REPORT NO. FAA-NO-70-13

AD723112

AN EXPERIMENTAL STUDY TO DETERMINE THE EFFECTS OF REPETITIVE SONIC BOOMS ON GLASS BREAKAGE

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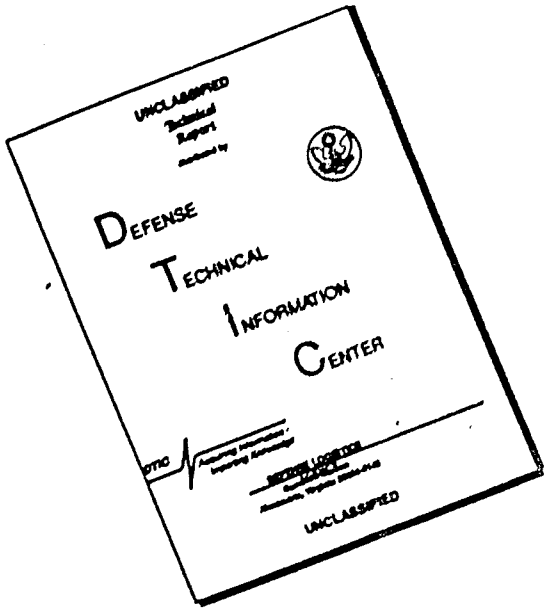

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TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FAA-NO-70-13		

4. Title and Subtitle	5. Report Date
AN EXPERIMENTAL STUDY TO DETERMINE THE EFFECTS OF REPETITIVE SONIC BOOMS ON GLASS BREAKAGE	June 1970
	6. Performing Organization Code: Copy No. 45
7. Author(s): George C. Kao	8. Performing Organization Report No.: WR 70-11
9. Performing Organization Name and Address: Wyle Laboratories - Research Staff, 7800 Governors Drive, West, Huntsville, Alabama 35807	10. Work Unit No.
	11. Contract or Grant No.: FA69WA-2204
12. Sponsoring Agency Name and Address: Department of Transportation, Federal Aviation Administration, Office of Noise Abatement, Washington, D.C. 20590	13. Type of Report and Period Covered: Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes

Details of illustrations in this document may be better studied on microfiche

16. Abstract

A pneumatic pistonphone simulator, developed by Wyle Laboratories, was used under the present contract to experimentally determine damage potential to single strength glass specimens when exposed to repetitive sonic booms. The glass specimen dimensions were typically 48" x 48" x 3/32". In these experiments, particular emphasis was placed on the cumulative damage from a large number of booms. Preliminary static strength tests were conducted on two sizes of new (previously unused) single strength glass to determine mean values and probability distributions of incipient failure pressures, and a few such tests were also conducted for used (scratched and weathered) glass specimens. As a by-product, these tests yielded data regarding nonlinear stiffness characteristics of glass panes and the effects of boundary conditions on this stiffness. Although the test data are limited, results indicate that sonic boom overpressures required to cause incipient failure are nearly comparable to static failure pressures, and the probability of glass failure at realistic sonic boom overpressures is quite small for properly mounted new glass. Further experiments will be required to validate and extend these results. A preliminary glass neighborhood survey was conducted to determine breakage rates under natural environments; however, because of the small sample size, the glass breakage statistics obtained were of limited value in formulating a realistic breakage probability model. A more comprehensive, national glass neighborhood survey is required.

17. Key Words	18. Distribution Statement
Simulation - Sonic Booms - Glass Breakage - Neighborhood Survey - Cumulative Damage	Availability is unlimited. Document may be released to the Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia 22151, for sale to the public.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	88	$ 3.00

Form DOT F 1700.7 (8-69)

PREFACE

The development of the research study, implementation of the test program, and collection of the information and data presented in the report represent a team effort of the Wyle Laboratories Research Staff. The responsibilities of the participating personnel were as shown:

- Mr. R.W. White - Program Manager: Static Test Program
- Dr. G.C. Kao - Principal Investigator: Sonic Boom Test Program
- Mr. F.M. Murray - Development of Sonic Boom Simulator Criteria
- Mr. J.A. Cockburn - Structural Response Studies
- Mr. V.M. Conticelli - Review of Sonic Boom Signatures
- Mr. R.C. Gray - Glass Neighborhood Survey

Acknowledgements

Thanks are extended to Mr. K.M. Eldred, Technical Director of Wyle Scientific Services and Systems (SSS) Group, for his criticisms and encouragement during various phases of the operations; to Mr. J.O. Bowman, Manager, Research Operations, for the management support; and Mr. N.E. Esslinger for implementing test programs.

Appreciation is also extended to Dr. J. Powers, Mr. K. Power, and Mr. S. Oleson of the Noise Abatment Office of FAA for many helpful discussions and guidance during the course of the program.

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1.0 INTRODUCTION

Only limited information is available concerning the probability of glass or glass windows being damaged by sonic booms. Planned experiments and accidental booms have indicated that glass windows can be one of the more damage susceptible building materials in the sonic boom environment. Without conclusive valid data, one could suspect that overland supersonic flights would result in significant increases in glass damage. Further, the validity of any damage claim attributed to sonic booms would be extremely difficult to access. This is especially true concerning sonic boom created damage versus common glass damage due to accidents and natural environments such as wind, temperature fluctuations and general overloading.

The lack of information available concerning the above problem area shows that research is necessary to technically assist in planning flight patterns and operational procedures for supersonic aircraft. Overflight experiments are costly, time consuming, and disruptive to the general public; hence, it would be a significant step forward if the sonic boom environment could be confined to a laboratory and simulated by relatively inexpensive techniques. In this way, numerous windows could be exposed and statistically analyzed for their damage potential within such an environment. This approach requires the development of sonic boom simulators within which a test specimen can be mounted in a realistic manner and subjected to an N-wave overpressure pulse that is characteristic of sonic booms. Several such simulators are in existence, and each has its own peculiar advantages and disadvantages. In an attempt to further the state-of-the-art, Wyle Laboratories has developed a small inexpensive simulator which operates on a unique principle, and which can subject glass windows up to 4 feet by 6 feet to an unlimited number of sonic booms of various wave forms with a few seconds duration between booms. Details of the Wyle sonic boom simulator are presented in Section 2.0 so that its application to this program can be understood.

In order to determine acceptable waveforms for testing, a comprehensive literature survey was conducted to review available information on sonic boom signatures and the related structural response problems. From the result of the survey, it was concluded that the controlling factors affecting glass failure are the overpressure magnitude, the wave duration and rise time. The determination of sonic boom waveforms used in the test program is given in Section 3.0. In Section 4.0, the test program used to conduct exploratory static and sonic boom testing on glass specimens is described. The static testing was performed on 35 specimens with typical dimensions of 20" x 20" x 3/32" and 30 specimens with typical dimensions of 48" x 48" x 3/32". The objective here was to determine the distribution of failure strengths and to determine the correlation of static strengths and the overpressure levels used in the sonic boom testing. A total of six panes of used glass were also tested statically to evaluate the effect of aging on glass strengths. The sonic boom testing was performed on 48" x 48" x 3/32" specimens only. These tests were confined to specimens mounted on a wooden frame. A total of 8 successful tests were performed by employing repetitive N-wave loadings.

A local (Huntsville, Alabama) glass neighborhood survey has conducted and an extensive review made of existing published data on glass breakage. The results of these studies

have shown that it is not feasible to formulate valid statistical prediction techniques for normal glass breakage. Information concerning glass breakage is summarized in Section 5.0. Finally, the conclusion drawn from the results of the present study are summarized in Section 6.0.

2.0 DESCRIPTION OF WYLE SONIC BOOM SIMULATOR

2.1 Design Criteria

Although the Wyle simulator was designed and developed to expose large panels to various pressure fluctuations over a large range of frequencies (down to 0 Hz) the description presented here is applicable to use in producing transients. The following operational criteria were considered in design for sonic boom simulation mode:

- Internal fixturing for test specimen support should be variable so that test specimens may have arbitrary geometry, edge mounting conditions, and size (up to 4' x 8' rectangular window).
- Cavity stiffness of the closed volumes on either side of the test specimen should be small relative to the bending stiffness of the test specimen.
- Simulated overpressures should be reasonably uniform over the surface of one side of the test specimen.
- The overpressure time history for a single simulated sonic boom should consist of a symmetrical N-wave with rise times of less than 10-20 milliseconds.
- The amplitude and duration of a simulated N-wave should be variable throughout the ranges of 1.0-100 psf and 50-400 milliseconds, respectively.
- The system should be capable of generating a continuous train of N-waves having the same amplitude and period, and having a constant time between N-wave pulses.

2.2 Structural Configuration

The sonic boom simulator is contained within a steel pressure vessel that has a cylindrical main section with shallow spherical end caps. The cylindrical section has a length of 9.0', a diameter of 7.0', and is constructed of 1/4" steel. The rear end cap is permanently welded to the cylinder; while the hinged front end cap acts as a door and is attached to the cylinder through a reinforcing ring by means of 24 high strength steel bolts. Under normal operating conditions, ambient internal pressure levels may range between 3 to 10 psi; and hence the containment vessel was designed to ASME codes and was proof tested to 45 psi.

Internally, the simulator is divided into three cavities by means of two bulkheads that extend along the full length of the cylindrical tank. The largest of these three cavities, referred to as cavity number 1, is shown in the photograph in Figure 2-1, which is a view looking aft through the open front door. As shown in the photograph, the left-hand side of cavity number

1 is bounded by a heavy vertical steel bulkhead that contains a 4.5' x 6.5' rectangular opening for mounting of test specimens. The other two cavities, which are referred to as cavities number 2 and 3, are located behind the flat bulkhead. These cavities can be seen in the cross-section drawing in Figure 2-2, which is a view looking toward the door opening. The small 58 cubic foot central cavity number 2 is the active pressure cavity within which sonic boom overpressure signatures are generated. The large water-filled cavity number 3 was introduced for the sole purpose of reducing the volume of number 2, and a water medium is employed to minimize vibration response of the 1/4-inch steel bulkhead which separates cavities 2 and 3.

The central bulkhead that supports the test specimens is designed to be very rigid so that vibrations of this bulkhead are minimized during sonic boom generation. This high lateral stiffness is achieved with shear plates that can be seen in Figure 2-1. With minor modifications, which do not effect the basic strength of the containment vessel, the rectangular opening in this bulkhead can be increased to 6' x 8' to accommodate larger test specimens. For smaller test specimens, the existing opening can be reduced in size by the addition of reinforced plywood panels. The fill-in panels used in the test program consisted of 2" thick plywood slabs bounded on both sides by 1/4-inch aluminum plates. These plywood panels, which are also used for calibrating sonic boom signatures, along with the test specimen frame are bolted to a steel angle that is welded to the interior periphery of the rectangular opening as shown in Figure 2-1.

When the panels and test specimen are in-plane, the central bulkhead provides a pressure seal between cavities 1 and 2. At the top of the simulator there are two pipe penetrations through the containment vessel. One of the pipes is connected to an air compressor which feeds high pressure air into the simulator; while the other pipe is used for exhausting air from the simulator into the outside atmosphere. Airstream modulation valves, which control the flow of air into and out of the simulator, are attached to the two pipe penetrations on the interior of the simulator. A photograph of these valves is shown in Figure 2-3.

During operations, the simulator is closed and cavities 1 and 2 are maintained at an ambient pressure level of about 3 psi. Ambient pressure equalization between cavities 1 and 2 is maintained by a small hand-valve. The flow rate through this valve is sufficiently small so that transient overpressures generated in cavity number 2 are not equalized in cavity number 1.

2.3 Airstream Modulation Valve

The Wyle patented airstream modulator valve is essentially a vibrating vane air valve which regulates large volumes of air at moderate pressure levels. The valve has a switching time capability within one or two milliseconds. The device is normally operated with a continuous input air flow to produce high intensity acoustic energy. Modulation is accomplished through rapid interruption of the airstream by a moving coil and a valve having sufficient stiffness to assure constant displacement characteristics throughout the valve's operating range. The basic units of the valve are shown in Figure 2-4 which is an exploded view of the entire assembly without the aluminum supporting frames. This figure shows the entire armature with its voice

coil, modulation slots, suspension slots and finally a solid ring at the top which serves as an attachment surface. This entire unit, excluding the voice coil, is machined from a single piece of aluminum tubing. The modulation slots are cut around the periphery of the armature so that the axial motion of the voice coil against the suspension will vary the openings formed by the two sets of slots in the armature and stator. The width of each slot is chosen to match the maximum allowable displacement of the suspension. The suspension stiffness is chosen to properly load the capabilities of the voice coil Thus, all the elements of the armature are strongly interdependent.

It may be seen that air pressure applied to either the inside or the outside of the armature would cause air to pass through the various slots cut in it. The stator, mounted inside the armature, has no spring slots and therefore prevents air from flowing through, but it does have an identical set of modulation slots. The stator and armature are mounted such that the beams between the modulation slots of the armature cover exactly half of the slots of the stator and vice versa. This condition is permanently set at the factory so that no misalignment of these two sets of slots can occur in the field. Thus, it may be seen that motion of the voice coil causes the area of the modulation slots to increase or decrease depending upon the polarity of the input electrical signal to the voice coil. This action breaks the airstream into pulses of air. These pulses may then be translated into pressure pulses inside the simulator.

2.4 Principles of Operation

The shaping of N-waves in the simulator is achieved by modulating the airflow through the two airstream modulating valves (the inlet and outlet valves) under a constant compressor pressure. The arrangement of various mechanical and electrical elements employed in the operation are illustrated in Figure 2-5. The air supplied to the simulator is provided by the compressor and is regulated by the inlet valve, while the venting of the compressed air into outside atmosphere is controlled by the outlet valve.

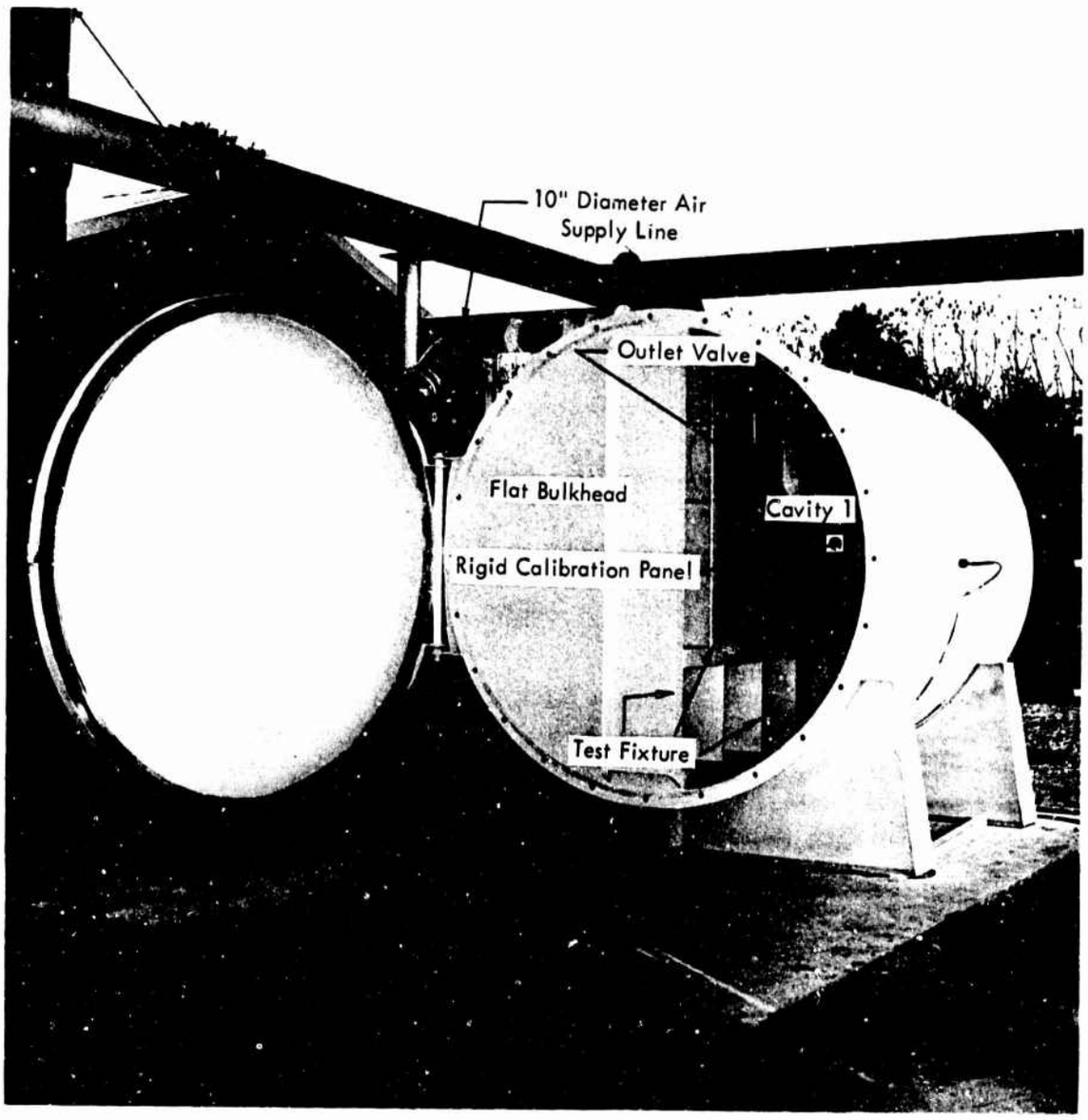


Figure 2-1. Side View of Interior of Sonic Boom Simulator

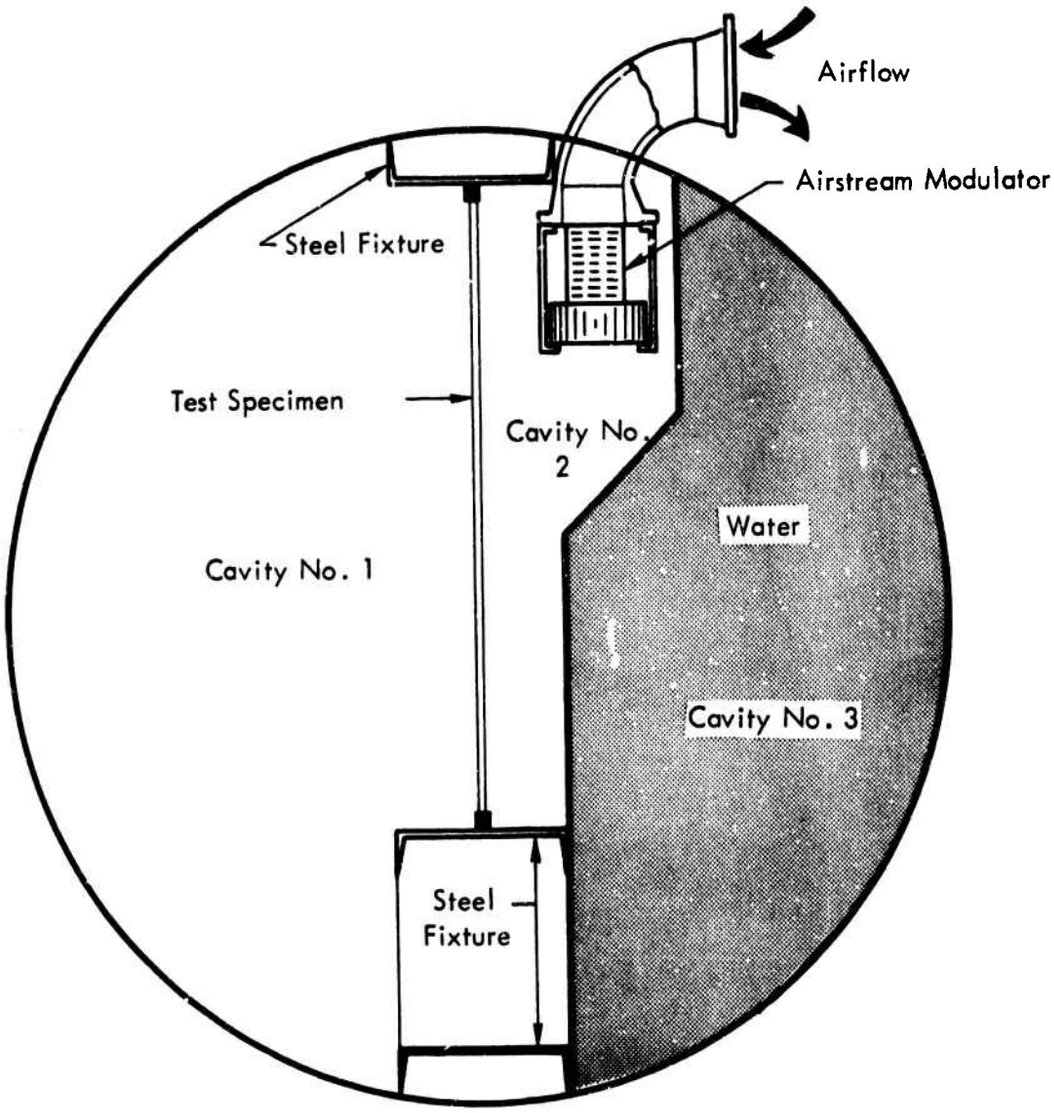


Figure 2-2. Cross-Section of Sonic Boom Simulator Showing Three Interior Cavities

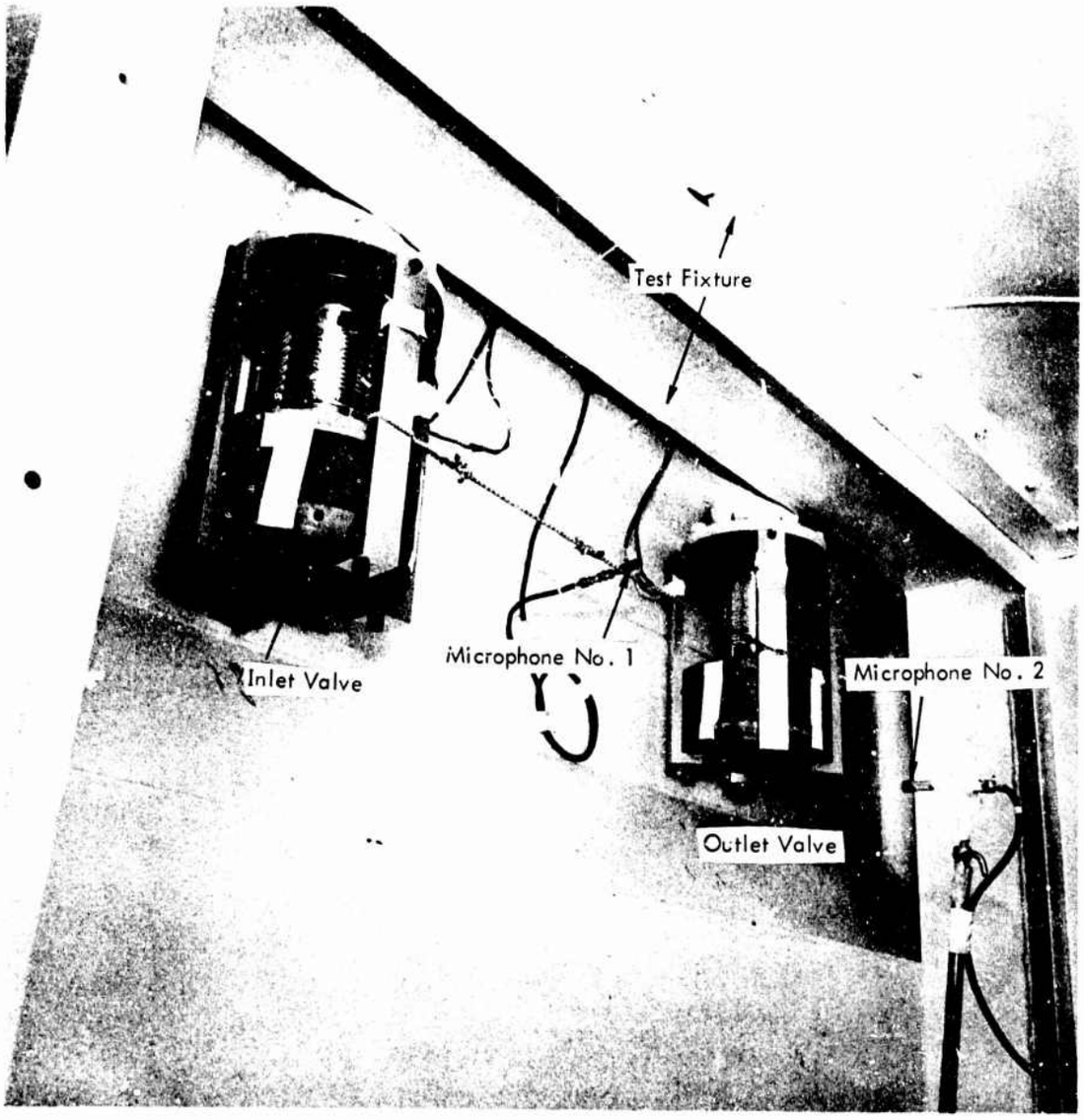


Figure 2-3. Interior View of Sonic Boom Simulator Showing Inlet and Outlet Air Flow Valves

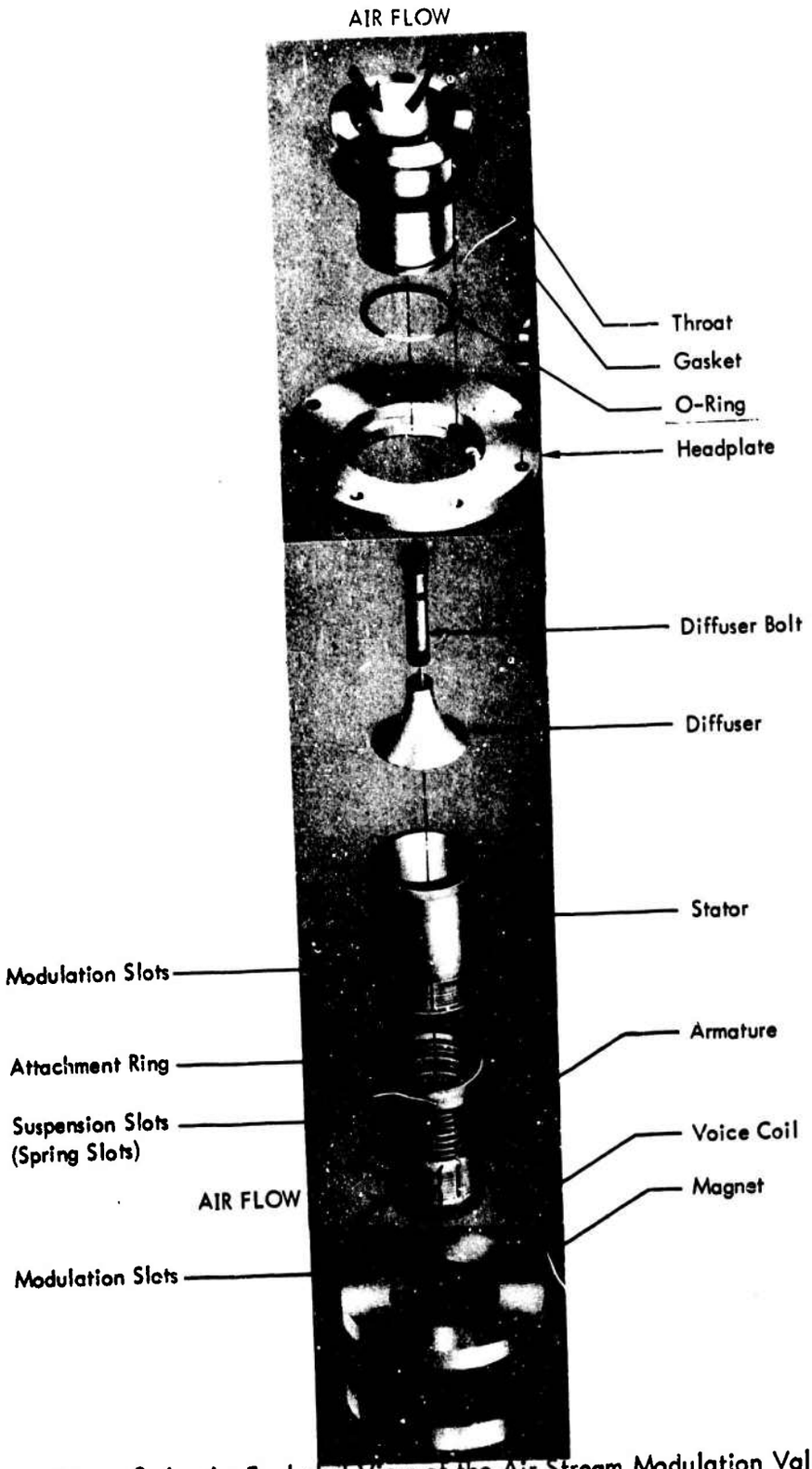


Figure 2-4. An Exploded View of the Air Stream Modulation Valve

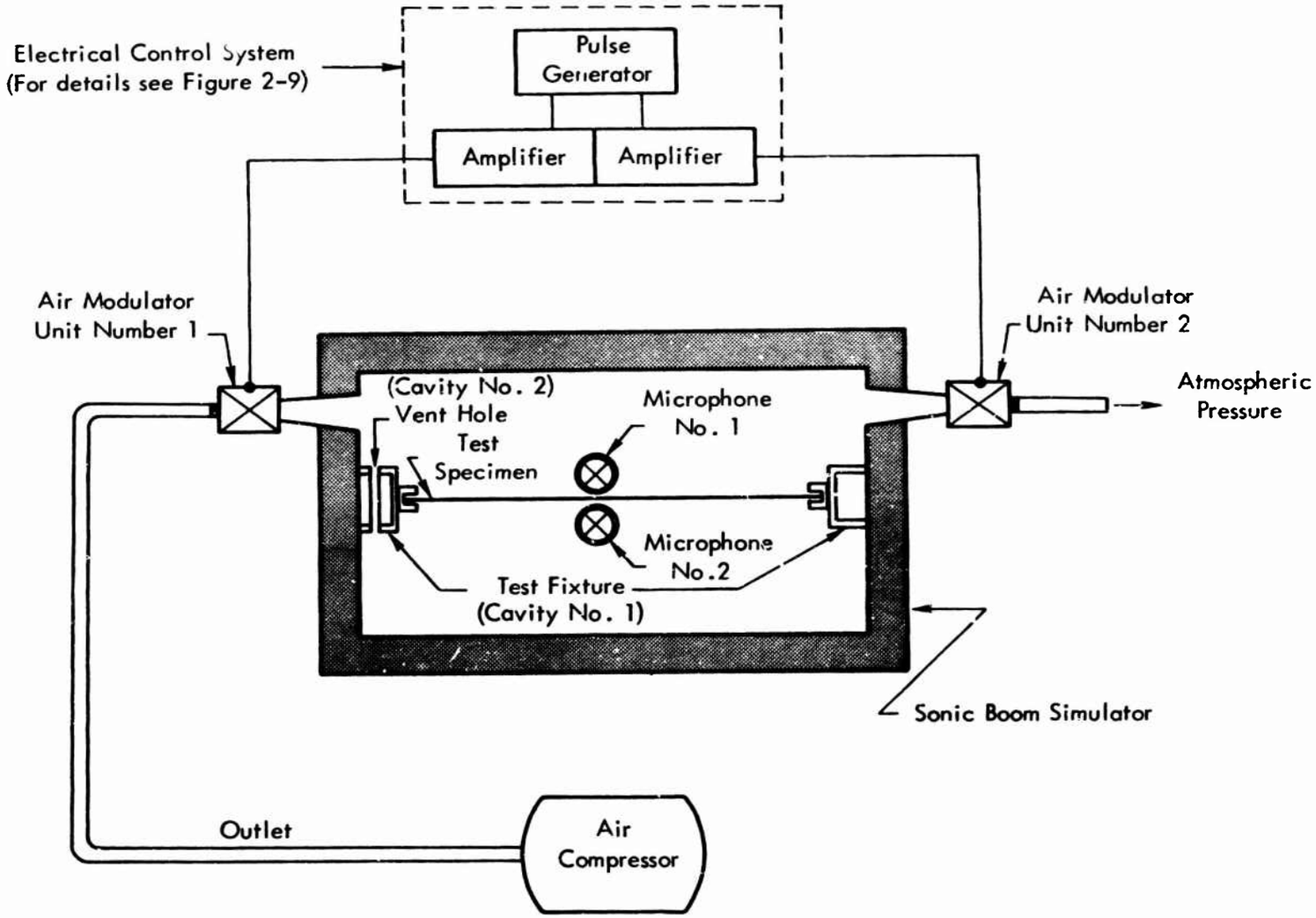


Figure 2-5. Schematic Circuit of Glass Testing Facility

The essential part of the entire waveform synthesizing cycle is the shaping of the electrical control signals used to generate a series of rapid interruptions of airflow through the valves. The electrical system which controls the open-and-close sequence of the valves are shown in Figure 2-6, and the corresponding control signals used in the simulating process are shown in Figure 2-8. Figure 2-7 lists the instrumentation used throughout the test program.

The input signal, which controls the inlet valve, consists of two half-sine pulses (Figure 2-8 (a)). The pulse widths determine the total opening duration of the valve and therefore regulate the rate and the total amount of air to be supplied to the simulator. The input signal which controls the outlet valve (Figure 2-8 (b)) is shaped in a manner such that the combined operations of the two valves would render the desirable acoustic waveforms.

Generally, the sonic boom synthesizing operations involve four sequential stages described as follows:

- Stage 1 - Generation of Steady State Pressure, P_a, in the Simulator
- Stage 2 - Generation of Positive Overpressure, ΔP, Relative to P_a
- Stage 3 - Generation of Negative Overpressure, ΔP, Relative to P_a
- Stage 4 - Repressurization to P_a

The four-stage operation can be represented diagramatically as shown in Figure 2-9, and the details of the operations are described in the following paragraphs.

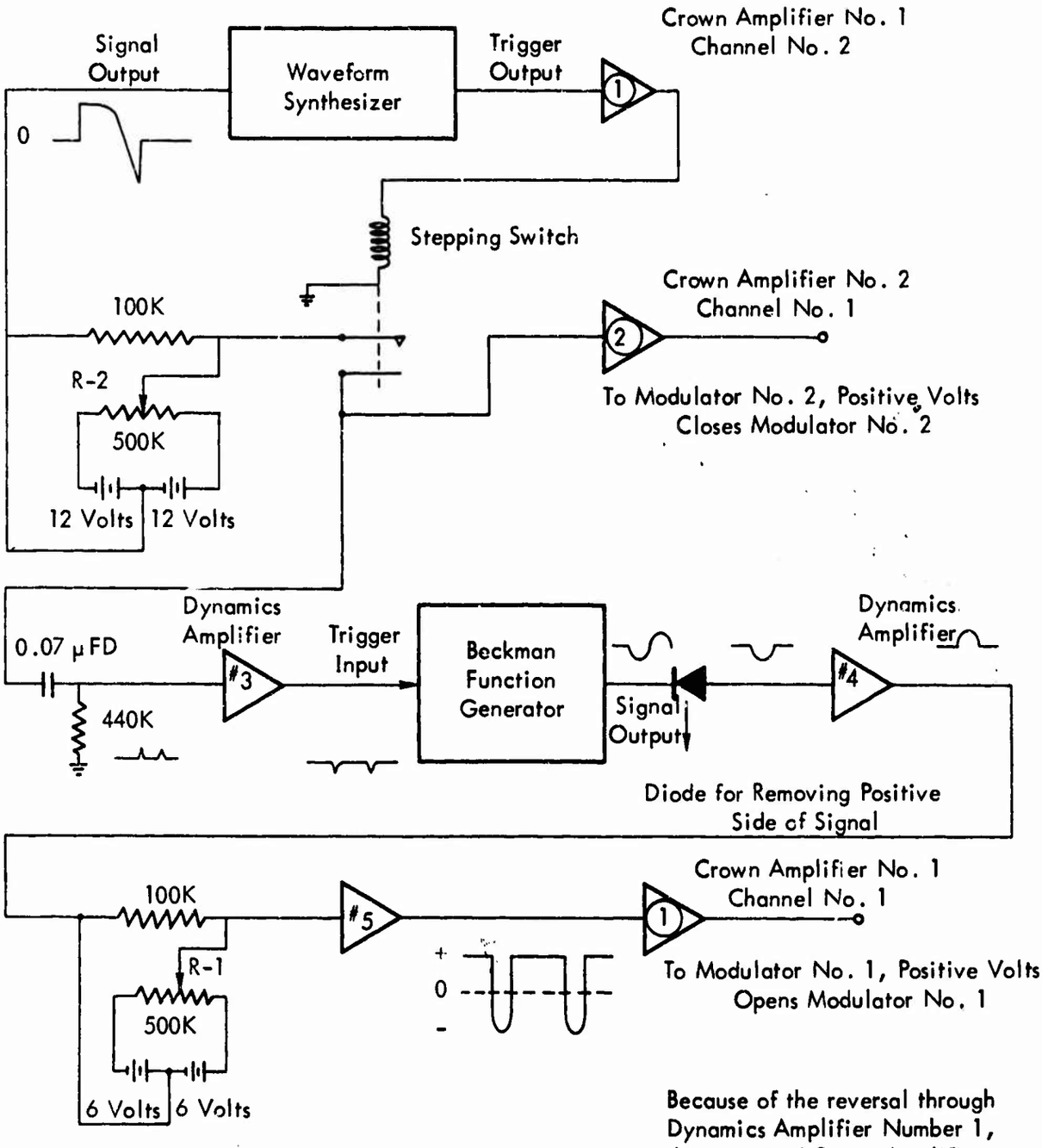
Stage 1: Generation of Steady State Pressure, P_a – At the initial stage of the operation, the outlet valve is completely open; the inlet valve is partially closed to allow only a small amount of air leakage into the simulator; and the compressor is operating under a constant line pressure, P_ℓ. The operations would permit the static pressure inside the simulator to maintain a very low level so that a very high pressure differential can be established across the inlet valve to allow rapid build-up of various overpressure levels. Since airstream modulating valves are designed to have 50 percent openings under no-load conditions, it is necessary to apply certain d.c. voltages to close and open the respective valves to achieve the required initial condition. This is illustrated in Figure 2-9, in which the voltages $+V_1$ and $-V_3$ are applied to the inlet and outlet valves, respectively.

Stage 2: Generation of Positive Overpressure, $+\Delta P$ – The operations required in this stage are (see Figures 2-9 and 2-10):

a) to close the outlet valve completely, and

b) to open the inlet valve with a half-sine pulse.

Both actions are initiated at time t_0.



R-2 - Adjust for "0" volt DC into Modulator No. 2

R-2 - Adjust for -2 volts DC with positive pulses that reach +2 volts DC at their peaks.

Because of the reversal through Dynamics Amplifier Number 1, the output of Crown Amplifier Number 1, Channel 1 has to be revised so as to produce the correct polarity into Modulator Number 1.

Figure 2-6. Instrumentation Block Diagram for the Electrical Control System

ITEM	MFG.	MOD. NO.	DESCRIPTION
Waveform Synthesizer	Exact Electronics	200	Provides from 10 to 100 individual and independent bits or incremental voltage levels, completely controlled in slope, amplitude and width.
DC Power Amplifier	Crown	DC-300	Dual channel, 300 watt amplifier with frequency response - DC to 20 K Hz.
DC Amplifier	Dynamics	4550	Single ended, high crurent amplifier ± 100 MA output current with gains from 1,000 to 0.1 and continuous adjustment.
Function Generator	Beckman	9030	Laboratory type instrument, generates sine, square, triangular and saw-tooth waves to cover the frequency spectrum from .0005 Hz to 1 M Hz.
Microphone	Photocon Research	520	A 5 psi, 60 dB dynamic range acoustic transducer. Frequency response-DC to 20 K Hz.
Microphone Amplifier	Photocon Research	DG-60-5-D	A radio frequency oscillator coupled to a diode detector circuit. Frequency response - DC to 20 K Hz.
True rms Voltmeter	Ballatine	320	Voltage range - 100 microvolts to 320 volts in 13 ranges, total range of 130 dB. Frequency range 5 Hz to 500 K Hz.
Microphone Calibrator	Photocon Research	PC-125	A self contained portable unit for calibrating the sensitivity and linearity of microphone systems. Frequency set at 1 K Hz. Sound levels of 100 to 160 dB.
Oscilloscope	Hewlett Packard	122/AR	A dual trace, 200 K Hz bandwidth oscilloscope range 5μs/cm to 200 ms/cm in 15 ranges.
Oscillograph Recorder	Honeywell	1508-A	A direct writing oscillographic recorder. Paper speeds from .05 ips to 120 ips and writing speeds in excess of 50,000 ips. Galvanometer linearity is ± 2 % of full scale deflection which is 8 inches peak to peak.

Figure 2-7. Instrumentation Equipment List

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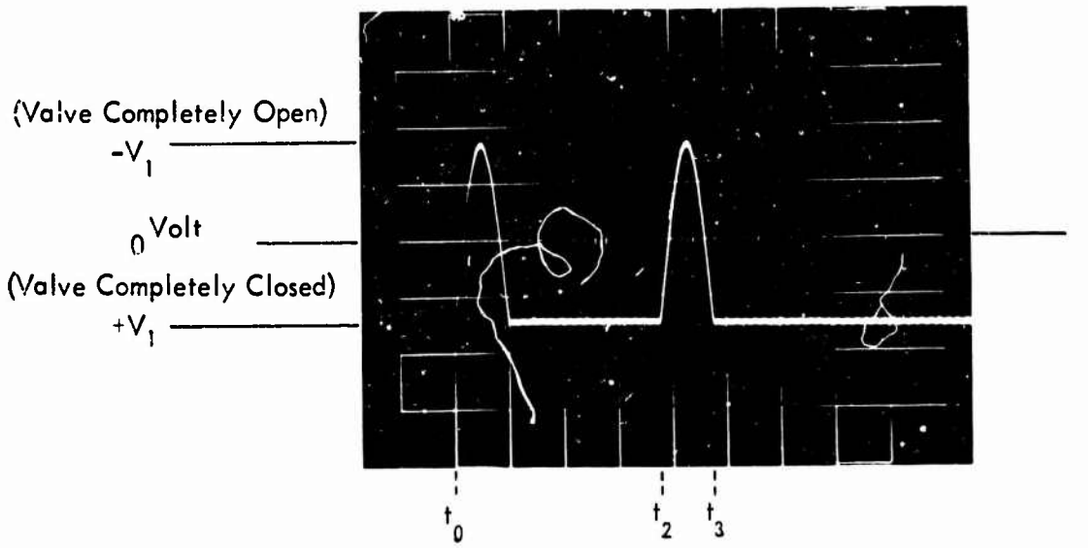
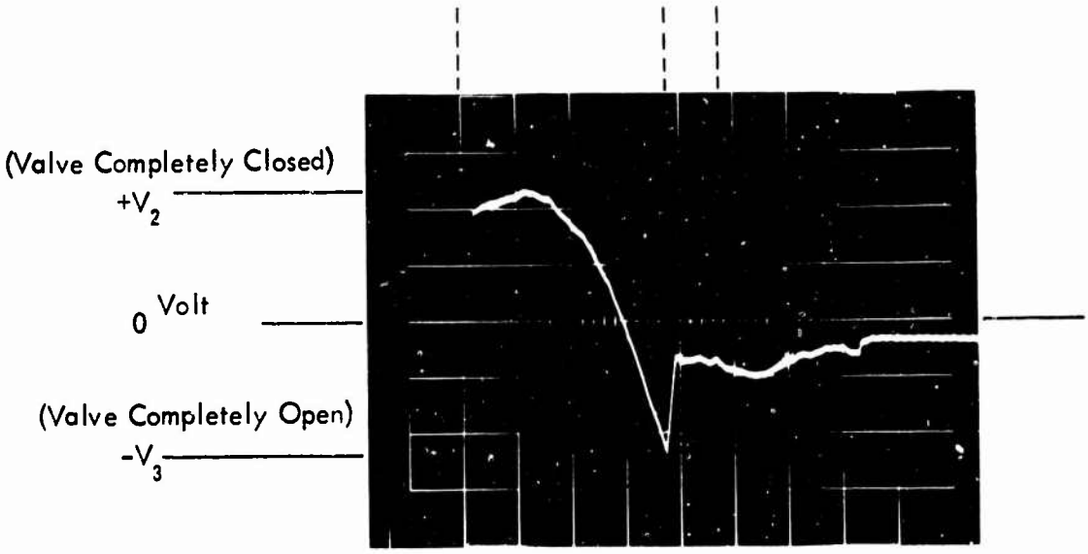


(a) Input Signal to Modulator Unit Number 1



(b) Input Signal to Modulator Unit Number 2

Figure 2-8. Input Signals for the Electrical Control System

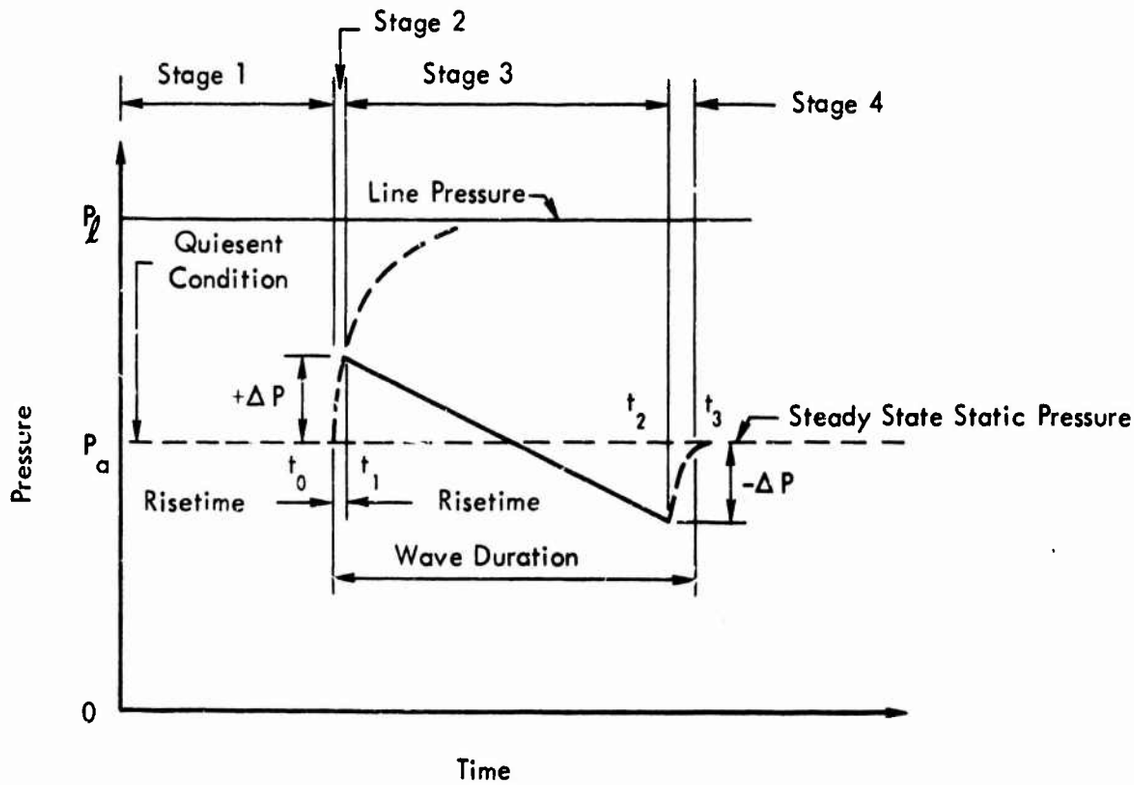


Figure 2-9. Operation Sequence of the Wyle Sonic Boom Simulator

As a result, the pressure inside cavity number 1 rises. The rate of the pressurization and the final pressure intensity at t_1 is dependent on the pulse duration and the amplitude of the input half-sine pulse.

Stage 3: Generation of Negative Overpressure, $-\Delta P$ – The reduction of the pressure level in cavity number 1 requires:

a) shut off the inlet valve completely to stop the airflow, and

b) open up the outlet valve gradually to vent the compressed air into the atmosphere.

The rate of air venting is controlled by the input signal as shown in Figure 2-9(b), and the entire operation is designed to be completed within the time duration of $(t_2 - t_1)$.

Stage 4: Repressurization – After the $-\Delta P$ level is reached, it is necessary to close the outlet valve so that the pressure level in cavity number 1 can be raised to its initial value, P_a. In order to achieve a faster recovery time, it is necessary to supply an additional volume of air from the compressor at time t_2. This is accomplished by applying the half-sine pulse signal to the inlet valve (Figure 2-9 (a)). The entire waveform synthesizing cycle is now complete.

Typical sonic boom signatures generated by the simulator are shown in Figures 2-10 (a) and 2-10 (b). These were obtained from tests using the rigid panel and a glass panel, respectively. The duration for both waveforms is 400 milliseconds, but the risetime is approximately 20 milliseconds for the rigid panel and 40 milliseconds for the glass panel. It is evident, as can be seen from the signatures, that a flexible panel yields a longer risetime.

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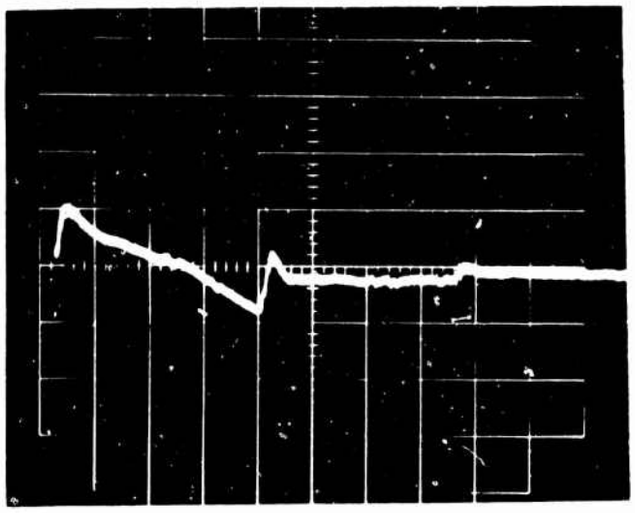


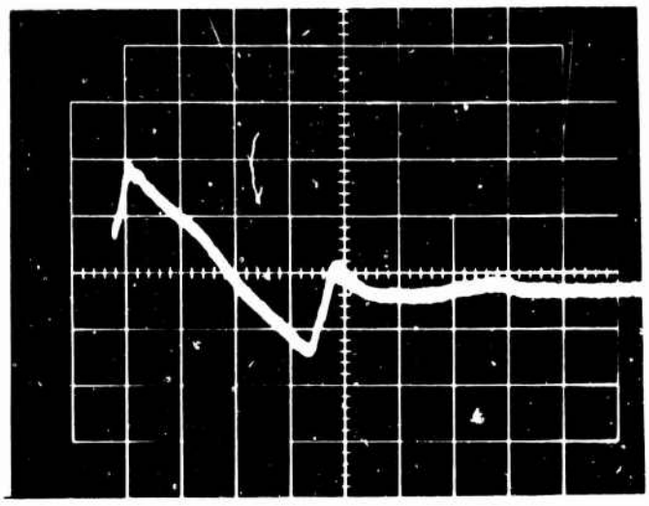
Vertical Scale:

1 cm = 10 psf

Horizontal Scale:

1 cm = 100 m.s.

(a) Sonic Boom Signature Obtained by a Rigid Calibration Panel



Vertical Scale:

1 cm = 11.7 psf

Horizontal Scale:

1 cm = 100 m.s.

(b) Sonic Boom Signature Obtained by Glass Panel

Figure 2-10. Typical Sonic Boom Signatures Generated by Wyle Simulator

3.0 SONIC BOOM SIGNATURE CRITERIA

3.1 Introduction

The prime concern of Wyle's sonic boom simulator is the creation of suitable environments to simulate the effect of sonic booms on structures. To achieve the objective, a careful evaluation on loading waveforms and the associated structural response phenomena would be required to insure that specific test requirements can be fulfilled by the simulator. Therefore, it is the purpose of this section to examine existing knowledge in the above stated areas and to define sonic boom signatures that are suitable for the study of structural effects under simulated conditions.

Assuming that the glass used in simulation tests are "perfect" specimens (so that the structural failure of glass is solely attributed either to overstress or to fatigue damage), the prime test parameters to be considered in the simulation tests are the sonic boom signatures, the dynamic characteristics of glass systems and the internal room acoustics. Recent investigations (Reference 1) have shown that the probability of Helmholtz resonance phenomena occurring in a room due to window response is quite low. Therefore, the influence of room acoustics on the response of window glass should be minimal under normal situations. Consequently, the parameters considered in the sonic boom simulation tests may be reduced to two; the external sonic boom signatures and the dynamic characteristics of window glass.

A review of sonic boom signatures obtained from overflight programs was performed, and the characteristics of these waveforms were compared based on their individual energy spectral density functions. After establishing the basic properties of sonic boom signatures and the dynamic characteristics of window glass, the criteria used to determine simulating waveforms for sonic boom tests were established.

3.2 Sonic Boom Signatures

The term "sonic boom signature" is used to designate the characteristics of the pressure disturbance generated by an aircraft flying at supersonic speed; it is characterized by its overpressure amplitude, risetime, and wave duration. The shape of a sonic boom is a function of aircraft configurations, atmospheric conditions, operating conditions and ground topology. Different aircrafts operating under various environments generate sonic boom signatures that are distinctively different from each other. Typical sonic boom signatures generated by F-104, B-58, and B-70 aircrafts are shown in Figure 3-1.

Efforts to gain a better understanding of the generation of sonic booms and their associated problems, such as effects on people and structures, have been attempted by numerous researchers and organizations. Excellent bibliographies on the above stated subjects can be found in References 2-7.

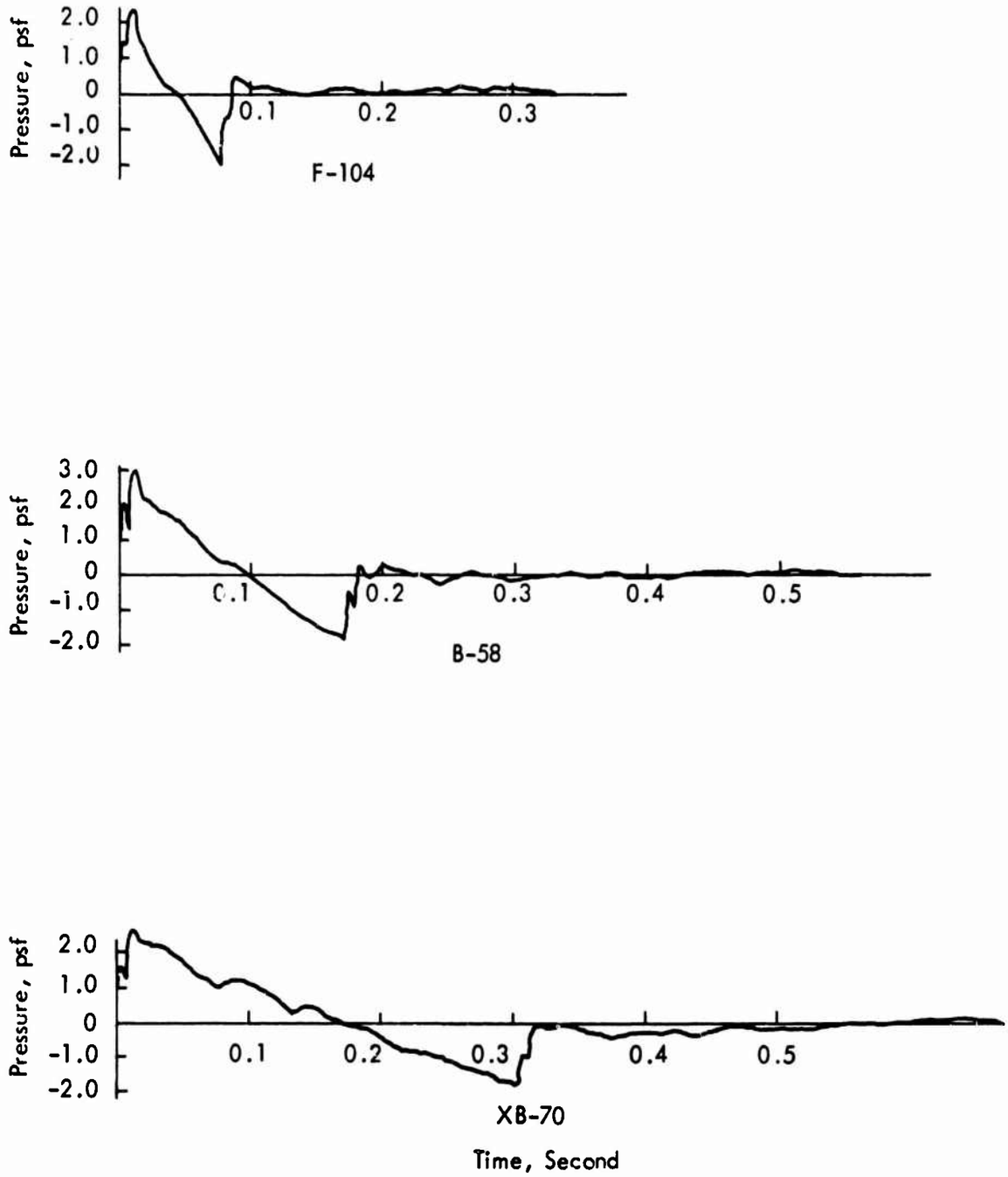


Figure 3-1. Typical Sonic Boom Signatures Generated by F-104, B-58, and XB-70 Supersonic Aircrafts (Reference 2)

To simplify the study of the effect of sonic booms on structural responses, the ordinary pressure-time history of the waveform can be converted into its corresponding energy spectra density form which is defined as follows:

$$\left| P(\omega) \right|^2 = \left| \int_{-\infty}^{\infty} p(t)\, e^{-i\omega t}\, dt \right|^2$$

where

$\left| P(\omega) \right|$ = energy spectral density

$p(t)$ = instantaneous pressure at time t

ω = frequency in radians

The above quantity is used to express the spectral distribution of the input energy of the N-wave.

To illustrate the importance of the wave duration effect, the energy spectra of sonic booms for various aircrafts and a hypothetical SST (Reference 8) are shown in Figure 3-2, in which the same value of peak overpressure is assumed in each case. Since most of the input energies are contained in the low frequency range, it is expected that the dynamic responses caused by sonic boom disturbances on large windows would be pronounced. For smaller windows, whose fundamental periods are much shorter than that of the wave duration, the structural response to sonic booms is directly proportional to the magnitudes of the overpressures.

3.3 Waveform Criteria

The present Wyle sonic boom simulator could be used to serve two purposes:

- To determine the breaking strengths of glass specimens (static and dynamic), and
- To determine the cummulative damage effect on glass caused by repetitive sonic boom exposures.

Since there exists a variety of sonic boom signatures that could be utilized to excite test specimens in the simulator, the logical criterion for selecting a proper test waveform is that the waveform employed for testing must be able to produce the probable maximum structural responses. A convenient scale which is frequently used by engineers to compare structural responses subjected to different dynamic loadings is known as the dynamic amplification function (daf), which is a dimensionless quantity and is defined as the ratio of the maximum response of a single oscillator to its static response under uniform peak pressure loading.

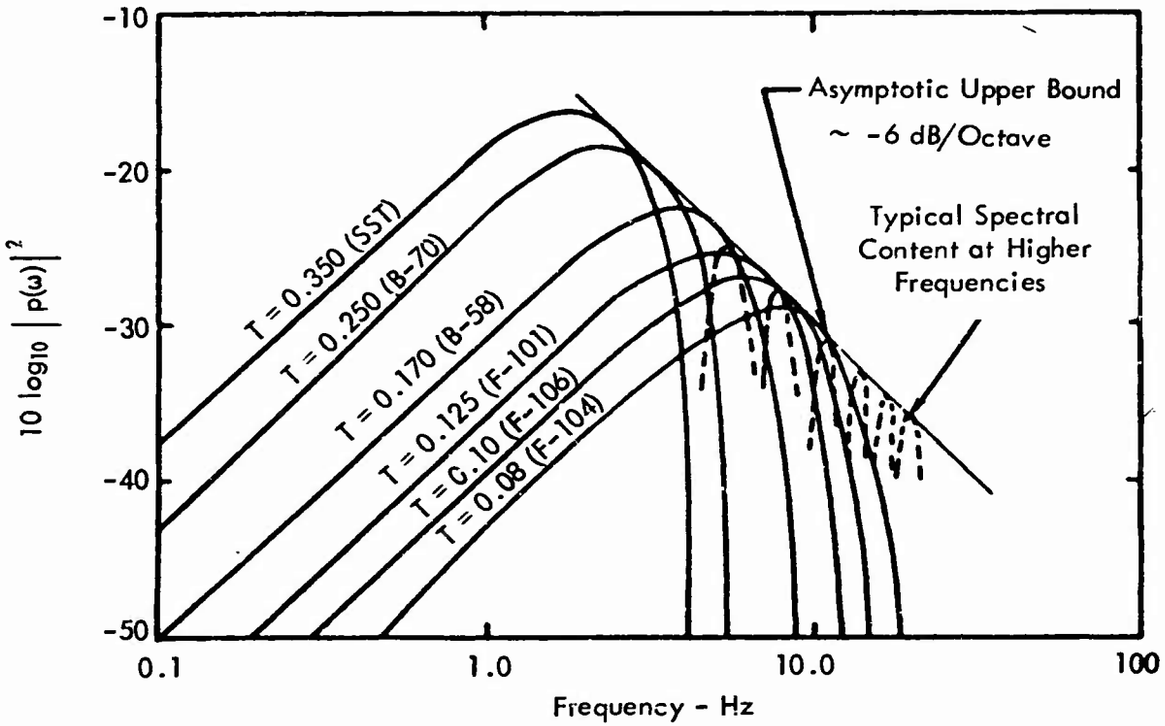


Figure 3-2. Energy Spectra of Sonic Booms for Various Aircraft and a Hypothetical SST (from Reference 8)

A comparative study on daf for simply supported uniform plates under five types of representative sonic boom signatures, as shown in Figure 3-3, has been recently reported by Cheng (Reference 6). He found that the response due to the pressure-pulse type loading is greater than that due to traveling-wave type loading; and the daf for different wave forms is dependent on the wave durations and the fundamental period of the plate. The latter results may be conveniently summarized in graphical form as shown in Figure 3-4, in which, the daf's for the five different waveforms are plotted agoinst the dimensionless quantity R, which is defined as the ratio of the sonic boom wave duration, τ, to the fundamental period, I, of a simply supported plate. Assuming that the wave duration of future SST's would be in the range of 300 to 400 miliseconds, it is obvious that the selection of simulation waveforms depends on the criteria described as follows:

- For smaller windows ($R > 2$), the daf's for the waveforms considered vary within the range of 1.5 to 2.5 and the generation of "exact" sonic boom signatures is not necessary. Adequate simulations could be achieved by employing either "C" or "Q" waves.

- For large windows ($R < 2$), the waveform characteristics have significant effects on respective daf's. Therefore, the knowledge of the approximate waveform would be required and the wave duration should be tuned to obtain the maximum dynamic response. If the information on the sonic boom signature is not available, the "R" wave should be used and tuned so as to obtain the probable lower bound overpressure level for test specimens.

Although the analysis performed for the above daf's did not include the effects of structural nonlinearity, participation of higher modes,and structural damping in the computation, it is considered that the omission of such factors would not alter significantly the overall characteristics of the computed daf's. For purposes of the Wyle experiments;

$$R = \frac{\tau}{T} = \frac{0.4 \text{ sec}}{0.033 \text{ sec}} \simeq 12$$

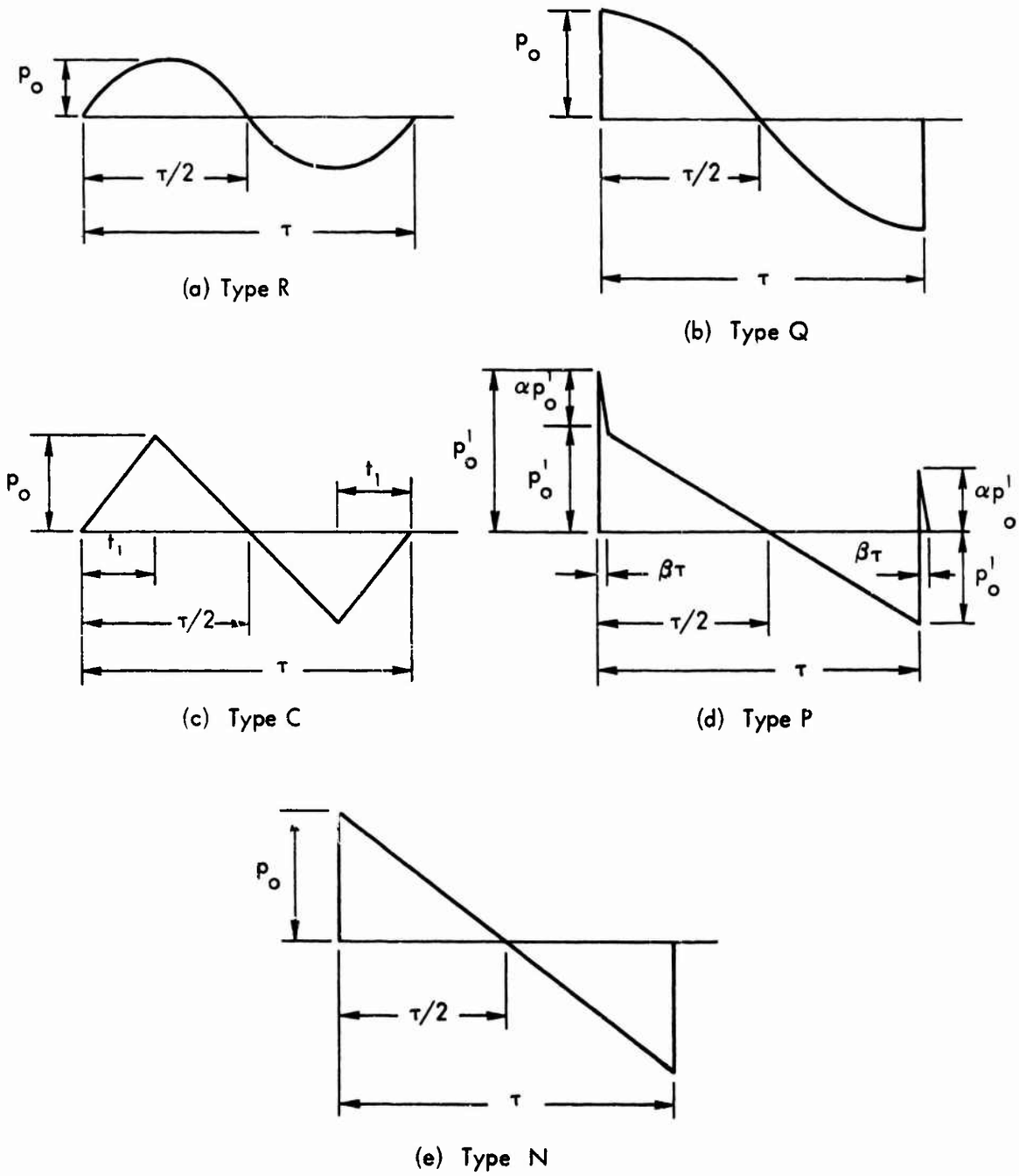


Figure 3-3. Idealized Sonic Boom Signatures (Reference 6)

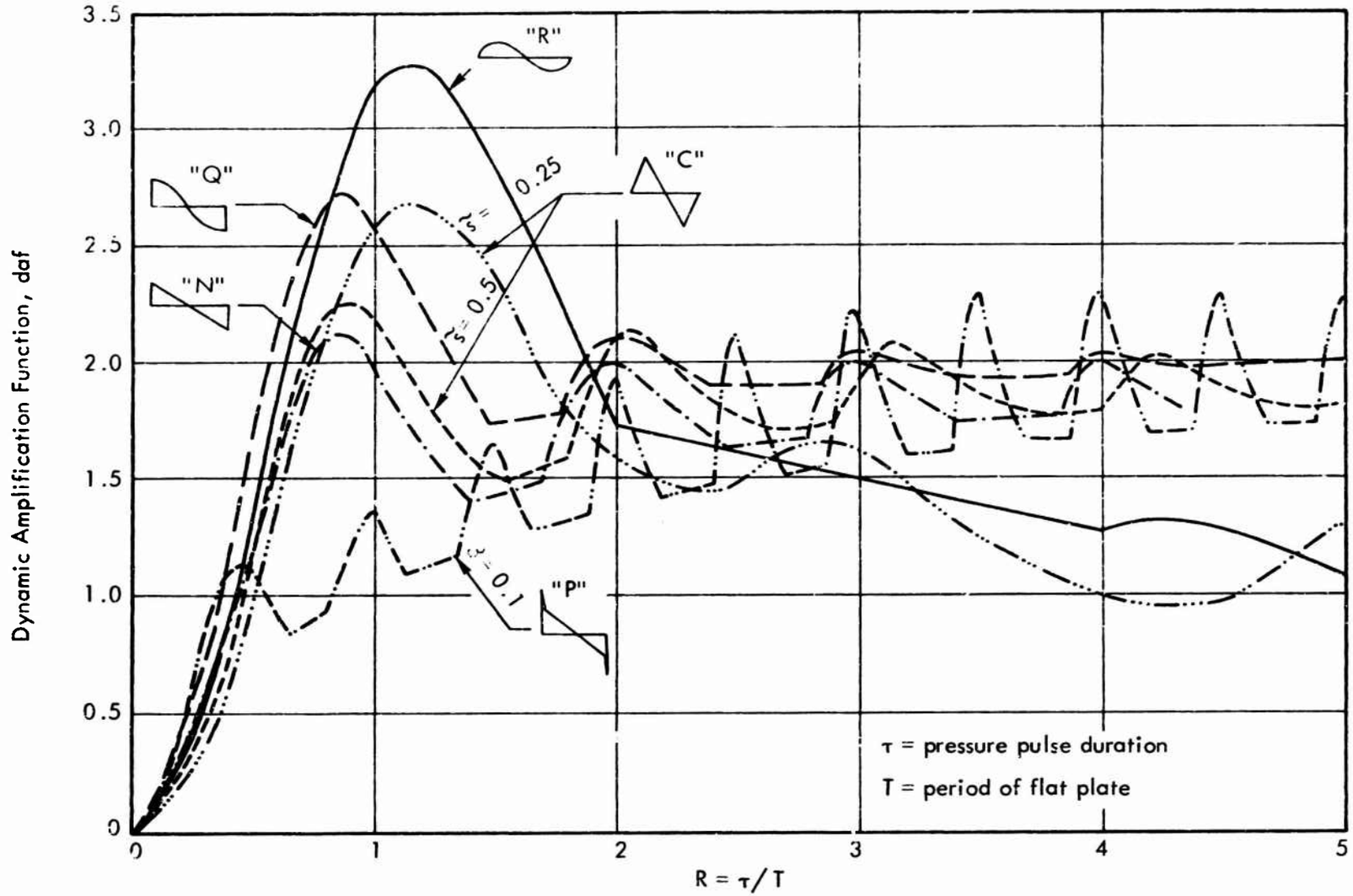


Figure 3-4. Comparison of Dynamic Amplification Functions for Five Different Types of Waveforms (Reference 6)

4.0 EXPERIMENTAL PROGRAM

4.1 Introduction

The main objectives of the experimental program were to determine breaking strengths of new glass under static and sonic boom conditions and to evaluate the effect of different edge conditions on the nonlinear characteristics of glass specimens. In all, a total of 114 panes of new and used glass were tested. The type of glass specimens used are as follows:

- 35 panes of 20" x 20" x 3/32" new glass
- 73 panes of 48" x 48" x 3/32" new glass
- 6 panes of used glass (various sizes)

The criterion for the sonic boom tests was to establish cummulative damage limits for glass specimens under various overpressure levels. Obviously, testing too many types of glass would significantly reduce test sample sizes, and hence, lower the confidence limits of test results. Therefore, the optimum approach for the test program was to establish the lower bound cumulative damage limit by testing the weakest member of the glass family in which the single strength glass was considered as the candidate.* The dimensions of test specimens were determined primarily by the largest single strength glass available in local retail stores. The final dimensions chosen for the tests were 48" x 48" x 3/32".**

The 48" x 48" x 3/32" specimens were also used in the static testing to determine the breaking strength under three types of boundary conditions; namely, the rubber and putty; the simply supported; and the clamped supported. The objectives for the static testing were two-fold:

- To correlate the breaking strengths of sonic boom tests and static tests; and
- To compare test results with existing test data.

In order to study the effect of specimen size on glass breaking strengths, additional static tests were conducted on 20" x 20" x 3/32" specimens with the rubber and putty edge conditions. Furthermore, several panes of used glass mounted in their original wooden frames were also tested to study the effect of aging due to natural environments.

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* For a given area, the single strength glass sustains the least load as compared with glass of thicker gages, see References 9 and 10.

** For a given area, a square panel would experience a higher stress level as compared to rectangular panels subjected to identical loadings.

A summary of loading and edge conditions employed in the test program is presented in Table 1.

4.2 Static Strength and Nonlinear Stiffness Experiments

4.2.1 General – In order to verify the static behavior of glass samples and to assess the effects of practical boundary conditions, experiments were conducted with 71 panes of single strength glass. The glass samples were divided into three groups, as follows:

- 30 panes of 48" x 48" new glass
- 35 panes of 20" x 20" new glass
- 6 panes of 25" x 25" (approx.) used glass

The first group of glass samples was edge supported by three different types of mounts; as follows:

- Soft rubber and putty
- Simply supported by wood on one side
- Clamped by wood on both sides

The second group of glass samples was edge supported on neoprene rubber and putty, while the used glass panes were tested in their original wood frames with putty on one side.

The static behavior of the glass samples was determined by pressure loading in the following manner:

- The 48" x 48" glass panes and the 25" x 25" used glass panes were loaded by a column of water
- The 20" x 20" glass panes were loaded by air pressure

The experiments utilizing water column loading were conducted in a plywood box as shown in Figure 4-1. Details of the three edge mounting conditions are also shown in this figure. To eliminate any air spring effect beneath the glass pane due to glass deflection under load, this volume was vented to atmosphere.

The experiments utilizing air pressure loading were conducted in a cylindrical pressure tank, the glass sample being mounted in one of the stiff flat end bulkheads. The edge support conditions for the air pressure experiments was similar to the rubber-putty support shown in Figure 4-1.

4.2.2 Time to Failure – The time required for a glass panel to fail under a constant load varies inversely with the magnitude of the load, as shown in Figure 4-2 of Reference 11. Using this figure, static strength data presented in Reference 11 are normalized to a "one-minute-to-failure" load; most static strength glass tests are conducted so that failure occurs within approximately one minute.

TABLE I – SUMMARY OF EXPERIMENTAL PROGRAMS

Type of Test	Specimen Sizes (in.)	Edge Condition	Total Number of Specimens	Type of Glass
Static	20" x 20" x 3/32"	Rubber and Putty	35	New
	48" x 48" x 3/32"	Rubber and Putty	31	New
		Simply Support	4	New
		Clamped-Clamped	2	New
	25" x 25" x 3/32"	Wooden Window (Mounted Condition)	6	Used
Sonic Boom	48" x 48" x 3/32"	Clamped-Clamped	36	New

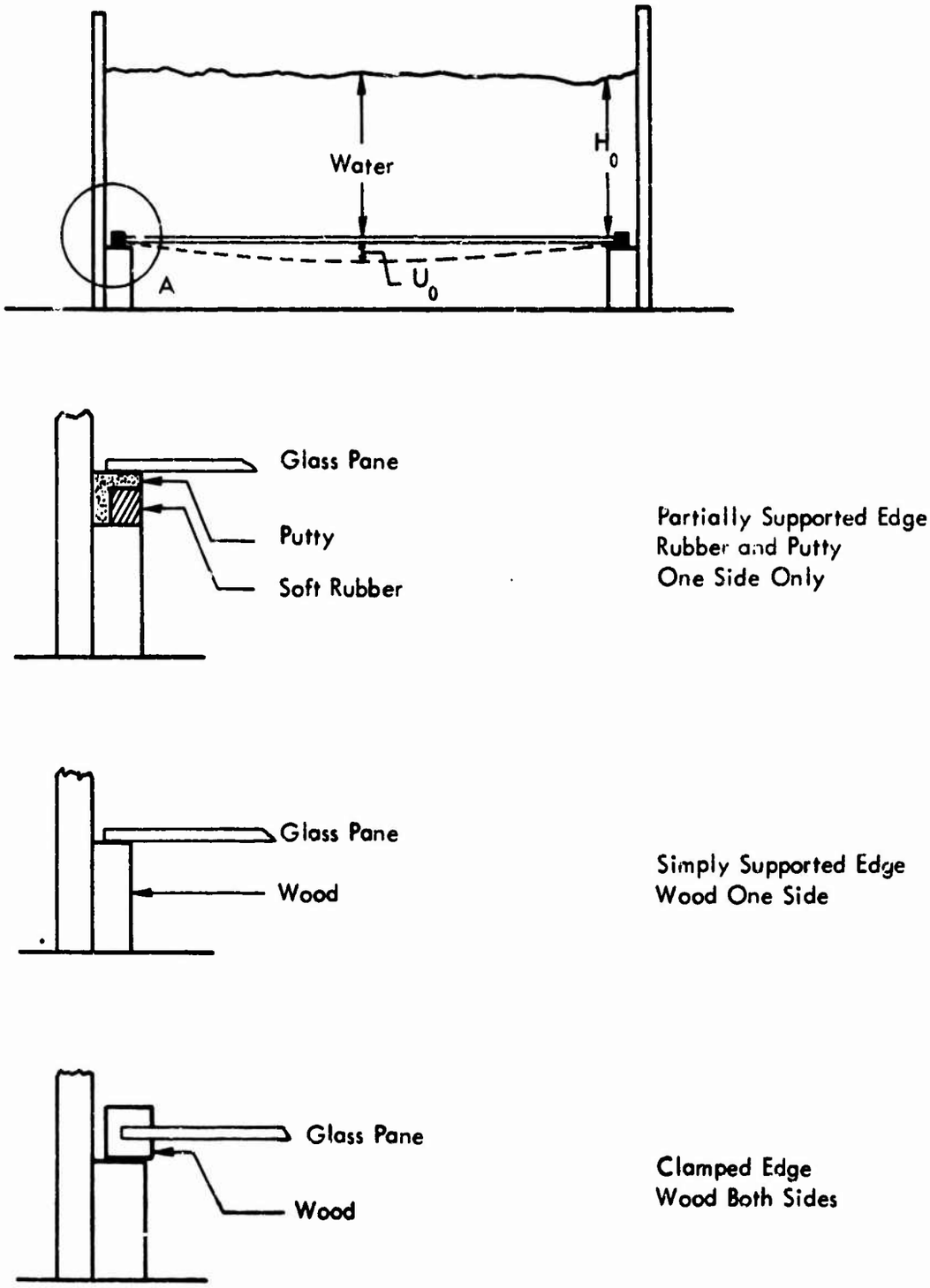


Figure 4-1. Arrangement of Plywood Box and Edge Support Conditions for Water Column Loading Experiments

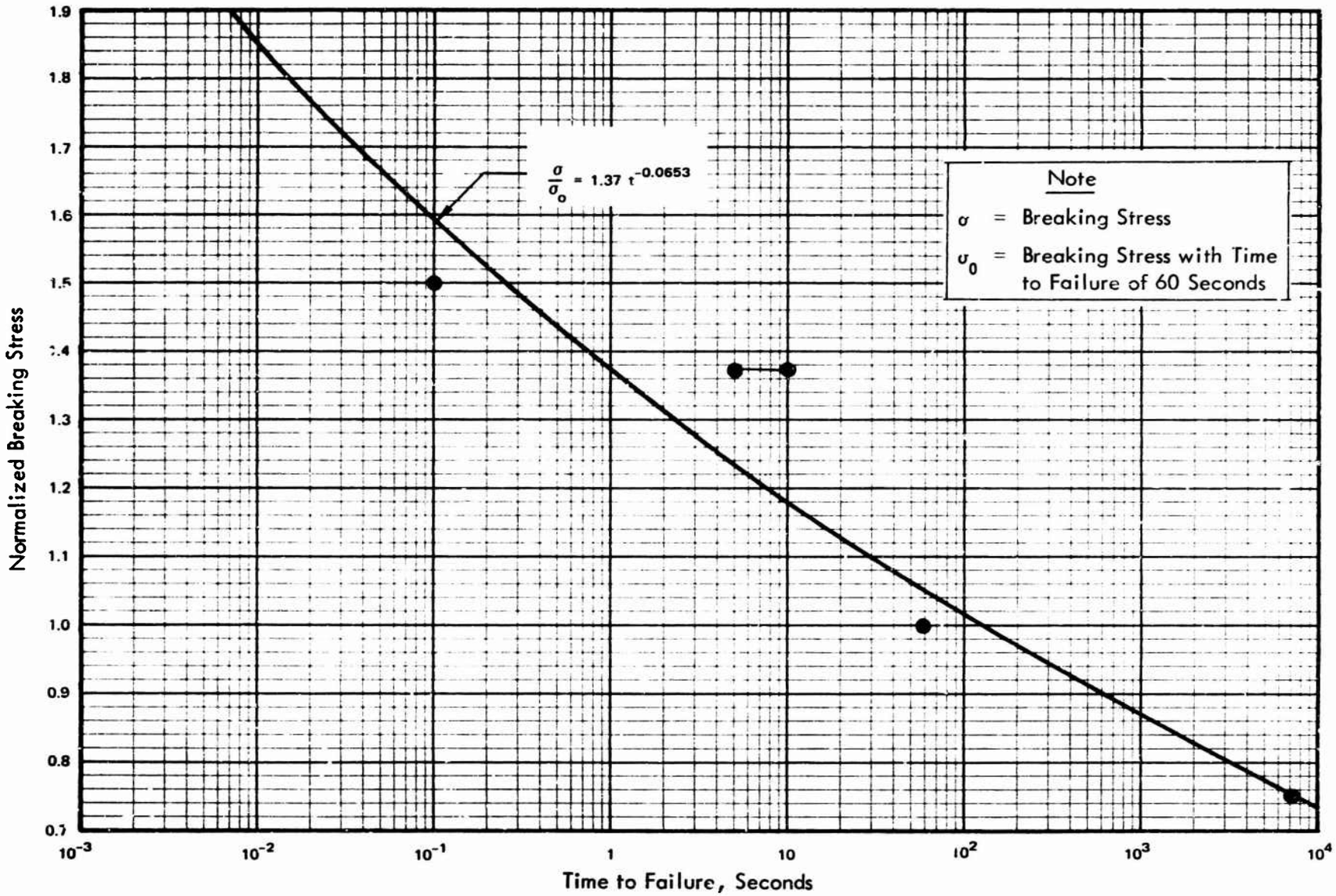


Figure 4-2. Effect of Loading Rate on Normalized Breaking Stress

Loading rates for the experiments performed by Wyle were such that failure occurred within the following time durations:

- 1-2 minutes for the 20" x 20" glass panes
- 5-10 minutes for the 48" x 48" glass panes and the 25" x 25" used glass panes

Adjustments in failure pressure levels to the "one-minute-to-failure" pressure levels were insignificant in magnitude and were therefore not applied to the data obtained in the Wyle experiments.

4.2.3 Failure Pressure Probability Curve – Sufficient static strength experimental data were obtained from the 65 panes of new glass to allow construction of a failure pressure probability curve for each of the two pane sizes. These curves are shown in Figure 4-3 for pressure levels normalized to a common mean value and standard deviation. The table which is included in the figure defines the actual mean values and standard deviation for failure pressure level of the two sizes of glass panels.

Utilizing these two probability distributions, a reasonably smooth curve can be constructed for the (approximate) failure pressure probability for any size of glass panel; this curve is also shown in Figure 4-3.

4.2.4 Non-linearity of Glass Behavior – During static strength testing of the 48" x 48" single strength glass panes, it was observed that prior to failure the central deflection of the glass was approximately five to ten times its overall thickness (which varied from 0.087" to 0.1" over all glass samples).

From plate theory it is known that deflections of this magnitude cause the middle plane of the glass pane to stretch (i.e., the membrane effect), thereby causing the effective stiffness of the glass pane to behave non-linearly with respect to the applied load. Membrane stress may significantly alter the overall stress distribution at failure, thus influencing the actual failure mechanism; in addition, the associated non-linear stiffness may significantly effect the response levels of the glass panes when exposed to sonic boom overpressure.

Previous analytical and experimental studies, reported in Reference 11, have been conducted to evaluate the effects of non-linearity of glass behavior. Similar experiments were conducted during the present investigation to check the consistency of results for practical boundary conditions against the results of Reference 11. The clamped edge experiments were conducted to assess the influence of edge conditions on the degree of non-linearity. As a cross-check, different experiments were performed for constant edge conditions; the two sets of experiments produced consistent results. Load-versus-deflection curves obtained from these experiments are shown in Figure 4-3. The non-dimensional load parameter and non-dimensional deflection parameter are identical to those utilized in Reference 11, and thus the experimental results are directly comparable. Figure 4-4 shows the load versus deflection characteristics for clamped edges, simply supported edges, and the rubber-putty support. The curve presented in Reference 11 is also included in this figure for comparison.

Legend	Dimensions	Static Failure Pressure	
		Mean	Standard Deviation
———	48" x 48"	25.6 psf	σ = 4.5 psf
- - - -	20" x 20"	239.0 psf	σ = 72.5 psf

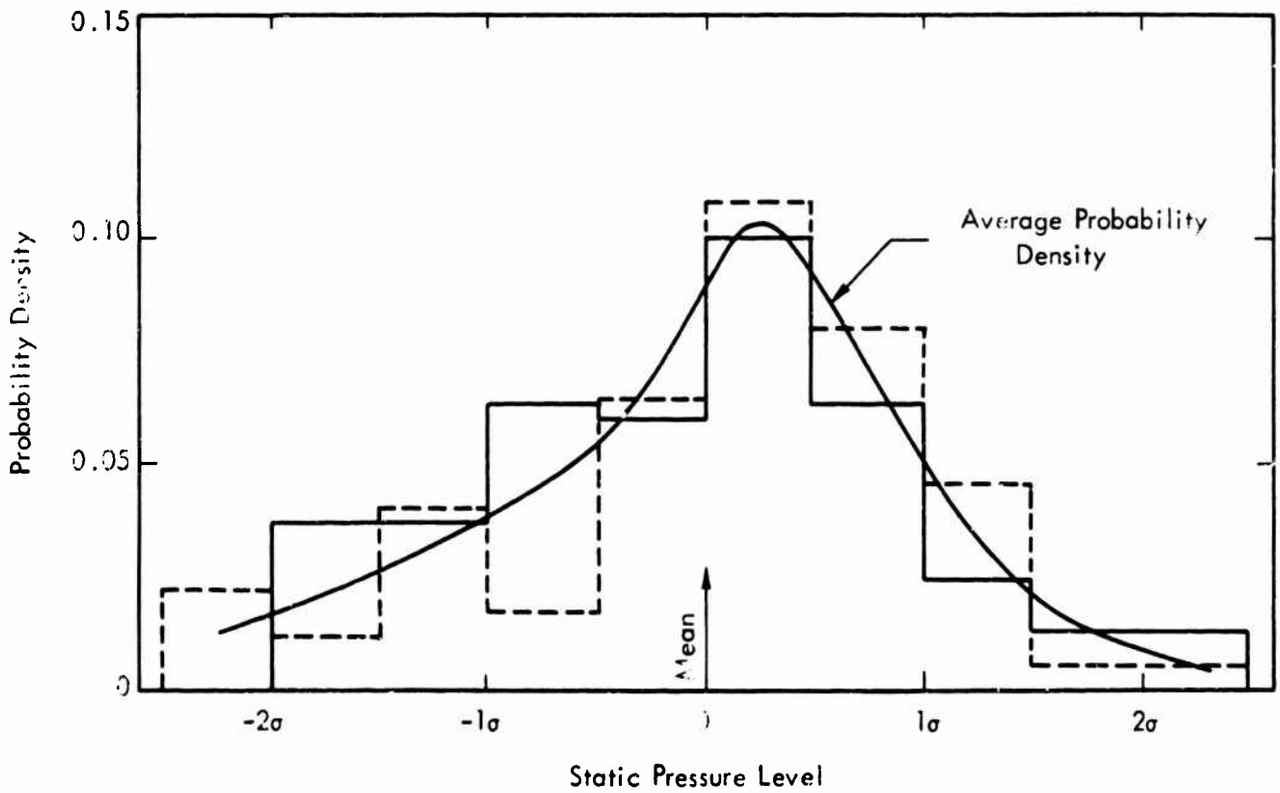


Figure 4-3. Probability Distributions for Failure of Single Strength Glass Under Standard Loading

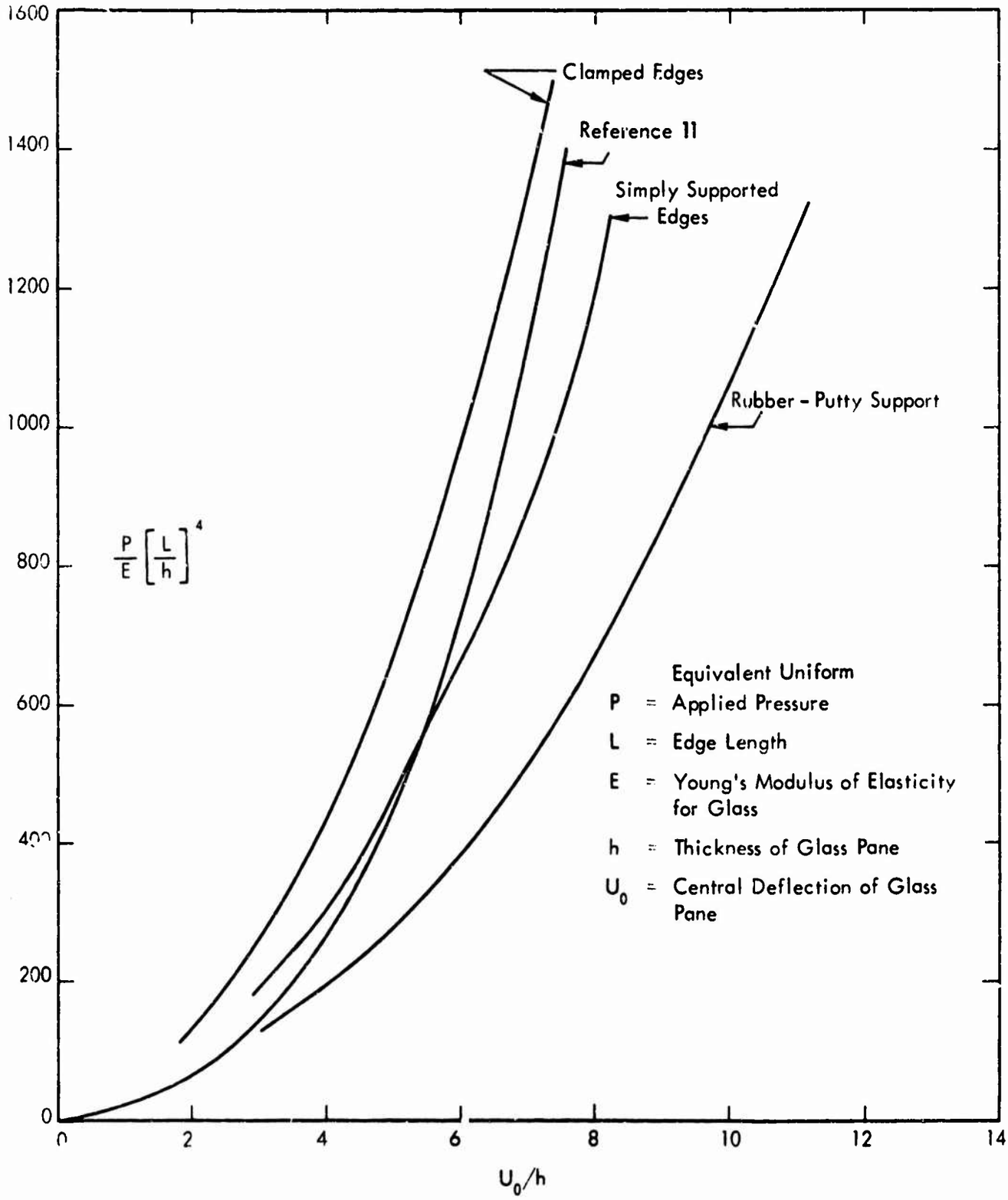


Figure 4-4. Non-dimensional Load versus Non-dimensional Deflection for Single Strength Glass

it is observed in Figure 4-4 that clamped edges result in a greater non-linearity in stiffness behavior than the simply supported edges; the rubber-putty edge support is considerably more linear than the other two support conditions.

4.3 Sonic Boom Testing of Glass Specimens

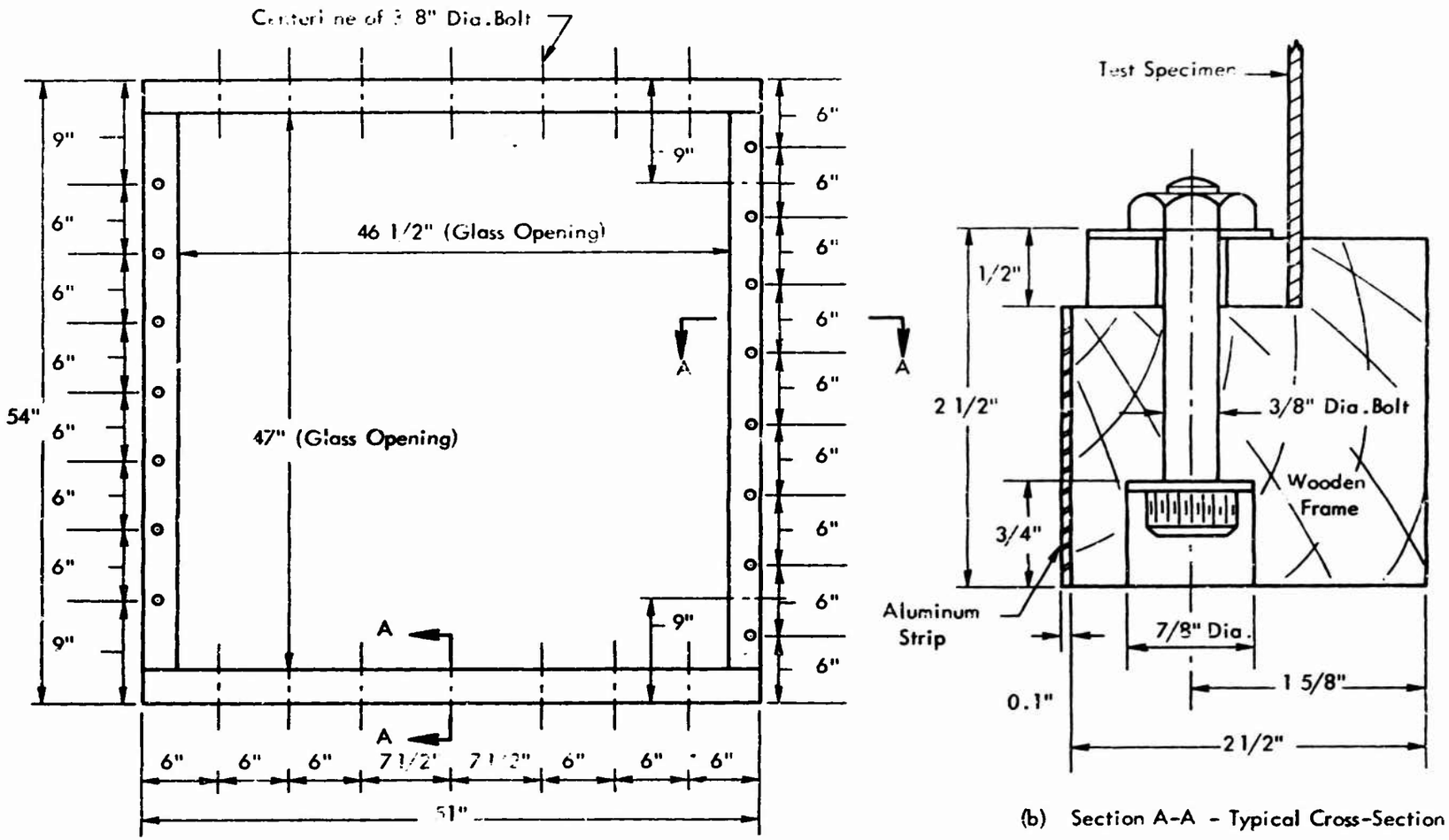
The objective of the sonic boom test program was to evaluate the cummulative damage of glass subjected to repetitive sonic booms. A total of thirty-six tests were conducted. However, due to a high percentage of glass breakage which occurred during initial pressure calibration stages, only eight sets of sonic boom test data are considered usable.

In order to minimize the effect of test variables associated with edge support conditions on the test results, glass specimens were mounted in a standard wooden frame with smooth supporting surfaces on four sides. Details of the sonic boom operations and the descriptions on specimens and fixtures are presented in the following sections.

4.3.1 Description of Test Specimen and Fixture – Test specimens used in the sonic boom test consisted of single strength glass with typical dimensions of 48" x 48" x 3/32". Each specimen was cut from an original sheet of glass which had a standard dimension of 54" x 48" x 3/32". Specimens were examined for surface and edge finish conditions. In general, most specimens exhibited no apparant surface flaws, but a few of the specimens showed certain edge imperfections which appeared in the forms of edge ripples. However, the specimens selected for testing consisted of those with no apparant defects on the surface or along the edges.

Each specimen was mounted in a rectangular wooden frame which had a net opening of 46 1/2" x 47". The details of the wooden frame is shown in Figure 4-5. Each specimen was held to the frame by 4 1/2" thick wooden strips which were bolted to the wooden frame by 3/8" diameter bolts, as shown by the typical sectional view in Figure 4-5(b). The wooden frame was, in turn, held against the steel fixture by tightening 3/8" diameter hex screws through corresponding steel anchoring plates as shown in Figure 4-6. The general arrangement of the test set-up is shown in Figure 4-7.

4.3.2 Test Procedures and Methods – The test procedures employed in the sonic boom test program included the sine sweep test and the sonic boom test. The sine sweep test was conducted at a relatively low pressure level and it was used to determine the resonant frequencies of the test specimens. (Such an acoustic test can be performed in the simulator in the same manner as a sonic boom test). The response signals of each specimen were monitored by a small accelerometer located at the center of the panel. In general, the measured fundamental frequencies were approximately 30 Hz and distinctive peak response amplitudes were observed at higher resonant frequencies. A typical sine sweep response curve is shown in Figure 4-8. Thus, the sine sweep signal provided a convenient check to examine the condition of a test specimen after it was mounted in the simulator. For example, Figure 4-9 shows the sine sweep response of a specimen which had a crack at the lower right corner. The early detection of flaws in specimens has significantly reduced the risk of obtaining invalid data.



(a) General Arrangement of Mounting Frame

(b) Section A-A - Typical Cross-Section

Figure 4-5. Details of Wooden Mounting Frame

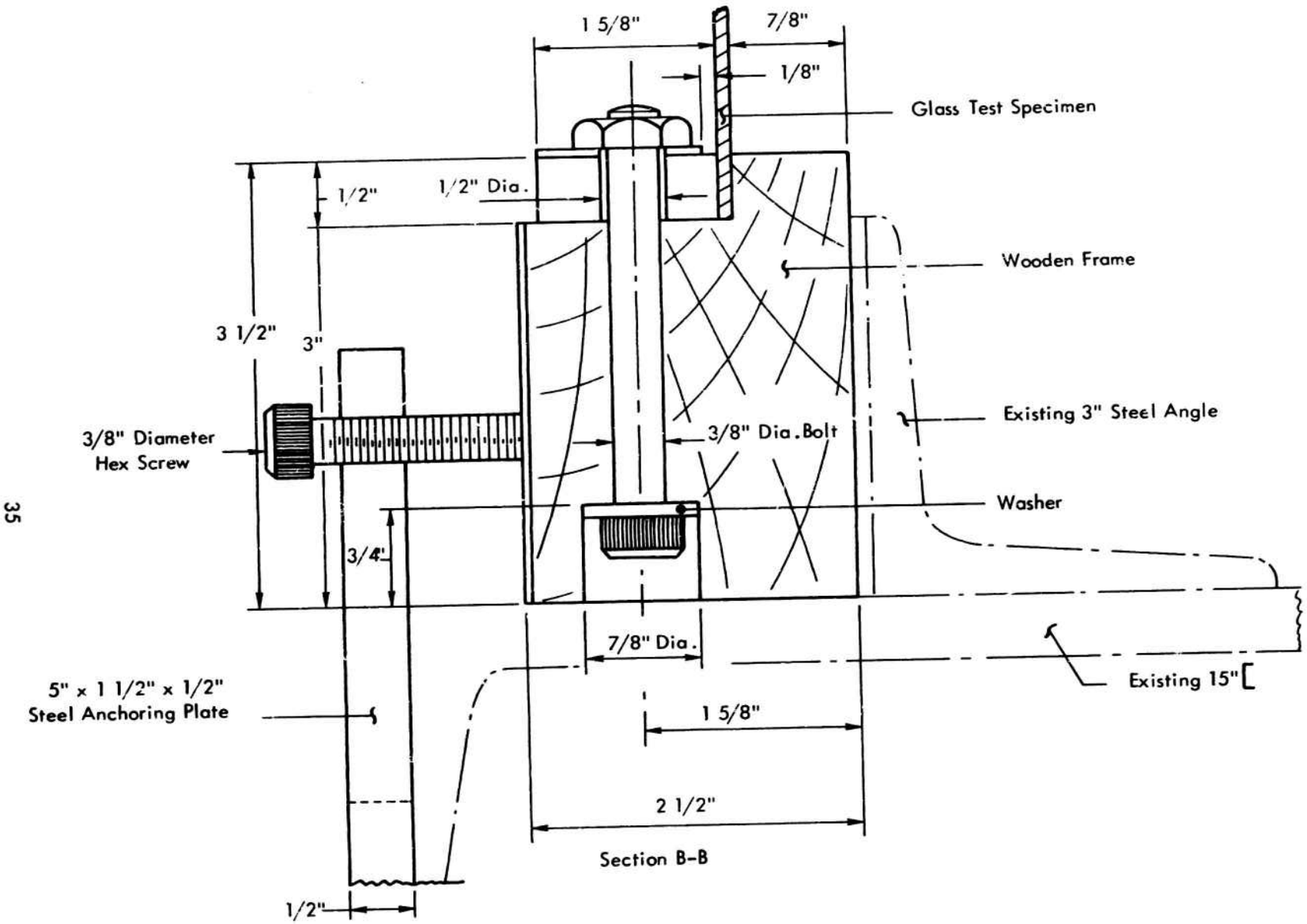


Figure 4-6. Method used to Fasten Wooden Frame to Steel Test Fixture

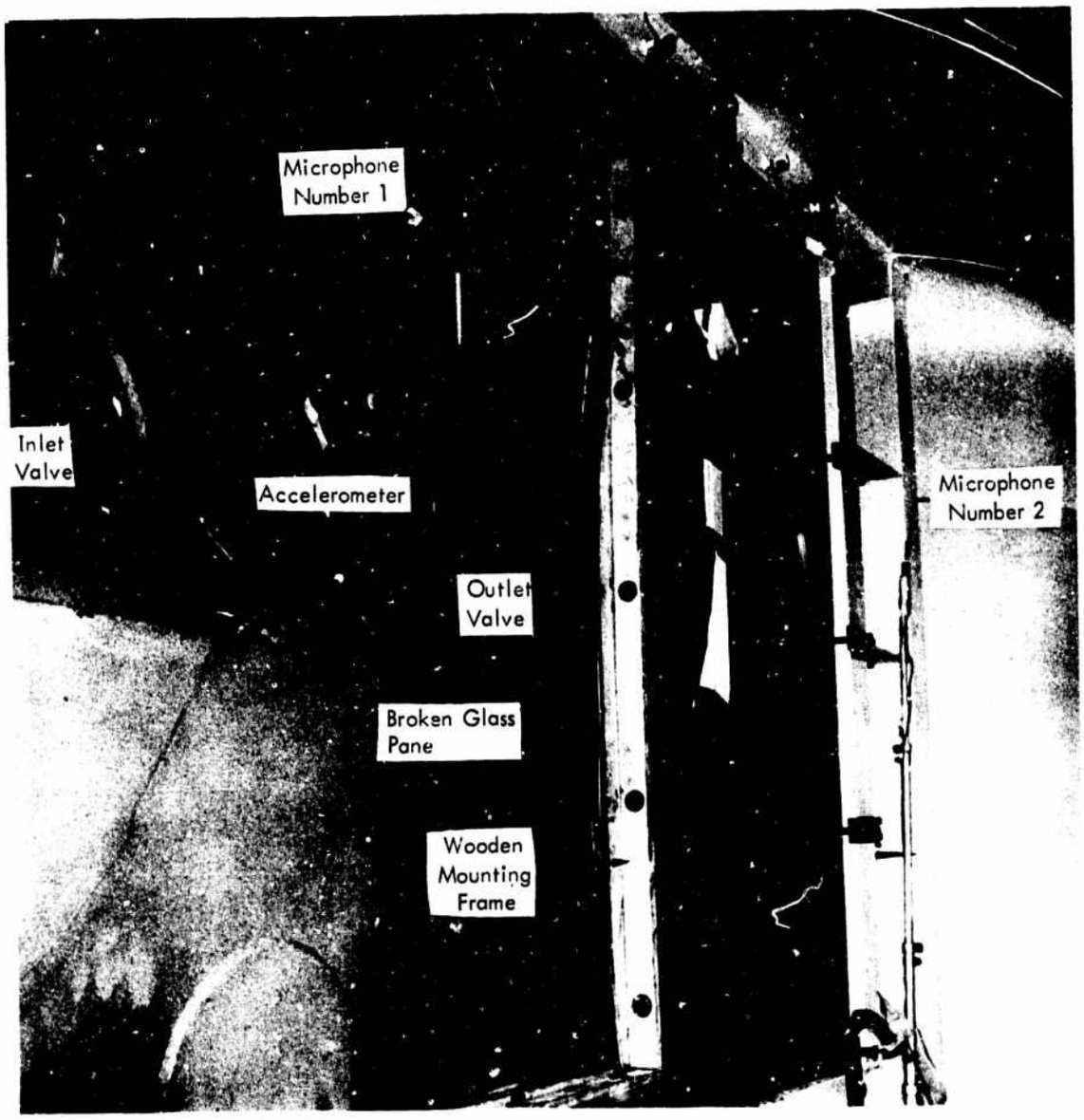


Figure 4-7. General View of Glass Testing Arrangement
(Note Broken Glass Pane)

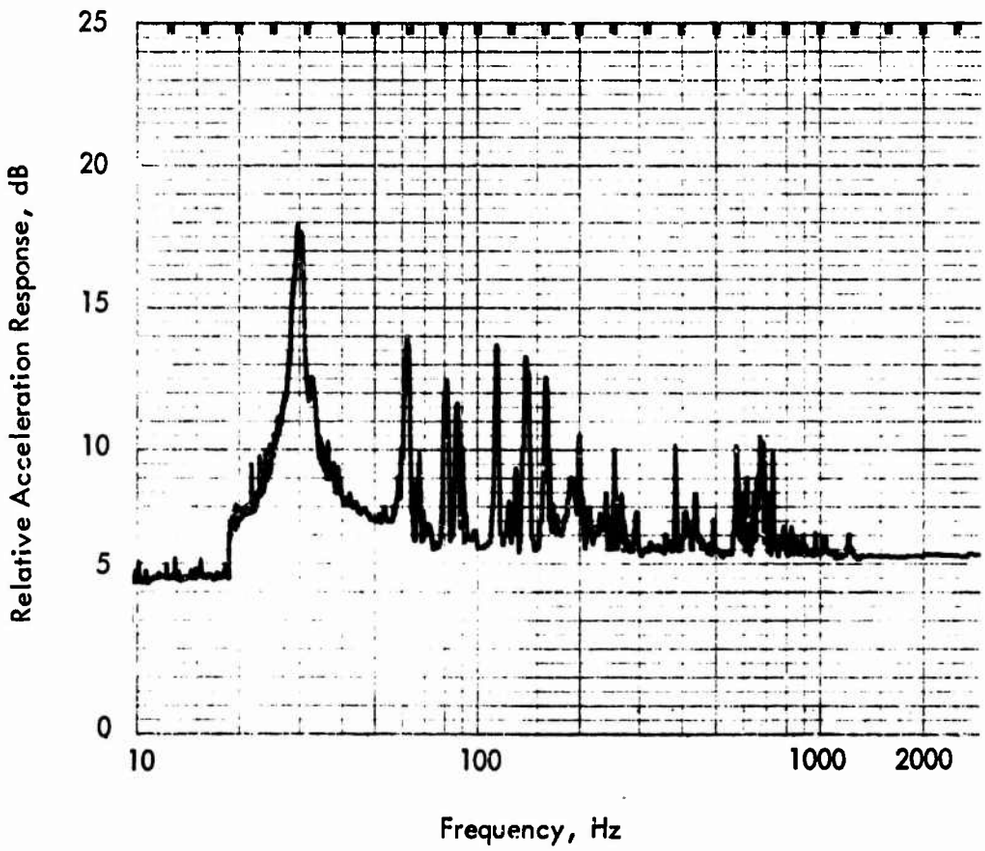


Figure 4-8. A Typical Acceleration Response Spectrum of a 48" x 48" x 3/32" Glass Specimen to Acoustic Sine Sweep Excitation

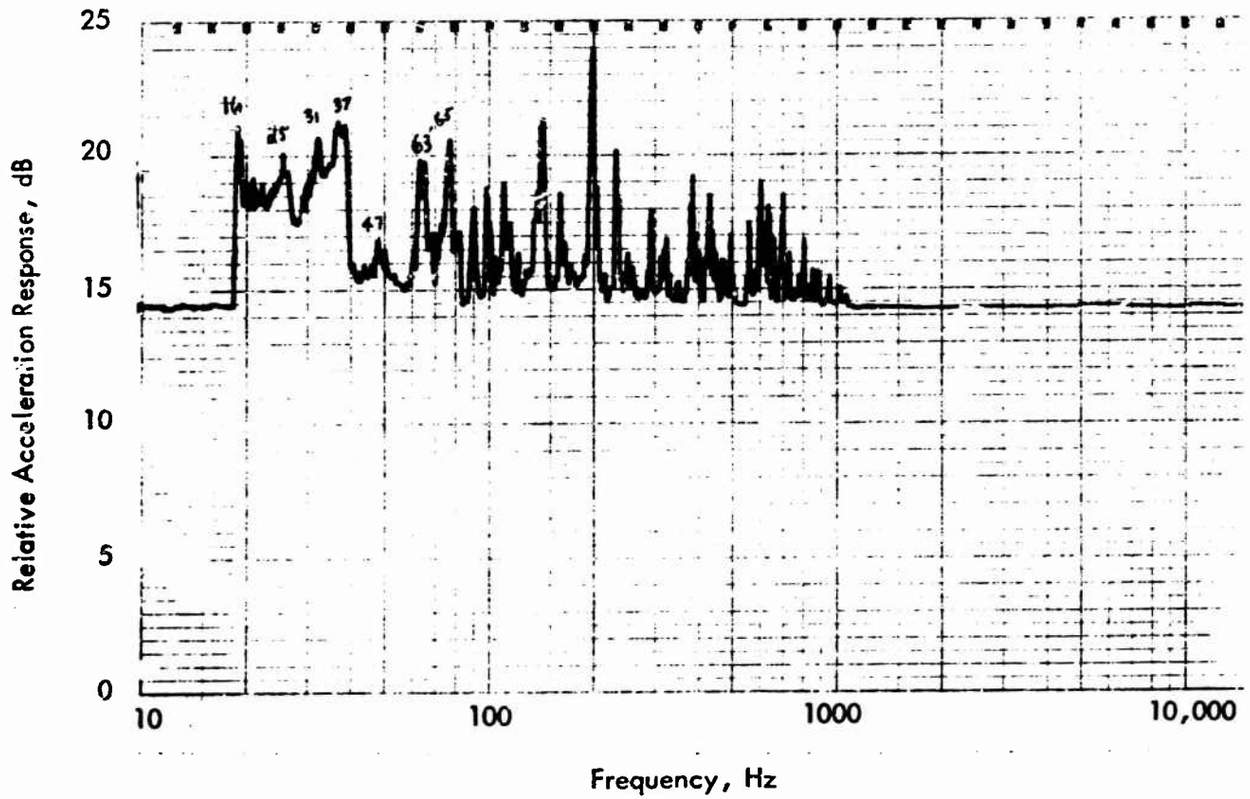


Figure 4-9. Sine Sweep Response Spectrum of a Test Specimen with Cracks in the Lower Right Corner

Two different sonic boom testing methods were used in the tests. The first method employed the "tuning" technique to tune the duration of an N-wave, which is a harmonic of the fundamental period of the test specimen,so that maximum responses of a test specimen could be achieved. The tuning process was carried out at low excitation levels to minimize the possibility of accidental glass breakage. However, due to difficulties encountered in stabilizing the line pressure and also the output signals of the waveform synthesizer, it was not possible to obtain satisfactory acoustic waveforms with durations less than 120 milliseconds. Therefore, only one test was performed under the "tuned" condition. The alternate method employed a fixed wave duration of 400 milliseconds. The complexities of frequency tuning were eliminated and clean N-waves were obtained for various overpressure levels. A total of seven tests were conducted in this manner.

4.3.3 Results of Sonic Boom Tests – The results of the sonic boom tests are summarized in Table II. Notice that the "tuning" method was used on test Number 1 only. Test Numbers 2 through 8 used a fixed wave duration of 400 milliseconds.

Test Number 1 employed the tuning technique to adjust the acoustic wave form to approximately 162 milliseconds, which was five times the fundamental period of the test specimen. The net overpressure level was adjusted to 4 to 4.6 psf. A total of 1400 booms was applied to the test specimen. No visible damage was observed at the end of the test. The net overpressure level for Test Number 2 was set at 22.5 psf which was approximately equal to the mean static failure pressure (22.6 psf) obtained from the static test program. The test specimen failed after 40 booms. In Test Number 3, the overpressure level was adjusted between 13 to 16 psf. A total of 10,000 booms were applied but no visible damage to the specimen was observed at the end of the test. The same specimen was used in Test Number 4, but the overpressure level was increased to 24 psf and the specimen failed at the end of 87 booms.

From the test results obtained from test numbers 1 through 4, it was obvious that, for overpressures under 16 psf, test specimens probably would not fail within 10,000 booms. Hence the decision was made to select a pressure level that would cause a breakage in less than 1000 booms. Consequently, the overpressure was adjusted between 18 to 20 psf in test number 5, and the specimen failed at the end of 490 booms.

In Test Number 6, the overpressure was adjusted between 18 to 20 psf and the specimen lasted for 435 booms. The specimen used in Test Number 7 broke at the substantially low overpressure of 13 psf. The failure occurred while attempts were made to increase the pressure to a higher level. A total of 37 booms was accounted for in this test. Test Number 8 was conducted at 19.5 psf level. The specimen failed after only two booms.

Typical acoustic and acceleration response signals for test numbers 1 through 8 are presented in Figures 4-10 through 4-17, respectively.

TABLE II – SONIC BOOM TEST DATA OF 48" x 48" x 3/32" GLASS SPECIMENS

Test Number	Net Overpressure ΔP, psf	Wave Duration Milliseconds	Number of Booms Applied	Figure Number Showing Partial Test Record	Remarks
1	4.0-4.6	162	1400	5	No Failure
2	22.5	400	40	6	Failure
3	13-16	400	10,000	7	No Failure
4	24	400	87	8	Failure
5	18-20	400	490	9	Failure
6	18-20	400	435	10	Failure
7	13	400	37	11	Failure
8	19.5	400	2	12	Failure

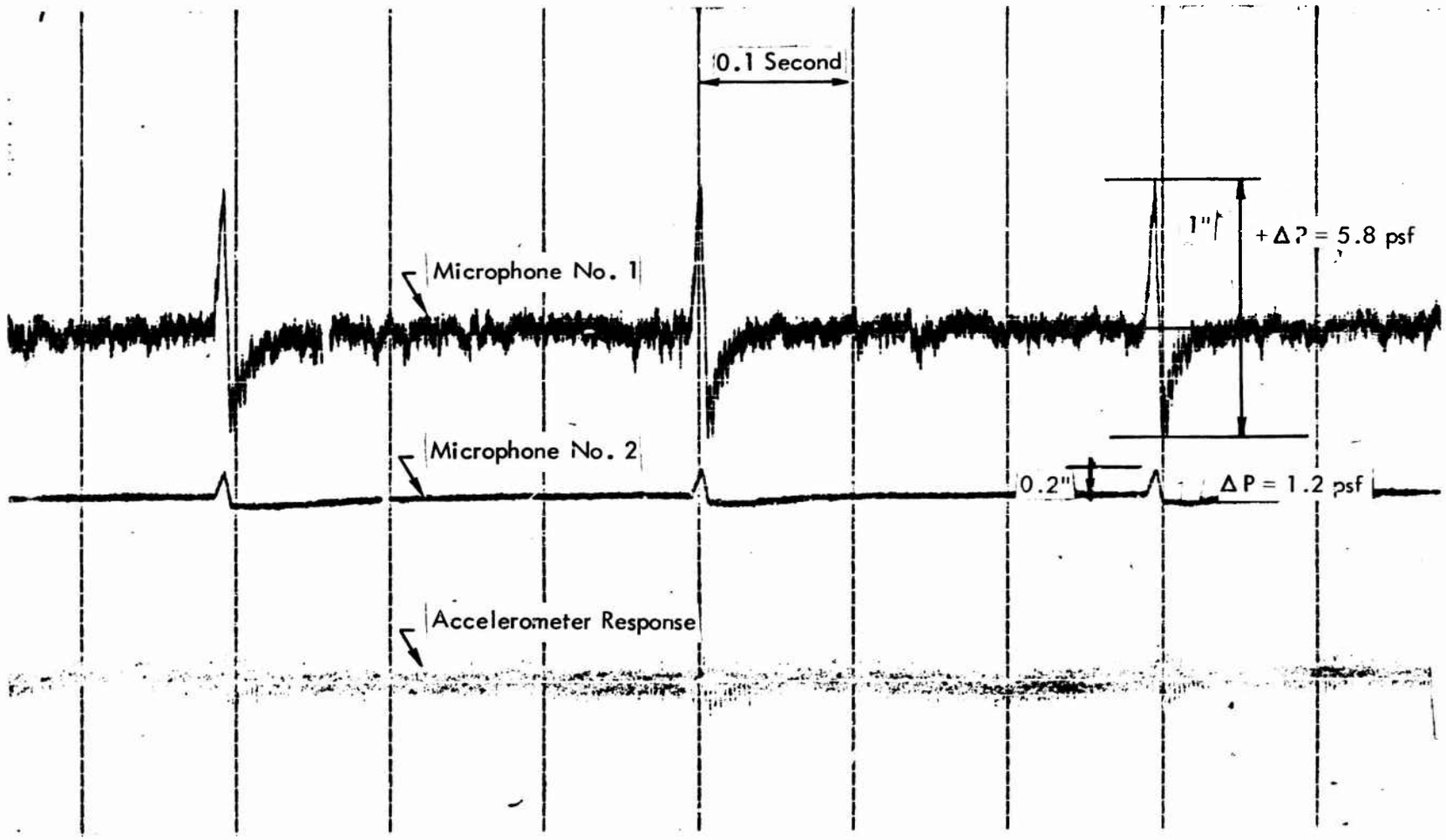


Figure 4.10. Acoustic and Accelerometer Responses of Sonic Boom Test Number 1

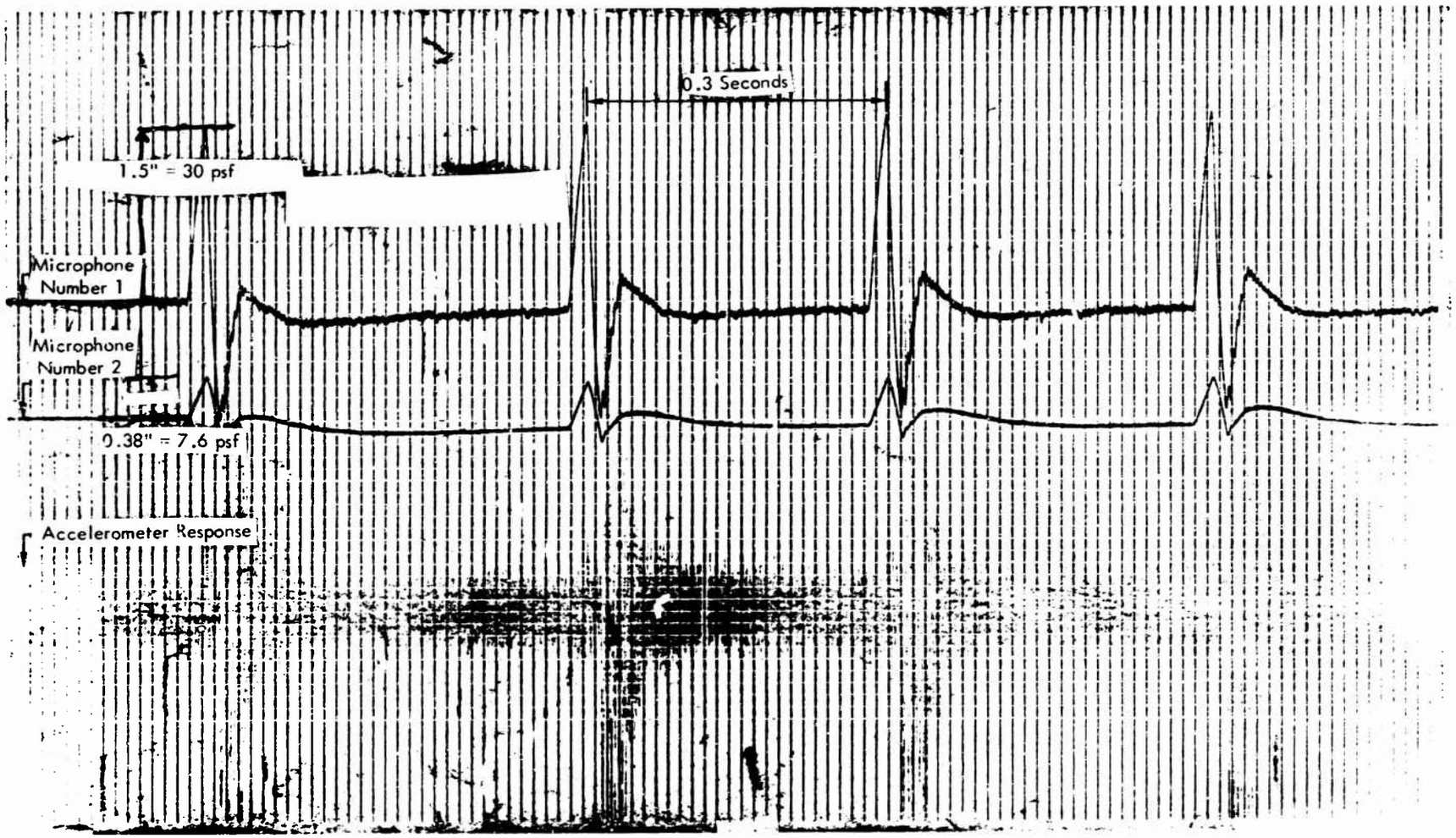


Figure 4-11. Acoustic and Accelerometer Responses of Sonic Boom Test Number 2

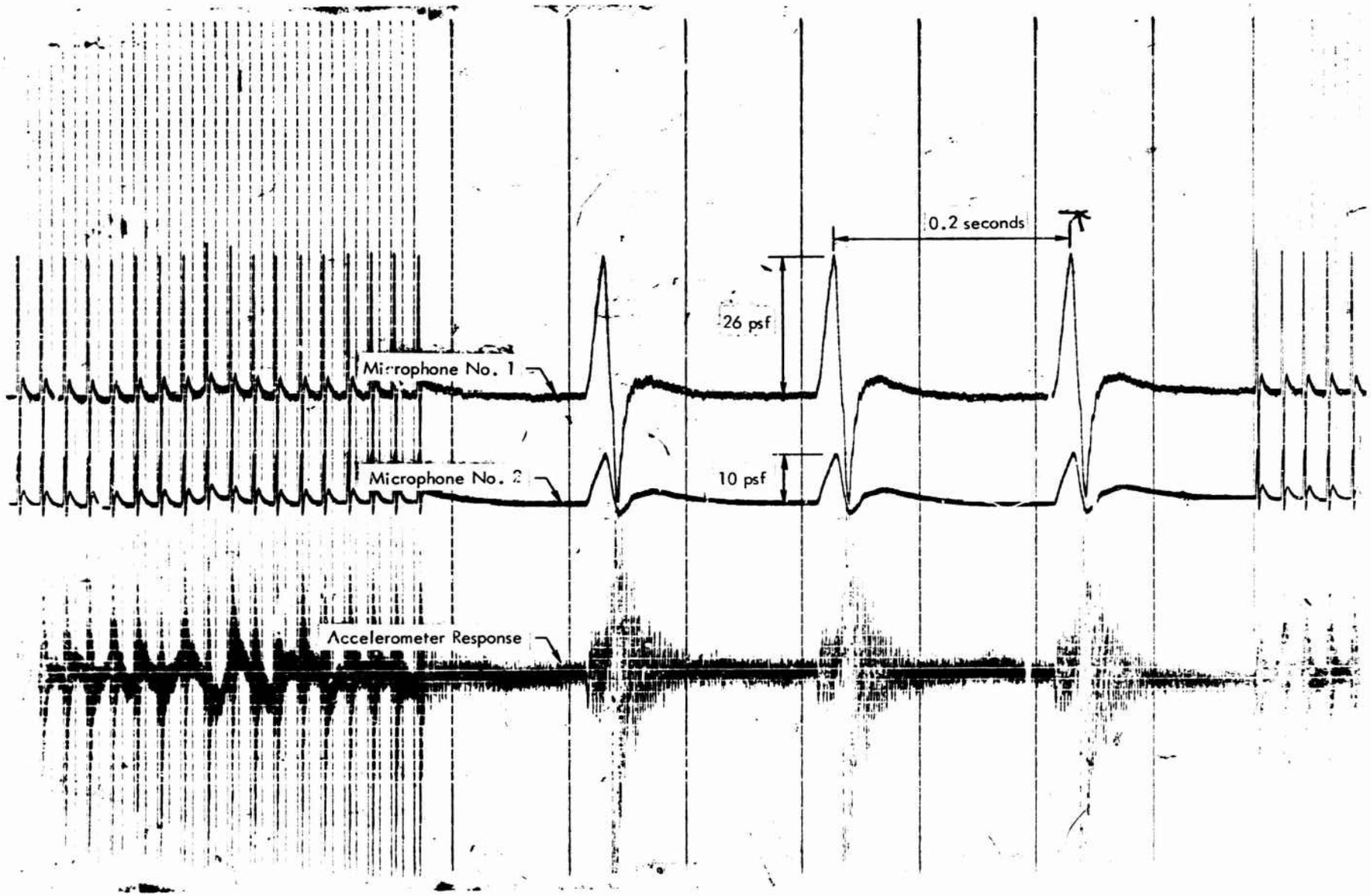


Figure 4-12. Acoustic and Accelerometer Responses of Sonic Boom Test Number 3

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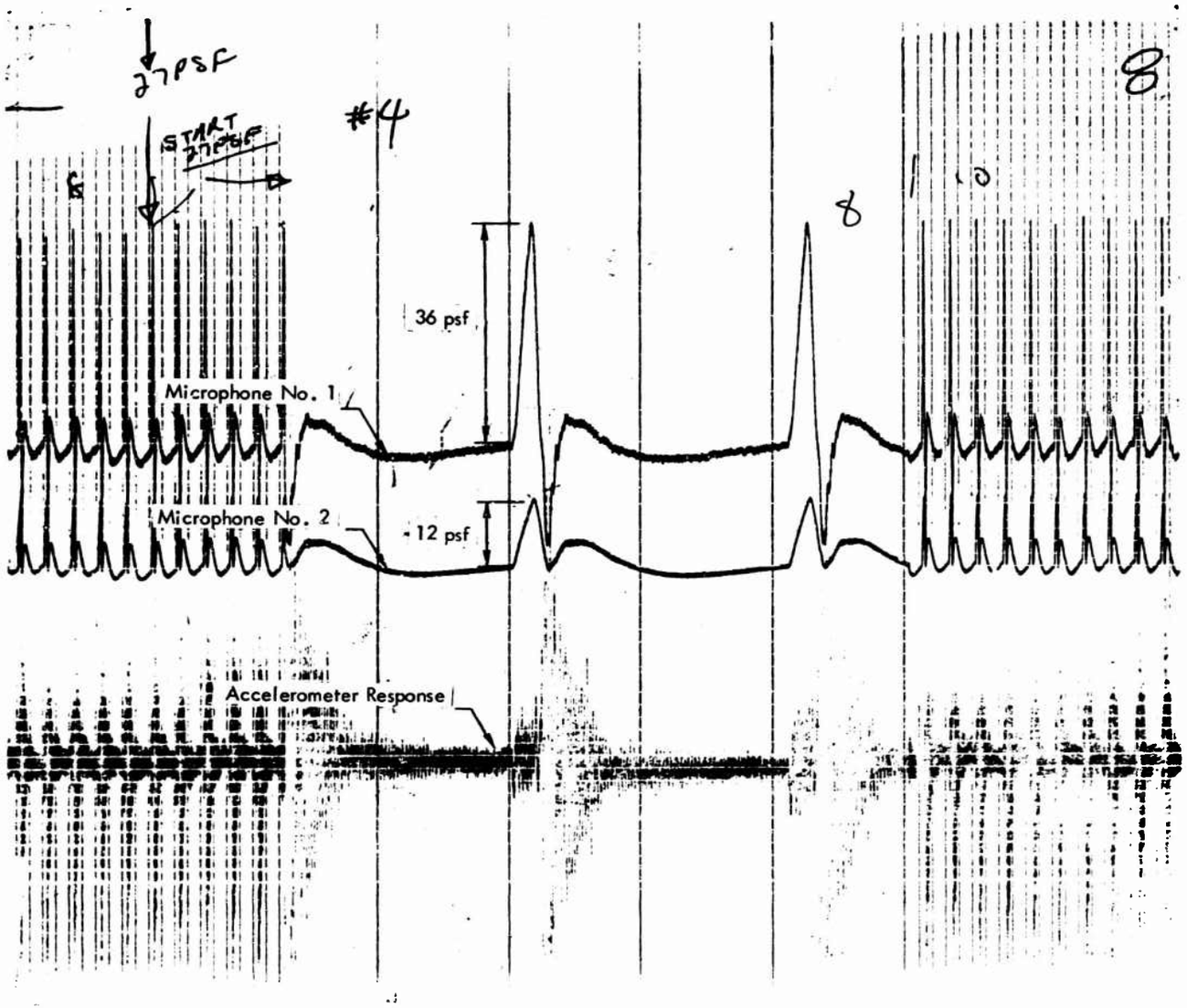


Figure 4-13. Acoustic and Accelerometer Responses of Sonic Boom Test Number 4

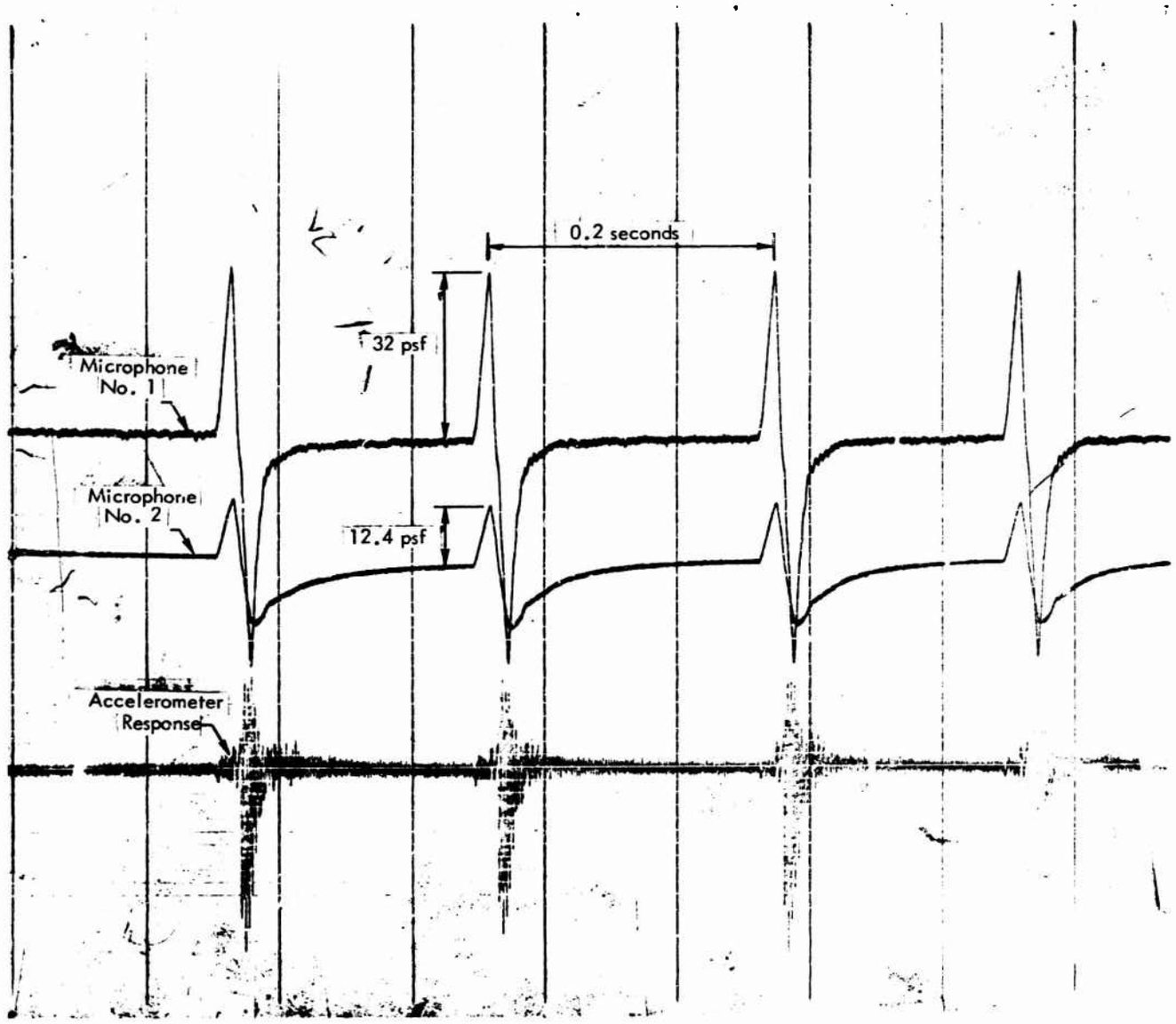
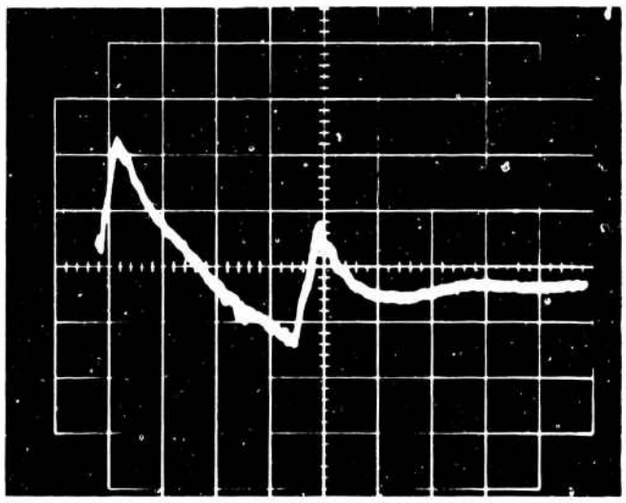


Figure 4.14. Acoustic and Accelerometer Responses of Sonic Boom Test Number 5

NOT REPRODUCIBLE



Vertical Scale:

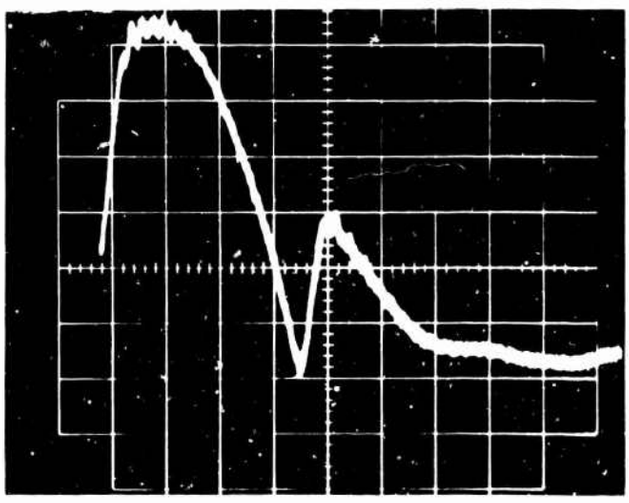
1 cm = 11.7 psf

Horizontal Scale:

1 cm = 100 m.s.

(a) Acoustic Response of Microphone Number 1

NOT REPRODUCIBLE



Vertical Scale:

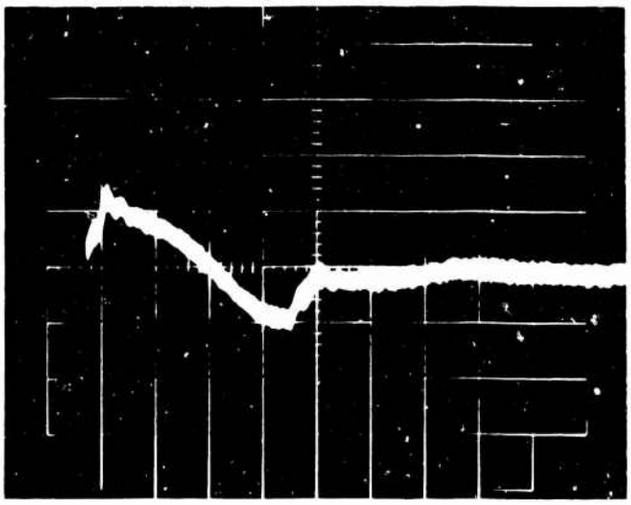
1 cm = 1.17 psf

Horizontal Scale:

1 cm = 100 m.s.

(b) Acoustic Response of Microphone Number 2

Figure 4-15. Acoustic Responses of Sonic Boom Test Number 6



Vertical Scale:

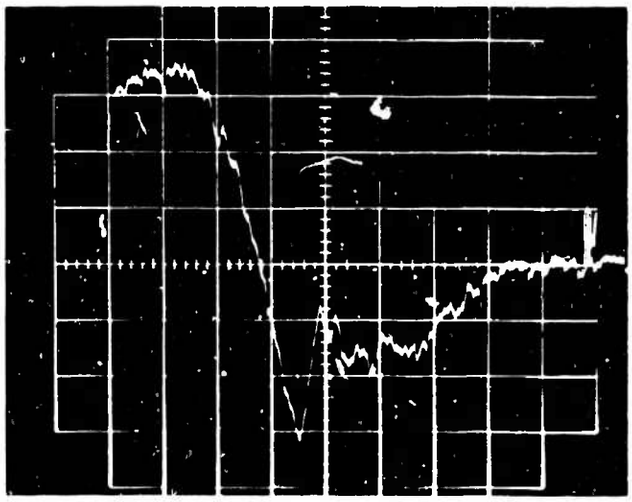
1 cm = 11.7 psf

Horizontal Scale:

1 cm = 100 m.s.

(a) Acoustic Response of Microphone Number 1

NOT REPRODUCIBLE



Vertical Scale:

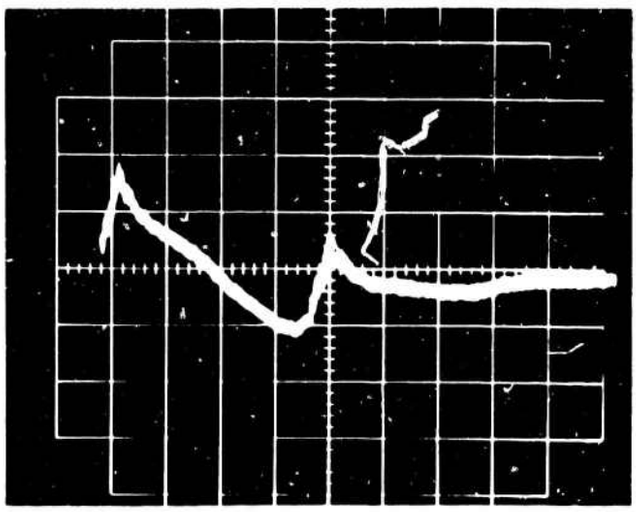
1 cm = 1.17 psf

Horizontal Scale:

1 cm = 100 m.s.

(b) Acoustic Response of Microphone Number 2

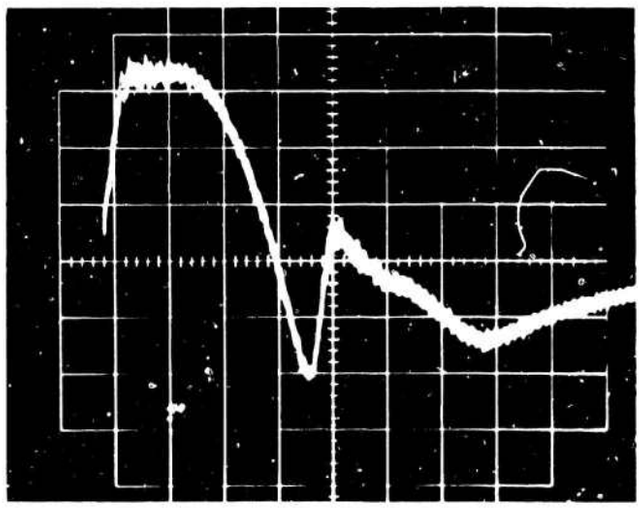
Figure 4-16. Acoustic Responses of Sonic Boom Test Number 7



Vertical Scale:
1 cm = 11.7 psf
Horizontal Scale:
1 cm = 100 m.s.

(a) Acoustic Response of Microphone Number 1

NOT REPRODUCIBLE



Vertical Scale:
1 cm = 1.17 psf
Horizontal Scale:
1 cm = 100 m.s.

(b) Acoustic Response of Microphone Number 2

Figure 4-17. Acoustic Responses of Sonic Boom Test Number 3

4.4 Discussion of Test Results

For the convenience of discussing the results obtained from the test program, the static and sonic boom data are summarized in Figures 4-18 and 4-19, respectively. The design criteria for single strength glass recommended by Pittsburgh Plate Glass Company (Reference 10) for both the static and sonic boom loadings are also presented in Figure 4-18 for the purpose of comparison. The conclusions drawn from the test results may be stated as follows:

Static Testing

- Edge support conditions have significant effects on the nonlinear stiffness of glass, thereby influencing the magnitude of static breaking pressures.

- Wyle static strength data appears to be low relative to the PPG curves. The phenomena might be attributed to the effect of rubber and putty edge conditions used in the majority of the tests and also the significant increase in the moisture content on glass surface due to water column loadings on the 48" x 48" x 3/32" specimens.

- The aging effect on used glass due to natural environments is quite apparant.

Sonic Boom Testing

- Under 4 psf overpressure level, the probability of failure of single strength glass under repetitive sonic boom exposure is extremely small.

- The strength endurance limit for the 48" x 48" x 3/32" specimens is estimated to be in the range of 14.5 to 16 psf. This value may be used as the lower bound for the glass family for all practical purposes.

Since the sample sizes used in the experimental program were extremely small, the above conclusions may bear little statistical significance as to be of practical application. Therefore, more tests would be required to improve the confidence level of the sonic boom test data. Nevertheless, valuable experience has been gained and can be utilized to provide guidelines for planning future test programs.

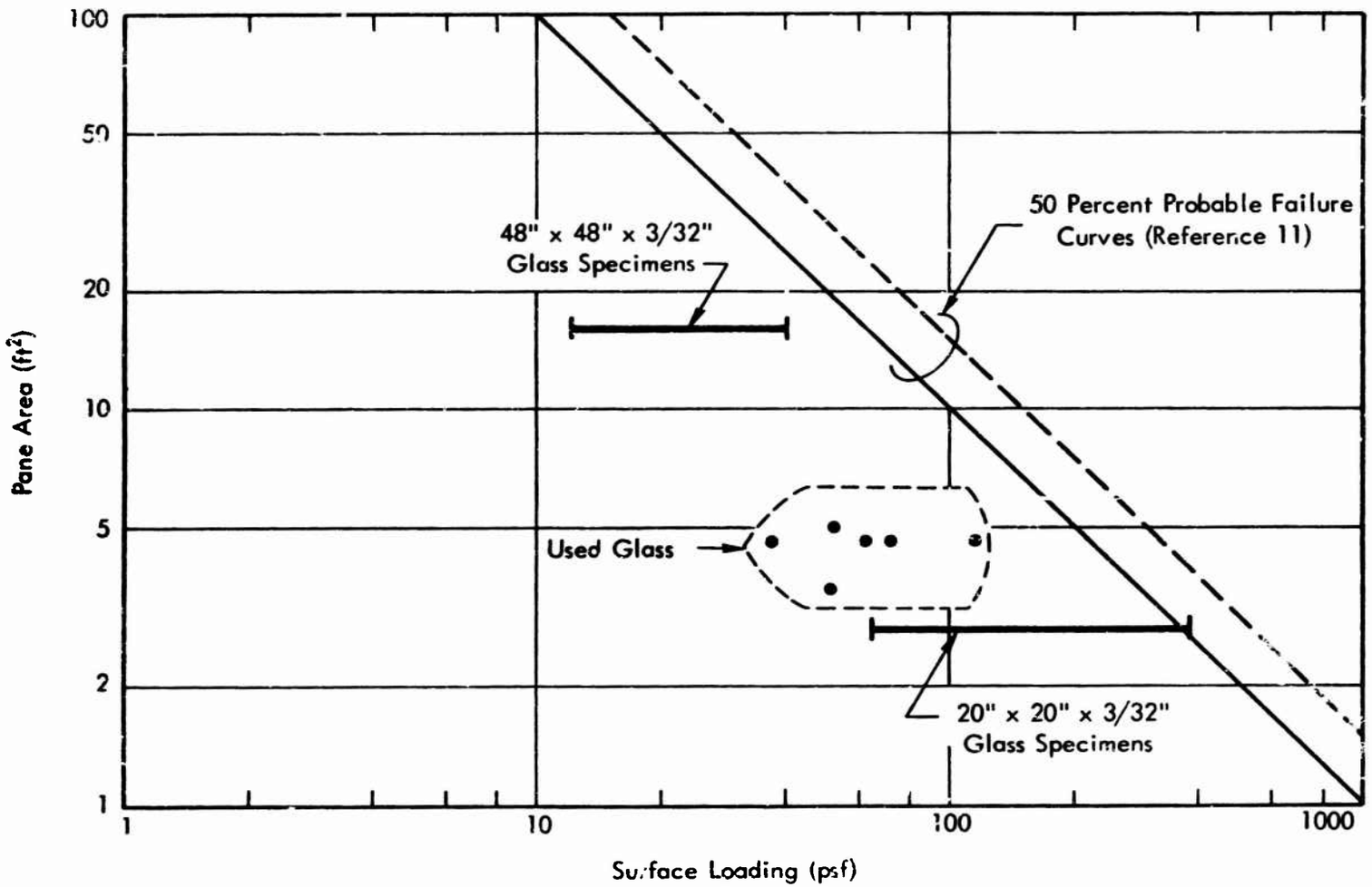


Figure 4.18. Summary of Static Testing Data

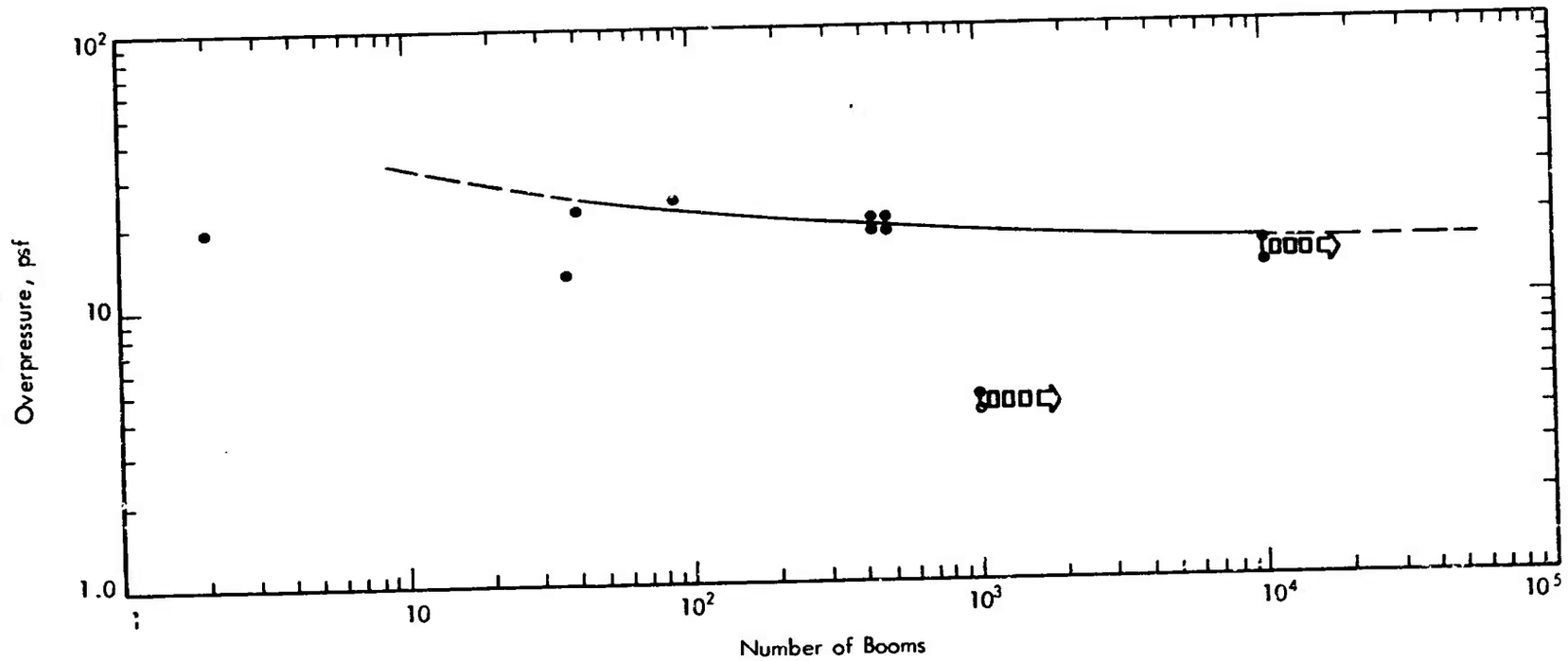


Figure 4-19. Summary of Repetitive Sonic Boom Test Results

5.0 EFFECT OF SONIC BOOMS ON GLASS BREAKAGE

5.1 Introduction

Glass breakage due to sonic booms, in general, may be grouped into two categories: incipient breakage; and cumulative fatigue damage. The incipient breakage occurs whenever stress levels in glass exceed their ultimate limits. Such overstressed conditions may be induced by three possible conditions described as follows:

- Direct Sonic Boom Loading Effects: Sonic booms with high overpressure levels would usually result in higher stresses in glass. However, certain critical stress levels could also be introduced due to the dynamic amplification effects caused by matching sonic boom waveforms.

- Effects of Mounting Systems: Distorted frames and the presence of stress raisers are the additional factors which would cause intensity stress levels under sonic boom excitations.

- Effects of Glass Aging: The prolong exposure to natural environments would lead to the reduction of glass breaking strength. The degree of strength reduction depends on the severity and the frequency of environmental variations. (Note, that existing old glass windows have survived natural environments and may therefore represent the higher strength members of the original old glass population).

Consequently, sonic booms are not solely responsible for all of the incipient failures occurring in glass; however, under certain circumstances, they are indirectly responsible for triggering failure mechanisms which initiate cracks. The cummulative damage failure is attributed to structural fatigue in glass. Unfortunately, present knowledge on the characteristics of glass fatigue under repetitive sonic boom loadings is quite limited. Adequate approaches towards solving this problem are still under various development stages and would require more effort and time before any workable techniques could be adopted for predicting fatigue damage in glass.

For the purpose of compiling present knowledge on solving glass breakage problems, attempts have been made in this section to review available test data obtained from previous overflight programs and to summarize results of existing analytical and statistical methods for potential application on glass related to the following areas:

- Design criteria for sonic booms
- Incipient glass damage criteria
- Glass breakage probabilities under normal and sonic boom environments

A brief discussion is also presented on the utilization of a statistical model to interpret test results obtained from limited number of experiments. The possibility of applying this method for planning future experimental programs is also outlined.

5.2 Previous Experimental Results

Previous sonic boom experimental programs have generally fallen into two major categories: full-scale supersonic overflight programs, and the development of sonic boom simulation techniques. Most of these programs have been concerned either with the responses of buildings as a whole, i.e., the structural responses of the walls, floors and the roof, etc., or with the community response and the nature of any damage claims. Relatively few studies have concentrated on the response of glass window panes to sonic boom overpressures.

One of the earliest systematic studies of the dynamic behavior of glass was performed by Freynik (Reference 12). A 3 foot square double strength glass pane of 1/8" thickness was mounted onto a test cubicle having a volume of 15 cubic feet. The fundamental frequencies of the glass pane, freely suspended, and mounted onto the test cubicle, were 21 Hz and 35 Hz, respectively. Strain gages were mounted on both sides of the glass to measure both membrane and bending strains, and the stresses were calculated using values of 1×10^7 lb/in^2 and 0.23 for the modulus of elasticity and Poisson's ratio, respectively. A typical result for static loading is shown in Figure 5-1 where the variations in membrane and bending stresses are plotted as a function of static pressure.

The dynamic stress resulting from window exposure to random noise concentrated in a one-third octave band is shown in Figure 5-2. For this series of experiments the one-third octave center frequency was 35 Hz, i.e., the input energy was concentrated at the fundamental resonance of the glass pane-cavity system. Figure 5-2 describes the variation in the peak tensile stress as a function of the overall sound pressure level in the one-third octave band. The horizontal line at approximately 4,000 lb/in^2 represents the suggested peak stress level above which glass breakage is expected to occur (References 13 and 14). At low sound pressure levels it was concluded that the membrane stresses were negligible and the system responded in the fundamental mode. At high sound pressure levels however, the membrane stresses were found to be comparable in magnitude to the bending stresses, and higher modes of vibration were severe.

The inherent variability of the breaking strength of glass, coupled with random variations in the sonic boom N-wave for a given aircraft, resulted in an appreciable variation in sonic boom damage for a given type of window design. This is illustrated in Figure 5-3 by the data from one series of controlled tests of sonic boom damage for conventional 3' x 3' window panes employing double strength (1/8"), and single strength (approximately 0.09") (Reference 14). No failures were observed for overpressures less than 20 lb/sq.ft. Even at overpressures in the range of 80-100 lb/sq.ft., approximately 35 percent of the windows survived without failure. On the other hand, results from other tests have shown that windows which were intentionally cracked before exposure to a sonic boom would fail at overpressures as low as 7.6 lb/sq.ft. (Reference 15).

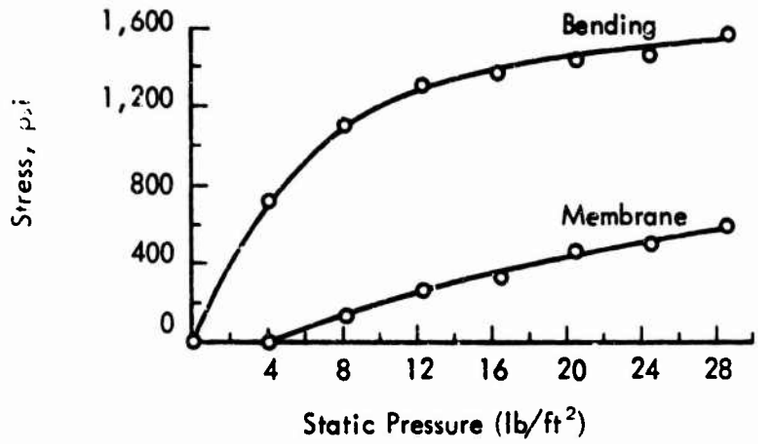


Figure 5-1. Measured Bending and Membrane Stresses at Center of Test Window Under Static Pressure Loading (Reference 12)

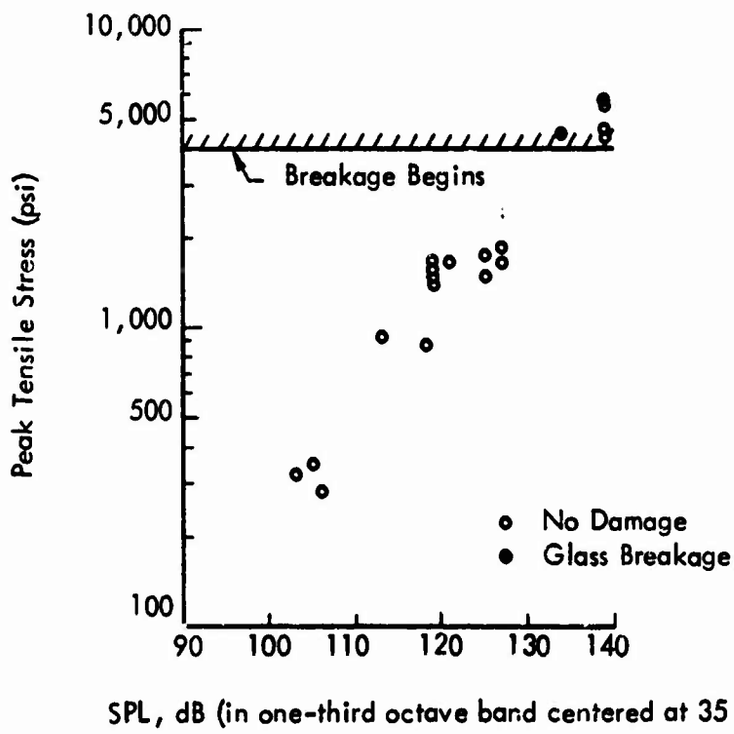


Figure 5-2. Measured Peak Tensile Stresses at Center of Window as a Function of the Sound-Pressure Level in a One-Third Octave Band Centered at 35 Hz (Reference 12)

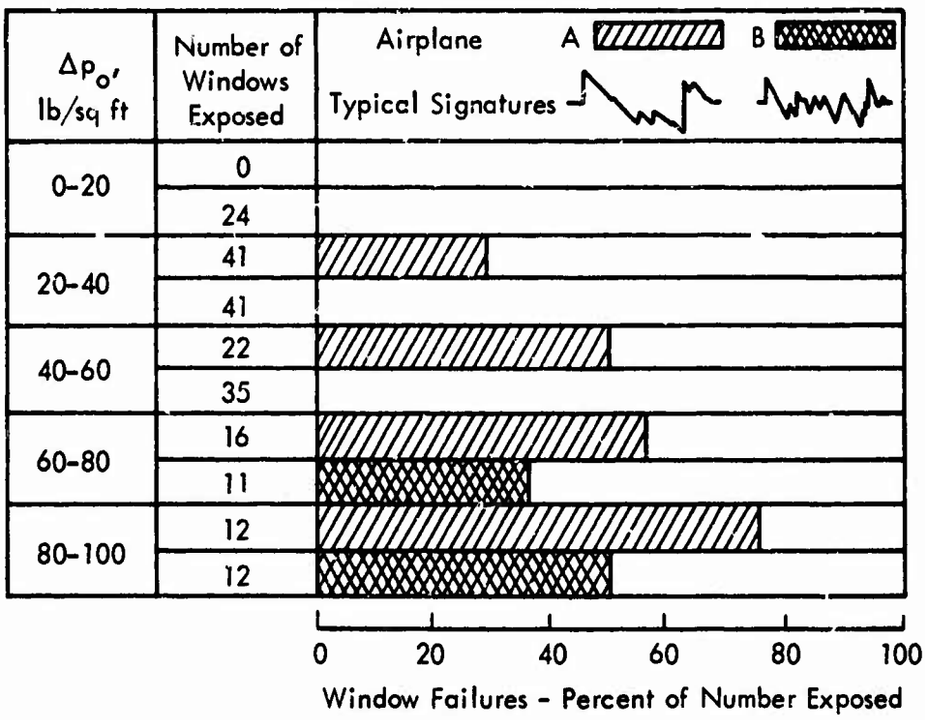


Figure 5-3. Summary of Results from Window Breakage Tests (Data from Reference 16)

Results from a number of different test programs on sonic boom damage of windows have been summarized in Reference 16. The results are shown in Figure 5-4 by a plot of a normalized loading parameter $p_0 (\alpha/h)^2$ as a function of the product $f_{1,1} \tau$ where α/h is the panel span to thickness ratio, $f_{1,1}$ is the fundamental natural frequency, and τ is the duration of the positive phase. A theoretically predicted value for the boundary between damage and no damage, derived in Reference 17, is also shown.

In a recent report summarizing the results of experiments conducted in Oklahoma City and White Sands (Reference 1), the possibility of Helmholtz resonance occurring when all doors and windows of the test houses were closed was examined. This was carried out in an attempt to explain an observed rapid decay of vibrations of a 5' x 10' window resulting from closed doors and windows. Experiments with a door open showed persistent vibration of the window for many cycles. Calculations showed that a Helmholtz type resonance had actually occurred but it was concluded that, in general, the probability of this resonance frequency coinciding with large window frequencies and causing damage was low.

5.3 Suggested Criteria for Glass Breakage

Revised criteria for sonic boom damage of windows have recently been proposed by Sutherland (Reference 18) based upon the experiments described in Reference 16 and 17. Sutherland's revised criteria were formulated as follows:

A critical examination of the data and test procedures for the results shown in Figure 5-4 indicate that a more conservative value is desired for this damage criteria line. Based on the non-linear load-deflection curve, as shown in Figure 5-5, the stress at failure is estimated (Reference 19) to be about 8000 psi. The recommended design value for breaking strength for regular window and plate glass for sonic boom loads is about 6300 psi, (Reference 18). Thus, one reduction factor to be applied will involve reducing the criteria to allow for a more conservative breaking strength.

Further examination of the procedures employed for the sonic boom tests reveals that a 16 cubic foot sealed cavity was placed behind the panel to insure a positive pressure differential across the window pane. However, this has the effect of increasing the effective stiffness of the panel due to the added "acoustic stiffness". The computed relative change in effective panel stiffness with the cavity is 1.77. A similar stiffening effect was observed experimentally in Reference 12. The net effect of this added stiffness would have been to require a correspondingly higher overpressure to achieve the expected failure stress. This, then, provides a second correction factor which would tend to reduce the damage criteria level indicated in Figure 5-4.

Combining these two corrections, the original "no damage" criteria for the parameter $p_0 (\alpha/h)^2$ at 1.8×10^6 lb/sq.ft (for values of $f_{1,1} \tau > 0.6$) is reduced to the following:

$$p_0 \left(\frac{\alpha}{h}\right)^2 \leq 0.8 \times 10^6 \text{ lb/sq.ft}$$

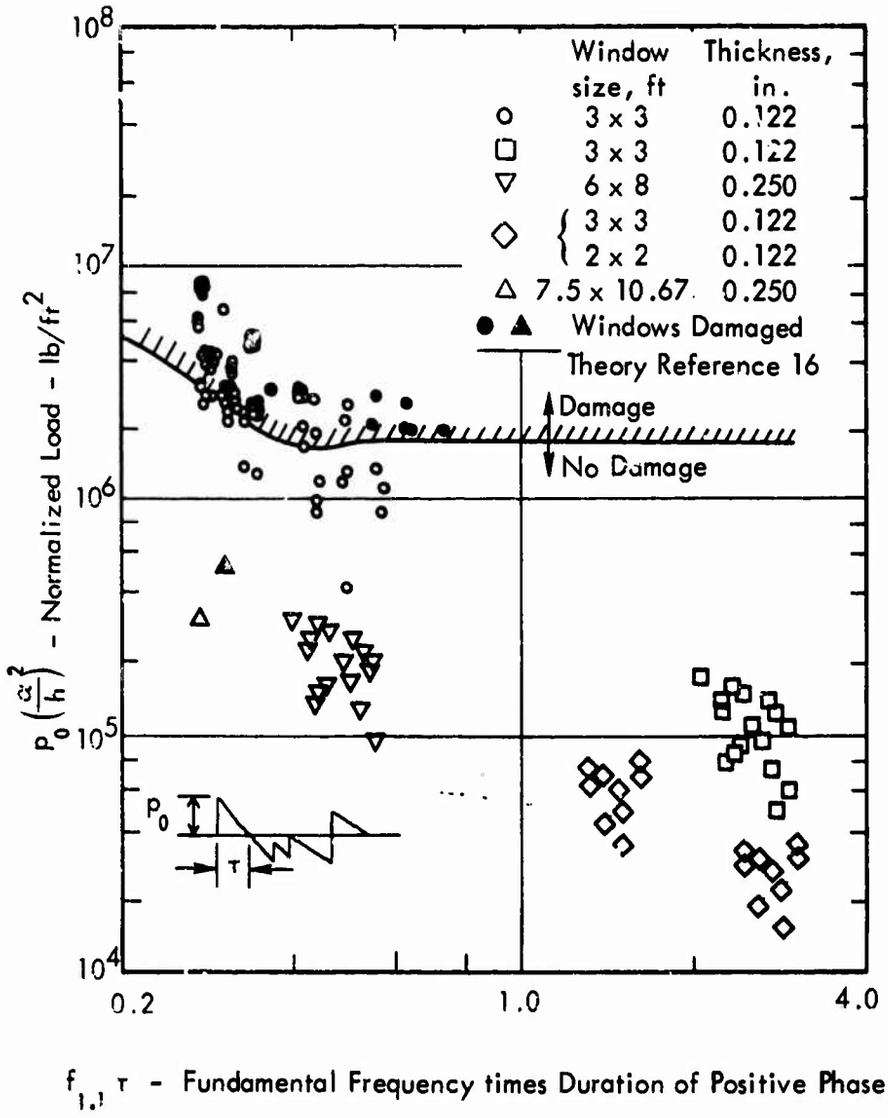


Figure 5-4. Summary of Window-Glass Breakage Experienced due to Sonic Booms. Load specified by the normalized parameter $p_0\,(\alpha/h)^2$ where α/h is the ratio of a side Length (α) to thickness (h). Data from a summary in Reference 16.

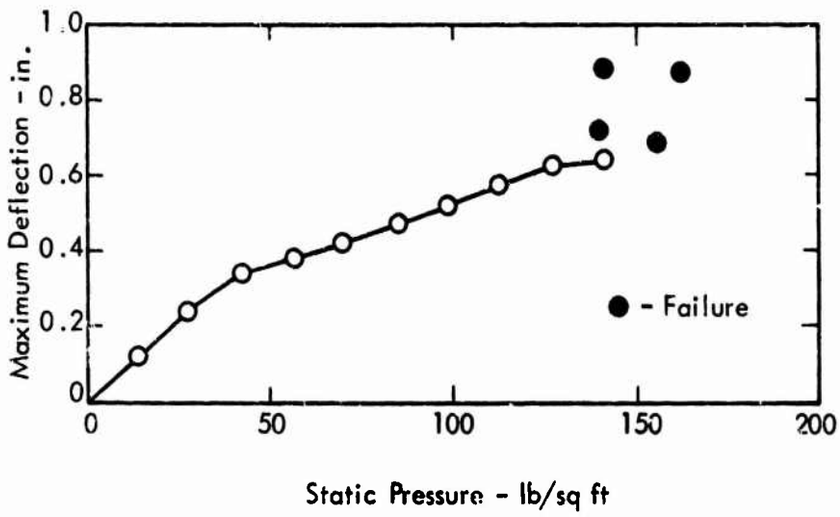


Figure 5-5. Static Load - Deflection Curve for 3ft x 3ft x 1/8 in Window Pane (Data from Reference 16)

where

P_o = sonic boom overpressure - lb/sq ft

L = [illegible] of approximate square window

t = glass thickness

f = fundamental frequency - Hz

τ = duration of positive phase

For values of sonic boom overpressure within the proposed limits for the SST and for windows whose length to thickness ratio meets standard building code requirements. This criteria indicates that normal quality windows should not be damaged (Reference 19).

Based upon the Oklahoma City and White Sands test data, Wiggins (Reference 1) has suggested the maximum safe ground overpressures for plate and window glass as shown in Figure 3-8. This figure, which shows the relation between glass area, glass thickness and safe overpressure is a modified version of the Pittsburgh Plate Glass Company's recommended practice (Reference 19).

3.4 Design Guide for Evaluating the Effects of Sonic Booms

In general, a window pane can be treated as a uniform rectangular plate having various boundary conditions. The dynamic response is considered to be due primarily to the application of the shockwave, i.e., the secondary effects arising from the interaction of the plate with the rest of the building are usually neglected. The dynamic response of uniform beams and rectangular plates having simply supported and clamped edge conditions and subjected to various types of pressure pulse has been studied exclusively by Cheng (References 6, 20 and 21). These studies include the effect of ideal N-shaped pressure pulses, traveling N-waves and traveling pressure waves of arbitrary shapes. Similar studies, including some experimental results have been presented by Crocker (Reference 22), and the agreement between Cheng's results and Crocker's results is remarkably good. In order to derive simplified methods, Cheng studied the theoretical damped dynamic responses of structural elements exposed to a group of typical sonic boom signatures (Reference 5). The essential results have been presented in terms of the dynamic amplification factor (DAF), defined as the ratio of the maximum dynamic moment to the static moment due to the uniform peak pressure developed at the same point in the structure.

It has been shown that the magnitude of the DAF depends upon the exact shape of the boom signature and upon the period ratio R. Since the DAF curves are asymptotic at large values of the period ratio R, the DAF can be assumed to be dependent only upon the fundamental period ratio (R_1) if the exact shape of the boom signature is known. However, in almost every practical case, the exact shape of the boom signature is difficult to determine accurately. In order to avoid the requirement that the boom signature shape be known, Cheng (Reference 6)

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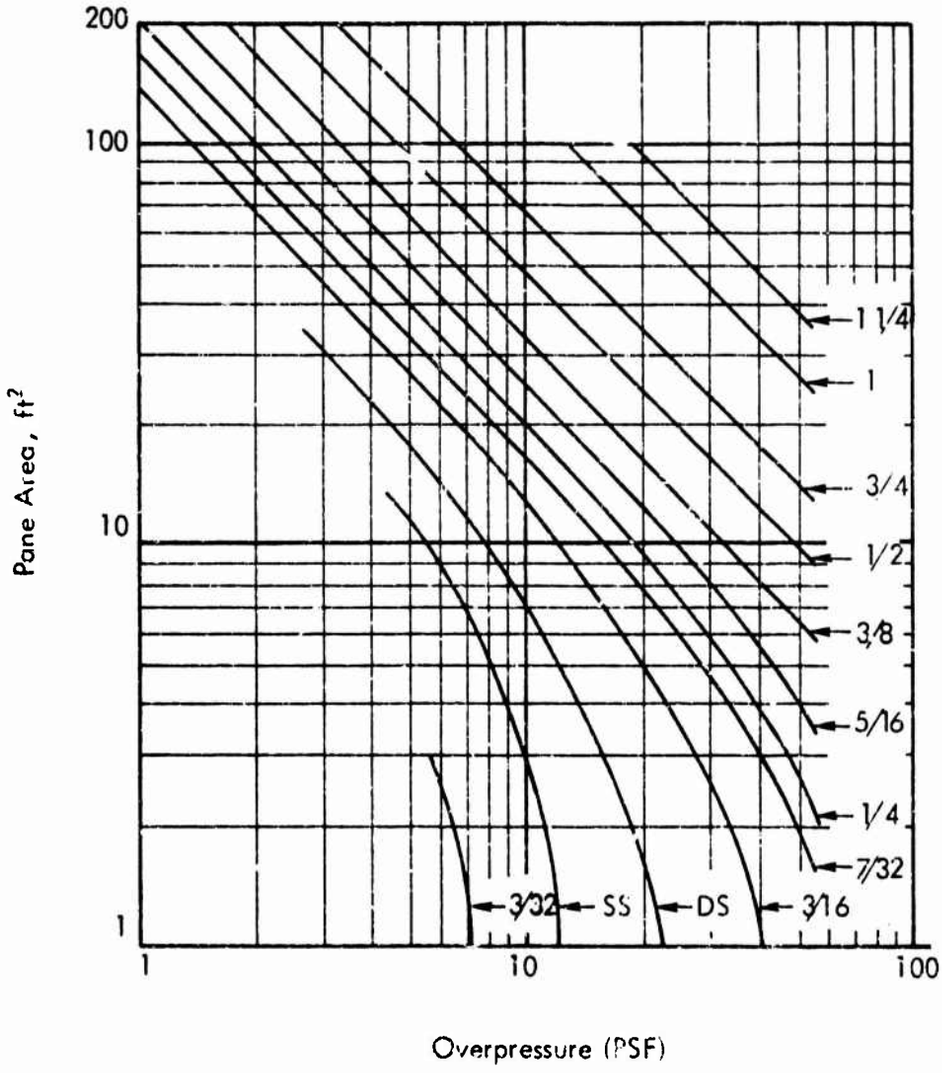

Figure 5-6. Maximum Safe Predicted or Measured Average Ground Overpressure for Plate and Window Glass (Reference 5)

devised a design approach to predict the magnitude of the DAF. This design approach, although slightly inaccurate, leads to the determination of the DAF as a function of the fundamental period ratio (R_1) only. To utilize this method, only the magnitude of the peak pressure (p_0) is required.

The design curve resulting from this method is shown in Figure 5-7. This figure describes the variation of the DAF for a beam or a square plate as a function of the fundamental period ratio R_1. To obtain the dynamic moment acting on the beam or plate, the corresponding daf is simply multiplied by the static moment (which is equal to $p_0 l^2/8$ for a beam or $0.0479\ p_0 a^2$ for a square plate, where p_0 = the peak pressure).

For the purposes of comparison, a similar curve proposed by Crocker (Reference 23) is included in Figure 5-7. The DAF envelope proposed by Crocker (Reference 23) is for use in assessing the structural response due to supersonic transport overflight and is based upon a boom signature similar to the type shown in Figure 3-3(d). A wide variation between the envelopes proposed by Cheng (Reference 6) and Crocker (Reference 19) is observed, this being due to the fact that Cheng's results include a boom signature having the shape of a sine pulse. If the results for the sine, pulse and the half-cosine pulse are ignored in the computation of Cheng's daf envelopes, then the resulting daf envelope is similar in magnitude to Crocker's results However, the two independent sets of DAF envelopes allow for the estimation of the structural response to a wide variety of sonic boom signatures.

5.5 Glass Breakage Due to Normal Environments

The determination of glass breakage probability under normal environmental conditions would require the knowledge of the distribution of glass population for regions where SST overflights are planned. To undertake this task in an efficient and economical manner, an adequate sampling method (Reference 24) is needed to acquire statistical information for a typical glass neighborhood. For example, one may choose a number of cities among several geographical areas, and select a certain number of households within each city to survey; or one may choose a state which is considered to be typical of all probable environmental conditions of those regions and carry out sample surveys in that state. In short, methods used to implement a survey objective are numerous, and the choice of a particular method depends entirely on the preference of the responsible individuals and the available fundings. Normally, a program with a large sample size would be very costly; but on the other hand, the data obtained from a small sample population may be biased and misleading. Hence the optimum approach is to define a reasonable objective and then design the survey program accordingly.

During the performance of this contract, a preliminary survey of the glass population in Huntsville, Alabama, was conducted. A total of twenty buildings were surveyed, and the distribution of these buildings surveyed is given as follows:

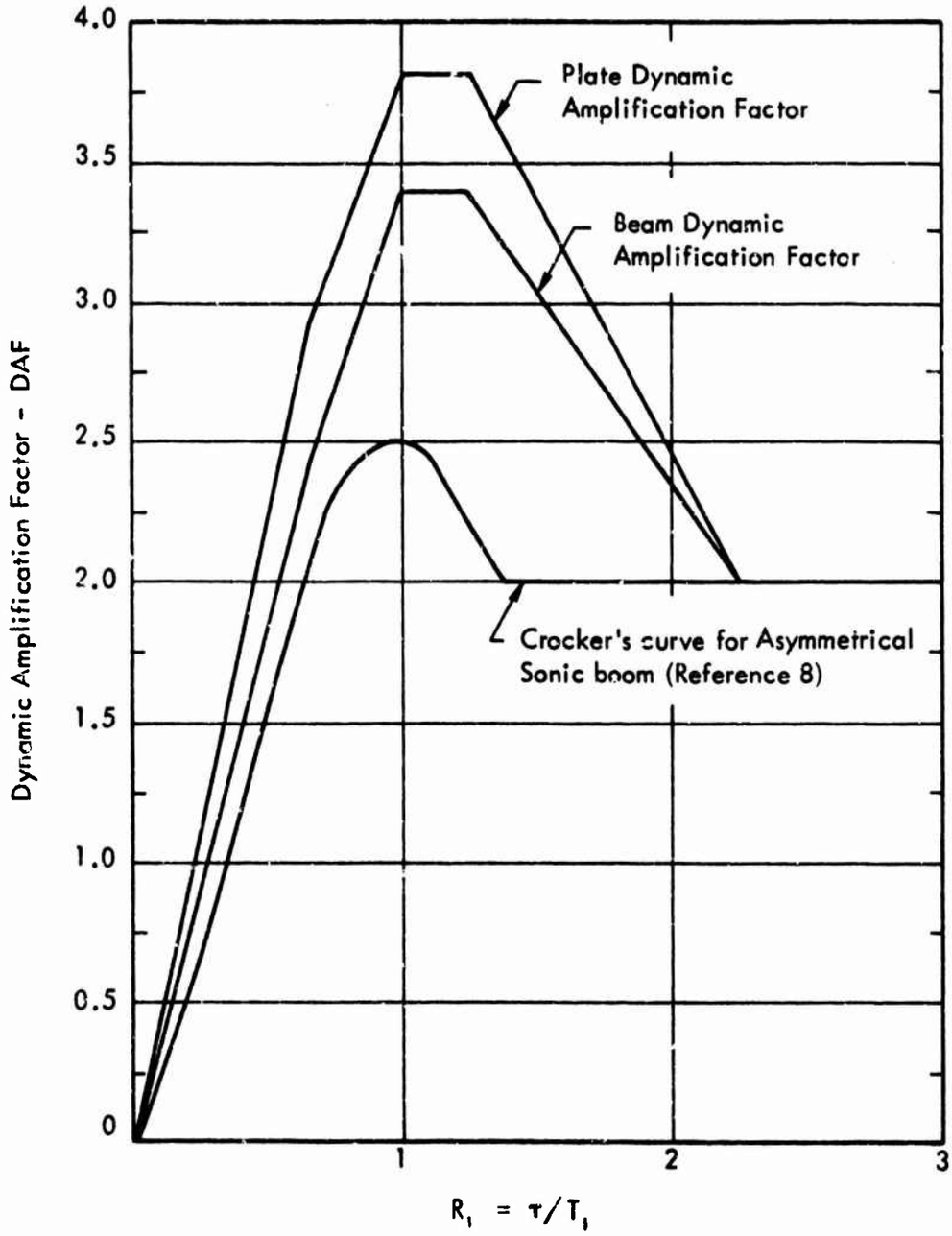

Figure 5-7. Simplified DAF Envelopes for Sonic Booms (References 6 and 23)

Type of Building	No. of Buildings
Commercial	10
Multiple Dwelling	3
Single Family Dwelling	7

The major causes of glass breakage are summarized as follows:

- Commercial Buildings:
  a) Burglary
  b) Winds
  c) Walk-in
  d) Shopping Cart
- Multiple Dwellings:
  a) Winds
  b) Accidental Slamming
  c) Cold Weather
  d) Accidents
- Single Family Dwelling:
  a) Rocks thrown by Mower
  b) Baseball
  c) Accidents

However, it was considered that the sample size was not large enough to provide a fair description of glass breakage in the neighborhood. Additional effort would be required to define the glass distribution and the normal glass breakage probability of Huntsville.

A glass survey was made on a nationwide scale in 1964 (Reference 25). Twenty consumer panels, eaching consisting of 1000 families, were forwarded questionnaires by mail. The results of the survey obtained from the 21 percent respondent who purchased and used glass in that year are summarized as follows:

- Repairing 77 percent
- Replacement, Unbroken 6 percent
- New Additions 7 percent
- Alteration 6 percent
- No use 4 percent

Recently, in Reference 26, an attempt was made to convert the above glass consumption rate to estimate the normal glass breakage rate for 1964. In the computation, the 4 percent "no use"

category was converted into that of the "repaired" and obtained the modified percentage of "repairing" at 80.2 percent. This value was multiplied by the percentage of respondents who used glass (21 percent), that gave 17 percent of U.S. households in which glass repairs were made in 1964. The information presented herein provides a gross picture of the glass breakage rate for that particular year. No known development has been reported in the "normal" breakage areas.

5.6 Glass Breakage Probability Due to Sonic Booms

Because of the brittle nature of the glass and other uncertain factors surrounding them, the prediction of glass damage to sonic booms could only be achieved by employing statistical approaches. In Reference 27, a study was made on the probability of glass failure under 2 psf overpressure. The analysis was based on two different assumptions that the strengths of window glass were either normally or log-normally distributed. The calculated probabilities were found to be 0.0002 and 10^{-9}, respectively, for the two cases indicated above. However, claim data show that the probability of damage is in the order of 10^{-6}. These values may suggest that the actual strength distribution of window glass might lie somewhere between the normal and log-normal. In Reference 5, attempts were made to fit available data on glass damage (References 28, 29, and 30) and the estimated overpressure levels with regression curves on log-normal papers. The final results have shown that these curves fit the test data satisfactorily at high overpressure levels, but no conclusive statement could be made on damage probability for overpressures under 3 psf.

Due to the lack of adequate test data from previous overflight programs, it is not feasible at this moment to formulate suitable statistical models for predicting cumulative damage on glass subjected to repetitive sonic booms. It is also unfortunate that the amount of test data taken during the present test program is limited in number; consequently, they could not be used to formulate the frequency distribution function for predicting failure. However, attempts have been made to utilize a non-parametric statistical model (Reference 31) to interpret test results in the future if more repetitive sonic boom test data becomes available.

Two basic assumptions are needed in applying the theorem; they are:

- Test specimens must be selected at random
- The frequency function of the basic test variables (i.e., the breaking strength of glass, number of booms to failure, etc.) must be continuous.

If N panes of glass were tested for a given overpressure level, and the maximum and minimum number of booms (designated here as the extreme values) required to break these test specimens have been obtained, then the probability, P, that a certain percentage of the total glass population (similar to the test specimens), H, would fall within the extreme values is given by the following equation:

$$P(H) = N(N-1)H^{N-2}(1-H)$$

A set of parametric curves used to represent the relationship among the three variables P(H), N and H is presented in Figure 5-8.

For example, if 10 panes of 48" x 48" x 3/32" glass were tested at an overpressure level of 20 psf, and the extreme value in terms of number of booms to failure were found to be 400 and 500, respectively, then one may state that the probability is 95 percent, and that 65 percent of the glass population would fail between the extreme limits as indicated above. Or, that the probability is 98.9 percent that 50 percent of the glass population would fail between the extreme limits, etc. It is important to note that the improvement in probability and population coverage can be achieved by employing more specimens in the tests.

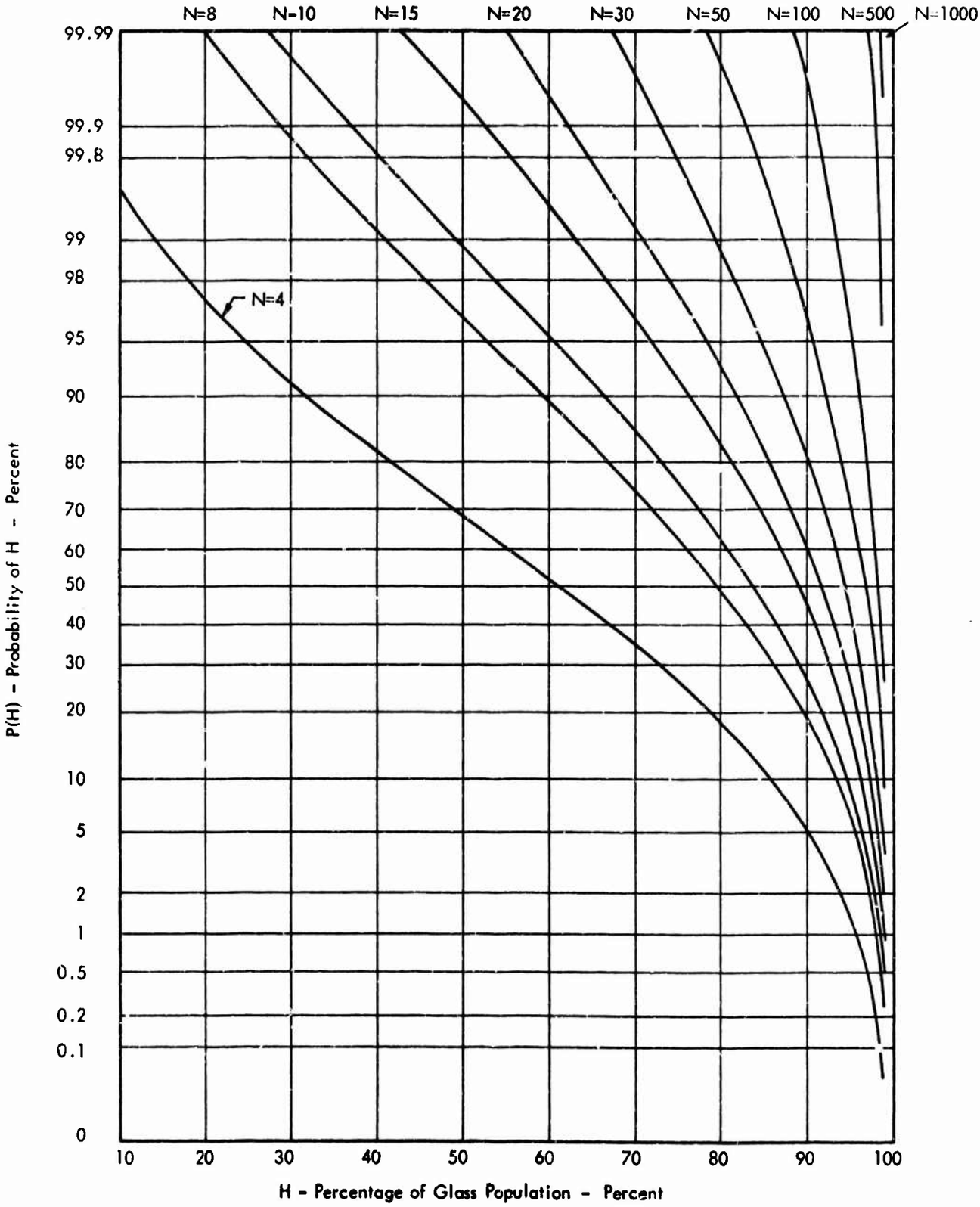

Figure 5-8 . Estimation of Probability of Test Result Versus Sample Population

6.0 CONCLUSIONS

The main objective of this program was to determine the cumulative damage effect of glass to repetitive sonic boom disturbances. In order to evaluate such phenomena experimentally, a pneumatic-pistonphone simulator was developed and used successfully to test glass specimens under simulated sonic boom overpressures. A limited amount of test data were obtained, however, preliminary understanding has been gained regarding the cumulative damage effect of glass to repetitive sonic boom loadings. The conclusions drawn from the research effort are summarized as follows:

- Sonic Boom Simulator – It is feasible to apply the pneumatic pistonphone concept to generate pressure disturbances for simulating sonic booms. The pressure signatures can be controlled and reproduced reasonably well to synthesize various sonic boom waveforms. The simulator can be used efficiently to perform repetitive sonic boom testing of structural panels.

- Cumulative Damage Effects of Glass Specimens to Repetitive Sonic Boom Overpressures – From the results of the repetitive test data, it is clear that: the probability of glass damage to specimens subjected to overpressure levels of less than 4 psf is quite small; the endurance limit for the specimens tested is estimated between 14 to 16 psf. But the test results suffer from statistical accuracy due to a small number of glass specimens tested. Hence, these data could not be utilized to formulate a statistical model to predict glass damage.

- Effect of Aging on Glass Strengths – From the results of static test data, it appears that the effects of natural environments have reduced the breaking strengths of the used glass as compared to that recommended by current design practices.

- Typical Glass Neighborhood Survey – It is felt that such a neighborhood survey should be conducted on a larger scale to cover various parts of the nation, so that the glass distribution spectra of different environmental conditions can be properly defined, and the results of such a survey would provide more accurate information on glass damage probability.

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