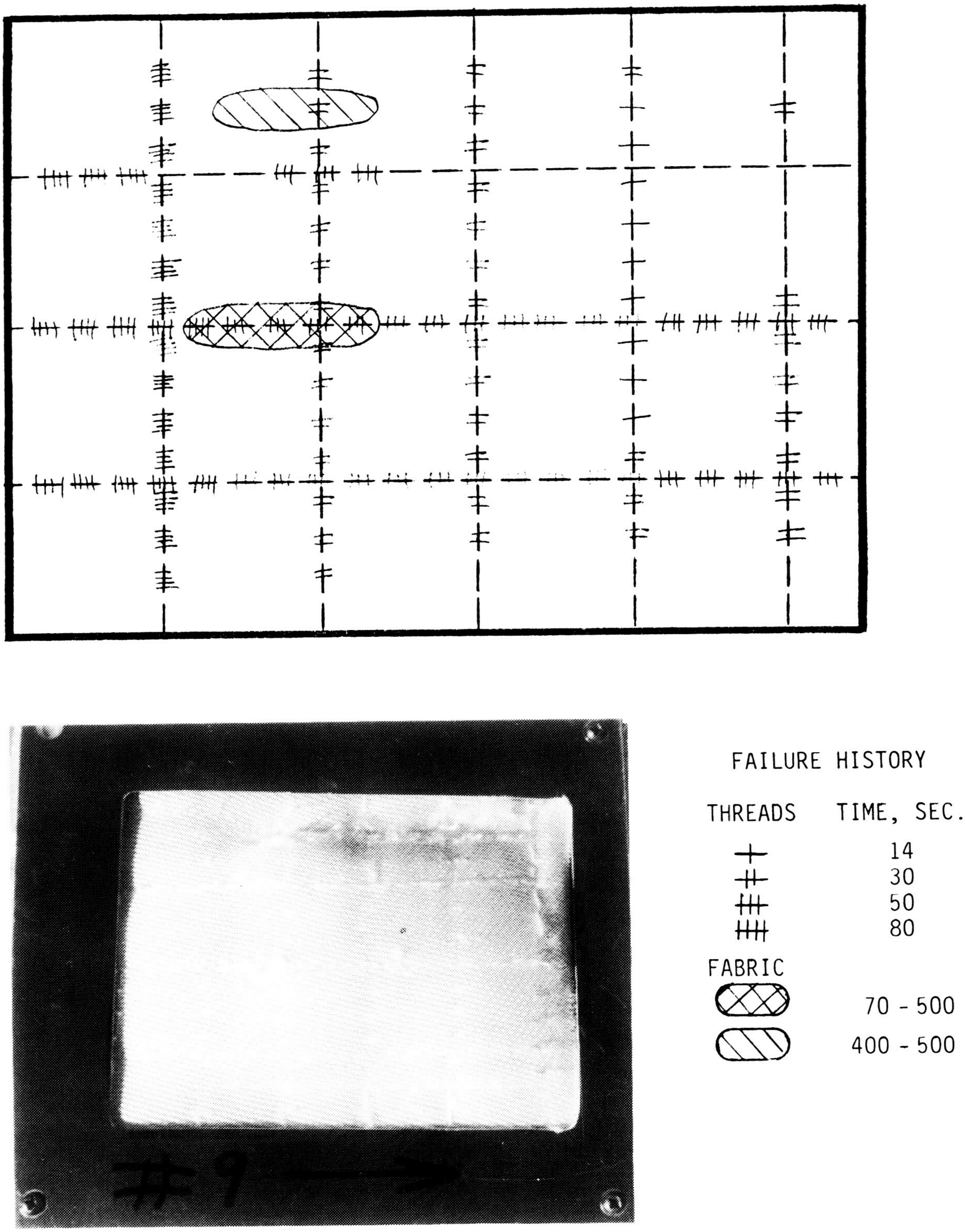


FAILURE HISTORY

THREADS	TIME. SEC.
┼	5
╫	25
╫╫	35
FABRIC	
(cross-hatched)	125 - 500
(hatched)	225 - 500

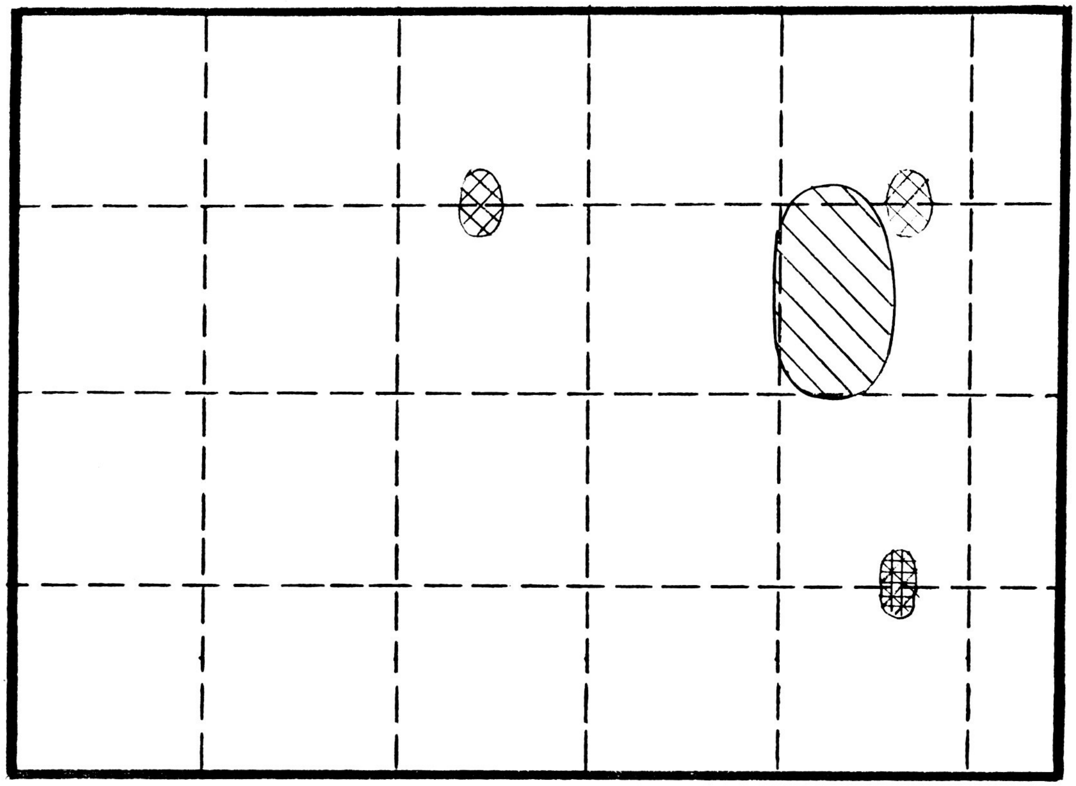
(c) Test article 8

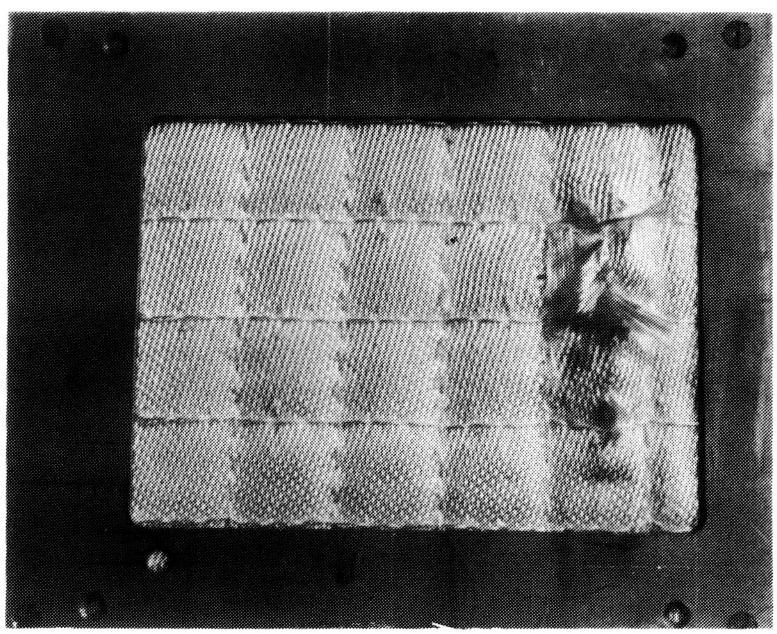
Figure 11. Continued.



(d) Test article 9

Figure 11. Concluded.

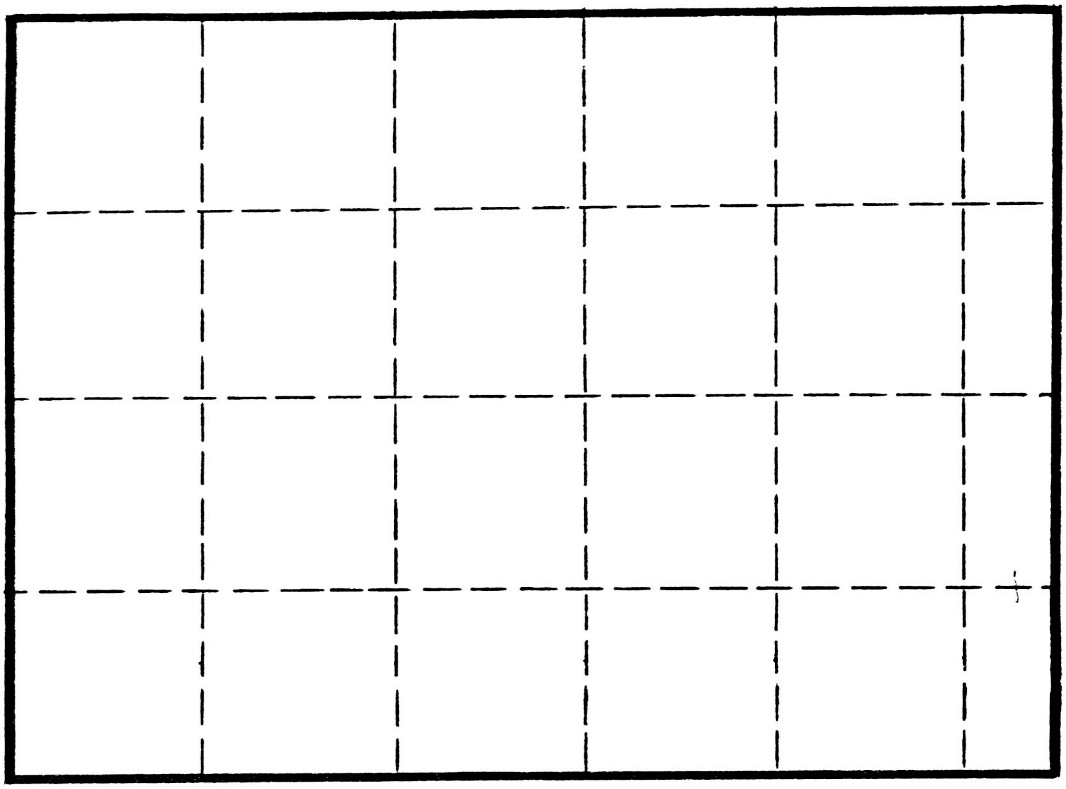


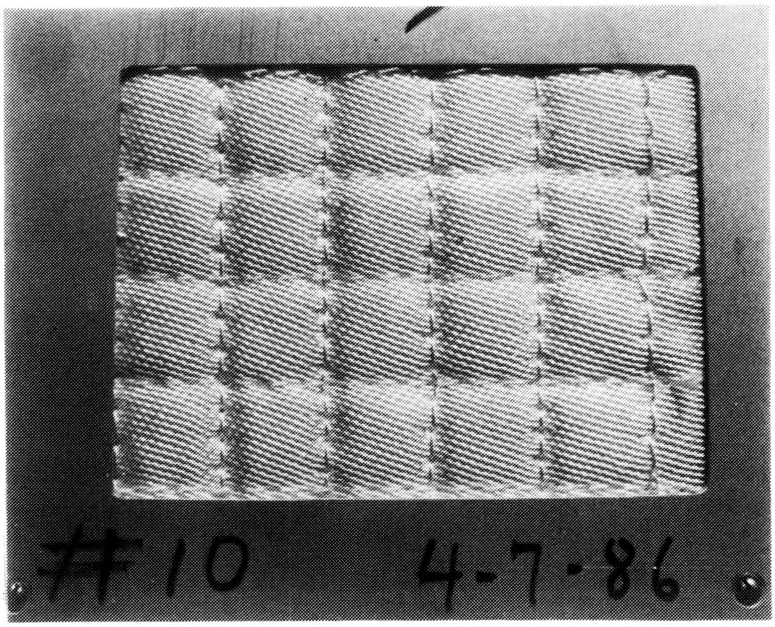


FAILURE HISTORY

FABRIC	TIME, SEC.
	14 - 500
	112 - 500
	200 - 500

Figure 12. Heat-cleaned AFRSI without entry-temperature preconditioning after exposure to $q = 280$ psf and $f_E = 200$ Hz.

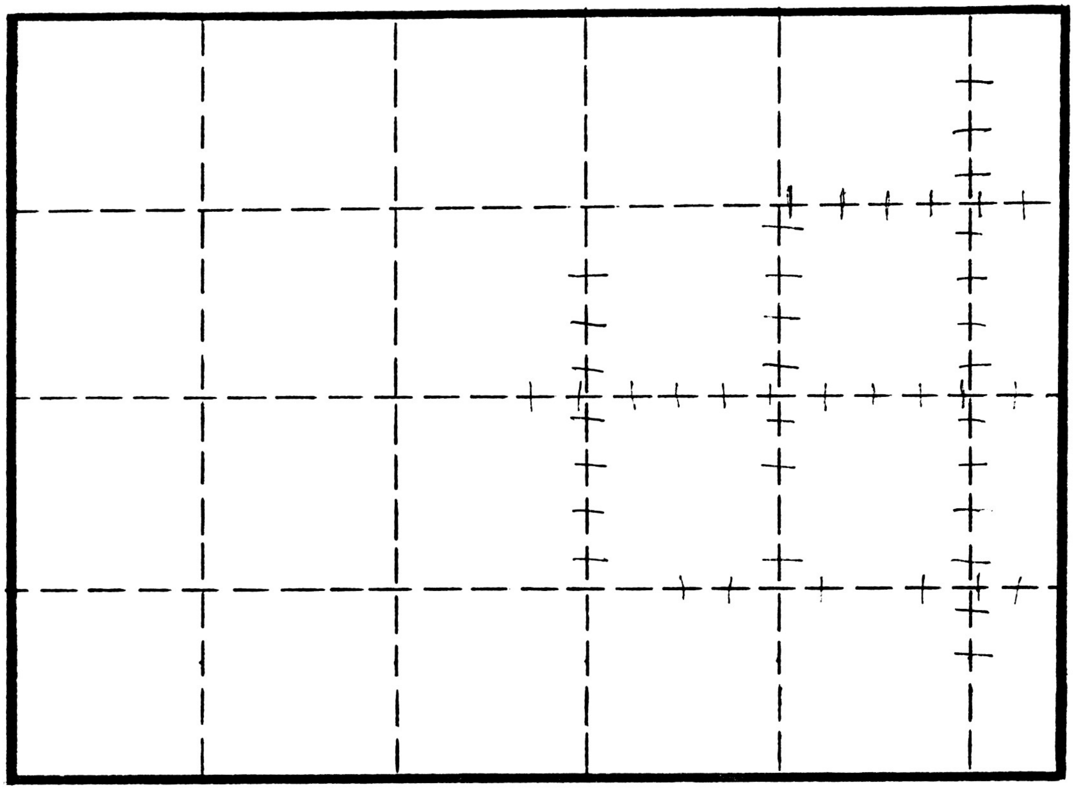


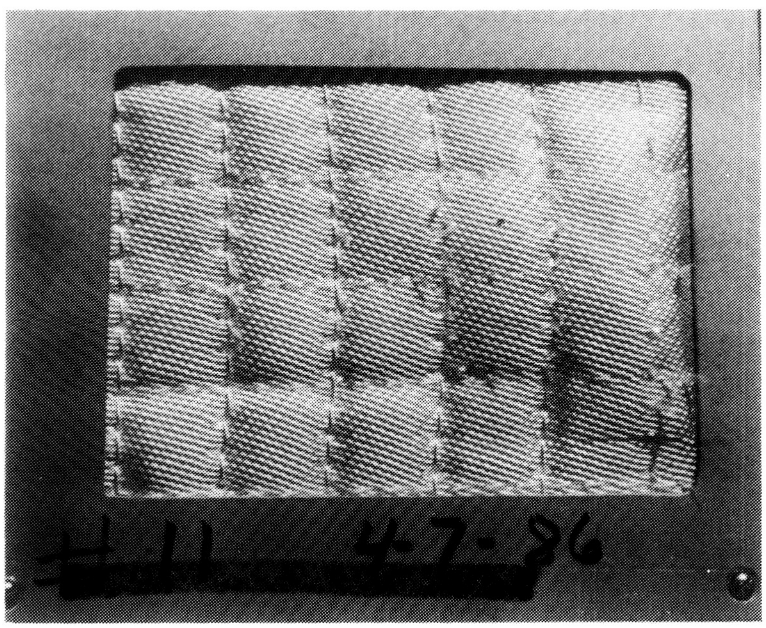


FAILURE HISTORY

THREADS	TIME, SEC.
+	500

Figure 13. Heat-cleaned and entry-temperature preconditioned AFRSI after exposure to $q = 280$ psf and $f_E = 0$ Hz.





FAILURE HISTORY

THREADS	TIME, SEC.	RPS
+	2	100
+	2 - 500	0

Figure 14. Heat-cleaned and entry-temperature preconditioned AFRSI after 2-second exposure to $f_E = 200$ Hz followed by 498-second exposure to $f_E = 0$ Hz, $q = 280$ psf.

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16. Abstract

Tests of small panels of advanced flexible reusable surface insulation (AFRSI) were conducted using a small wind tunnel that was designed to simulate Space Shuttle Orbiter entry mean-flow and pulsating aerodynamic loads. The wind tunnel, with a 3-inch wide by 1.75-inch high by 7.5-inch long test section, proved to be capable of continuous flow at dynamic pressures q near 580 psf with fluctuating pressures over 2-psi RMS at an excitation frequency f_E of 200 Hz. For this investigation, however, the wind tunnel was used to test entry-temperature preconditioned and heat-cleaned AFRSI at $q = 280$ psf, $p_{rms} \approx 1.2$ psi and $f_E = 200$ Hz. The objective of these tests was to determine the mechanism of failure of AFRSI at Orbiter entry conditions. Details of the test apparatus and test results are presented in the report.

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