ACOUSTICAL FATIGUE TEST PROCEDURES USED IN AIRCRAFT INDUSTRY AND THEIR LIMITATIONS

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ABSTRACT

A broad review of acoustical fatigue testing practices used in the aircraft industry and associated groups is made in which descriptions of the rather substantial variations existing in the experimental and analytical approach to the problem are included. Some of the more important controversial questions, such as type of acoustic environment simulation required, the type and use of test facilities, test objectives, and the analytical philosophy from group to group, are discussed. Some description of new facilities being designed and built is also given.

I. INTRODUCTION

The adoption several years ago of high thrust turbojet engines to power modern aircraft introduced an entirely new testing challenge to the aeronautical field. The development of the somewhat standard techniques now used to test aircraft structure under flight-induced loads underwent, to a great extent, a lengthy growth paralleling that of modern aircraft design itself. It has not been so with acoustical fatigue testing, however. Noise-induced fatigue failure became a fairly sudden problem and laboratory analytical and testing procedures were not available to handle the requirements.

The first major test programs on acoustical fatigue of aircraft structure in the United States were full scale tie-down tests of complete aircraft. The two prime examples were the tests conducted by the Boeing Airplane Company on both the B-47 and the XB-52 jet bombers (1)* and the tests on the RB/B-66 jet bomber by Douglas Aircraft Company in California and Alaska (2,3).

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*Numbers in parentheses refer to Bibliography.

The initial decision to run these full scale aircraft tests illustrated several very important facts about the views toward noise-induced structural fatigue and what to do about it. First, even though the idea of noise-induced structural vibration introduced itself years before in the case of fuselage sidewall excitation from propeller tip noise, the occurrence of major fatigue failures from jet engine noise was generally not taken into consideration in the design of existing aircraft. As a result, a prodigious task faced the airframe companies in analyzing the problem, locating the trouble areas, and determining what modifications in design and construction would satisfactorily put out the fires. Experience has shown that, in some cases, the resulting remedies left much to be desired since there was a limit to the modification possible on an existing aircraft. Another important fact illustrated was that a full scale tie-down test was chosen to provide the desired acoustic environment over other techniques despite the fantastic expense associated with it. Certainly, the lack of alternate techniques which had been proven was the basis for that decision. It is significant to note that the opinion today seems to be that we must still rely on experience under service conditions for the ultimate proof that a design can resist acoustical fatigue.

Interest grew, with good reason, throughout the airframe industry in the development of laboratory facilities. First, enormous expense was involved in full scale testing; next, a test procedure was needed to study anticipated problems on designs not yet built; and, finally, there existed a need for procedures adaptable to efficient, convenient laboratory scale experimentation. A survey begun in 1956 by the Aircraft Industries Association of some fourteen airframe manufacturers dramatically illustrated the general state of infancy existing in the acoustical fatigue area, especially in regard to laboratory test equipment and procedures (4-7). Aside from the unified agreement that the acoustic excitation of structure constituted a serious problem badly in need of a solution, there was little agreement on such questions as the type of test to perform, equipment to use, instrumentation necessary, test conditions to consider, and so on. It was in this atomosphere of uncertainty and urgency that many of the initial test programs were designed and started and plans laid for test facilities.

Several types of test facilities have been put into use by the aircraft industry in the last few years for experimentation on a variety of problems. The manufacturers and users of electronic gear, for example, are interested in subjecting the components to the appropriate noise environment which is normally obtainable with reverberant chambers, plane wave and resonant tubes, and the like driven by loudspeakers. Since airframe manufacturers found it difficult, if not impossible, to provide the necessary environment for structures with this type of source, other types were adopted in which both the direction of propagation of the sound could be controlled to some degree and the necessary high sound intensities could be produced. It is the purpose of this paper to present a discussion of the second of these types of facilities. Some of the variations found in equipment design and use, test techniques and objectives, and analysis procedures which characterize the state-of-the-art in the aircraft industry today are discussed.

II. RANDOM VERSUS DISCRETE FREQUENCY TESTING

Most of the acoustical fatigue facilities used by structures test groups can be categorized into two general types: those which produce a discrete frequency or pure tone and those which produce a random noise. Since the acoustical fatigue problem is the result of structural vibration due to random acoustic excitation, it is easily understood why the preference might lie here. Unfortunately, it is also here that the greatest costs by far, and usually a considerable degree of inconvenience, are found. It is undoubtedly for these reasons that variations in practice exist.

Opinions vary among investigators on the merits of using discrete frequency testing of structures and whether the results give any significant insight into the performance of the structure under random loading. The trend toward the use of discrete frequency facilities, such as the siren, was prompted by the almost prohibitive inefficiency of available random noise sources (8) and by the need for a simple, convenient laboratory tool.

Usually, one of possibly two objectives are in mind with the use of a discrete frequency test program. First, some groups are interested only in comparing two or three test panel designs under the same acoustic conditions in order to choose the "strongest" one. Excitation of a normal mode at its fundamental frequency is accomplished at a single sound pressure which is estimated to prevail at the point of interest on the aircraft. The basic assumption here, true or not, is that on the aircraft the panel will respond significantly to the acoustic loading only in the above fashion. For this type of qualitative test, therefore, discrete frequency excitation is assumed to be adequate. The second objective is to arrive at the siren operating conditions to represent the random loading through a deliberate mathematical interpretation of the loads and the rate of accumulation of fatigue damage (9-11). The performance of a panel can then be interpreted in terms of performance under random loading so that a measure of the adequacy of the design is possible.

Recent experiments at NASA (12,13) made to compare random and discrete frequency loading of specimens under otherwise identical conditions effectively demonstrated the importance of correctly interpreting test results and recognizing the proper significance of test data. Figures 1, 2, and 3, taken from a study by Hess, Herr, and Mayes (13), show the possible variation in interpretation of the fatigue life under random and discrete frequency loading. In Figure 1 for example, panel life under random loading is shown to be greater than for discrete frequency loading when interpreted on the basis of overall noise level. This is probably because a smaller percentage of the impinging random noise corresponds to the panel's natural frequency and is accepted by the panel than in the case of the discrete noise which corresponds totally to the panel's natural frequency. In Figure 2, a replot of the data shows a shifting of the random noise fatigue curve for different bandwidth analyses. And finally, in Figure 3, a comparison of data in terms of the root-mean-square stress demonstrates the higher fatigue life under discrete frequency loading; the stress excursions from the rms stress under random loading at times greatly exceed the constant excursion under discrete loading and result in greater fatigue damage.

There are many who feel that the test results obtained with a siren give only marginal quantitative guidance for the prediction of the life of a design under random acoustic loading. The discrete frequency simulation of random noise can involve over-simplification where a system capable of vibration response in several modes is involved (8). It is generally considered not possible to duplicate with a siren the complicated spatial pressure distribution of pressure which exists in the case of a panel excited by a jet engine. This is an important consideration since the response of a panel is sharply influenced by space correlation effects (14).

Because of the excessive time requirements of a one-to-one test, some sort of scaling of time is normally performed. In a recent paper, Baruch clearly pointed to the extreme caution which is mandatory in assuming a scaling law for accelerating test time under random loading, such as with a jet engine, by increasing the level of the noise (15). He points out that, for example, because of air-non-linearities and structural response non-linearities, changes in the wave distortion distance function with increased noise level and the increase in the importance of extreme-values, a valid scaling law is not yet available. A research effort is described by Baruch to study this question.

III. THE USE OF SIREN FACILITIES

The most used, and certainly the most developed, discrete frequency sound source for structural testing is the high intensity siren. The siren is quite simple in basic design, is very economical to operate, and for the most part, has been quickly and effectively adapted to laboratory use. With very few exceptions, siren facilities operated in the industry have been designed and manufactured by the company using them.

Test practice with siren facilities in the industry varies considerably, as might be expected. The buildup of test equipment and the development of testing practice within a given company at the outset of experimental work several years ago was usually accomplished with the minimum of knowledge of the details of the techniques in a sister company. This was not especially due to any reluctance to share experience, but rather to the fact that attempts to solve the problems were generally exploratory in nature and there was little to report on in the way of standard procedure. As a result of the relatively meager exchange of information, and because test objectives were different in many cases, variations exist in such matters as siren specifications, angle of sound wave impingement, variations in the method of mounting test panels, type of instrumentation used, and method of monitoring tests.

A. Siren Specifications

Despite the fact that the basic siren components are essentially identical, operating characteristics vary over a fairly wide range. In most of the cases, siren designs have in many respects followed the analysis of R. Clark Jones who pointed out the important requirements of an efficient siren in 1946 (16). Included were requirements such as a large compressor air flow at low excess pressure for low shock wave losses, chopper port perimeter small compared to the sound wavelength, short transition times for opening and closing ports since resistive losses are at their highest at this time, and the proper choice of the horn for correct impedence transformation to the test section. The design and consultation work of Rudnick and Leonard of the Physics Department at the University of California at Los Angeles on several of the sirens now in use is also worthy of mention (17,18).

In the design of a siren to produce high intensity sound, a compromise of the desired conditions outlined by Jones is necessary. To get high sound levels, a large air flow is needed. In order to maintain a low initial pressure to keep shock losses to a minimum, a larger orifice size is usually used. It is between the initial pressure and the orifice size that the compromise is usually made since too large an orifice again results in back-reflection losses. The design of the horn for impedence matching involves another compromise between such conflicting horn requirements as the minimization of shock-wave losses and the optimized physical matching between the siren and the test section.

Although the basic elements of the siren are essentially the same from unit to unit, siren configuration falls roughly into two categories. In one group are those sirens used for excitation at a grazing angle of incidence. Here the siren is physically coupled to the test section via a transition section, as illustrated in Figure 4. In the other group are those sirens used for the normal excitation of panels, as shown in Figures 5 and 6. In these cases, there is no physical coupling of the horn to the test panel. More will be said of these variations later in the discussion.

To illustrate the variations which characterize the siren facilities in use today, Table 1 is included, in which a representative group of facilities is listed. It is noted that maximum rated sound intensities vary from 160 to 180 decibels, plenum chamber pressure from 2 psi gauge to as much as 50 psi gauge; compressor flow rates vary from about 1200 cubic feet per minute to around 6000 cfm, and operating frequency ranges vary from a few hundred cycles per second to over 2000 cps.

B. Angle of Incidence: Normal Versus Grazing

An important controversial question existing today is the merit of various test panel locations relative to the sound wave direction. Siren facility operators are split rather evenly between the placement of test panels normal to and at a grazing angle to the sound wave. The two schemes are illustrated in Figure 7 taken from Regier and Hubbard (8).

A survey of opinions regarding the question uncovered a number of reasons for making a particular choise. Some feel that in practice, an aircraft panel experiences excitation from an exhaust primarily at grazing incidence, while others are of the opinion that reflections from the runway and from the aircraft itself during the significant damage periods, groupd runup and takeoff, result in mixed or nearly normal impingement.

Still other considerations are behind the choice of some groups. For economical reasons, some investigators adopted normal incidence since they felt that the siren is more versatile; it can be moved within a test chamber to vary the acoustic conditions or relative to the test panel to vary special conditions such as intensity. Secondly, by exciting a panel at normal incidence, it is possible, if desired, to obtain the effect of pressure reinforcement by standing waves without increased airflow. Since the objective of some tests is to seek out the "weakest link" in a design, qualitatively, the maximum excitation of the fundamental mode with the least power is of prime interest. To go further, some feel that the normal modes of aircraft panels are the only ones significantly excited, and since the panels exposed to normal impingement vibrate predominantly in the lowest order normal modes, the test representation is correct, or at least sufficiently accurate (19).

However, the users of grazing incidence facilities have a somewhat different interpretation. The strongest argument set forth in support of the use of grazing incidence is that the excitation of unsymmetrical modes, which are considered the most important ones in some cases, would be extremely difficult, if not an impossibility, with normal impingement loading, and therefore, accurate response simulation cannot be accomplished. Some analyses also recognize stress contributions made by higher than fundamental modes to the rms stress under jet loading (9,20). It is pointed out that a part under the random loading of a jet engine responds simultaneously to the same modes excited singly under a discrete frequency siren load. Therefore, an accurate exploration of the frequency response, including the higher modes, is necessary to determine the correction that must be applied to the siren-induced stress for a more accurate representation of jet-induced stresses.

Another disadvantage of using normal incidence is thought to be, in this regard, the difficulty in obtaining accurate frequency response information because of the extreme frequency sensitivity of standing wave systems which may be set up. The choice of grazing incidence testing, stated in another way (19), is due to the feeling that at certain sound frequencies, a structure receiving a wave at grazing incidence experiences stress maxima in higher modes, resulting from standing elastic waves due to reflections from transverse supporting frames, a condition which could not be accounted for with normal impingement testing.

Not to be overlooked in a discussion of impingement angle is the possible influence of coincidence reinforcement (21). An experiment conducted by Kamperman and Doelling (22) illustrated the occurrence of the maximum response of a simple structure to sound excitation when the coincidence frequency and the resonant frequency of the structure coincide. Although the critical, or lowest coincidence, frequency is usually high compared to the structural response frequency of concern in aircraft design, it can be seen from Equation (1) that, as stiffness increases, as may be the case when the resonant response of a part is reduced, the critical frequency <u>decreases</u> toward the resonant frequency of the structure and could become significant under the proper conditions:

$$f_{cr} = \frac{{c_s}^2}{2\pi} \left(\frac{\rho A}{EI} \right)^{1/2} \qquad \text{Equation (1)}$$

where E = Young's modulus

I = Moment of inertia

ρ = Mass density

A = Area of test specimen cross section

c_s = Speed of sound in the surrounding medium

To illustrate the dependence of this acoustic coupling on the angle of sound impingement, Figure 8, reproduced from Kamperman (22), is shown. Note that for the simple structure illustrated here a 20° impingement creates a maximum response. The value of the coincidence frequency is minimum at grazing incidence and approaches infinity for sounds arriving perpendicular to a surface.

There are some experiments being planned by several groups for the deliberate investigation of the relative merits of normal and grazing impingement tests and the quantitative difference between them (11,17,22,23). These studies will add materially to the answer of this controversial question.

C. Panel Attachment Conditions

The method of attaching test specimens to a holding fixture for acoustic loading can and does take on many forms. The actual attachment can be expected to vary according to the type of specimen being tested, the type of facility being used, and the type of test information desired, but variations exist within these categories as well. As can be expected, attachment problems are relatively few in number in a test of production structures on an aircraft type mounting with actual or duplicated boundary conditions and excited by a turbojet engine. A major problem does present itself, however, in a test of a specimen or panel section which is mounted in a fashion designed to be representative or at least analyzable, yet not geometrically duplicating a practical boundary. It is well established that boundary conditions have a profound influence on panel response and not enough attention is paid to them at times (13,24-26). Figure 9 for example, illustrates the differences in the behavior of identical panels under identical acoustic loading as a function of the type of mounting. Since most test panels have size limits of something like a foot square to three or four feet by five at most, it is probably not possible to duplicate accurately the correct attachment stiffness, and, therefore, the panel impedence, of aircraft mounted panel members. The goal here is usually to realize at least a reasonable, acceptable degree of simulation. The nature of the scatter of the test data is such that large error probably does not occur; however, error can exist to some degree and should be accounted for somewhere in the interpretation of test data. Figure 10 shows some typical attachment schemes in current use. Illustrated by (A) and (B) are two typical mountings of a panel section subjected to "qualitative comparative tests." Shown by (C) and

(D) are two types of mounting used for the attachment of a production-design panel where duplication of the actual response characteristics is of greater interest.

The question of using a baffling or sound insulating box on the side of a panel or test specimen opposite that exposed to sound waves is another source of variation. Some groups mount a panel to a frame which is placed near the siren in the test cell in such a way that the front is exposed to the siren output with the back unprotected from the environment of the test cell. In some cases, this is done due to the need to have access to the back to mount instrumentation as illustrated in Figure 11. Those who advocate isolation of the back of the panel do so because of the opinion that, without it, the pressure differential from front to back which excites the panel would not equal the measured pressure. In most test cells, especially those with fairly reflective walls, undesired standing waves can exist at the panel or reflected sound from various directions can interfere with the desired panel response. One group is known to use isolation boxes in the engine test cell when making acoustical fatigue tests.

D. Instrumentation

Fewer variations are found in instrumentation techniques than in most of the other aspects of test practice. Standard techniques, with some modifications, have been found to be adequate in most respects for measuring panel response. Panel deflection is monitored directly by several means, although one method appears to be the most popular. This method utilizes the varying output of a transducer which is proportional to its distance from a metallic panel. The output signal can be converted by appropriate means to provide either visual or graphical test monitoring. A similar measurement is made by some with the use of a condenser microphone with the diaphragm removed and used as a capacitive vibration pickup where the panel serves as the second electrode (18).

A second method of monitoring deflection is with accelerometers attached directly to the vibrating panel. The accelerometer output is proportional not only to the displacement but to the square of the angular velocity as well and is therefore not as straightforward a measure of deflection. Also, there is often trouble in keeping the devices attached to the panel throughout the test. An additional disadvantage can become important if the accelerometer mass is sufficient enough to alter panel response characteristics.

Another method used on occasion is to measure with a microphone the excitation of the air next to the vibrating panel. The difficulty immediately brought to mind is the distortion which can possibly result from a mixing of sound waves reflected from the test cell walls.

In a number of cases, the deflection of a panel is not so much of interest as stress. The measurement of stress directly by means of strain gages mounted at various points on a panel is often accomplished without the aid of instruments. In the early days of testing most groups experienced a degree of trouble in placing gages where the desired strains could be measured without intolerable gage attrition through fatigue. Improved bonding, elimination of lead wire flexing, and, where possible, location of gages where lower deflections occur have helped to minimize trouble.

Sound pressure is usually measured by means of microphones located at several points around the test area. Another method reported to be useful in accurately measuring differential acoustic loading (13) is with the use of miniature electrical pressure gages which can be conveniently placed at a number of stations on test items (27).

E. Broad and Narrow Band Sirens

The present day siren, being a discrete frequency sound source, cannot duplicate the random nature of jet engine noise and, therefore, is limited in what it can do. There is some experimental work being conducted in this country, however, to develop what would amount to a randomized-tone, high intensity siren. One such device is the two component, narrow band, modulated-frequency siren designed by Bolt Beranek and Newman, Inc. for the Air Force contract (28,29). The system is designed to produce sound with a variable ratio of peak-to-rms pressure at overall levels up to about 174 decibels. Sound with a frequency ranging from 50 to 10,000 cps is amplitude modulated by a signal containing frequencies in a band of 0 to 50 cps. Two sirens are mounted onto a manifolding structure which attaches to the test section duct. A high frequency siren which operates from 500 to 10,000 cps is mounted perpendicular to the flow direction and its sound is reflected by an acoustic mirror through an angle of 90° into the test section. A low frequency siren, operating from 50 to 2,000 cps, produces sound which is transmitted through the mirror to the test section. Either of the two sirens can be operated independently to produce a pure tone while together they produce a combination. The modulation system is designed to control the peak-to-rms ratio to values of from 3 to 20 db and is driven by an electro-hydraulic servo system actuated by a tape recorded signal of random noise. The facility is expected to introduce 22,000 watts of acoustical power to a one foot square test panel.

Another approach to the design of a siren for producing wide-band sound is that reported by von Gierke and co-workers (30). Some model siren designs are being studied by the group in which efficient irregular modulation of an air stream can be accomplished. Basically, irregular modulation is achieved mechanically by a series of overlapping rotors irregularly slotted and rotated at speed ratios such that any instantaneous combination of rotor positions will not repeat except over long time intervals. Preliminary measurements indicated that wide-band power spectra can be obtained and that the spectrum shape can be changed by changing rotational speed ratios of the rotors. The new principle shows considerable promise.

IV. THE USE OF TURBOJET ENGINE FACILITIES

Engine test cell facilities are in use by several airframe manufacturers for testing structures in acoustic environments. These facilities are usually characterized by a higher noise level and distorted spectrum for the sound at the structure being tested, compared with that at the equivalent point on the aircraft outdoors. The response of the structure, the mode of failure, and the fatigue life are normally affected to various degrees by the distortion of the noise field, thus further complicating the already complicated task of interpreting test data. Recognition of this disadvantage in using existing test cells did little good when cell testing was first adopted several years ago, since in most cases neither time or available funds were adequate to allow the construction of acoustically ideal engine test cells.

Existing test cells have provided test groups with a variety of problems. Specifically, the noise levels within cells are up to as much as 10 decibels higher than experienced on the runway because of reinforcing reflections for the side walls. Standing waves are usually generated because of the present configuration of most cells. As a result of the above, the spatial distribution and spectrum of the sound of an engine in the cell is considerably modified, thus making it virtually impossible to subject a structure specimen to the preferred acoustic load.

A number of steps are sometimes taken in practice to reduce the distortion of the noise field in cells and to correct the acoustic loads applied to structure specimens. For one thing, locations in test cells where standing waves are set up are, in some cases, covered with sound absorptive materials to reduce reflections. Also, test specimens are usually carefully positioned in the test cell, when not integrated into permanently located built-up structures, so that standing waves are not set up at the specimen.

Test procedure among several investigators is normally to instrument a test panel and mount it on the appropriate aircraft. A sound survey is then made in which both pressure levels and stress responses are recorded for a number of engine operating conditions. Brittle lacquer is sometimes used to indicate the proper places to locate strain gages. The analysis of power and stress spectral density made from these data are then used to determine the engine settings in the test cell to duplicate the loading on the specimen. By using these criteria to determine engine settings, it is believed that the effects of distortions due to the cell walls are minimized. A practice of simply duplicating the overall noise level in the test cell, as indicated by microphones, is followed by some.

Several engine test cell facilities used by the industry are shown in Figures 12 through 15. In all cases, the installations duplicate the mounting for a particular aircraft model in that a particular engine series is mounted by means of a pylon to a lower wing surface structure. In Figure 12, the J-71-A-11 engine installation used at Douglas Aircraft for tests on the RB/B-66 jet bomber is shown (3). Figure 13 is a view of a test panel located near the exhaust. Figure 14 shows a similar installation used by Convair-Fort Worth for tests on the B-58 jet bomber. Here, a J-79 engine is mounted to a simulated lower wing surface with an appropriate pylon structure. With this facility, actual production flaps and secondary wing structure can be integrated into simulated aircraft installations and be subjected to acoustic loading. For the test program performed by Douglas on the wing trailing edge and flap designs for the DC-8 transport, a JT3C-4 (J-57) engine was mounted on an open air test stand in the appropriate geometric configuration. That program is reported in part in a paper by Belcher, VanDyke, and Eshleman (9).

One step further than the cell facilities is the half-wing setup operated at Boeing-Wichita. The starboard half of a production B-52 wing, with two J-57-P43W engines mounted on each of two pylons, is used for full scale tests of flap and wing structure in the proper acoustic environment of all engines. The setup is illustrated in Figure 15. The geometric relationship between the wing and the runway is maintained so that runway reflections of noise are duplicated for runup and takeoff conditions.

V. MISCELLANEOUS TEST FACILITIES

The search for facilities for producing random noise to duplicate or at least closely simulate jet engine noise more economically is a continuing effort. One of the more important developments of a source of random noise of a high level, other than the turbojet itself, is the air jet. High volume, high pressure air is passed through a pipe and exhausted into a test area in which test structures can be placed. The distinct disadvantage with the air jet is the rather large air requirements; for example, in the order of 100 pounds per second and more. Such a device is currently in operation at NASA-Langley Field (31).

The air jet is an ideal facility for the Langley Research Center of NASA since an ample supply of compressed air is readily available from their wind tunnel air tank farm. The farm can store air from four compressors, totalling 18,500 horsepower, in the 135,000 cubic foot tank installation at 600 psi. A 12 inch diameter jet receiving air from the farm can produce an overall noise level of about 157 db with a spectrum similar to a 10,000 pound thrust jet engine from 150 to 1200 cps as shown in Figure 15 taken from a paper by Edge (31). The high noise levels and the desired spectrum shape are obtained primarily because of four 90° bends in the pipe upstream from the exhaust. This arrangements can be seen in Figure 16. By adding heat to the jet air, further increases in the noise level can be produced. A number of very successful experiments have been reported to date using this facility.

Another device receiving some renewed attention is the air stream modulator which utilizes the voice coil from, or similar to that of, a loudspeaker. One such device designed by Stanford Research Institute is in use at Lockheed (32). The flow of air at low pressure is modulated by a valving orifice which is controlled by the displacement of a voice coil. With proper amplification, sound pressure levels around 120 db are attainable between 400 and 2000 cps. A similar device has been designed by Altec-Lansing and is under experiment at Boeing (33). An amplified random signal from an electronic noise generator is fed to a voice coil through a "spectrum shaper" composed of octave band filters. The random coil displacement, as in the Lockheed device, modulates the air at a valving orifice. The goal with this device is to realize up to 170 db over a 40 square inch test panel up to 800 cps.

Experiments were recently completed by Midwest Research Institute for the Air Force to determine the feasibility of using electrostatic loading to excite panels under simulated acoustic conditions (34). A feasible design was developed where a time varying electrostatic field of 400,000 volts per cm would be set up between an electrode and a test panel which would be placed at least 5 mm apart. The time variation of the electrostatic field could feasibly be either periodic or random in nature. It was concluded that, although the appropriate equipment could be developed (which would include an A.C. generator with 200,000 peak volts, an electrode plate, and a pressure chamber to enclose the test panel under 9 or 10 atmospheres of sulfur hexafluoride to prevent corona discharge), the facility would be, of necessity, quite complex and too expensive to warrant its use.

There are a number of other devices and facilities in use or in various stages of development and experimentation for the production of sound. Included are a variety of speaker-driven reverberant chambers, plane wave and resonant tubes, whistles, etc., used primarily for the testing of electronic gear. It is outside the scope of this paper, however, to discuss this type of equipment beyond noting that usually these devices do not provide enough power to test structures satisfactorily and are, as a result, not normally of interest to the structures testing groups.

VI. TEST DATA ANALYSIS TECHNIQUES

It is not the purpose of this discussion to give a treatise on the various analytical techniques put to use on test data by workers in the acoustical fatigue area. This information has become and is becoming adequately available in the literature. It appears to be worthwhile, however, to make some comments regarding several of the more prominent variations in approaches to the problem currently in use.

The current state-of-the-art is not advanced to the point where we are able to predict analytically the response and fatigue life of aircraft structure. Assumptions are therefore used to idealize the problem to allow a prediction. These assumptions follow set lines. For example, it is generally assumed that fatigue damage accumulates according to Miner's linear damage rule (35):

$$D = \sum \frac{n_n}{N_n} = 1 \qquad \text{Equation (2)}$$

where cumulative fatigue damage D equals unity at the time of failure, and that the distribution of the peak values of pressure or stress can be described by a probability density function, most notably by Rayleigh's equation:

$$P(x) = xe^{-\frac{x^2}{2}} \qquad \text{Equation (3)}$$

It is also generally, although not exclusively, concluded that the most fatigue damage will occur in the least damped mode of a lightly damped structure which will respond significantly only at its resonant frequency.

Variations in analyses occur at this point. One widely used reponse analysis is Miles' treatment of a linear, single-degree-of-freedom system under random excitation (36) wherein an expression for an equivalent stress is developed. It is postulated that this steady stress is equal in damage potential to the random stress of distributed amplitude. An extension of this analysis was developed by Belcher and co-workers (9) to provide a method of relating siren test data to the equivalent stress which would occur from jet noise. In this analysis, the influence of non-linear behavior is accounted for by a correction factor determined from a measured plot of sound pressure versus resulting stress. Also included is a correction factor to Miles' analysis which accounts for the stress increase due to vibration in more than the one mode under random excitation.

Another analytical interpretation is the one advanced by Getline and co-workers (10) wherein damage is related to the total sound pressure energy applied to a structure rather than the amount of stressing to which it is subjected. The fundamental difference in the analyses of Belcher and Getline appears to be that, in the first, the accumulation of fatigue damage is in accordance with Miner's hypothesis and is measured in terms of stress while, in the second, a definition is made of the number of pressure peaks to be expected in the desired structure life (expressed by a probability density function describing the expected environment) and damage is measured in terms of the occurrences of pressure peaks in the test. The validity of both analyses are reported to have been satisfactorily demonstrated within acceptable bounds. A jet transport aircraft now in service has been designed acoustically by each of these analysis procedures and each has, to date, performed satisfactorily.

The analysis of Miles has also been subjected to rigorous test as reported by Hess, Lassiter, and Hubbard (37,38) and more recently by Belcher (39). They found excellent agreement between measured stresses in panels exposed to both turbojet and air jet noise and the stresses calculated with Miles' equation.

VII. CONCLUDING REMARKS

This paper has presented what is intended to be at least a broad review of some of the current test practices and an unbiased discussion of the rather substantial variation in technique which characterizes much of the acoustical fatigue work conducted in the United States. It has been shown that, because the general entry into the acoustical fatigue problem area several years ago was quite abrupt, because the needs and objectives of various groups have been different in some cases, and because environment simulation and data analyses pose problems, a significant degree of variation in practice in industry prevails.

It is the feeling of the author that if the discussion promotes perhaps a more serious examination of the pros and cons of controversial questions, then indeed, a service has been performed. What may prove to be the greatest future contributions to the state-of-the-art of analysis and experimentation is not only an increase in the relatively meager amount of actual research on acoustical fatigue phenomena by industry, and a subsequent greater exchange of information between groups, but also a stronger effort by design and test groups to combine their ideas and standardize procedure for greater interchangeability of test results and an overall advancement of the technology.

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TABLE I

OPERATING DATA ON SOME SIREN FACILITIES

Facility	Sound Level (db)	Frequency Range (cps)	Plenum Chamber Pressure (psig)	Compressor Air Supply (cfm)	Test Section Dimensions	Angle of Incidence
Soundrive Engine Co. Newhall, Calif.	161	60-300			up to 4' x 5'	Grazing
Douglas - Santa Monica, Calif.	163	50-1000	5	4080	up to 4' x 5'	Grazing
Convair - San Diego	170	50-1000	2	1800	22" x 44"	Grazing
Convair - Ft. Worth	170	150-1000	10	2000	---	Normal
Convair - Ft. Worth*	170-180	100-2500	10	6000	---	Normal
Boeing - Wichita	160-170	to 1000	5-40	1200	---	Normal
Boeing - Seattle	170	100-650	50	1400	---	Normal
Boeing - Seattle	170	100-950	50	1400	---	Normal
Boeing - Seattle	160	100-2000	50	1400	---	Normal
Martin - Baltimore (three sirens)	160	40-4000				

* Under construction

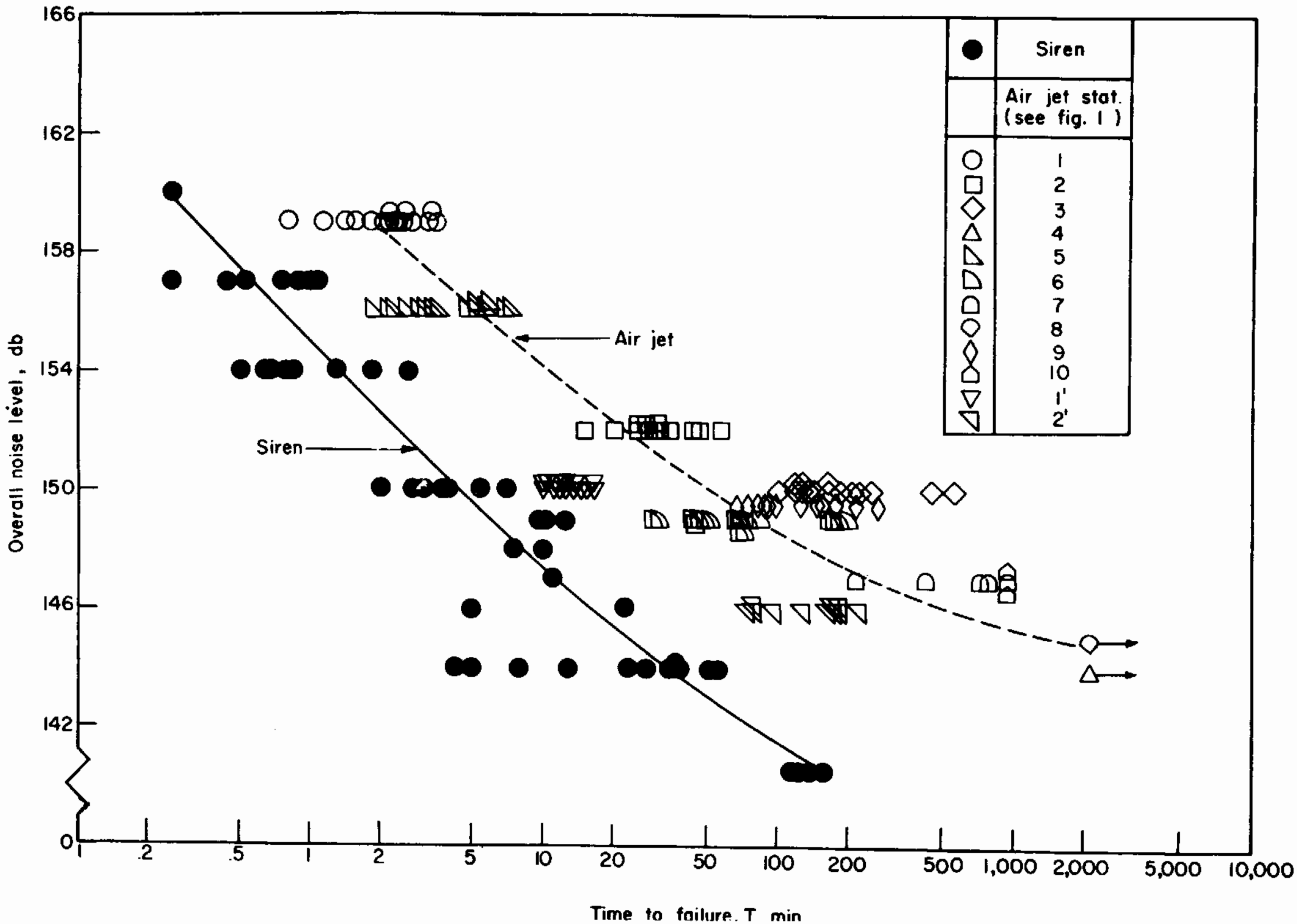


Figure 1. Fatigue Life of 0.032-inch Panels as a Function of Overall Noise Level for Both Discrete and Random Loadings (Ref. 13).

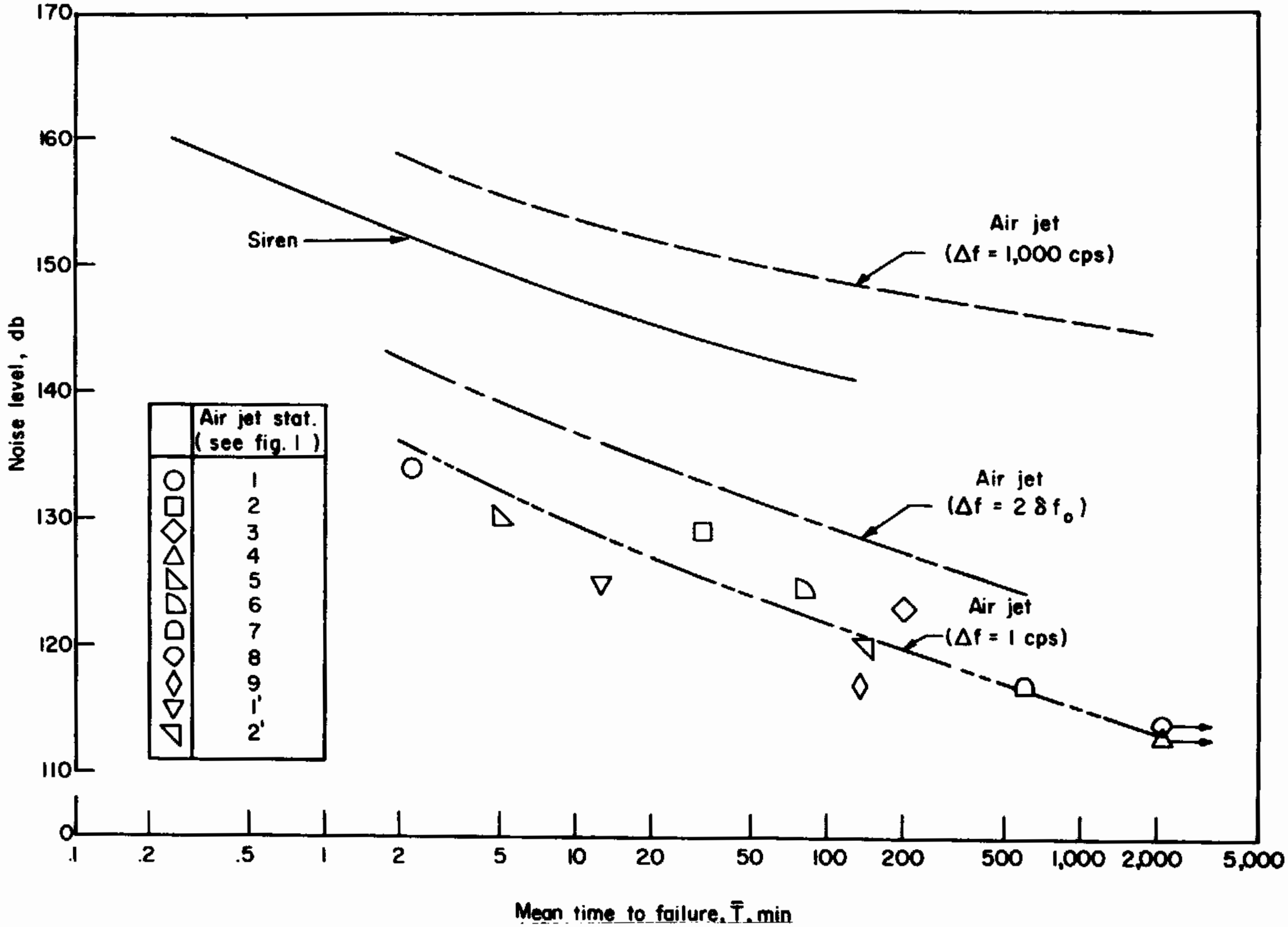


Figure 2. Fatigue Life of 0.032-inch Panels as a Function of Siren and Air-Jet Noise Levels for Various Band Widths (Ref. 13).

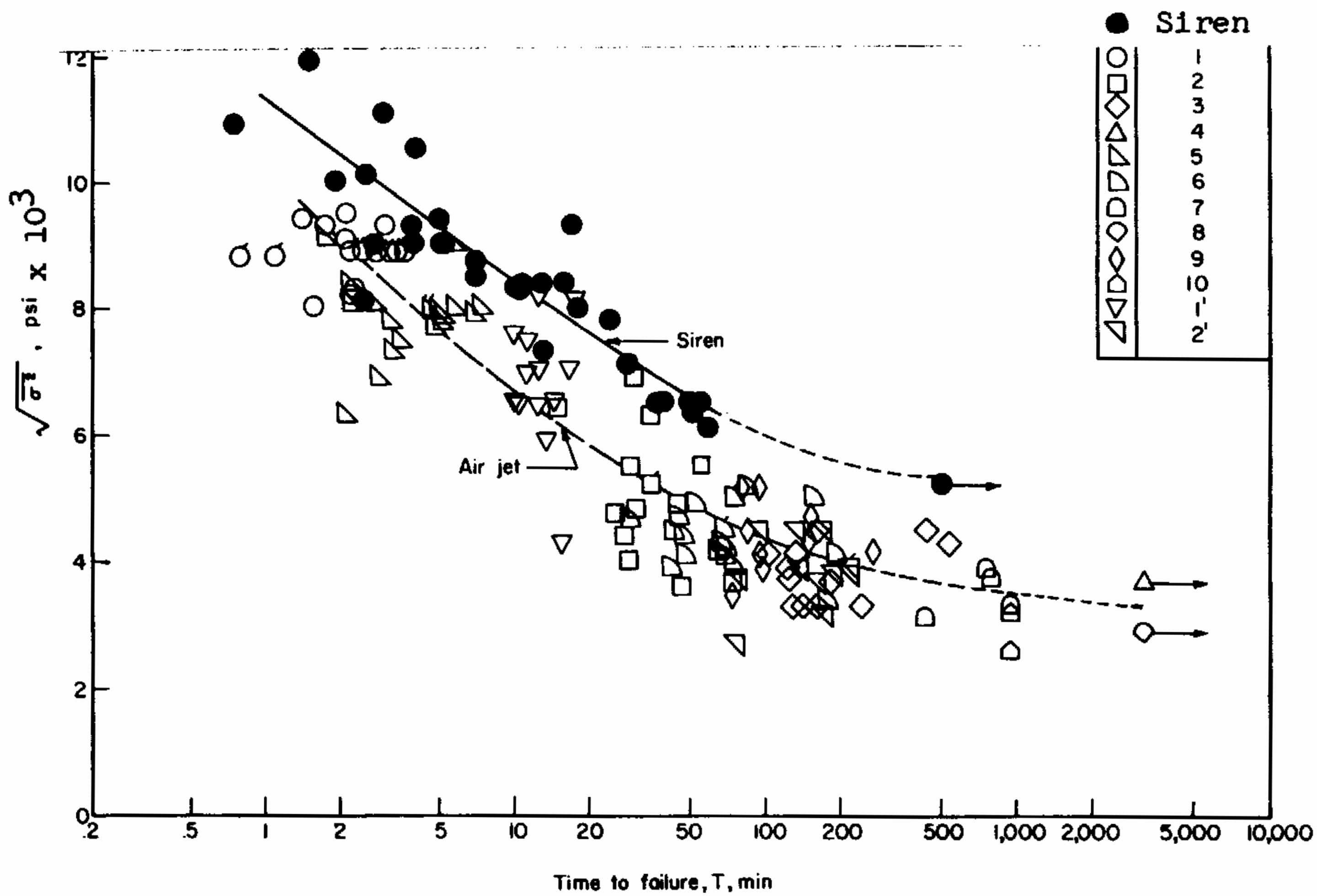


Figure 3. Fatigue Life of 0.032-inch Panels as a Function of Root-Mean-Square Stress for Both Discrete and Random Loadings(Ref. 13).

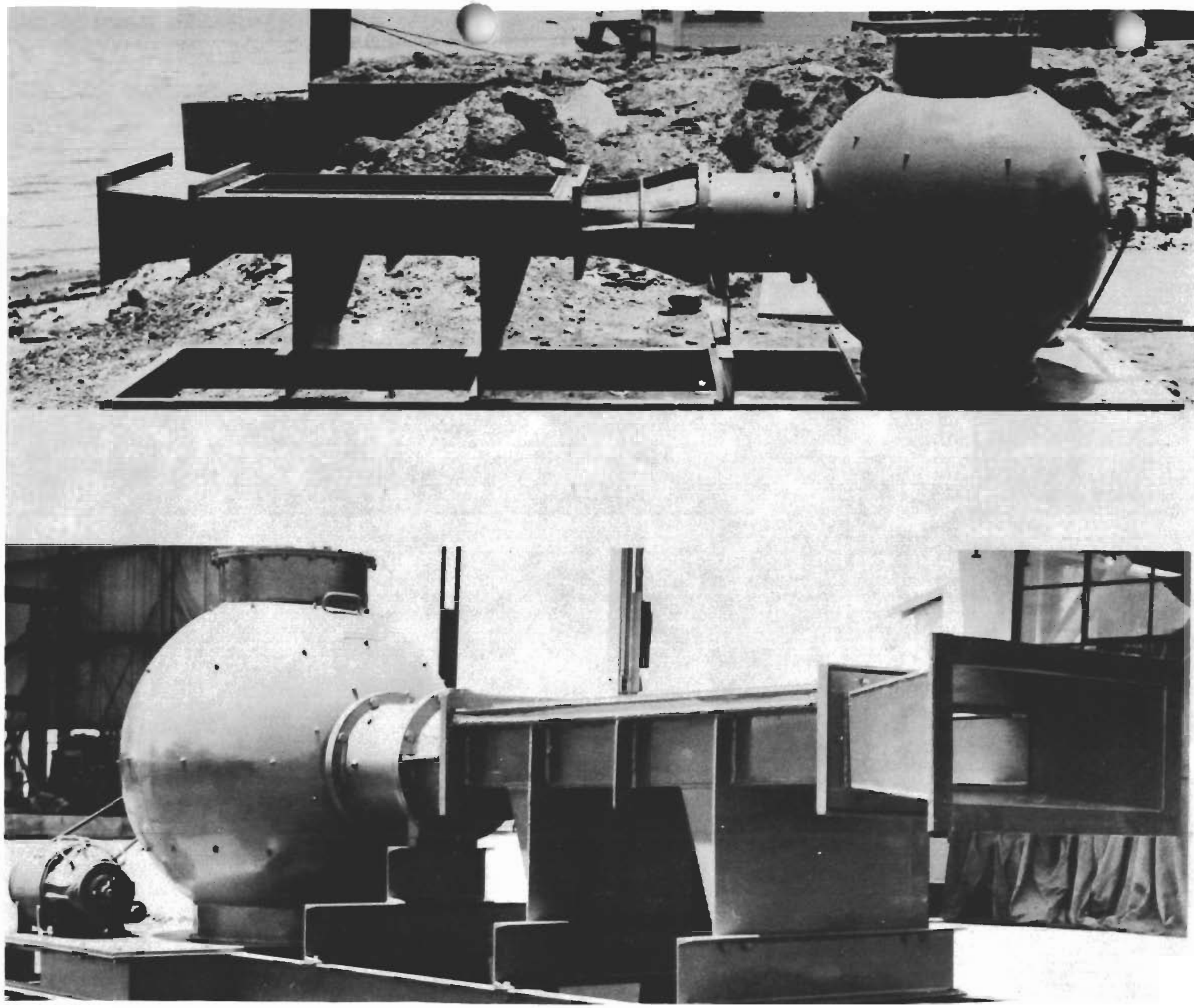


Figure 4. Typical Siren, Transition Section and Test Section for Grazing Incidence Loading (Courtesy Convair-San Diego).

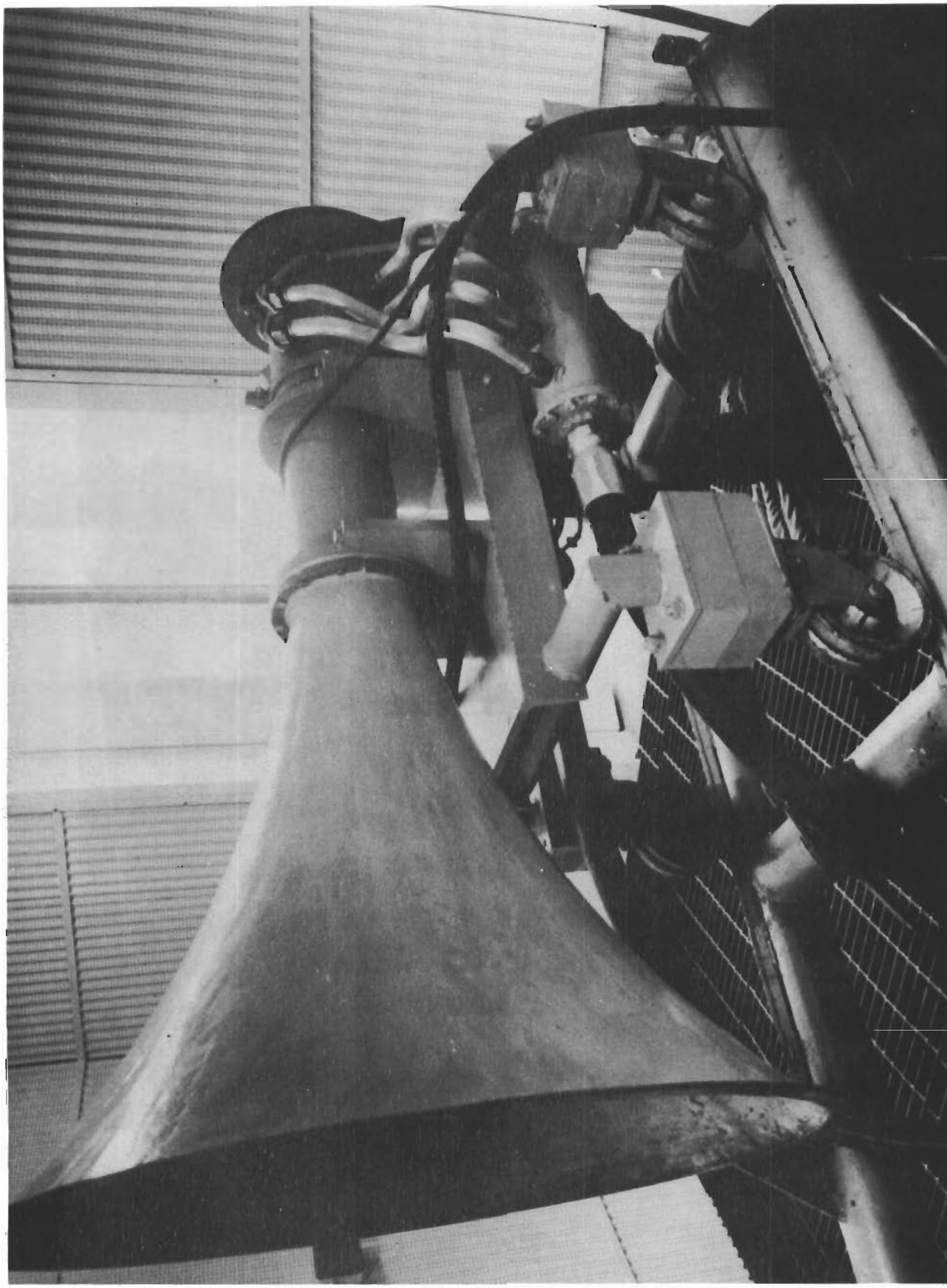


Figure 5. Typical Siren and Horn Configuration for Normal Incidence Loading
(Courtesy Boeing-Wichita)

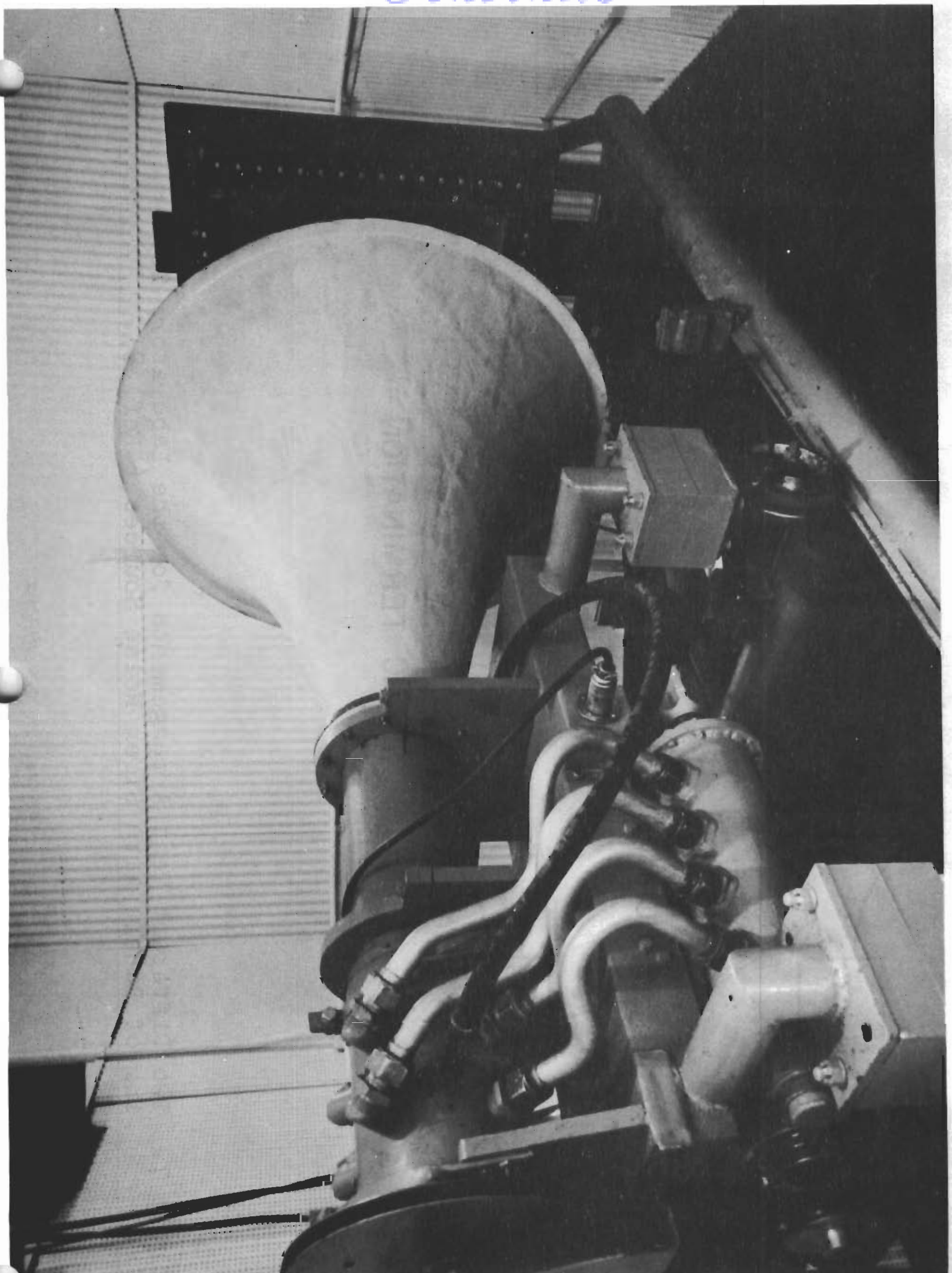


Figure 6. Typical Siren and Horn Configuration for Normal Incidence Loading Positioned for Testing Panel (Courtesy Boeing-Wichita).

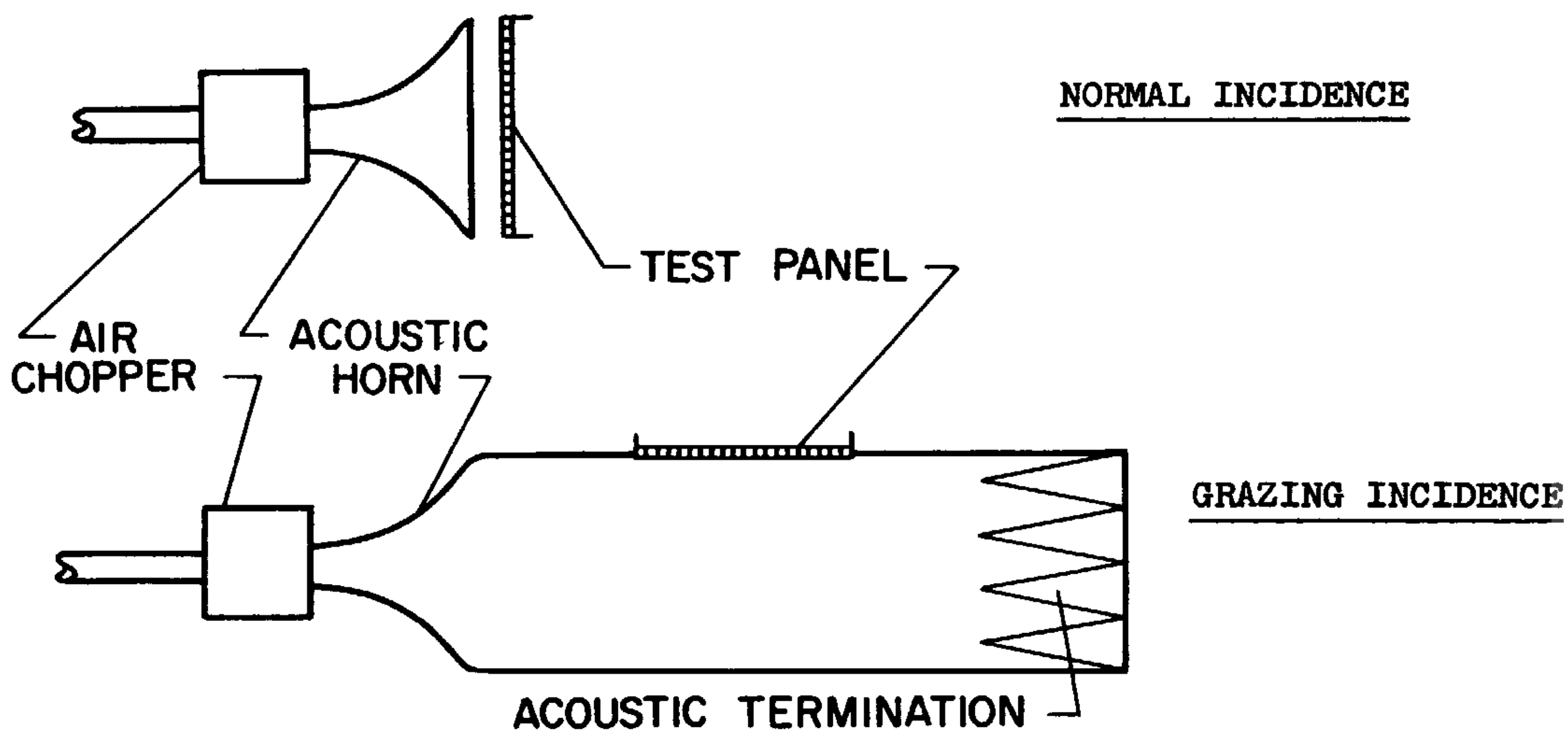


Figure 7. Two Different Test Arrangements for the Laboratory Testing of Panels with Siren Noise Sources (Ref. 8).

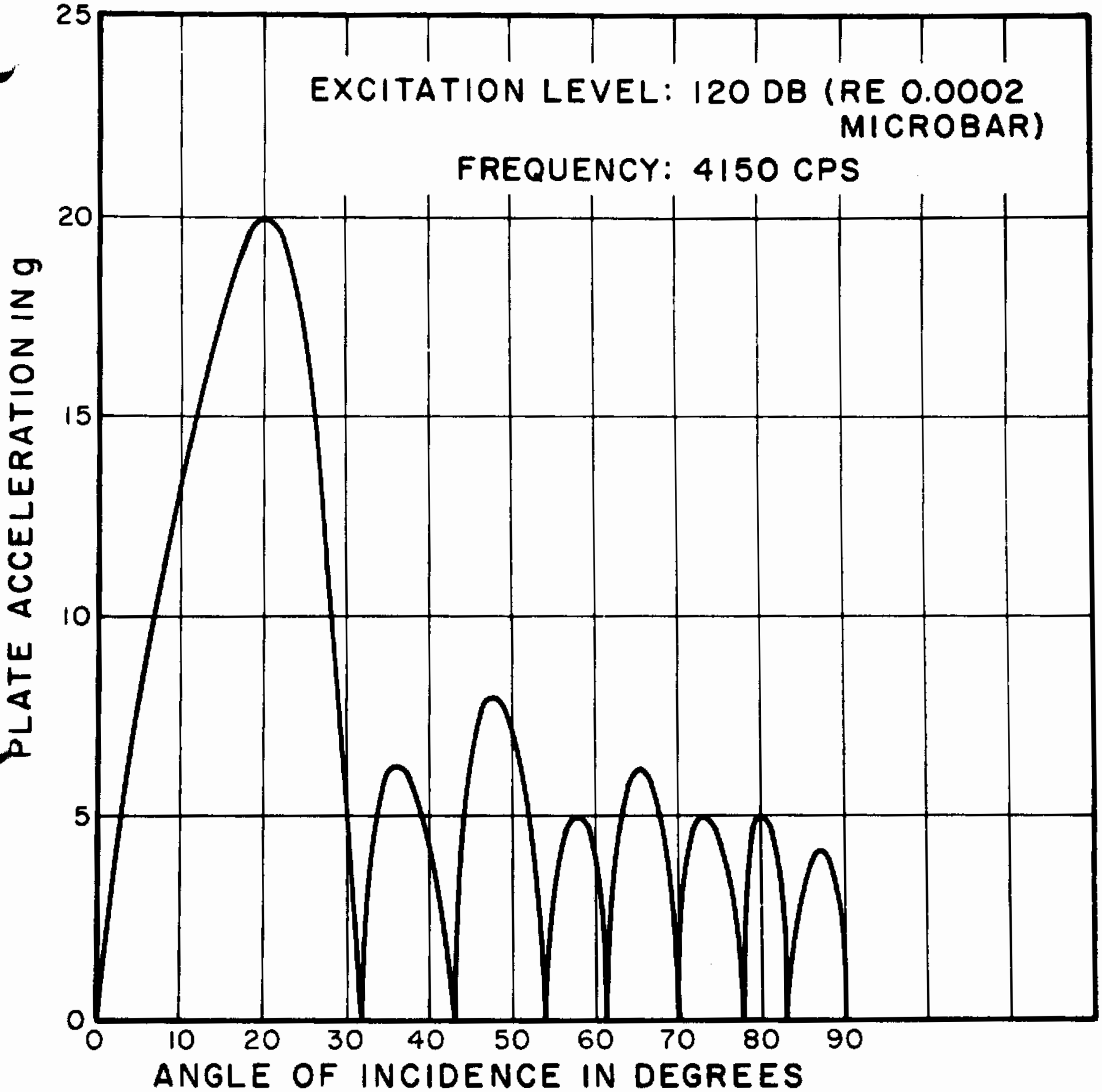


Fig. 8 - Acceleration Response of a Plate as a Function of Angle of Incidence (Ref. 22)

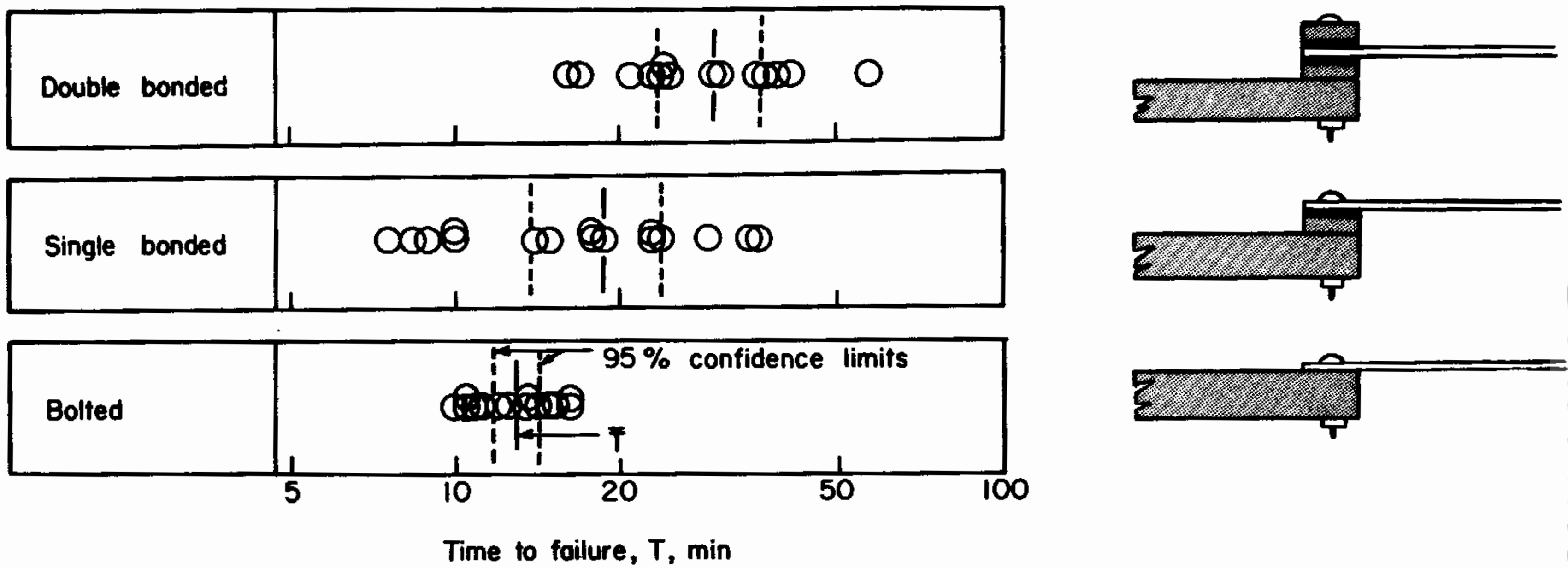
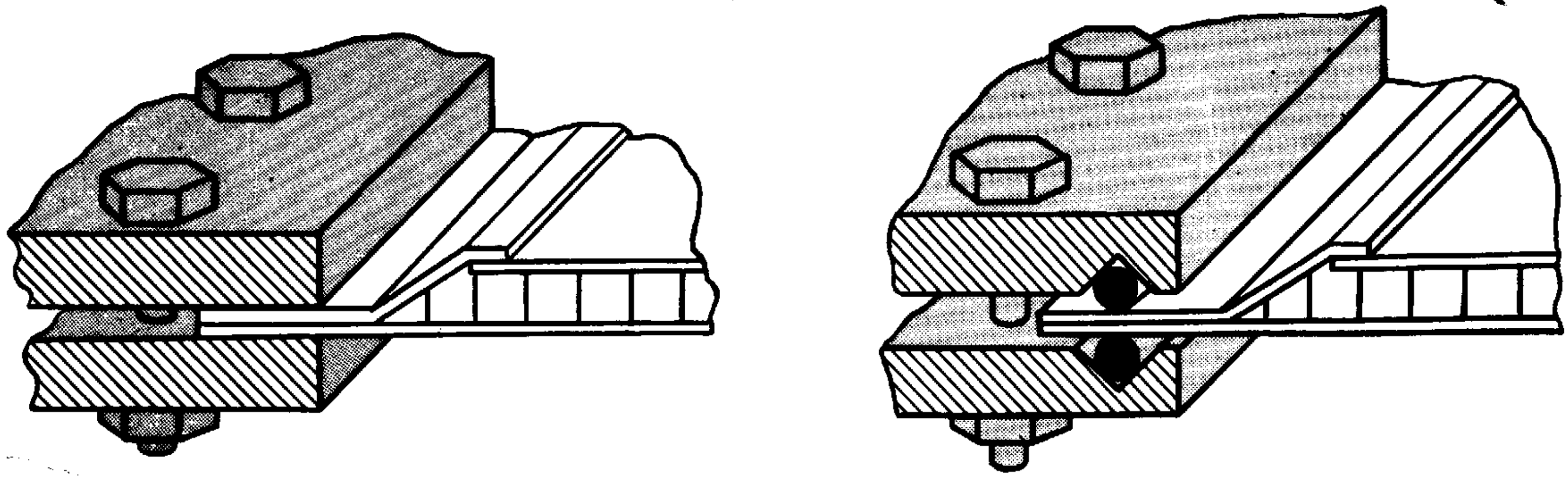
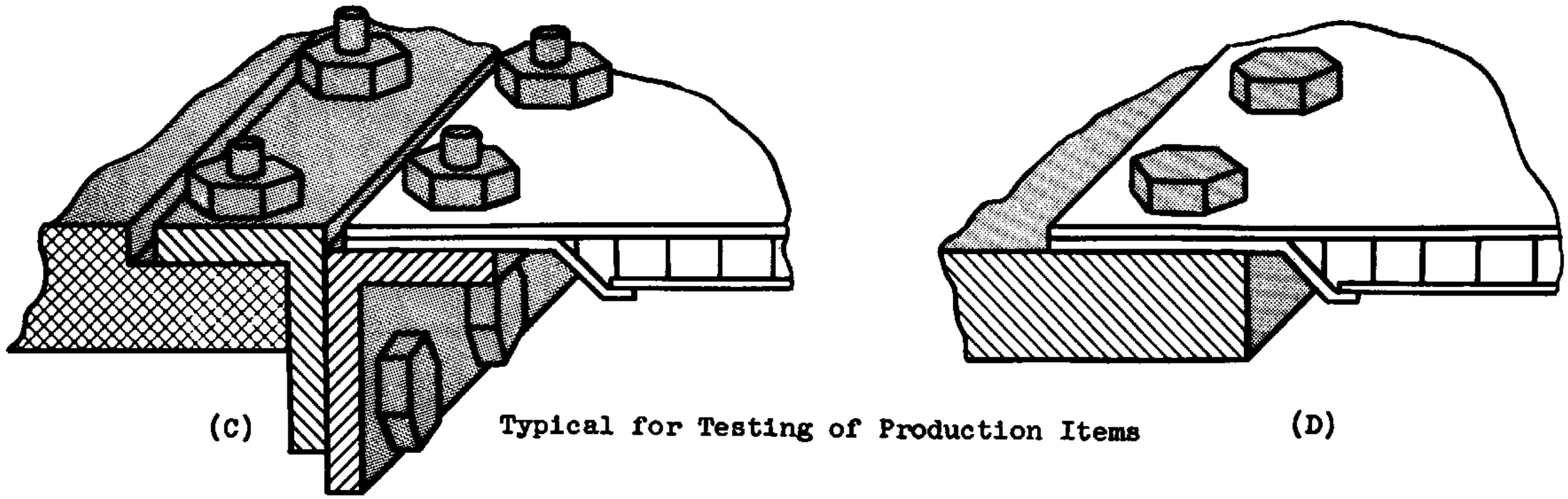


Figure 9. Comparison of Fatigue Life of 0.032-inch Panels With Three Edge Clamping Conditions (Ref. 13).



(A) Typical for Qualitative Comparative Testing (B)



(C) Typical for Testing of Production Items (D)

Figure 10. Some Typical Test Panel Attachment Schemes.

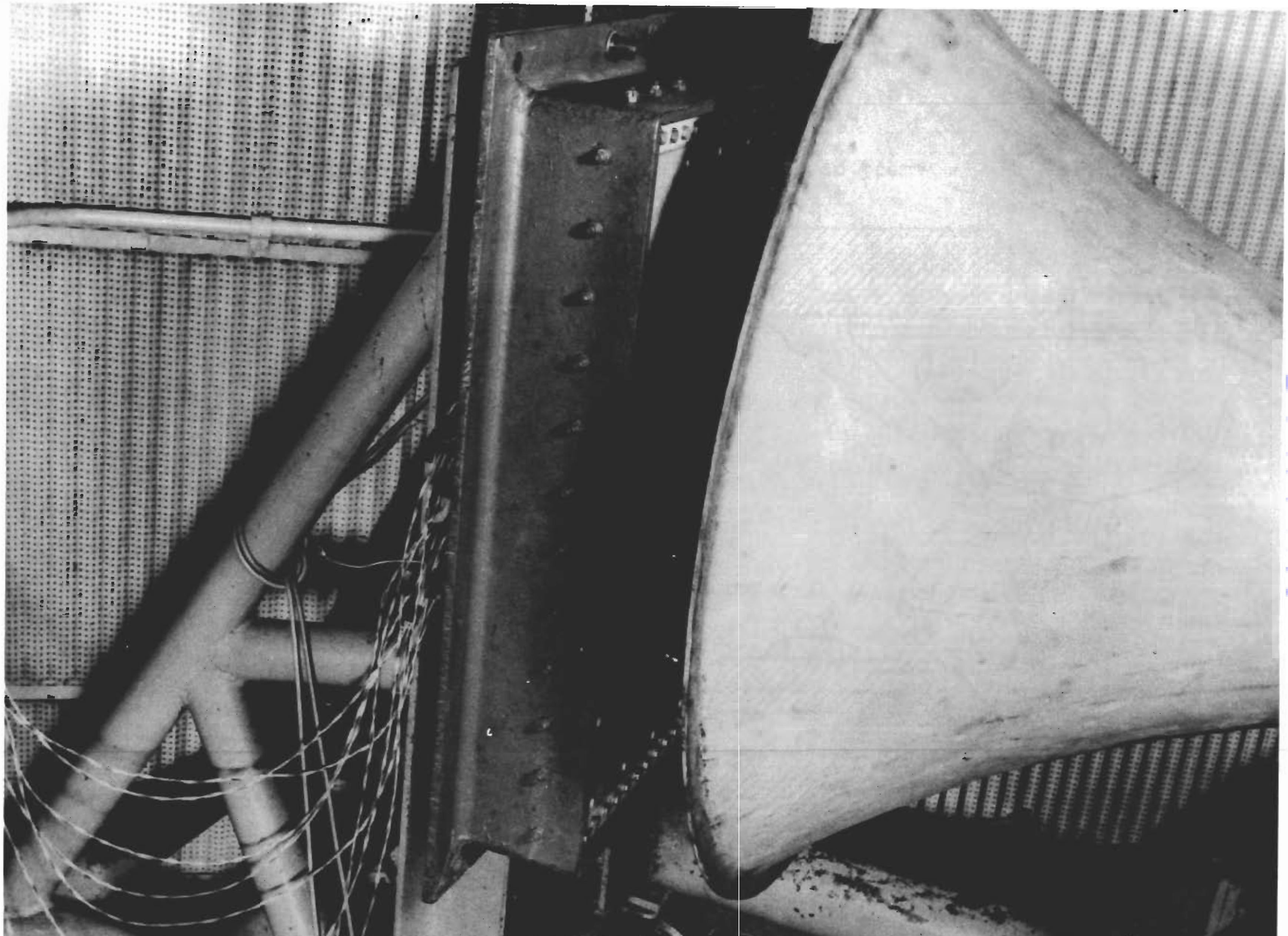


Figure 11. Panel Mounting Scheme for Normal Incidence Testing Showing Instrumentation (Courtesy Boeing-Wichita).

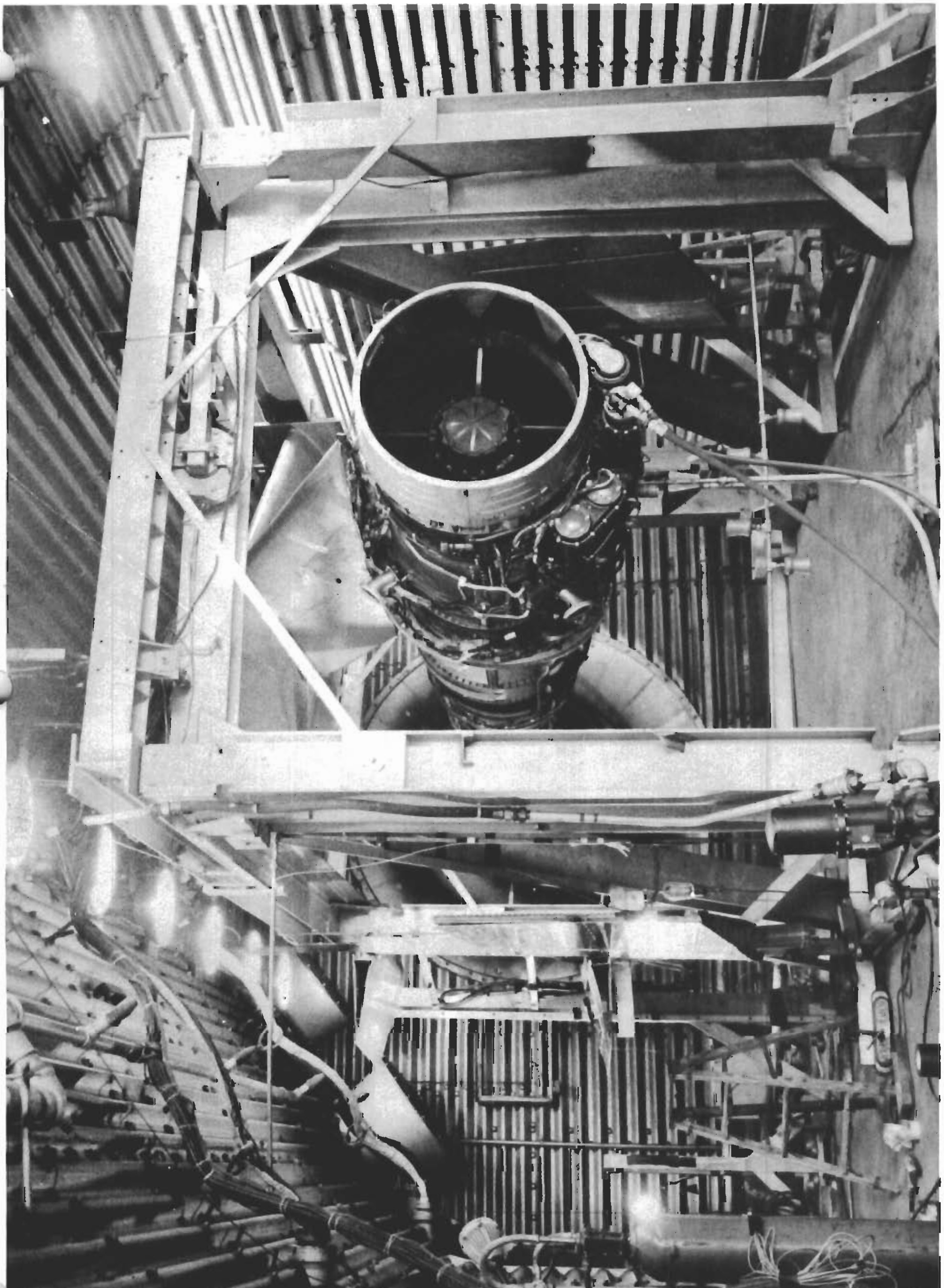


Figure 12. Douglas Aircraft Engine Test Cell.

Figure 13. Test Specimen Location in Douglas Engine Test Cell.

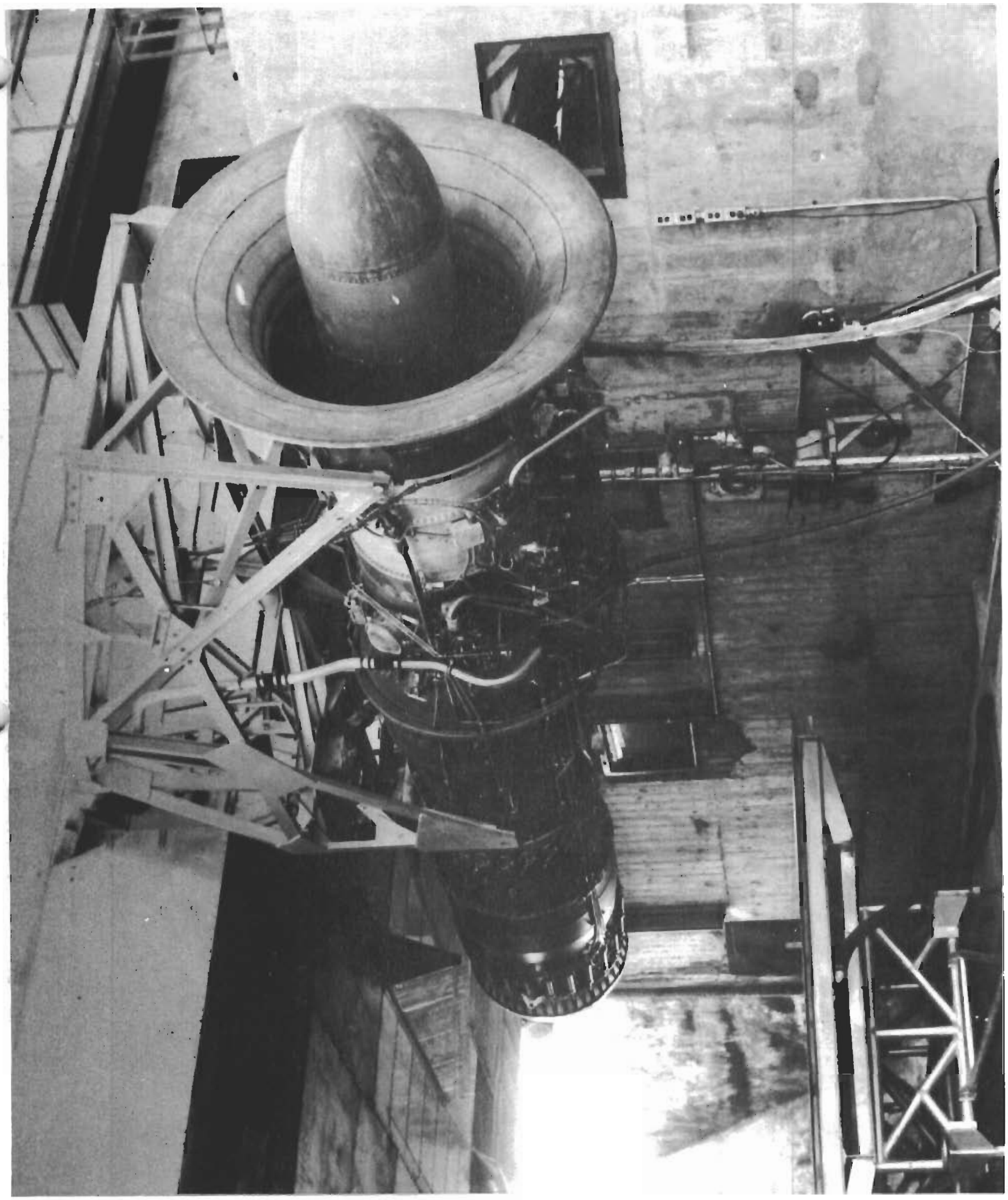


Figure 14. Convair-Ft. Worth Engine Test Stand.

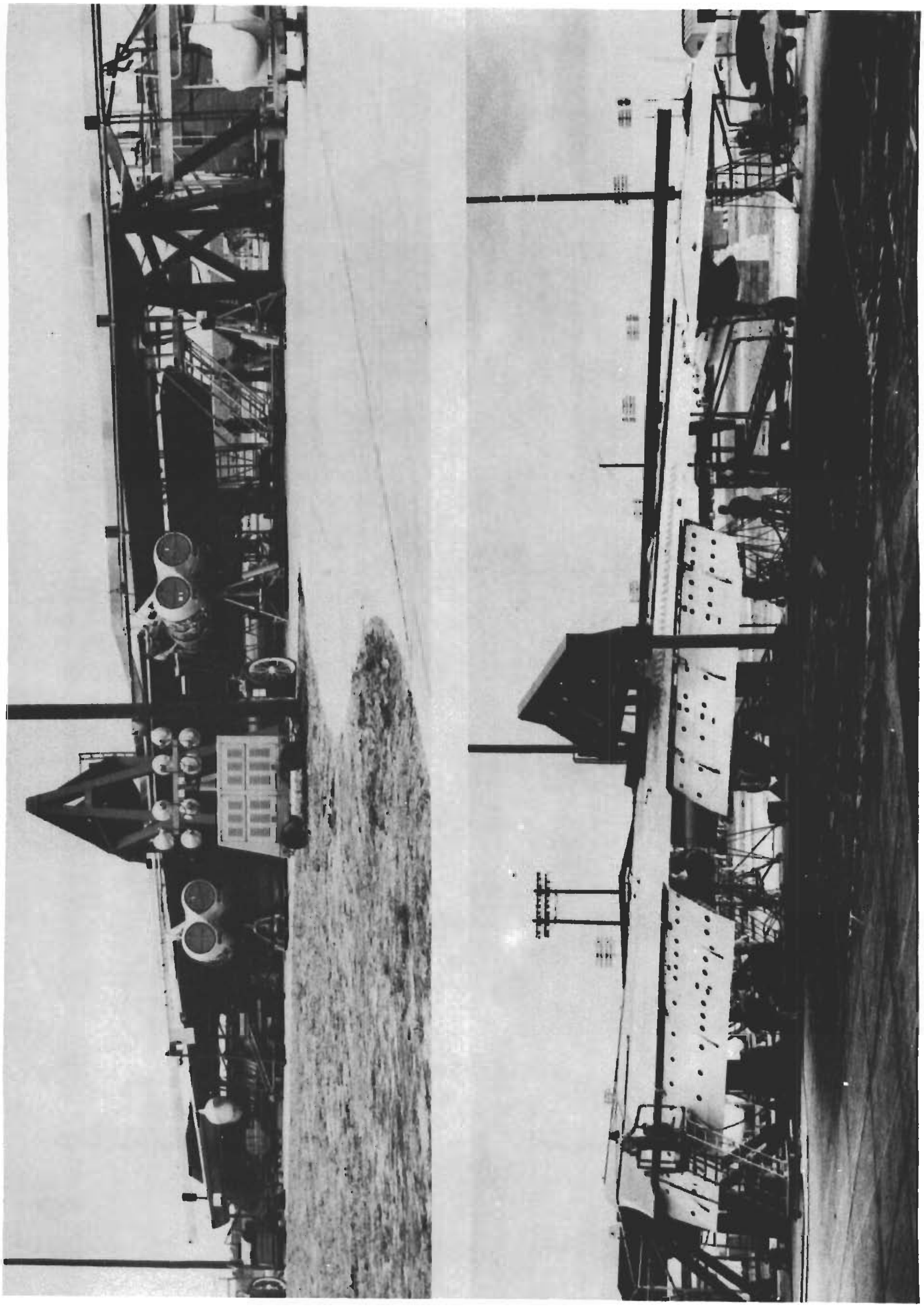


Figure 15. Boeing-Wichita B-52 Half-Wing Engine Test Facility

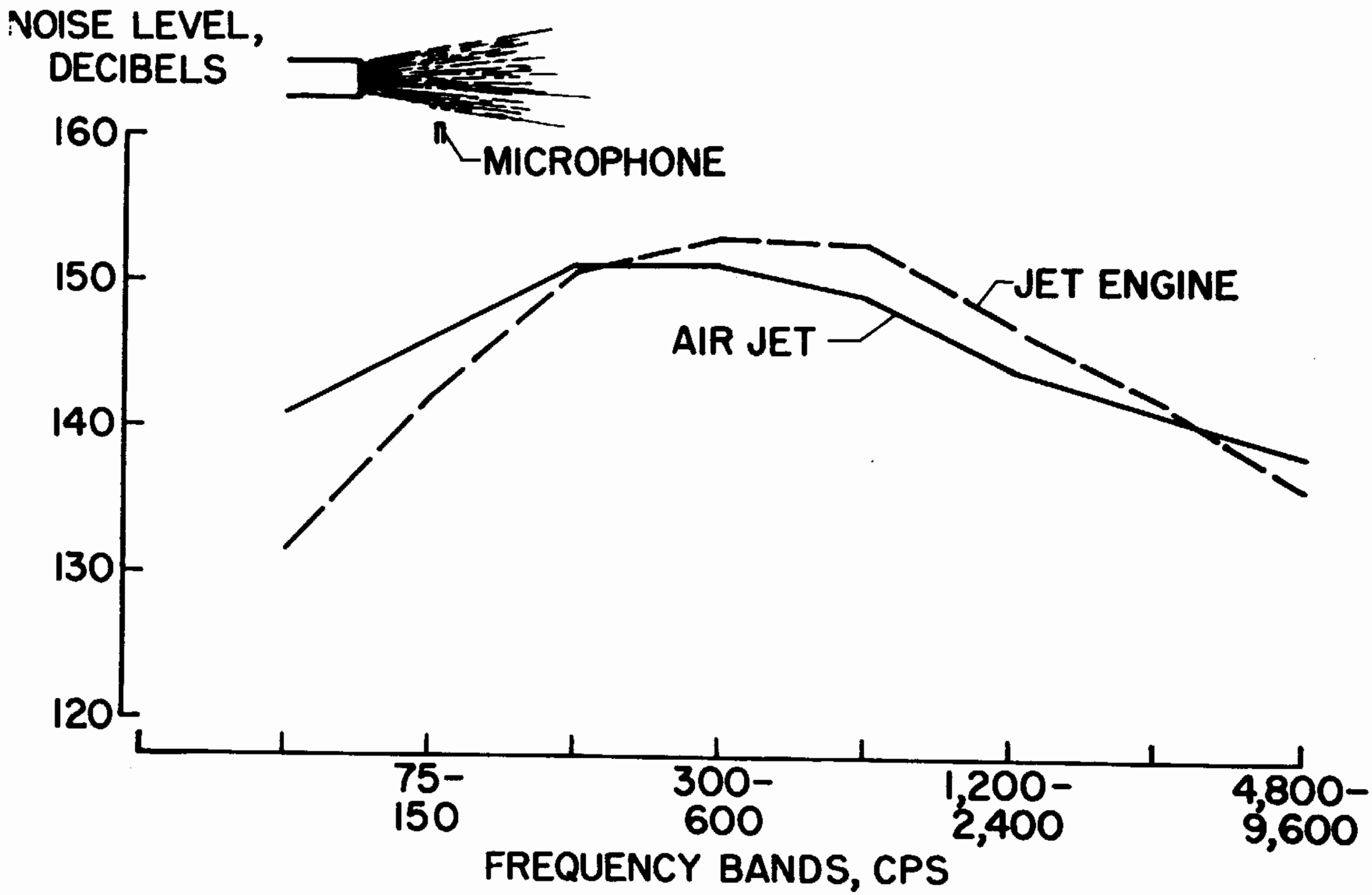


Figure 16. Comparison of Noise Spectra for Air-Jet Facility and for Jet Engine (Ref. 31).

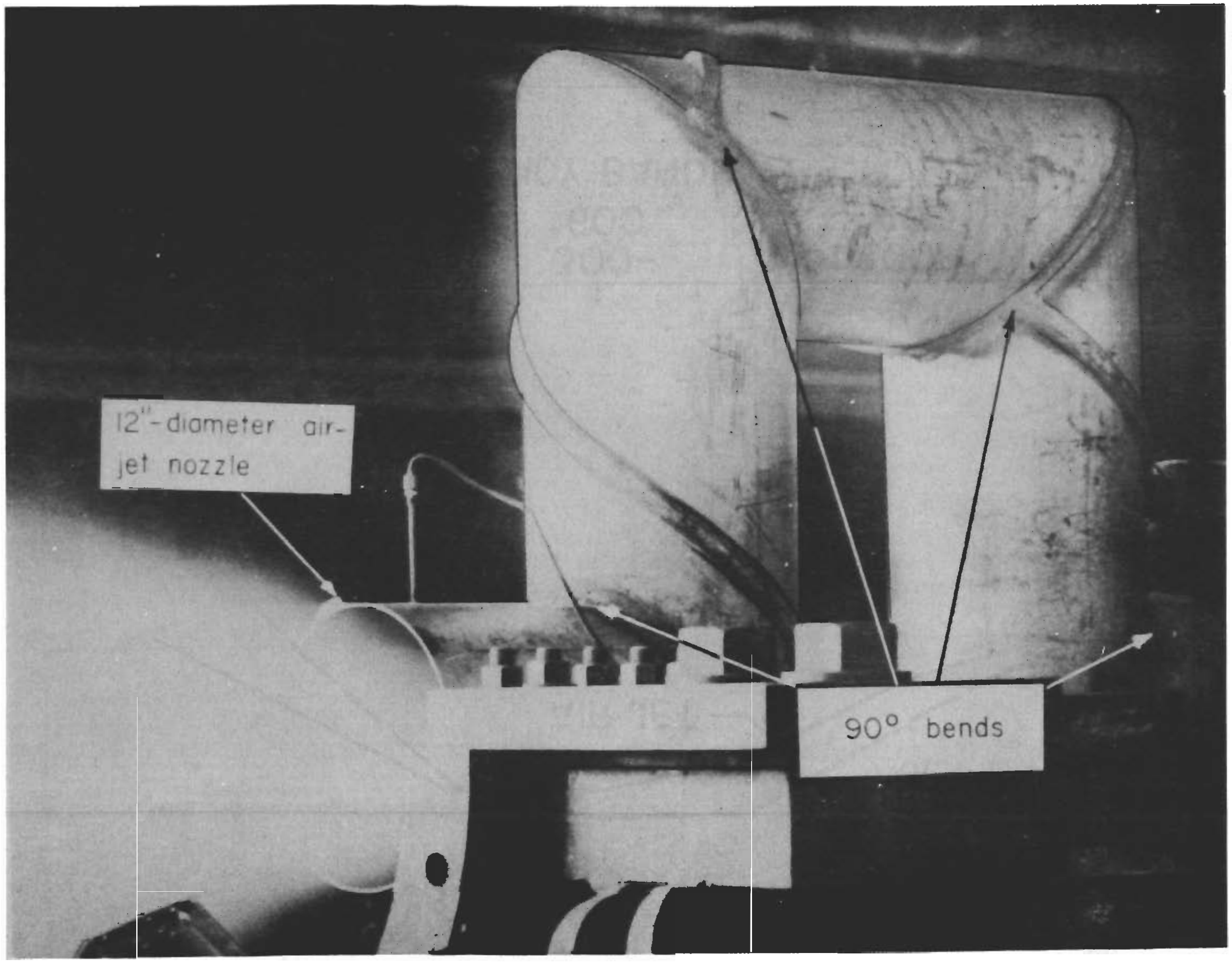


Figure 17. Side View of Air-Jet Test Setup Showing 90^{o} Bends in the Pipe Upstream of the Nozzle (Ref. 31).