SST REPORT NO-65-18

FINAL REPORT

CONTRACT NO FA-SS-65-12

THE EFFECTS OF SONIC BOOM ON STRUCTURAL BEHAVIOR

— A SUPPLEMENTARY ANALYSIS REPORT —

OCTOBER 1965

PREPARED FOR

FEDERAL AVIATION AGENCY

OFFICE OF SUPERSONIC TRANSPORT DEVELOPMENT

JOHN A. BLUME & ASSOCIATES RESEARCH DIVISION

SAN FRANCISCO

NOTICES

The information contained herein is a part of the supersonic transport research program sponsored by the Federal Aviation Agency with technical support provided by the Department of Defense and the National Aeronautics and Space Administration.

FINAL REPORT

Contract Number FA-SS-65-12

THE EFFECTS OF SONIC BOOM ON STRUCTURAL BEHAVIOR

- A Supplementary Analysis Report -

October 1965

Prepared by

John H. Wiggins, Jr.

JOHN A. BLUME & ASSOCIATES RESEARCH DIVISION
612 Howard Street - San Francisco, California

ACKNOWLEDGEMENTS

John A. Blume & Associates Research Division analyzed the data collected on the test programs. The principal in charge was: Mr. John A. Blume. Contributing Blume personnel were: Dr. John H. Wiggins, Jr., Senior Research Engineer; Mr. Jacques Proulx, Statistics Engineer; Mr. Pao Chung Chen, and Mr. Robert Runge.

The number and design of test structures, complete instrumentation plan, and data collection during the White Sands tests was provided by John A. Blume and Associates Research Division. Datacraft Inc. were the instrumentation engineers.

The instrumentation plan and data collection during the Oklahoma City tests was provided by Andrews Associates Inc. and Hudgins, Thompson and Ball and Associates Inc. The National Aeronautics and Space Administration supplied the instrumentation.

ABSTRACT

Response and Damage data from the Federal Aviation Agency Sonic Boom Tests at Oklahoma City, Oklahoma, and White Sands, New Mexico, are analyzed and effects on structures summarized. Parameters governing the free-field and near-field boom waves are also studied and their influence on scatter in the data estimated statistically. This report then conservatively summarizes the results in a damage prediction table and chart. Insurance adjusters are given guidance on the treatment of sonic boom damage claims along with the chart. Finally, recommendations for future work in sonic boom, structural behavior studies are made.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION:

In the early part of 1964, the Federal Aviation Agency conducted an extended program in Oklahoma City, Oklahoma, [1,2,*] aimed at determining the community acceptance of repeated, high altitude, low intensity sonic booms over an extended period of time. Structural response monitoring studies[3] were also conducted but were of secondary importance since prior research indicated that booms of nominal 1 to 2 psf intensity were below the threshold of structural damage. Since the Oklahoma City tests, an extensive program was designed and has been conducted for the primary purpose of determining what boom strengths above 1 to 2 were necessary to cause damage.[4]

This report is intended to supplement the findings in the four reports referenced above and to be used together with them. It summarizes the findings in the Oklahoma City and White Sands reports and incorporates the pertinent work and findings done by other investigators in the general area of sonic boom. For example, accidental sonic boom damage investigations are examined further in light of the White Sands tests.

The specific objectives of this report are to:

1. Examine the results of the Oklahoma City and White Sands studies in light of further analyses of the data;

2. Incorporate the findings of other sonic boom studies, where necessary;

3. Prepare a supplementary analysis document on the effects of sonic boom on structural behavior, including discussions of free-field, loading, response, intensity, and structural damage;

4. Prepare a provisional guide which may be used by sonic boom damage claims adjusters; and

5. Make recommendations for future work required to update present knowledge of sonic boom damage to structures, structural materials and components.

The scope of work includes the supplementary analysis of data taken during the White Sands and Oklahoma City test programs and description of the meaning of the analyses in light of other sonic boom studies. The work time period extends from April 16 to October 1, 1965, at which time the report is to be submitted to the Federal Aviation Agency.

A number of simplified expressions are used throughout the report which may be unfamiliar to the reader. A number of these are defined in the Glossary of Terms at the back of the report.

*Superscripts refer to references in the bibliography

II. SUMMARY AND CONCLUSIONS:

A. Summary:

The sonic boom investigations conducted to date are summarized in the text of this report and their results directed at understanding structural loading, response and damage. This report is designed to supplement program reports already published[1,2,3,4] and to be used together with them.

Discussion proceeds in a logical manner from free-field to loading and response and finally to damage observations and a provisional guide for sonic boom adjusters. Recommendations for future research and a discussion on "Boom Intensity" round out the major topics examined.

Many parameters influence the energy and time character of boom waves in their travel from source to site. Aircraft design and flight characteristics, meteorological conditions, ground reflection properties, and ground position, all cause the real boom wave to differ considerably from the ideal. It is shown that theory predicts peak boom pressure rather well, but wave duration theory needs further study.

The load on a structural element is simply the free-field wave which is modified by house design and stiffness, the presence of near reflecting surfaces, angle of wave attack, height of element above the ground, and aircraft vector. Studies of dynamic amplification factor spectra, computed from the vast amount of data, comprise most of the text on loading. Correlation of response with peak loads was discussed in detail in the White Sands report[4].

Structural elements respond in a predictable manner within a rather large scatter band. Some of the reasons for the prediction difficulty under controlled flight conditions stem from variation of loading strength and time character as well as variation of natural frequency and damping properties within structural members. These features along with participation factors of large windows, Helmholtz resonance of buildings, effect of aircraft vector on window and wall response, are investigated and their meaning discussed.

Response data may vary in a random manner, but is the variation predictable from knowledge of some simple boom property? The report addresses itself to this question and concludes that no simple quantity, such as peak pressure, positive impulse, etc., is better than any other for indicating response. Reasons behind the difficulties in discovering a simple load dependent quantity that would correlate with response are mentioned, and suggestions for boom monitoring gages are made.

In addition - response damage studies were conducted in the Federal Aviation Agency test programs wherever observers kept detailed records of the conditions of structures in the boom area. The data has been examined before, but it is reexamined in an attempt to uncover any hidden meaning that may have escaped detection. From these examinations and from studies of free-field loading and response data a provisional guide for adjusters including a damage index table and chart for various materials completes the report.

B. Conclusions:

Conclusions are presented in references 1 to 4 on the effects of meteorological conditions on free-field boom waves and the associated statistical variation. In addition, specific conclusions on damage and general conclusions about loading and response are made. Those to follow refer only to the supplementary analyses made in this report.

Free-Field

1. Free-field peak pressure, wave duration and positive impulse data are normally distributed within practical limits, say, three standard deviations.

2. For all practical purposes White Sands soil has a reflectivity coefficient of 2.0. Other sites should not have values lower than about 1.95.

3. Aircraft vector has no effect on reflection coefficient.

4. Reflection coefficient is independent of overpressure magnitude below 16 psf and for the shock wave angles generated at Mach 1.5 and below.

5. Standard deviation of free-field overpressure increases with increasing flight altitude.

6. Statistical analysis of the data reveals that headwinds do increase the overpressure under a flight track as theory predicts.

7. Rise time increases with altitude and is independent of aircraft size.

8. A wide range of scatter is present in rise time data.

9. The volume theory predicts overpressure for the B-58 better than the lift theory at flight altitudes of 19,500 ft. above the ground.

10. Wave duration varies less with flight altitude than that predicted by the (-¼) exponent theory.

11. The angle of incidence of the shock wave on the ground is larger than the Mach angle at the aircraft. This difference increases with flight altitude.

Loading

1. Maximum loading pressure data and dynamic amplification factor (DAF) computed from the data are normally distributed within practical limits, say, three standard deviations.

2. Secondary pulses in a boom wave generated by aircraft design features modify both free-field and loading (DAF) spectra. F-104 booms amplify the second harmonic about 14 percent more than predicted by a theoretical N-wave spectra. The first harmonic is amplified somewhat less than the theoretical value of 2.3.

3. (DAF) spectra computed from records taken on a wall differ from free-field spectra and depend on aircraft vector with respect to wall surface. Inbound vector booms lower the first harmonic (DAF) and raise the second. Trailing vector booms cause the opposite to occur.

4. Stiffness of a wall does not change the (DAF) spectrum of the loading wave markedly.

5. Peak boom pressures can be increased in a predictable manner when the boom wave travels into a corner.

6. (DAF) increases with height above ground. The rate of increase depends directly on the N-wave duration. Since peak pressure decreases with height, effective load should no more than equal load on near-ground, (one story) structures.

7. The net load on a window (outside minus inside) differs from the outside load. The effective static load is lower than that computed from the outside load only.

8. Racking loads (front minus back) on inbound and diagonal vector booms have associated response spectra which are slightly larger than those associated with only the front wall load. Sideon boom racking spectra are lower than those associated with only a single wall record.

9. Spectra computed from records taken at various points on a wall vary from one another but the effective loads are equal, on the average.

Response

1. Response data is normally distributed within practical limits, say, three standard deviations.

2. B-58 booms, when normalized to peak pressure, cause lower response of wall and ceiling elements than smaller F-106 or F-104 aircraft in 4 out of 5 tests of sample data taken at Oklahoma City and White Sands.

3. Inbound vector booms can stress windows up to four times as much as trailing vector booms.

4. Inbound vector booms can displace walls in the diaphragm mode more than twice as much as trailing vector booms.

5. Natural frequency of various structural elements is variable.

6. A mean damping factor value for elements of residential type structures other than glass is 4.5 percent.

7. No alteration of natural frequency and damping was caused by booms. These quantities may be too insensitive to relate to cumulative damage, depending on the definition of cumulative damage.

8. The effective damping of a large window is variable.

9. Higher modes can participate in the vibration of large (5ft. x 10ft.) windows on inblund vector F-104 booms and cause stresses larger than those predicted from a static deflection study.

10. Trailing vector F-104 booms cause primarily the first mode to participate in the vibration of large (5 ft. x 10 ft.) windows.

11. The probability of Helmholtz resonance frequency agreeing with large window frequencies and causing damage is low.

12. Dynamic amplification factor computed from net load correlates best with the theoretical deflection of large windows.

Intensity

1. Due to the many variables involved a perfect or even very good correlation of response computed from loading with actual response is improbable except for structural elements that are definitely impulse-sensitive. This is true for items whose periods are less than about half natural boom wave period.

2. Dynamic response is governed by many structural and loading parameters which vary randomly in space and time.

3. For a given airplane, peak projected pressure, P_m, is the most practical, simple measure of intensity for $\tau/T > 0.6$. Positive impulse is the most practical, simple measure of intensity for $\tau/T < 0.6$ ($\tau =$ boom wave duration and $T =$ natural structural period).

Damage Observation

1. Observer technique governs the quality of structure condition surveys.

2. There is an inference that the type of structures tested at White Sands may begin to crack more rapidly under F-104 booms at a mean free-field pressure of 10 psf than under non boom conditions.

3. There is no evidence of cumulative damage occurring in the Oklahoma City test structures.

4. Glass breakage is caused primarily by impact against stress raisers.

5. Plaster damage in order of severity is characterized by:

   a) spalling of old cracks;

   b) hairline extension of existing cracks; and

   c) falling plaster.

III. RECOMMENDATIONS FOR FURTHER STUDIES ON STRUCTURAL BEHAVIOR UNDER SONIC BOOM LOADS:

A. Introduction:

All of the research done in the area of sonic boom is ultimately intended for incorporation in a sonic boom effects manual. This manual cannot be limited in any way since over 200 million Americans will experience the boom and many will file claims, damage or no damage. The manual must supply an answer. Several major test programs and a continuing effort of study are suggested below which are designed to gather and analyze information pertinent to manual requirements.

B. Development and Analysis of Basic Data:

This continuing program embraces three prime areas of study:

1. Free field, loading and structural response data analysis and test program design;

2. Laboratory testing, designed to understand the dynamic behavior of materials and bric-a-brac under controlled conditions; and

3. Destructive testing of actual structures with dynamic shakers and pull-test machines to obtain full-scale damage data and establish damage criteria for a representative range of structural elements.

(1) Data Analysis and Maintenance of Technical Responsibility:

The basic objective of this continuing program is to understand the phenomena associated with the sonic boom and the statistical limits of the many and varied parameters involved. Functions performed should consider, reconcile, and codify each with the other:

(a) Studies and tests done by others;

(b) All important parameters;

(c) Statistical analysis of field test data;

(d) Simple intensity definitions and monitoring techniques;

(e) Future program requirements as well as data from past programs;

(f) Theoretical investigations of structural and bric-a-brac behavior;

(g) The characteristics of structures within the United States; and

(h) Methods of damage index chart presentation.

Parameters:

A discussion of the general parametric groups influencing damage and its identification follows:

i. Criteria for structural element failure: Structural elements (plaster, glass and other skin materials) can behave near elastically under dynamic loads up to different peak, equivalent static loads depending on strain rate characteristics (a), external pre-load (b), internal residual stress (c), strength (d), history of loading (e), and stress raisers (f), in the structural elements. To define incipient failure, criteria must be established.

A_{cr}=F (a,b,c,d,e,f) = structural failure criterion.

ii. Criteria for bric-a-brac failure: Bric-a-brac moves relative to its support as the result of motion imparted to the support by boom pressure, not by boom pressure directly. It may fall (may not necessarily break) when the motion exceeds the stability (g), or the coefficient of friction (h), of the object. In the latter case proximity to a ledge (i), is necessary for falling. Four base support surfaces are present in structures--external walls, internal walls, floors and ceilings. Such things as shelves and furniture are called sub-base supports.

B_{cr}=F (g,h,i,v(t)) = bric-a-brac failure criteria, where v (t) represents 3 components of acceleration. These alter the normal force pressing two objects together and the natural characteristics of the items.

iii. Response: Stiffness (j), natural frequency (k), internal damping (l), and time character of the "effective" load, P_d (t), govern response up to the point of "failure".

U(t)=F(P_d(t), j, k, l) = stress, strain, etc., time response.

iv. Loading: The "effective" near-field load generated by a boom wave striking a structure or structural element is modified in peak pressure and time-character by the structural design (m), structural reflectivity coefficient (n), nearby complex of reflecting bodies (o), and transmissibility (p).

P_d(t)=C(t) P_o(t)= near-field dynamic load where C(t)=F(m,n, o,p,t) = dynamic coefficient which modifies free-field pressure, P_o (t).

v. Free-field: Herein the atmosphere through which the boom travels (q), the maneuvers of the aircraft (r), and the reflectivity coefficient of the ground (s), influence peak pressure and modify boom signature.

P_o (t)=F (q,r,s,t) = free-field boom wave.

Without going into great detail the above equations describe only some 20 "families" of variables within the parameter "group". There are many more which may or may not be important to boom damage prediction.

The flow of information obtained from research delineating the influence of each parameter is depicted in Figure III-1. The scheme of assessment is shown to depend on the size of a monitored signal obtained within a populated area. Other curves could be formulated, knowing only the free-field characteristics. But for reliability to be equal, the criteria would necessarily be more conservative.

Statistical Analysis:

Modern statistical analysis, which permits the testing of hypotheses about the meaning of data, is a very powerful tool to advance knowledge. In view of the many parameters influencing damage it is the only objective analysis method which can be used in damage criteria development. However, the courts are beginning to accept probability and reliability as appropriate evidence in judgments.

Statistical techniques also provide for design of optimized new test programs supplying basic data. For example, based on what was or was not learned from the White Sands tests and the Oklahoma City tests, improved programs can be designed. The first things to consider in ddsigning such programs are the methods of analyzing the observations. These considerations are governed by whether the objectives are to answer questions, to test hypotheses of equality or inequality, or to estimate effects.

If the statistical test of experimental data is performed in order to answer a question, the designer must program the experiment so as to eliminate the variables which may affect the experimental observations. These variables may be weather conditions, instruments, and even other statistical tests of secondary importance, if necessary. The same elimination of variables is necessary for effects measurement or hypothesis testing.

Therefore, new field as well as laboratory experiments should be designed for unanswered or partially answered questions, comparisons, and effects. Requirements of the manual development program must influence full-scale field tests, structural damage criteria tests, and laboratory test designs and data gathering schemes where new data, pertinent to the manual, are obtained.

Confidence or reliability in the findings depend to a large extent on the size of the sample interrelated with the standard deviation of the data.

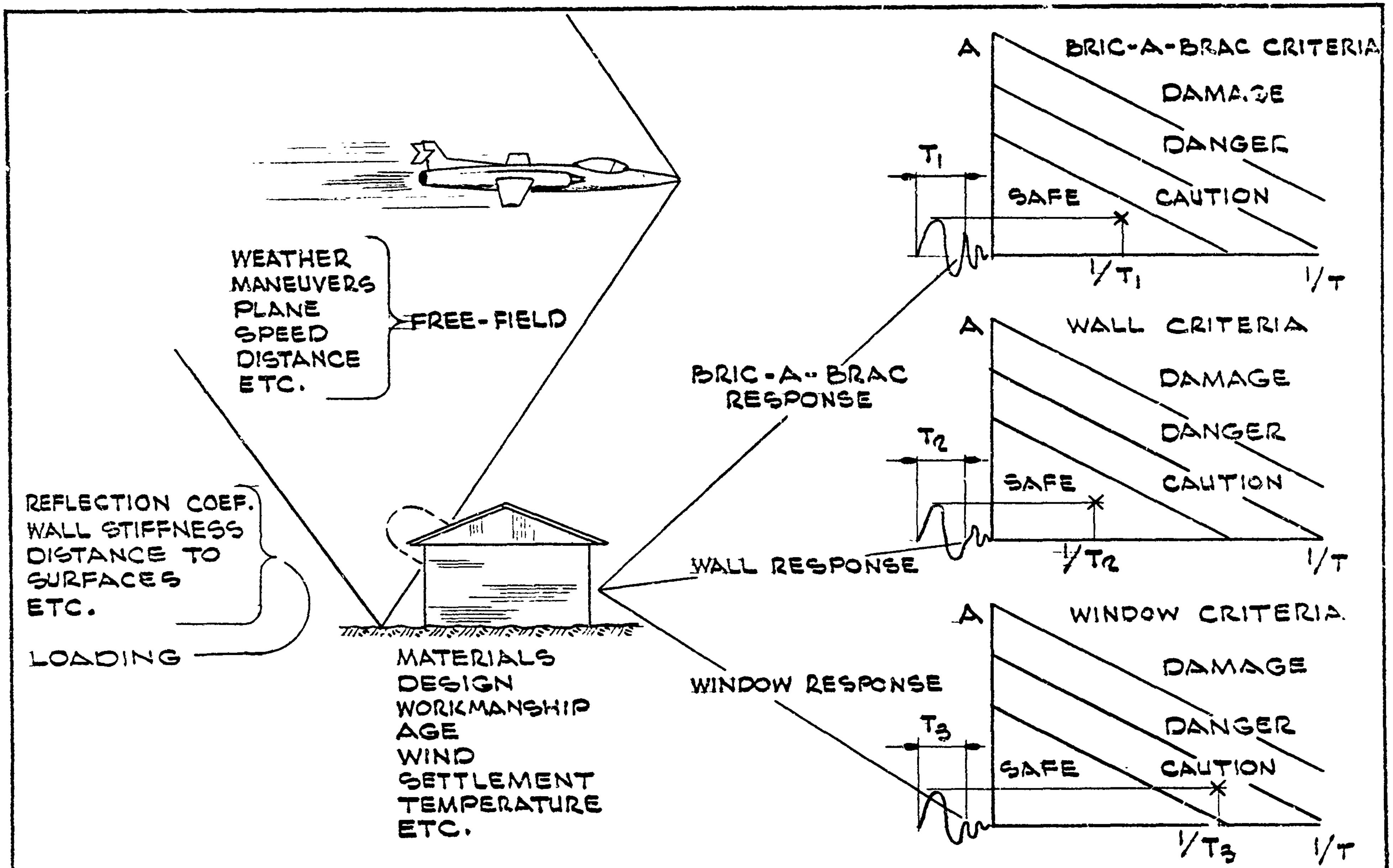


FIG. III-1. FACTORS INFLUENCING BOOM DAMAGE ASSESSMENT

The larger the standard deviation the larger the sample necessary to provide confidence in the conclusions. Reliability must be the watchword of the manual development program.

In addition to using statistical analysis for the evaluation of field and laboratory test data, it may be useful in developing in situ evaluation criteria for adjusters. Certain types of bric-a-brac contained in homes may be built-in gages for home damage prediction. If, for example, hooks on walls supporting pictures have not been disturbed, a statistical relationship may exist based upon estimated picture weight, wall material and hook type. Further, structural element types and designs across the country can be cross-sectioned, physical characteristics and condition statistically determined, and percentages of types compared with claims percentages to estimate reliability of claims. Correlation of damage claims of specific types with those predicted, compared with other correlations, could supplement information in claim studies.

Intensity:

The quantity which best relates intensity of a dynamic vibration to structural damage, whether it be supplied by a boom or not, is and has been a matter of opinion and point of controversy for many years. Damage is usually related to response. Experience in structural dynamics has established that the rather complicated response spectrum technique is the best means for relating peak pressure (load) to dynamic action (response) and from there to damage. However, certain simple rudimentary measures such as acceleratio n, velocity, or displacement (response quantities) and peak pressure or impulse(load quantities), would be more rapid means for estimating boom intensity within frequency bandwidths of representative structural elements.

The studies to date indicate that a calibrated structure would probably be the best boom monitoring gage. For example, peak pressure or positive impulse is usually correlated with altitude, Mach number, weather conditions, and design characterisitcs of an aircraft. Response of certain structural elements can also be correlated with these quantities. One possible monitoring setup is shown in Fig. III-2, Therein houses (probably occupied) with inexpensive, durable instruments attached, constitute the sensing elements. Just as the deflection of a piezoelectric crystal or a condenser plate in a microphone relates to the pressure, so too does the deflection of a house element. The house element is more closely related to another house element than is a piezoelectric crystal.

In Fig. III-2 telephone lines connect the gages on the house to the Federal Aviation Agency center. These lines can be easily rented for about $3.00 per month each. Television survey companies often monitor the public's television sets via telephone lines to evaluation program appeal. The gages can be manufactured inexpensively, whereas the slow-moving seismographh is an off-the-shelf item. Oil well drilling

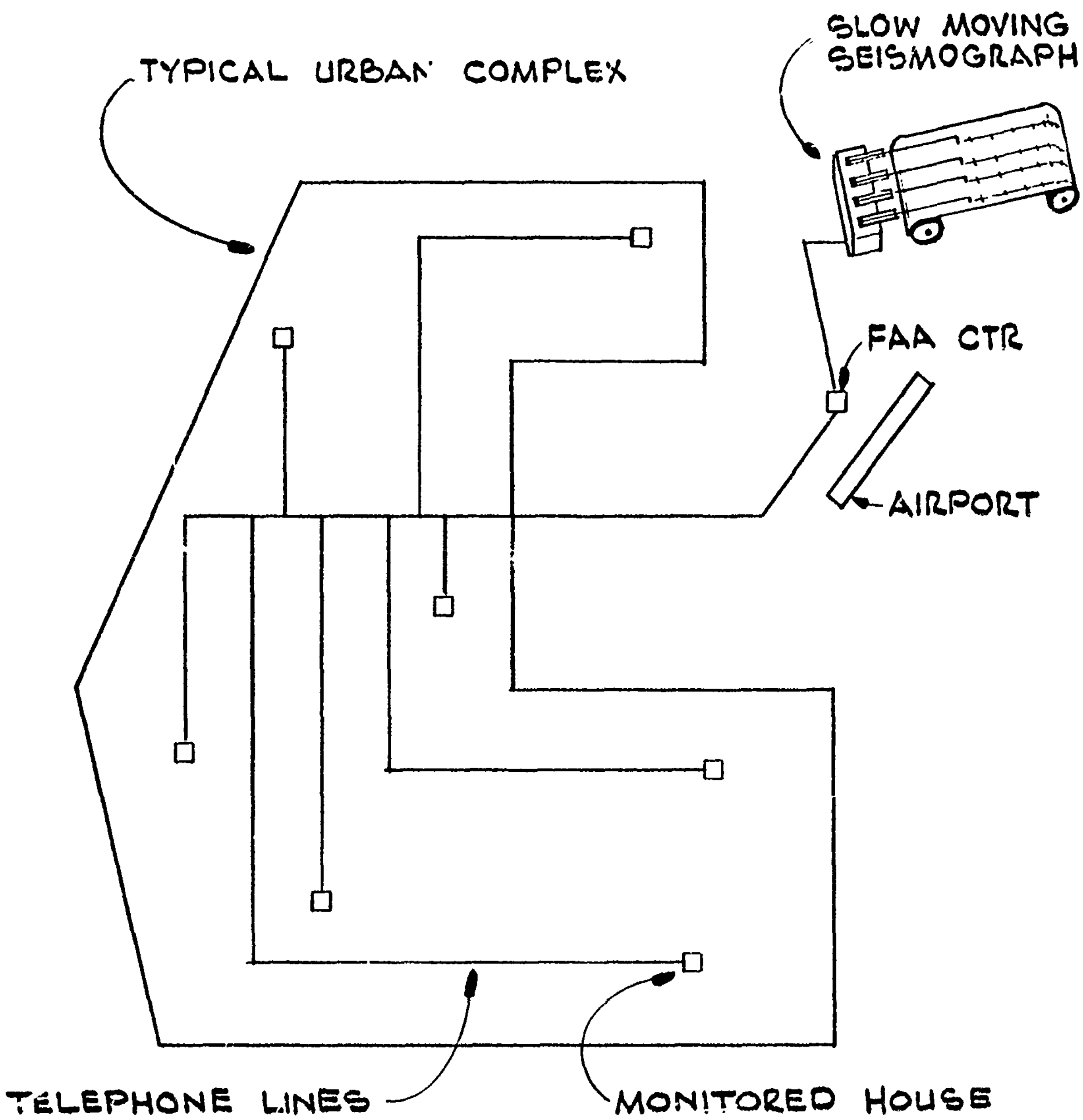


FIG. III-2. MONITORING SCHEME FOR A TYPICAL CITY.

supply companies supply other, more rugged types of off-the-shelf drillograph machines recording up to 7 parameters. These are crude but could be adapted to the boom problem.

If monitoring during SST flights is not accomplished, an effective intensity can be computed from theory and knowledge of the variation in boom data. It would be necessary to design criteria charts and procedures for claims adjustment in a more conservative manner, however, since actual readings would not have been taken during any boom flights.

Data Analysis:

Many further analyses of the White Sands and Oklahoma City data can be performed. As time passes and the boom problem has a chance to mature in the investigator's mind, new and more meaningful studies of the data can be performed. One of the big problems is to design future tests to supply data deficiencies or eliminate parameters which confuse present data. Wind, temperature, pressure, and lateral spread effects have been determined within broad limits. These limits need to be narrowed and the contribution of each important parameter identified. Future maneuver tests may reveal the extent to which turns, dives and climbs control data spread. Other problems of interest include studies of:

1. The influence of instrument recording characteristics on data quality.

2. The effect of mach number and mach angle at the surface on ground free-field pressure variations.

3. The magnitude and reason for variation in ground reflection coefficient over various soils.

4. The deviation of loading from free field response spectra.

5. The influence of structure rigidity and open windows and doors on loading response spectra.

6. The transmissibility of windows and walls.

7. Correlation of response computations with measurements.

8. The magnitude of aircraft vector influence on item response.

9. The nature of seismic motion.

10. The frequency and damping characteristics as a function of boom strength and natural conditions.

11. Helmholtz resonance and its probablistic implications.

12. Upper and lower envelopes of response spectra and computation of spectra by stochastic processes.

13. Correlation coefficients and correlation functions for nail popping, cracking, etc., versus boom and other conditions.

14. Observer calibration factors to determine ability of people to identify cracks.

15. Correlation of complaint with response and natural condition data.

Some of these studies have already been begun in the following report; others cannot be made from the data available at this time because too many parameters confuse the analysis. Future tests should be designed to supply the data necessary in order to complete these and other studies to be conducted in the future.

The importance and coefficient of variation of each influencing parameter must be known. Then the effects of combinations of parameters and the coefficient of variation of these combinations can be known and understood.

Theory:

Empirical data analysis must always be reconciled with the theory in order to determine mechanism. It is true that prediction can be made if regions in question are bounded on all sides by data, but it is prediction without logic. For example, racking response spectra computed from the effective load (front minus back pressure) should be compared with one computed theoretically. Comparison with known response should then be made. If there is disagreement, questions both of the data and the theory should be asked. In the case of agreement, an extrapolation can be performed with confidence, within limits.

Some structural elements respond to both loading and foundation motion induced by the load through adjacent structural elements. Theoretical studies of plates under these combined loads is necessary.

Structural flexibility modifies the load. Theoretical studies can determine the mechanism and suggest extrapolation of data to structures other than those tested.

Theory can provide an understanding of the major parameters affecting various parts of response spectra. From this knowledge, factors underlying boom intensity can be forecasted and compared with statistical analysis. Even alteration of aircraft design to provide a more tolerable boom may be possible.

The time response of structures to boom loads is known. The supposed approximate load on the structure is also known through microphone pressure records. Theoretical studies should be performed on the response date to work backwards and solve for the actual effective load on the structure and comparisons made with that measured by microphones. In this way the effectiveness of microphone records to represent effective loading on a structure can be derived.

Structure Survey:

Laboratory tests, full-scale field tests, tests of actual structures by means of vibrators, theory and analysis of the data, will provide input to criteria studies, but since there must be a million or more types of different structural elements and designs or bric-a-brac combinations, only major categories of structural element types should be examined. However, a certain amount of data extrapolation can be made with theory.

It is necessary, therefore, to determine from design codes and conferences with various city engineers and building officials the stiffnesses, ages, strengths, class of workmanship, procedures, etc., generally found in or used in fabrication of buildings in various sample cities. Knowledge of the structural population will permit design of the sample types and numbers to be studied in the laboratory under certain confidence limitations. It will also aid insurance companies in predicting the number of valid boom claims during SST flights.

This portion of the study should be conducted by extensive literature survey and conferences with city engineers and planners.

Index Charts:

Finally, damage index charts formulated under this continuing program should be developed so as to reflect all of the conditions and types of claims that an adjuster might meet. It has clearly been established by the Federal Aviation Agency, Oklahoma City tests wherein some 4,793 formal claims resulted in $17,330.74 payments to midyear, 1965; by the U. S. Air Force, Chicago tests, wherein some 2,520 formal claims resulted in $65,492.22 payments to midyear, 1965; by boom accidents resulting in U. S. Air Force payments made before 1964 of $813,591.00; and by the AEC test near Hattiesburg, Mississippi, where there may be $600,000.00 in claims, that one single criterion such as plaster damage suggested by the U. S. Bureau of Mines, was insufficient as a prediction basis to cope with the human factor in the claims problem.

The main difficulty in preparing meaningful, simple and accurate damage charts is that probability and statistical variation of both load and response can be large. It will therefore be necessary for those who will decide what damage risk or response limit is acceptable to use charts that can supply input to sound judgment. Some damage can be done at any pressure level. Structures crack due to creep under gravity loading, for example. The question is, how much is tolerable?

Design Code changes can be made with useful index charts. This may be necessary for design of new structures in the "SST age".

(2) Laboratory Tests of Structural Elements:

In order to draw criteria curves for damage, one must have damage data. Very little is available in the sonic boom literature, and virtually none of the above-ground blasting references supply data to boom-pressure ranges. Coupled with this, an understanding of the response characteristics of various types of materials such as plaster, glass, stucco, brick, concrete block, etc., under conditions of varying temperature, humidity, settlement and other causes of pre-stress, is needed in order to supply judgment to the design of criteria charts.

Laboratory tests will primarily involve studies in fatigue, cumulative damage and bric-a-brac behavior under controlled conditions. Walls and windows of different ages and in various conditions of repair should be obtained for these purposes. There are many types of loading machines which can duplicate a boom load input and, which is probably more meaningful, a boom response input. Laboratory tests, therefore, can supply an understanding of how structures crack.

The actual number and types of test panels and environmental conditions to be studied will depend on a thoroughly prepared test plan. This plan is beyond the scope of these recommendations and will depend to a large extent on the results of exploratory tests and the structure survey.

(3) Damage Criteria from Field Vibrator Tests:

The laboratory is an excellent tool for studying the influence of various parameters under controlled conditions but it is virtually impossible to test existing structures in the laboratory which have certain unknown amounts of built-in prestress. Whenever anyone brings materials into the laboratory, the conditions are changed. For this reason, in situ damage studies of existing buildings are necessary to obtain damage data and, if possible, correlate damage data with that taken in the laboratory.

This should be made possible using buildings which have been condemned or are being demolished by freeway contractors; abandoned farmhouses are also prevalent throughout the country with the advent of the city farmer. These could be excellent subjects for test.

Before testing the structures it must be decided by statistical analysis of the structural population what size and type of statistical sample are representative for test.

C. A Guide for the Evaluation of Damage Claims:

The documents prepared in the foregoing programs would be addressed primarily to those people most interested in how the facts are derived, as well as the implications. The document prepared under this section addresses itself primarily to laymen interested in the facts and how they apply to their particular problem. Several major items to be contained in the document are discussed below.

The claim form is probably one of the most important items in the book. It must include all pertinent information about the claimant's house and damage. It also must be simple and easy to complete by an adjuster. Herein, survey of all existing claims forms by various agencies could prove very useful in formulating one for boom.

A series of questions to the property owner could identify associated damage or non-damage. Correlation of these observations with a claim could be made from studies conducted in the technical program. For example, correlation of bric-a-brac movement or window deflections with crack damage may be possible.

The age of a crack is difficult to determine, but old versus new can usually be determined. One result of the technical studies conducted in the laboratory and possible in the field vibrator program may be a procedure for checking crack or damage age. Crack width, for example, may be an important parameter in correlating age. This information should be included.

The next door neighbors could be questioned for house damage. If none is present, the probability of damage happening next door may prove useful for an adjuster.

An adjuster must be made aware of how buildings react under normal circumstances and must be able to identify these causes, such as settlement. He also must be able to convey these ideas to a claimant in a nice way. Education, in other words, of adjuster and claimant alike is critical for mutually satisfactory claims adjustment.

Along with the discussion on what natural forces cause damage must be a section educating the adjuster as to what boom damage is, what it looks like, and what boom strengths were required to cause it. For example, it must be shown that glass breaks at stress points beginning at the frame boundary, that boom cracks in plaster are hairline in nature and can barely be seen because of no associated permanent set, etc. Many pictures from laboratory tests, and full-scale field tests, would be required in the section.

The manual must include a section dealing with the basic meaning behind the statistically derived lines in the index charts. Examples of probability must be used frequently.

In preparation of the laymen's edition of the boom manual, it is suggested that a team made up of insurance agents, attorneys, engineers, adjusters, government officials, airline officials, and whoever else might be interested in the results of a report such as this, be engaged to read the draft and take a test to identify areas that need clarification. Only in this way can the authors of such a document be sure of reaching their audience.

D. City Test II:

The basic objectives of the City Test II Program are to study the response of a cross-section of structural elements. It is suggested that one sample city be selected for study. It should be examined during boom time and during non boom times for some length of time in order to determine actual cumulative damage and the extent to which cumulative damage may occur.

It is suggested further that this town be small enough so that virtually every structure within the town can be observed. But it should be large enough so that a representative sample is obtained. The standard deviation of the data is expected to be quite high.

Another objective of booming a town is to determine the ability of typical home dwellers to assay whether or not damage occurred to their premises. Studies have indicated that human beings are not good gages for determining whether damage occurs or not. Studies of the premises made by engineers correlated with possible damage claims made by the homeowner could prove interesting in assessing the validity of claims made later during SST flights.

A cross-section of the response characteristics of a number of structural elements could also be attained through the city tests. Correlation with theory would prove useful in extrapolating test data to the whole United States.

It has been shown that simple scratch gages mounted on windows or other structural elements, when properly calibrated, can measure boom intensity. It is suggested that a number of these items be placed throughout grid networks in the city to record the lateral variation of boom overpressure at closely spaced intervals. Booming aircraft should then be maneuvered as well as flown at straight and level paths to test whether maneuvers actually caused increased structural reaction and damage. One interesting question that could be answered is the possible increase of standard deviation of maneuver versus level flight data.

Various simple methods of boom monitoring could also be perfected during the city tests. The scratch gage is one technique. There may be others discovered during the design or testing period.

Various means of adjuster procedures for handling claims could be examined and tested. Damage will be known to have or have not been caused by the boom and the adjuster's techniques can be tested for accuracy.

The question of whether boom causes permanent set in structures or not can be laid to rest. Accurate survey instruments capable of recording up to a milli-inch could be used throughout the town to record change before and after boom.

A final objective for the city test would be to confirm the lower limits of damage established during the White Sands tests. Due to the low sample number at White Sands, necessarily low limits were stipulated for conservatism's sake in the attached report.

The site chosen for the City Tests II Series should be near a base where B-58's and, if possible, an XB-70 could be used as the flight vehicles. Herein, vehicles more closely approximating the size of the SST would generate the boom and human reaction to this sound could be correlated with that measured in the Oklahoma City program werein small aircraft were used.

E. Structures Tests II:

Because high boom loads will not have been generated in City Test II and because upper limits and range of limits of damage is still a necessary requirement, a structures test similar to that run at White Sands in 1964-1965 should be made.

The primary objectives of these tests would be to determine the upper and lower limits of damge to new as well as old structures. This necessitates using the original White Sands test structures which should effectively be quite old by the time the test is performed. The weather and soil conditions rapidly "age" a structure at White Sands. These structures should be duplicated along with new ones in order that the age effect be tested.

Further checks on adjuster manual charts can be made to completely verify that the manual is accurate within the limits stated.

One final objective of the program would be to test those items which are determined to be the most critical from the standpoint of claims, that is, real claims, Simple plaster cracks and glass breakage make up by far the largest proportion of claims filed in Oklahoma City. However, there may be some items buried in the mass of claims that truly are susceptible to boom-type loads. It is hoped that by the time the test series is performed, these items will have been determined during City Test II.

F. The Supersonic Transport Prototype Tests:

In 1969 the supersonic transport should be in the flight testing stage. It would be desirable that the flight test airfield be near City II where B-58 and XB-70 tests were performed so that comparisons can be made with the data taken with the B-70 and B-58. Also, one final checkout with the adjuster claims forms and procedures could be made on the actual prototype. At the end of these tests, the manual should be complete for SST operations.

A time table is shown in Fig. III-3 for all of these test series and continuing program studies. Note that the final manual is scheduled to be completed prior to SST flights.

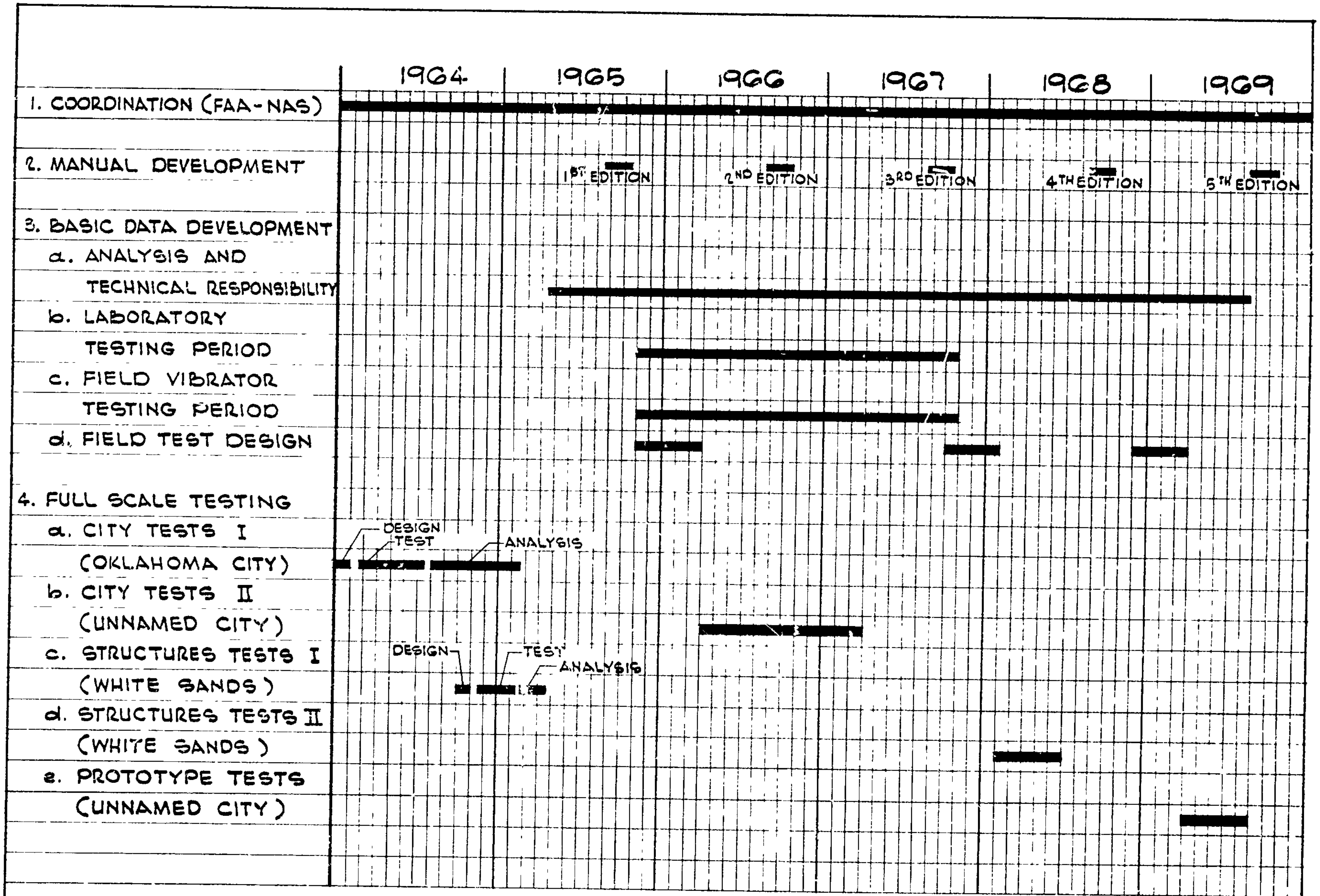


FIG. III - 3 TIME SCHEDULE OF PROGRAMS ARE RELATED TO MANUAL DEVELOPMENT

IV. FACTORS AFFECTING THE MAGNITUDE AND TIME VARIATION OF FREE-FIELD BOOM WAVES:

A. Introduction:

Although this report has as its prime mission the examination of structural loading, response, and damage data and the meaning derived therefrom it is extremely important that the building research engineer be familiar with factors affecting free-field wave behavior. Knowledge of this behavior will complement his understanding and ability to predict structural behavior.

The free-field boom wave, that which is unmodified by near reflecting surfaces, has been the subject of detailed investigation for many years. References 2, 4, 5 and 6 give comprehensive bibliographies and discussion of the subject. For this reason and because the study to follow is supplementary to references 1-4 it does not attempt to duplicate any derivations or describe the evolution of thinking about the importance of various parameters on boom strength and wave shape. Rather, selected samples of the massive amount of data collected during the Oklahoma City and White Sands tests are compared in different ways with theoretical results to expose trends and give insight into the data.

One fact that immediately confronts one examining sonic boom data, whether it be free-field, near-field (near the structure, that is), response or damage data, is the scatter. The scatter is caused by the interaction and interdependency of a host of parameters, almost too numerous to list. Can an understanding of the importance of each parameter be sifted from data like this? To answer the question the data is first tested to see if it is statistically normally distributed. If it is, then statistical tests of equality or inequality and determinations of expectancy values can be made. Then, studies of major parameter families which influence the free-field boom wave are examined in light of the data.

The basic equations describing boom strength, N wave time duration and positive impulse are presented in simple engineering nomenclature as indicated in Table IV-1*

*Symbols are identified in the Glossary of Terms listed at the back of the report.

Table IV-1 Free-Field Equations

Theory		Reflectivity	Atmosphere	A/C Design	Flt. Conditions	Eq. No.
(vol) ΔP	=	K_1	$(P_a P_o)^{\frac{1}{2}}$	$K_2\, d\, l^{-\frac{1}{4}}$	$(M^2-1)^{1/8}\, r^{-\frac{3}{4}}$	(1)
(Lift) ΔP	=	K_1	$P_o^{\frac{1}{2}}$	$K_3 W^{\frac{1}{2}} L_w^{-\frac{1}{4}}$	$(M^2-1)^{3/8}\, M^{-1} r^{-\frac{3}{4}}$	(2)
τ	=		C_a^{-1}	$1.9\, d\, l^{-\frac{1}{4}}$	$(M^2-1)^{-3/8}\, M\, r^{\frac{1}{4}}$	(3)
(vol) I +	=	K_1	$C_a^{-1}(P_a P_o)^{\frac{1}{2}}$	$.48\, d^2 l^{-\frac{1}{2}} K_2$	$M(M^2-1)^{-\frac{1}{4}}\, r^{-\frac{1}{2}}$	(4)
(Lift) I +	=	K_1	$C_a^{-1} P_o^{\frac{1}{2}}$	$.48\, d\, l^{-\frac{1}{4}} W^{\frac{1}{2}} L_w^{-\frac{1}{2}}$	$r^{-\frac{1}{2}}$	(5)
Parameters		Ground Impedance, Incidence Angle, Topography, Texture.	Wind, Temperature Humidity, Pressure, Turbulence.	Length, Weight, diameter, Shape, Lift.	Speed, Altitude, Flt. Direction, Maneuvers, Lat. Distance.	

These equations are, of course, only engineering approximations of the parameters listed. The shape of the pulse is assumed to be a saw tooth (N wave).

B. Statistical Distribution of Free-Field Data:

Hilton, et al.[1] and Kane and Palmer[2] used a log-normal method of displaying the Oklahoma City data. Kane and Palmer reason that a normal distribution assumes data to vary from minus infinity to plus infinity. Since this is physically impossible a log-normal fit is assumed. They further predict that an upper and lower bound in the data should exist. Warren[7] also assumes a log-normal distribution.

Figs. IV-1 to IV-13 present overpressure, duration, and positive impulse data for different aircraft and altitudes. The data in virtually all instances follow a straight line on normal probability paper. If the random variables are normally distributed, the points of the

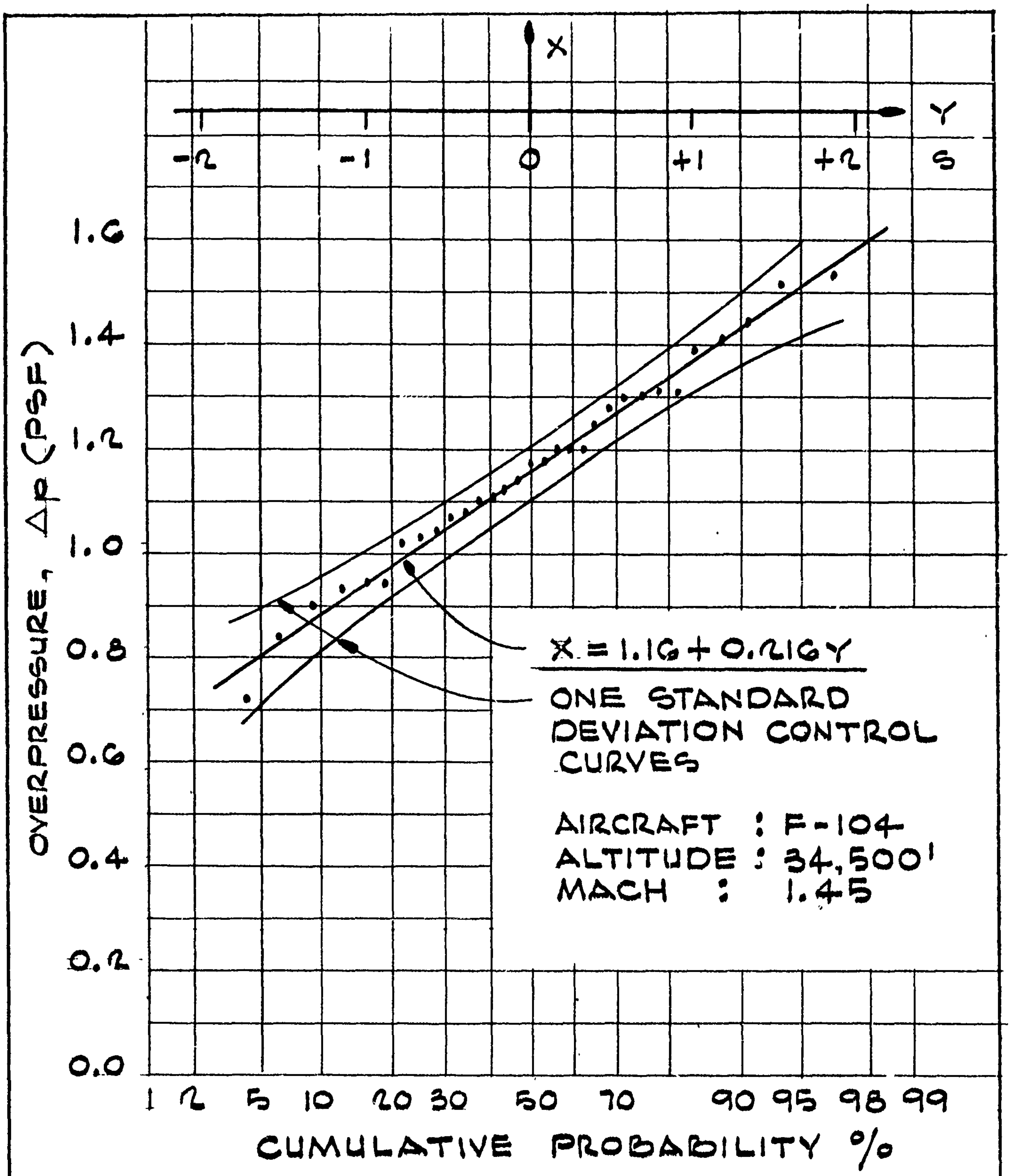


FIG. IV-1 PROBABILITY DISTRIBUTION OF THE FREE FIELD OVERPRESSURES (34,500 FT.)

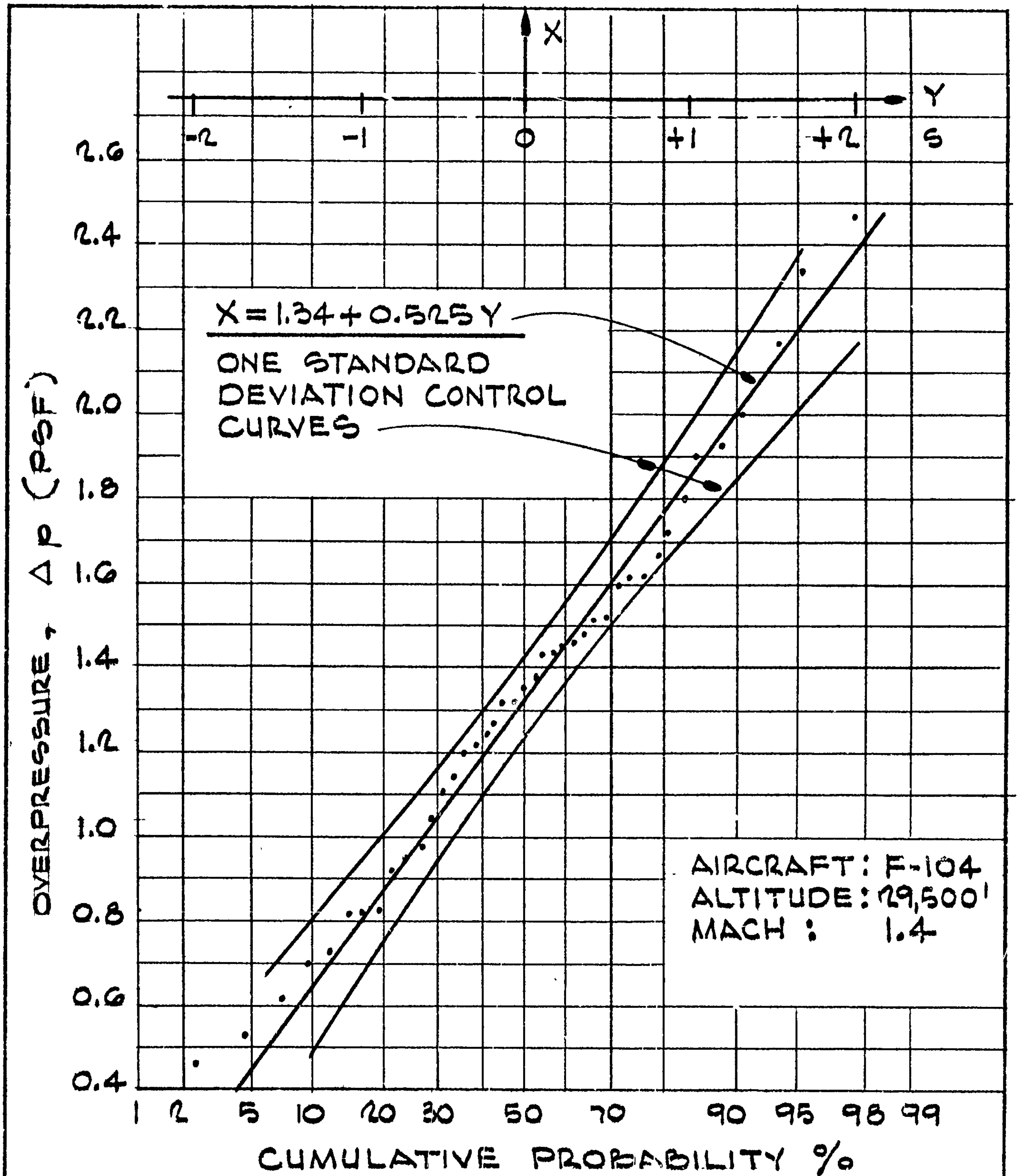


FIG. IV-2 PROBABILITY DISTRIBUTION OF THE FREE FIELD OVERPRESSURES (29,500 FT.)

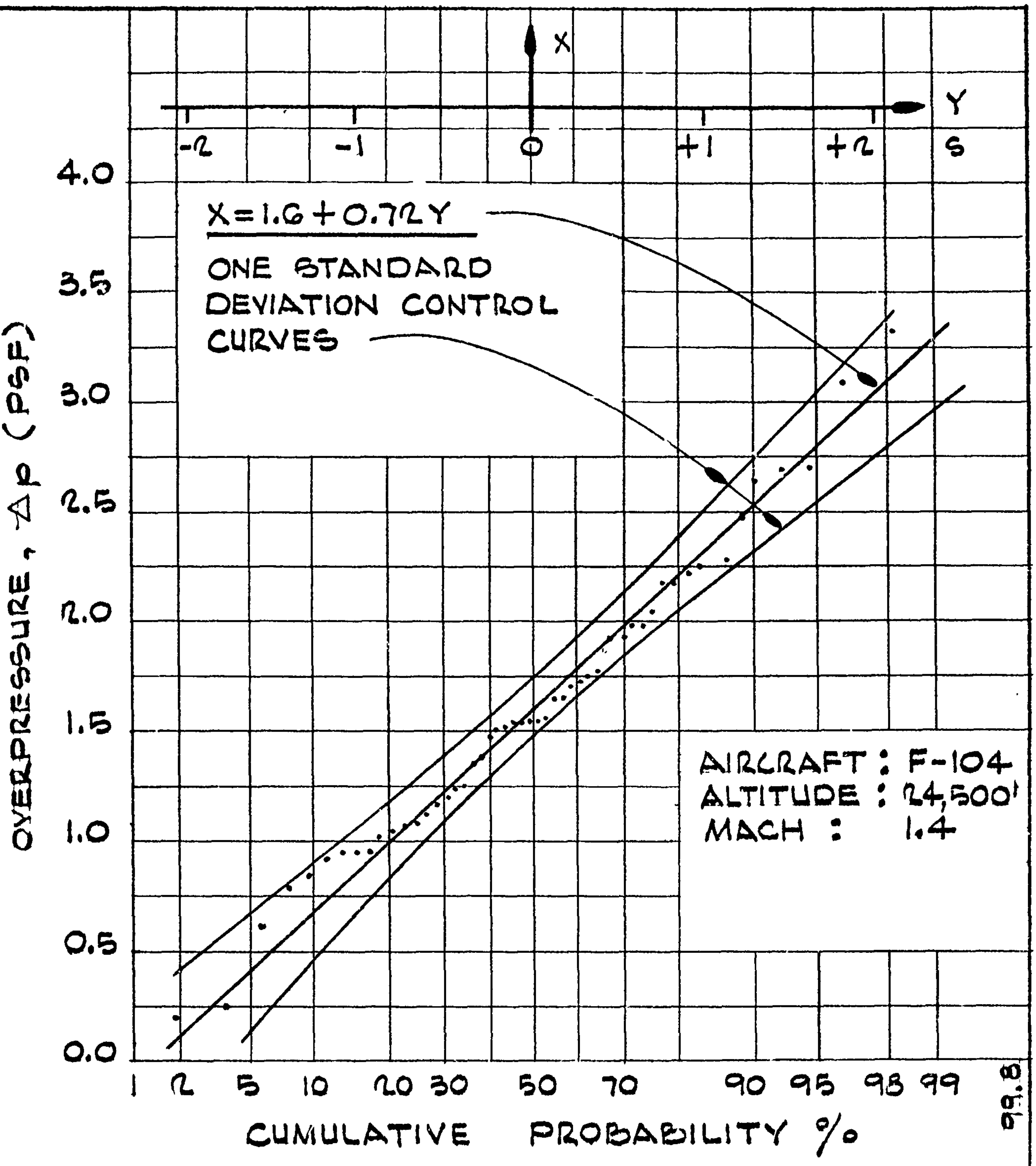


FIG. IV-3 PROBABILITY DISTRIBUTION OF THE FREE FIELD OVERPRESSURES (24,500 FT.)

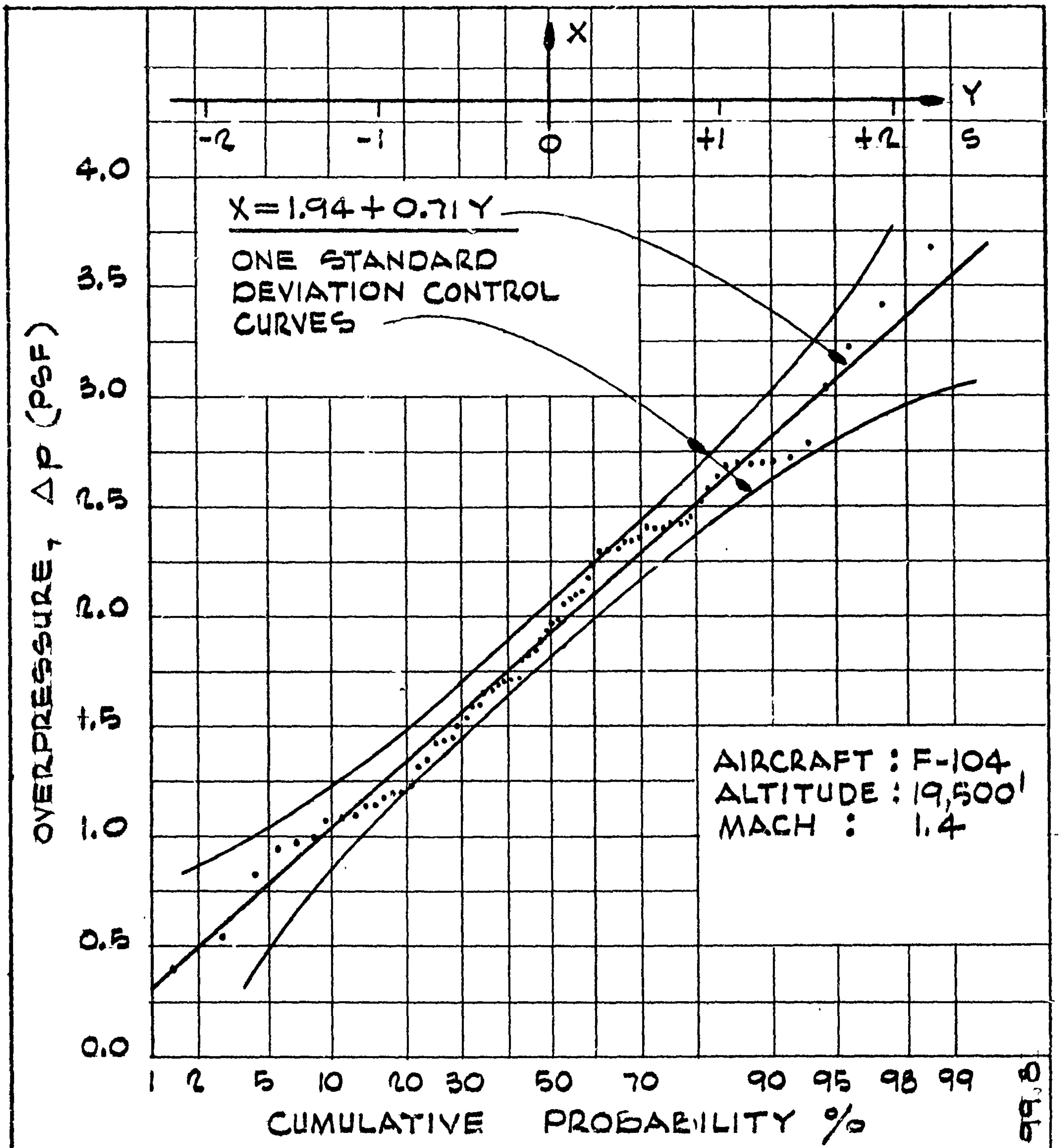


FIG. IV-4 PROBABILITY DISTRIBUTION OF THE FREE FIELD OVERPRESSURES (19,500 FT.)

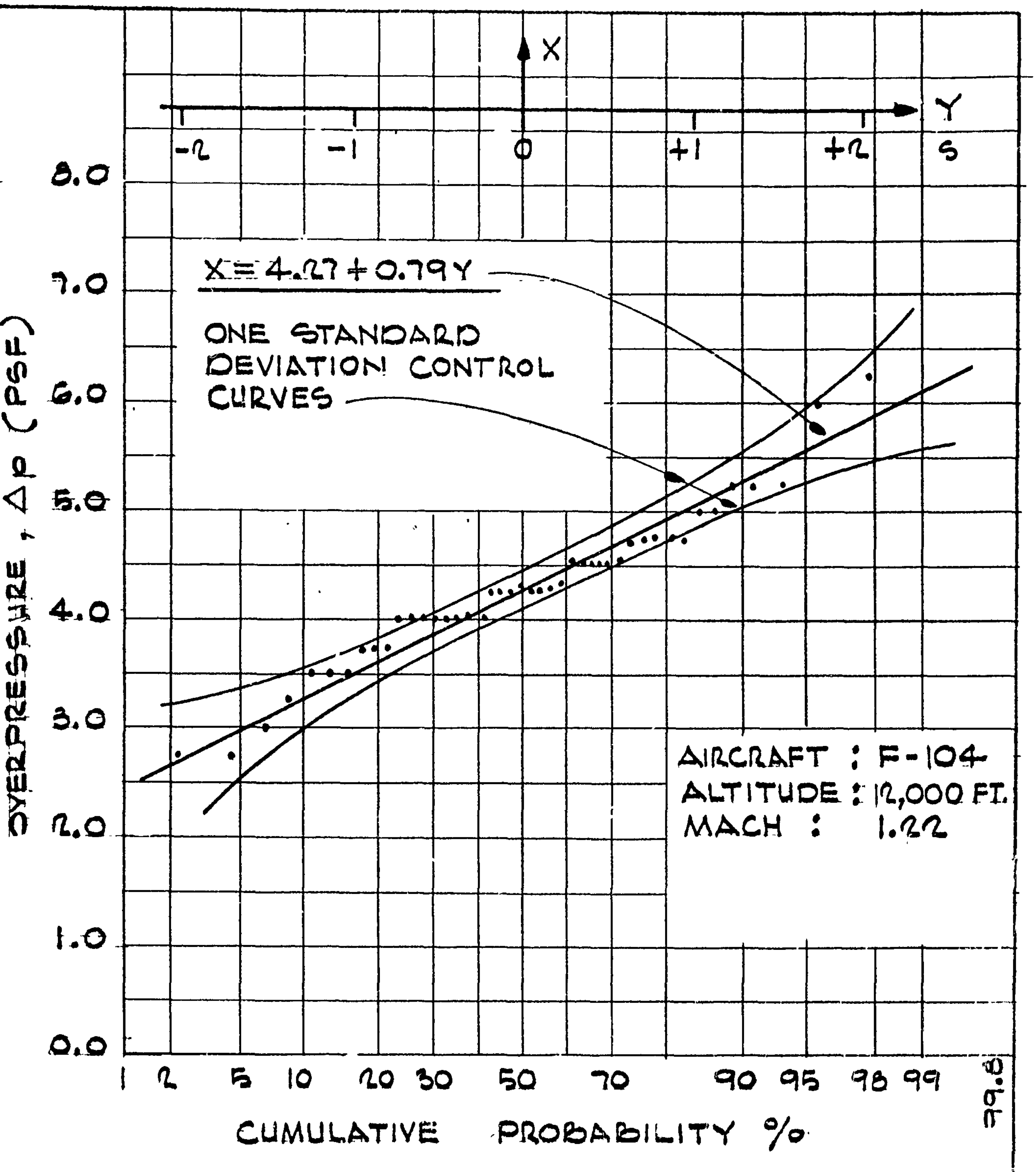


FIG. IV-5 PROBABILITY DISTRIBUTION OF THE FREE FIELD OVERPRESSRES (12,000 FT.)

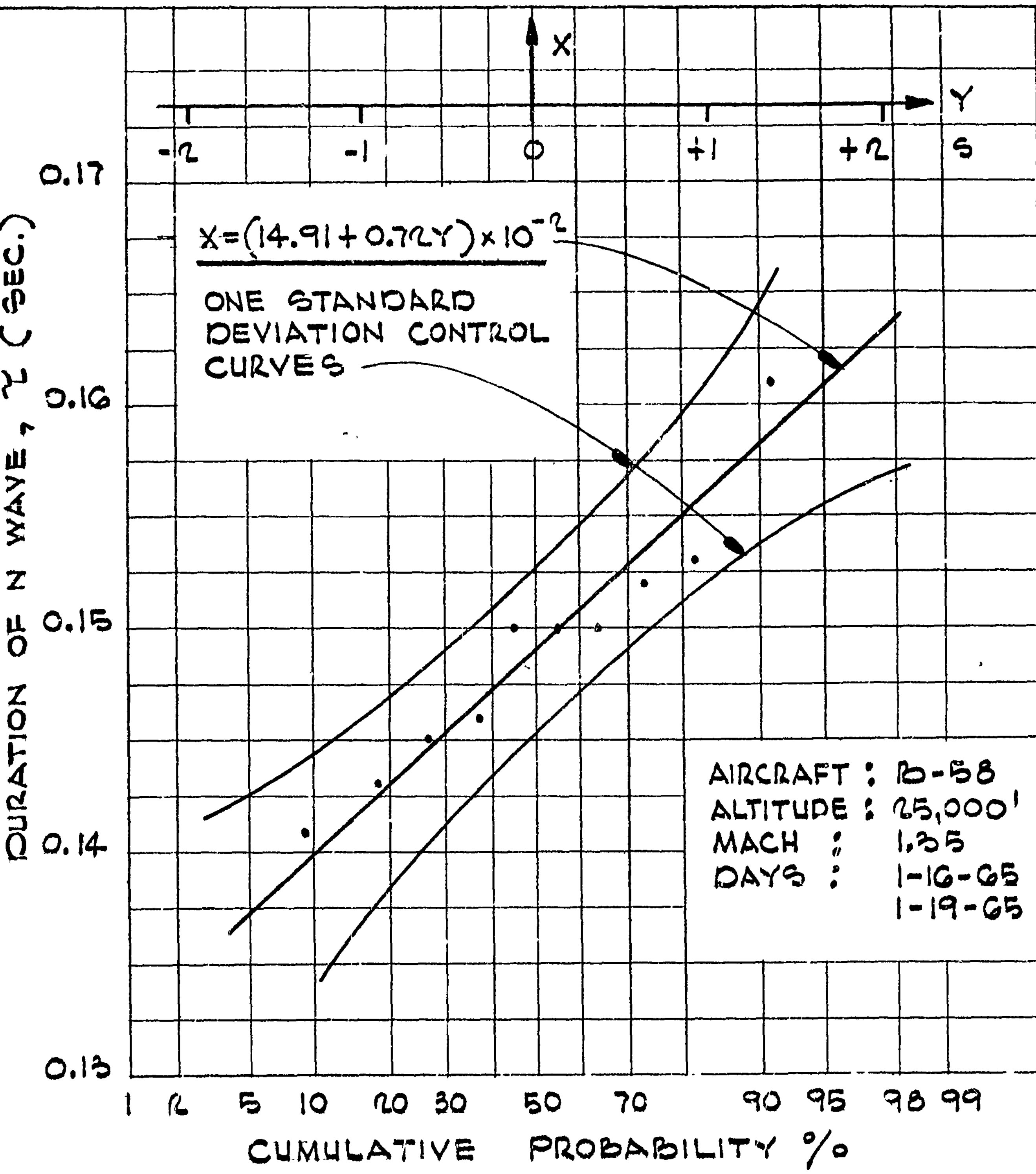


FIG. IV-6 PROBABILITY DISTRIBUTION OF THE DURATION OF THE N WAVE, FREE FIELD (25,000 FT.)

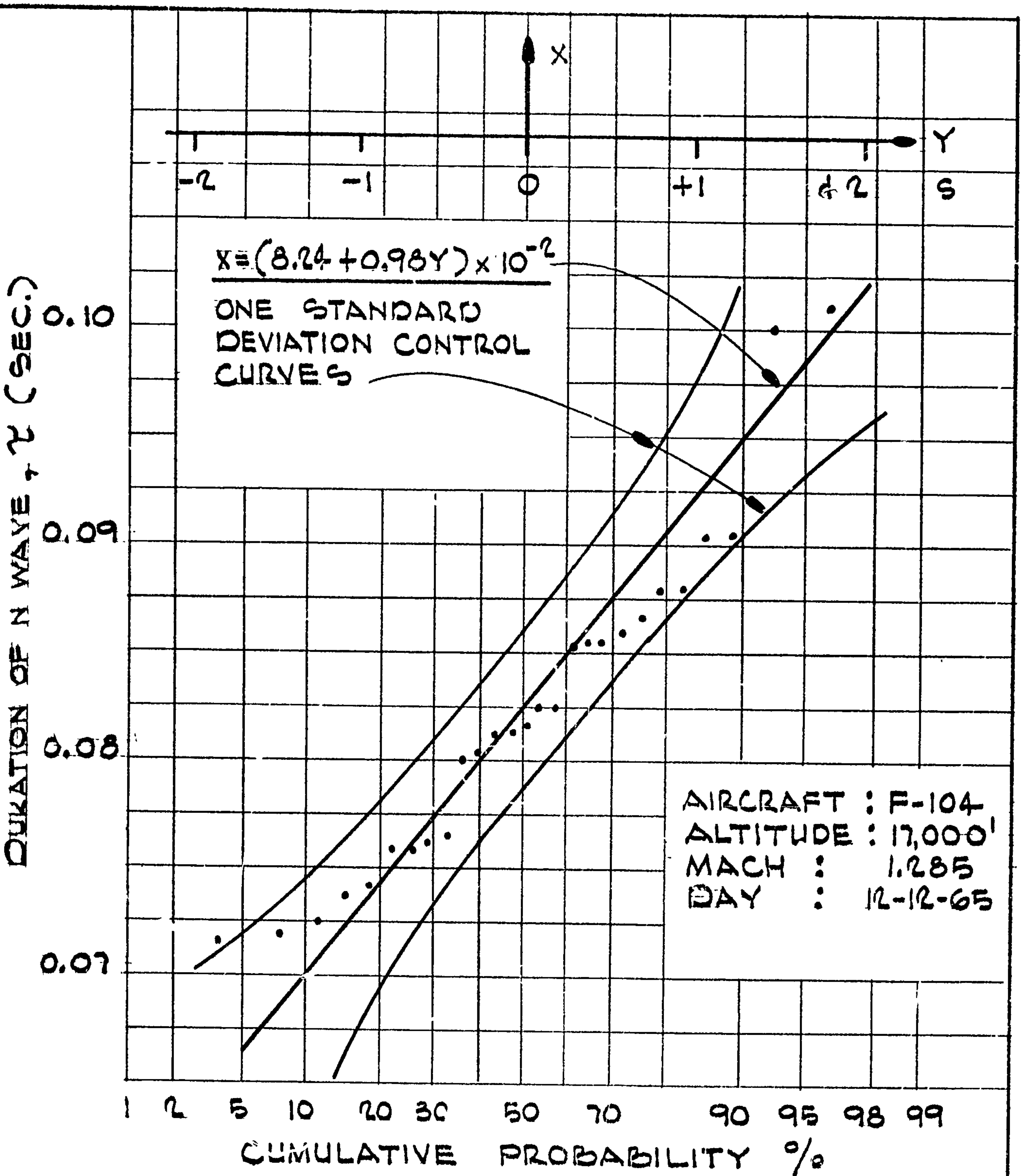


FIG. IV-7 PROBABILITY DISTRIBUTION OF THE DURATION OF THE N WAVE, FREE FIELD (17,000 FT.)

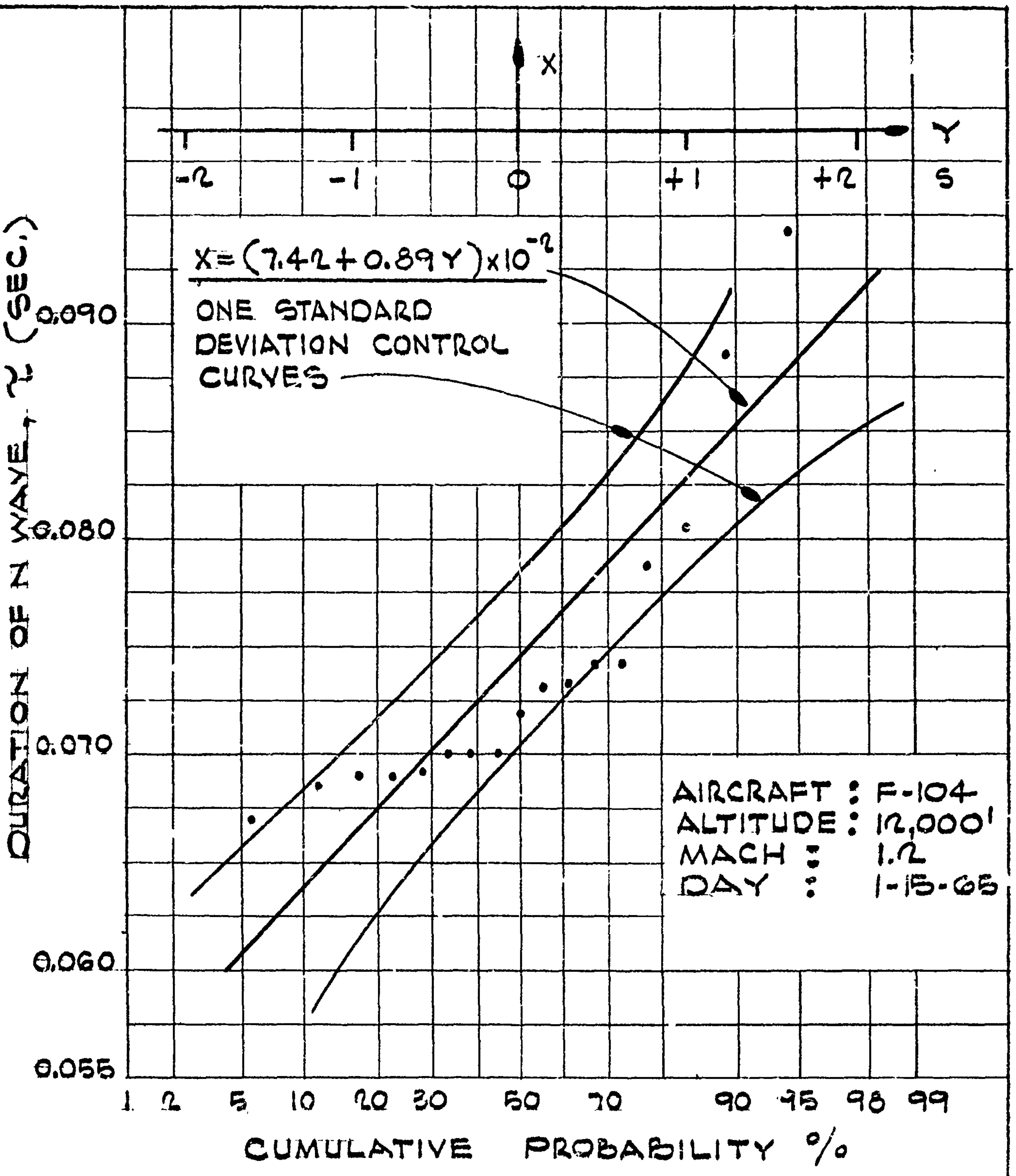


FIG. IV-8 PROBABILITY DISTRIBUTION OF THE DURATION OF THE N WAVE, FREE FIELD (12,000 FT.)

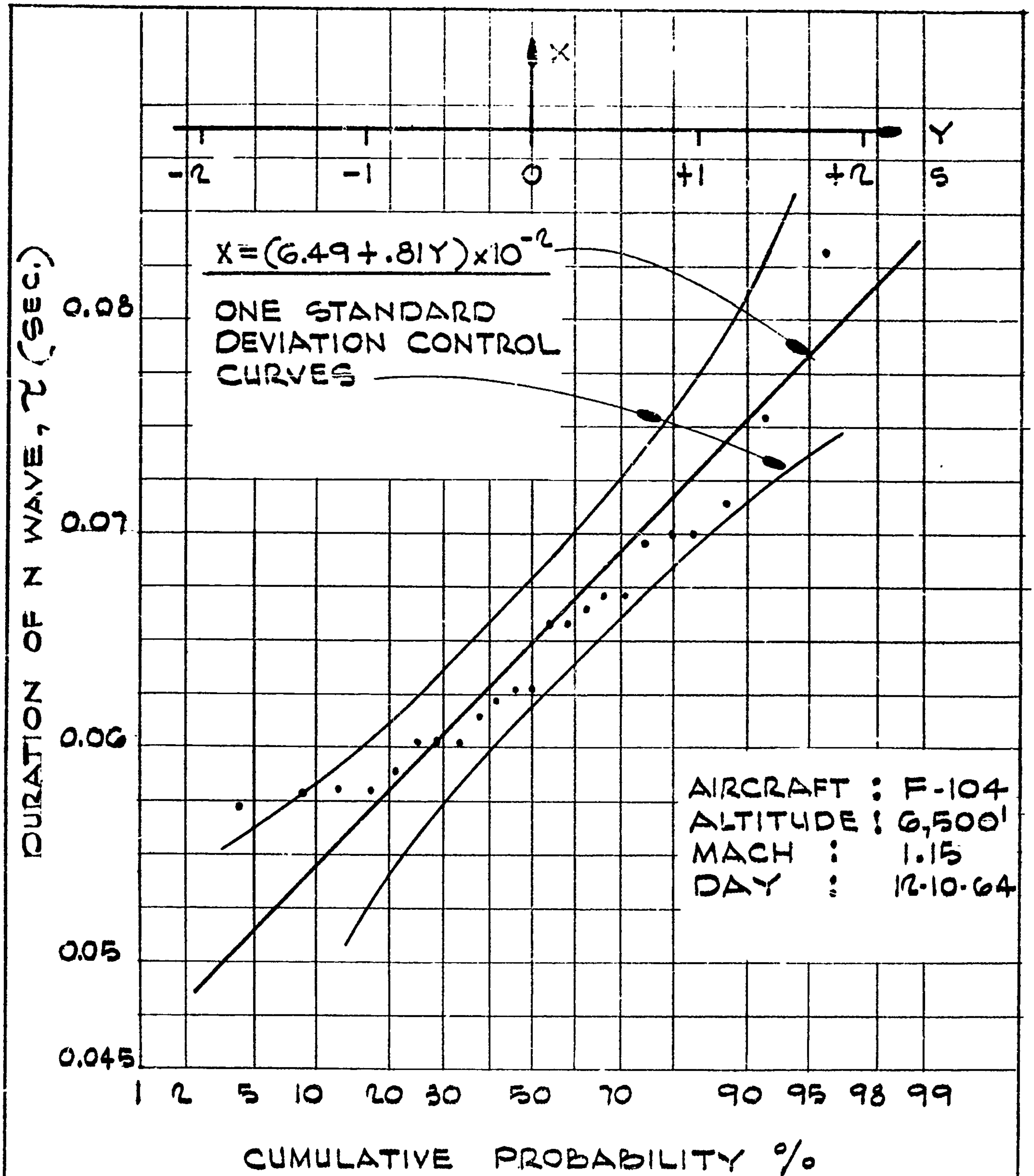


FIG. IV-9 PROBABILITY DISTRIBUTION OF THE DURATION OF THE N WAVE, FREE FIELD (6,500 FT.)

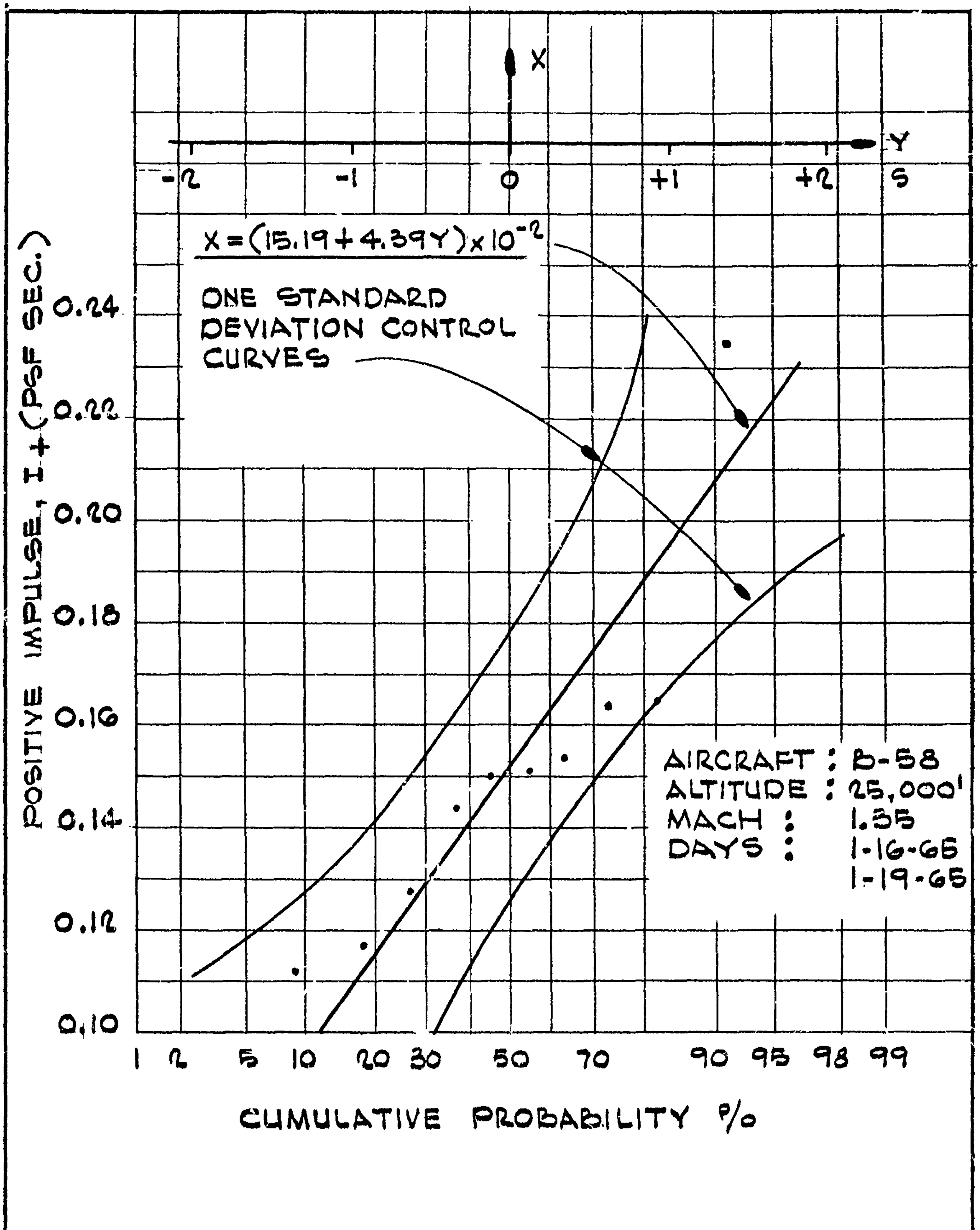


FIG. IV-10 PROBABILITY DISTRIBUTION OF THE FREE FIELD POSITIVE IMPULSE (25,000 FT.)

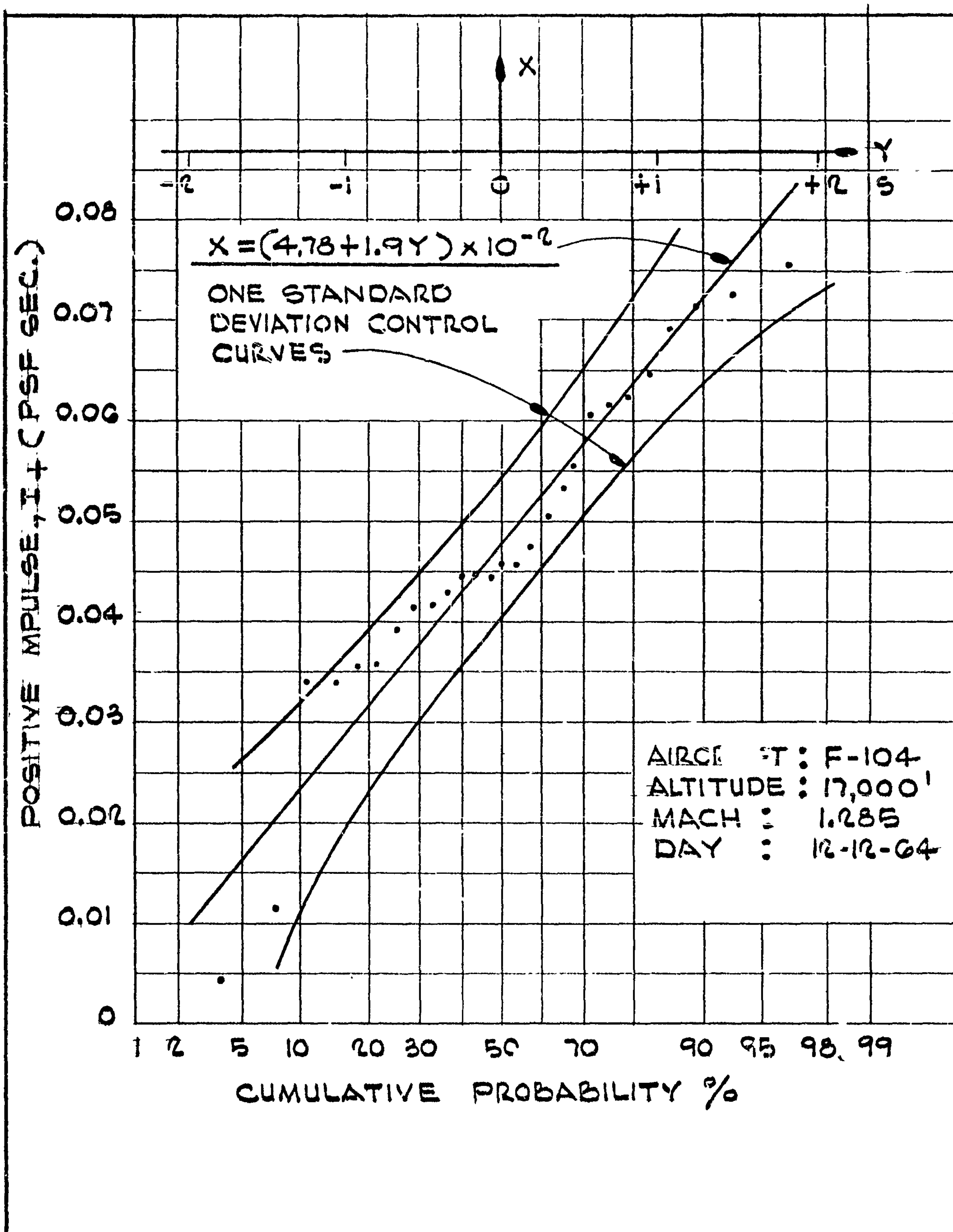


FIG. IV-11 PROBABILITY DISTRIBUTION OF THE FREE FIELD POSITIVE IMPULSE (17,000 FT.)

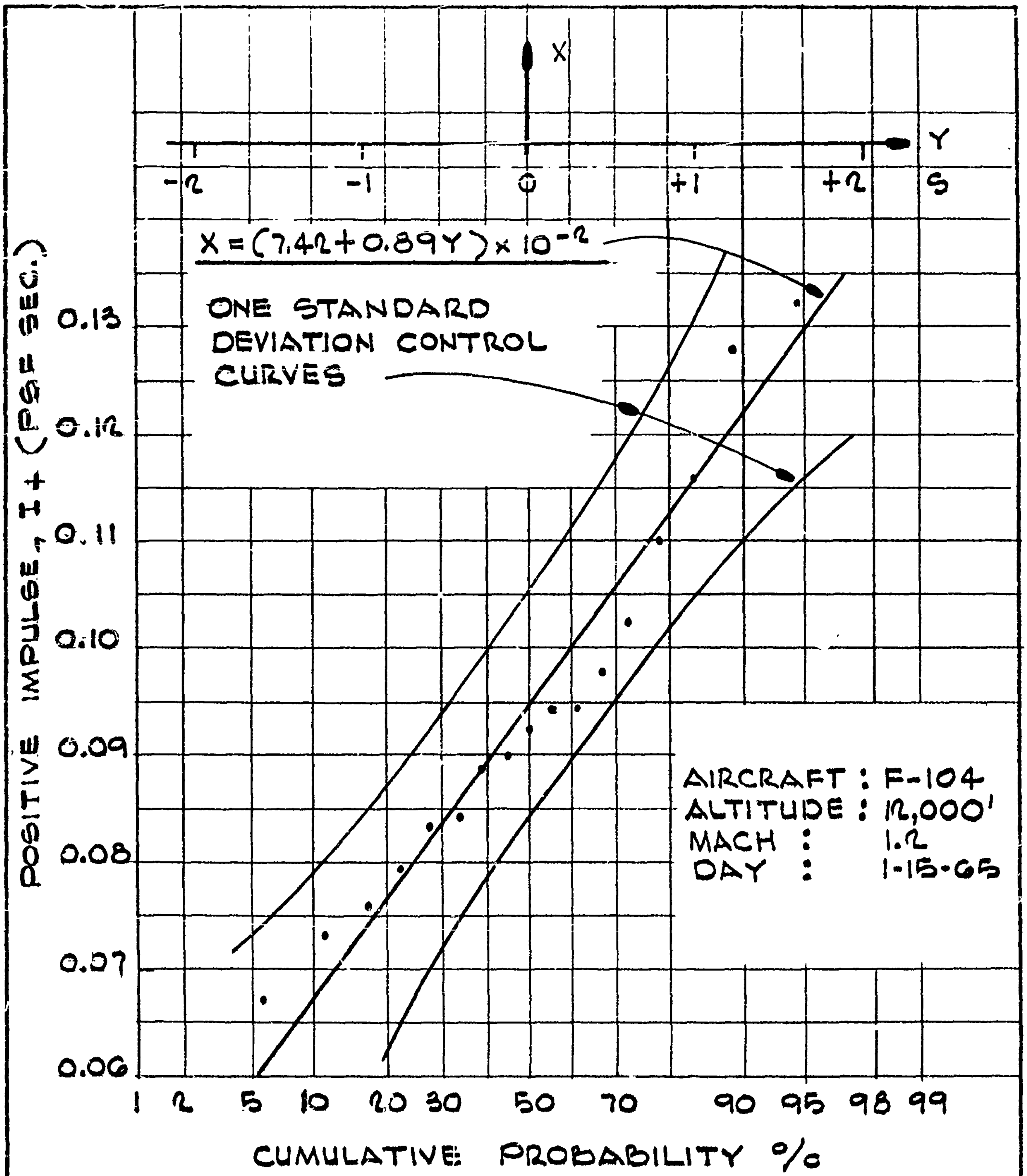


FIG. IV-12 PROBABILITY DISTRIBUTION OF THE FREE FIELD POSITIVE IMPULSE (12,000' FT.)

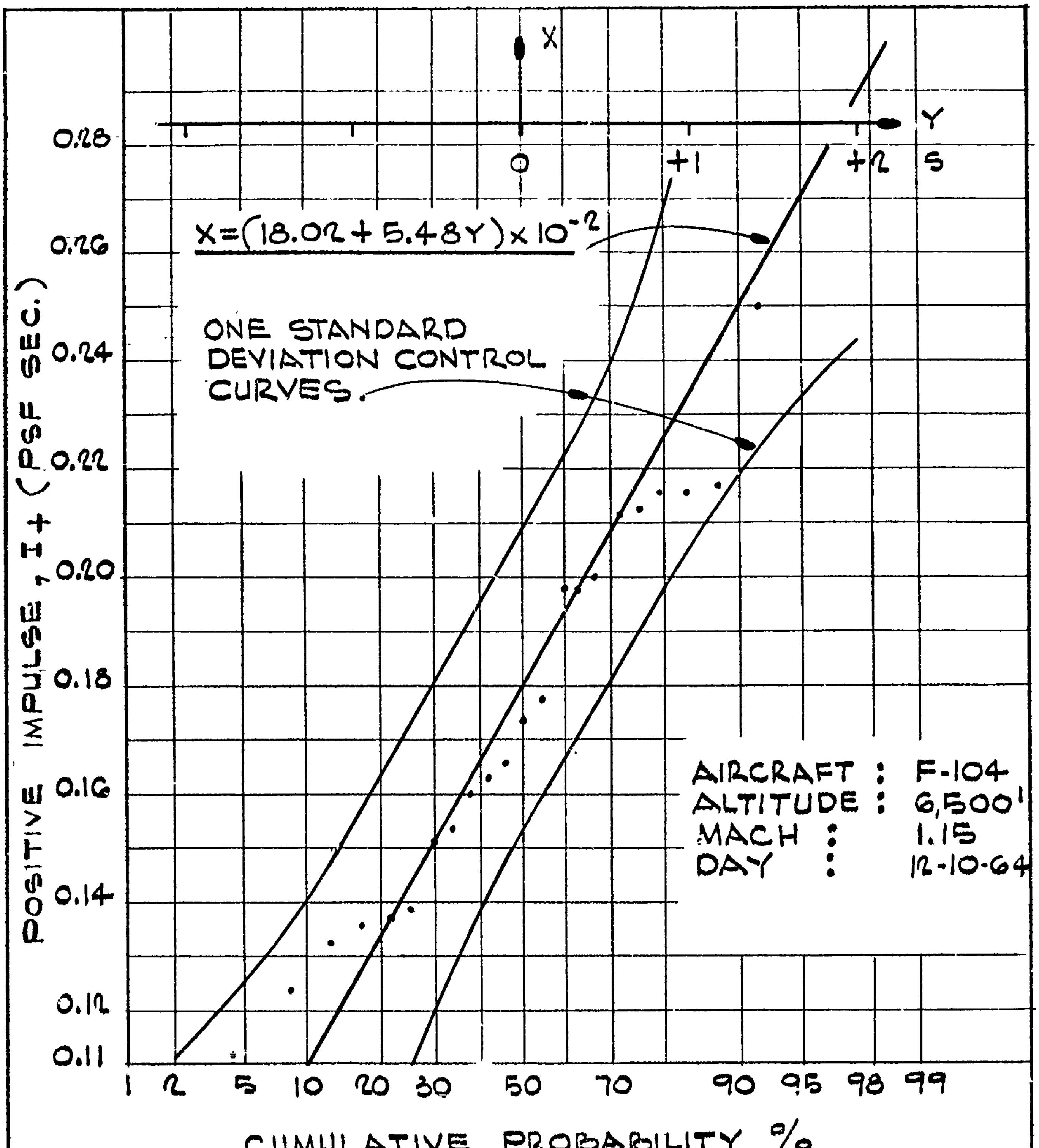


FIG. IV-13 PROBABILITY DISTRIBUTION OF THE FREE FIELD POSITIVE IMPULSE (6,500 FT.)

graph should be in a straight line, with the sample mean at a probability of 50 percent and a slope equal to the standard deviation. In order to verify the preceding statement, a regression line of the observations, x, versus the normalized standard deviation, y, is drawn through the plotted points. If the random variables are normally distributed, they should also be normally distributed about the regression line. For this to be true at least 68 percent of the observations should be contained within the one standard deviation control curves. This is true for all figures.

The equation of the regression line is:

$$x = \bar{X} + \frac{S_n}{\sigma_n} y \qquad (6)$$

Where $\bar{X}$ = sample mean, S_n = standard deviation, and σ_n is the normal standard deviation.

The control curve points, for specific probabilities, are obtained as follows:

Cumulative Probability	Control Curve Point
50%	$\frac{Sn}{\sigma_n \sqrt{n}} \times 1.253$
30%-70%	$\frac{Sn}{\sigma_n \sqrt{n}} \times 1.318$
15%-85%	$\frac{Sn}{\sigma \sqrt{n}} \times 1.532$

Because the data easily fall within the control curves defined above, because they do not curve on normal probability paper at low probability values[10], and because they do curve without exception at low pressure or impulse values (Ref. 1. Figs. 6-9) as would be the case for normally distributed data plotted on log-normal probability paper, it is concluded that the data are normally distributed within practical limits, say three standard deviations.

C. Ground Reflectivity:

Maglieri and Carlson[11] conclude that the value of reflection coefficient is 1.8. In Reference 12 Maglieri, et al., measure a value close to 2.0 but attribute the higher value to the fact that the testing ground was a hard lake bed. At cutoff the reflection coefficient was reduced to one (1). The theoretical value of air to top soil coupling should be 1.977 according to Rayleigh in his well known Theory of Sound. Cox and Reed[13] and Reed, et al.[14], showed that 2.0 was a practical value. The White Sands report averaged the reflection coefficient considered to be the first free-field pulse plus the second or reflected pulse (recorded on a microphone some distance above the ground) and the sum divided by the first pulse. The mean was found to be 1.97.

The White Sands data was tested statistically (see Appendix IV-A) to determine whether or not the value of 2.0 for a reflection coefficient is valid. The mean and standard deviation of the ratio of the first pulse to the second pulse are 0.97 and 0.21 respectively. Since we are dealing with a normally distributed variable the probability of having a ratio: (1) equal to or greater than one is 43 percent, or (2) smaller than one is 57 percent. It therefore can be concluded that the reflectivity coefficient is very nearly 2.0 for this site and reflection angles. It should not be much lower than 2.0 for many other types of earthen surfaces.

Another question regards the functional relationship between reflectivity coefficient and overpressure. Fig. IV-14 plots first pulse overpressure against the ratio of first to second pulse and indicates the range of scatter in the data. The least squares line shows that ratio increases with pressure decrease. Due to scatter of the data a statistical test at the 95 percent confidence level yields the hypothesis of the slope being equal to zero to be true.

Vector of aircraft also has no effect on the reflection coefficient at a 95 percent confidence level of testing. Westerly winds prevailed during the test, but no effect of this factor could be identified.

To investigate the relation between standard deviation of peak pressure and flight altitude we computed the regression lines for the first pulse, second pulse, sum of the first and second pulses and ground overpressure versus coefficient of variation. The conclusion that may be drawn with 95 percent confidence is that standard deviation of peak pressure increases with decrease in peak pressure or increase in altitude (Fig. IV-15).

No experiments were conducted on the effects of topography on overpressure. But Wilton, C., et al.[15], showed by model experiments that a 30-degree valley slope could cause a pressure increase of about three to one at the bottom of the valley compared to that on a plane surface. Future testing in topography effect is suggested.

D. Steady State Atmospheric Conditions:

Steady state in the above title implies non-turbulent conditions. We believe that the steady state atmosphere modifies the energy available in a boom area while turbulence influences the time history. The latter distorts the wave, in other words[2]. Therefore, because the response of structures is a function of both energy input and wave

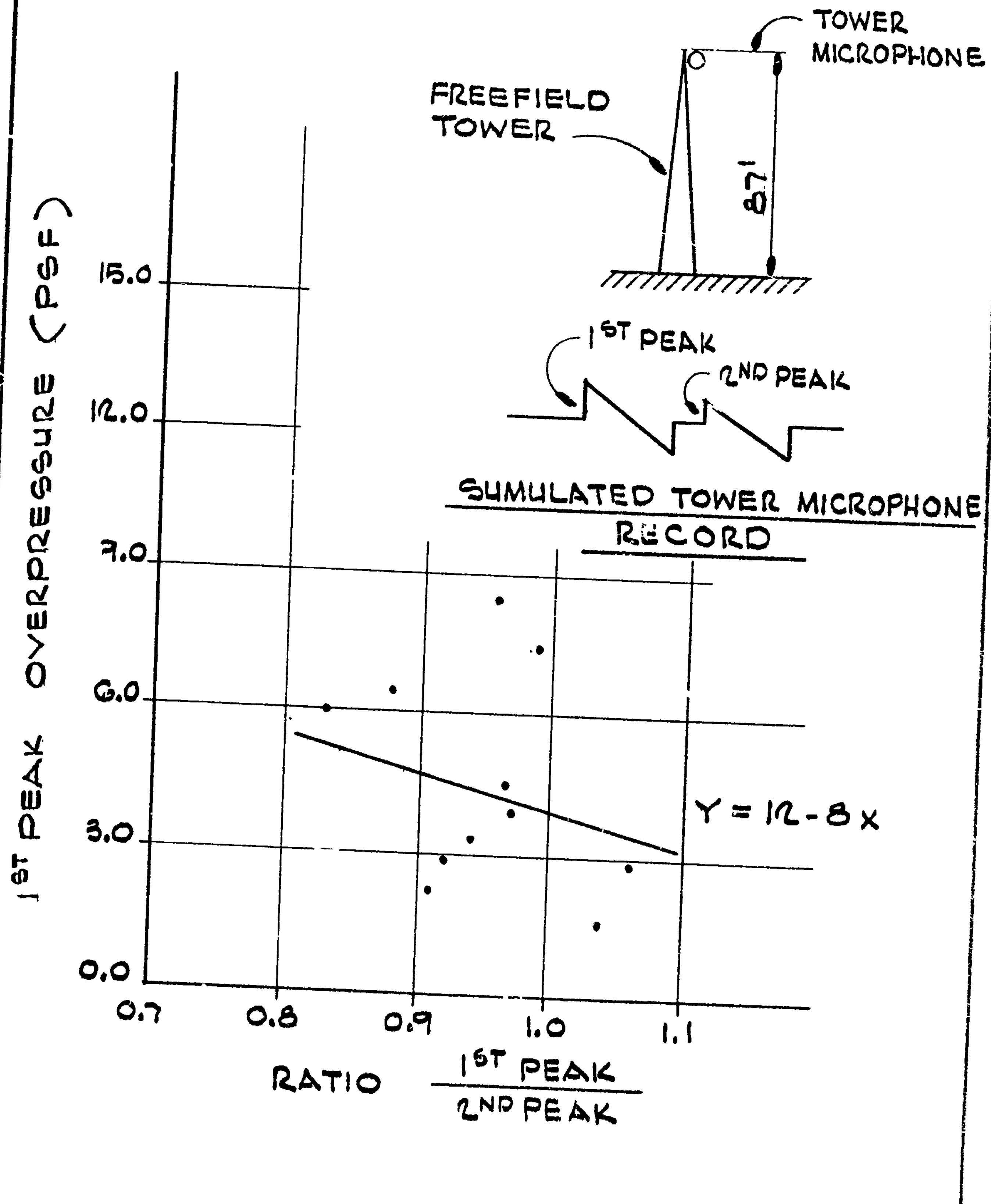


FIG. IV-14 RATIO OF 1ST PEAK / 2ND PEAK TOWER OVERPRESSURES IS INDEPENDENT OF OVERPRESSURE MAGNITUDE

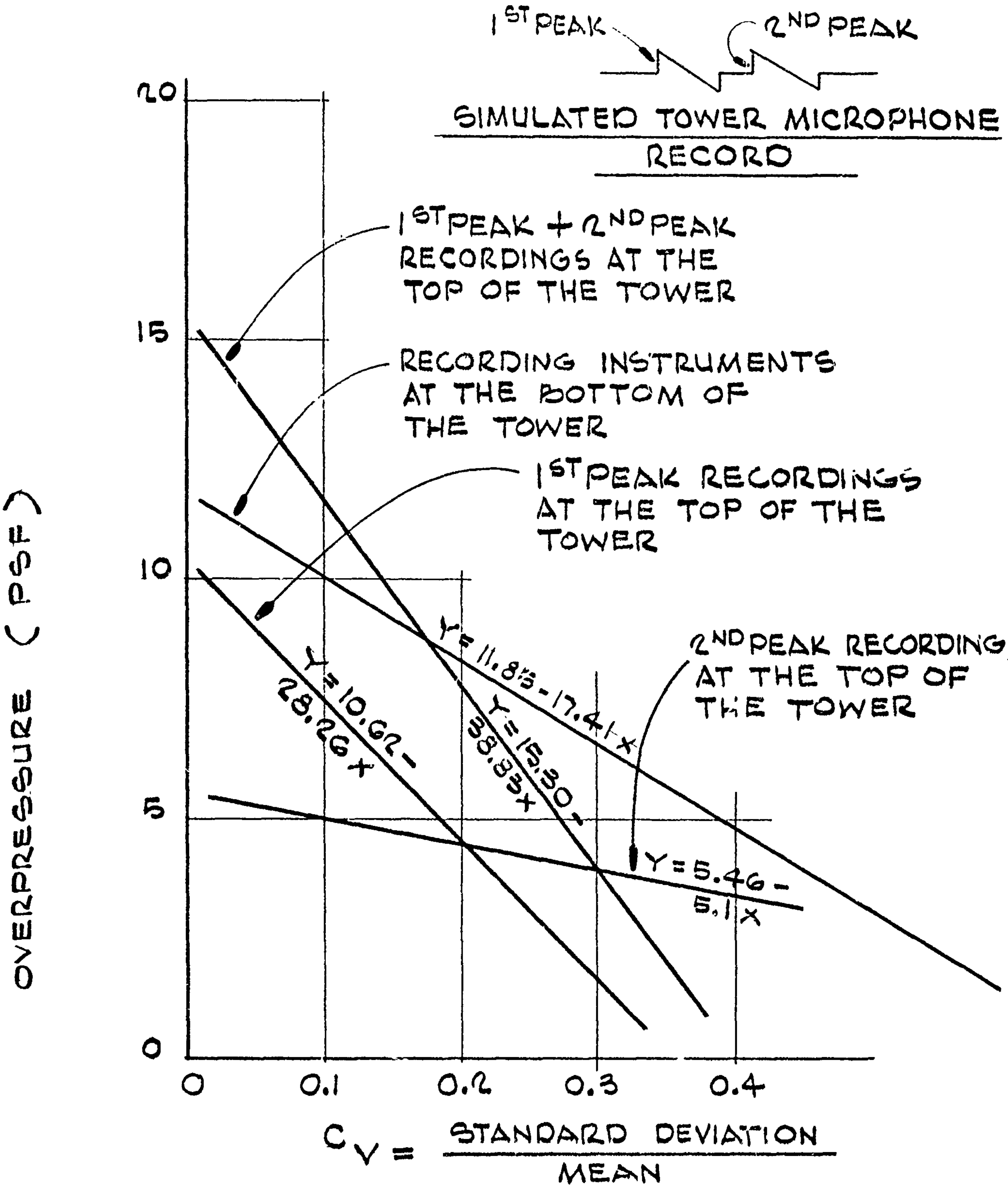


FIG. IV-15 VARIATION COEFFICIENT DECREASES WITH INCREASING PRESSURE OR DECREASING FLIGHT ALTITUDE form, these two conditions are treated separately.

The parameters generally considered as steady state are: wind magnitude and gradient; temperature magnitude and gradient; pressure magnitude and gradient.

Kane and Palmer[2] examine the effects of these parameters in detail. They find that ground temperatures lower than standard generally reduce overpressure, while higher temperatures increase it. The extreme variation due to this effect may be ± 15 percent at Mach 1.2. For Mach numbers less than 1.3 headwinds increase the boom while tail and side winds decrease it. Winds may cause extreme variations as high as ± 20 percent at Mach 1.3. The influence of pressure appears to be slight and Mach number does not vary the influence. Normalizing equations are given which include the variations of these parameters when known.

Others, cited in the bibliographies of refs. 2,4,5 and 6, have studied the effects of these variables but not as completely as Kane and Palmer. The main feature mentioned is the significant influence of weather on pressure variation when Mach number is lower than 1.3 and the low variation that may be expected at higher Mach numbers. This is brought about by the wave fronts being more nearly parallel to the atmospheric layering, allowing for a lower likelihood of focusing. This same phenomenon has been observed by exploration geophysicists in reflection prospecting (wave fronts parallel to layering) in comparison to refraction techniques (wave fronts traveling perpendicular to bedding). The seismic situation becomes even more complex since shear as well as compressional energy is propagated.

Reed[6] and Kane and Palmer[2] call attention to the anomalous conditions that may arise to cause a high boom or no boom at all. The frequency of occurrence of these types of booms should be low, but even so a normal distribution curve can predict them within practical limits, say 3 standard deviations. Reed explains that, "atmospheric explosion foci have been associated with so many instances of what appeared to be anomalous blast damages that they cannot be dismissed." It is well to recognize that focusing can and does occur, but to associate focusing with damage or vice versa may be premature. Discussion in Chapter VIII inidcates the weaknesses involved in using visual identification of damage by untrained observers, especially when damage is not widespread.

During the White Sands test program booming aircraft were flown as low as 1600 ft. as well as 30,000 ft. above the ground. On the 1600-ft. overflights the distance travelled at supersonic speed was less than that at the high altitudes. Radial distance from the low altitude boom to Alamogordo, New Mexico, to the south was greater than that from the high altitude boom. Yet, the booms generated at low altitudes were quite audible in Alamogordo and the populace thought them objectionable even though 60 miles (supposedly safe distance) separated the low altitude boom from the town. No objections were made from the higher flights.

The probable reason for this anomaly is that at low altitudes the booming plane was within the inversion layer, often greater than 2000 ft. above ground. The boom could then be channelled in this layer with little attenuation for large distances.

The data on wind effects analyzed in the White Sands report has been reanalyzed statistically. The new analysis was performed on overpressure data for days when the wind directions and intensities were almost constant. Eleven days were found to be suitable.

First the mean and standard deviation of the data along headwind and tailwind vectors was computed. Then the hypothesis of the means being equal was tested along with the alternatives of the mean headwind pressures being greater or smaller than tailwind pressures. At a 95 percent level of significance, for surface and aloft winds, the results are as follows:

Headwind overpressures are greater:	0.55
Headwind overpressures are equal:	0.30
Headwind overpressures are smaller:	0.15

Headwinds of the type encountered in the test cause overpressure to increase 55 percent of the time. If the greater velocity winds only were used this probability should increase.

Rise time, like overpressure, can be influenced by the atmospheric conditions. It has been hypothesized that the viscosity in the atmosphere causes the high-frequency components of a saw tooth boom wave to attenuate more rapidly than the accentuation processes which tend to build a shock front. If this were the case the rise time of a shock front might increase with increasing distance from source to site. Rise time has been observed by Maglieri et al.[12] to increase with increasing flight altitude.

Rise time data from the White Sands study was examined for various altitudes (MSL) of overflight (Fig. IV-16). It increases with altitude, but large extremes in the data are also present. Note in Fig. IV-16 that the B-58 data plots closely with the F-104 data indicating that boom strength (B-58 boom is greater than F-104 boom at similar altitudes) does not affect rise time, at least at the altitudes studied. Some hope is given that high-altitude booms from an SST might be less objectionable to the ear than low-altitude booms of a small aircraft (at equal strength) since the high frequency components are attenuated more.

An attempt was made to analyze the effect of sound speed at flight altitude, C_a, on wave duration, τ. Unfortunately, however, C_a varied so little at the same altitude and τ varied so much that the analysis was impossible.

E. <u>Flight Characteristics and Aircraft Design</u>:

Theories about the influence of flight characteristics and aircraft

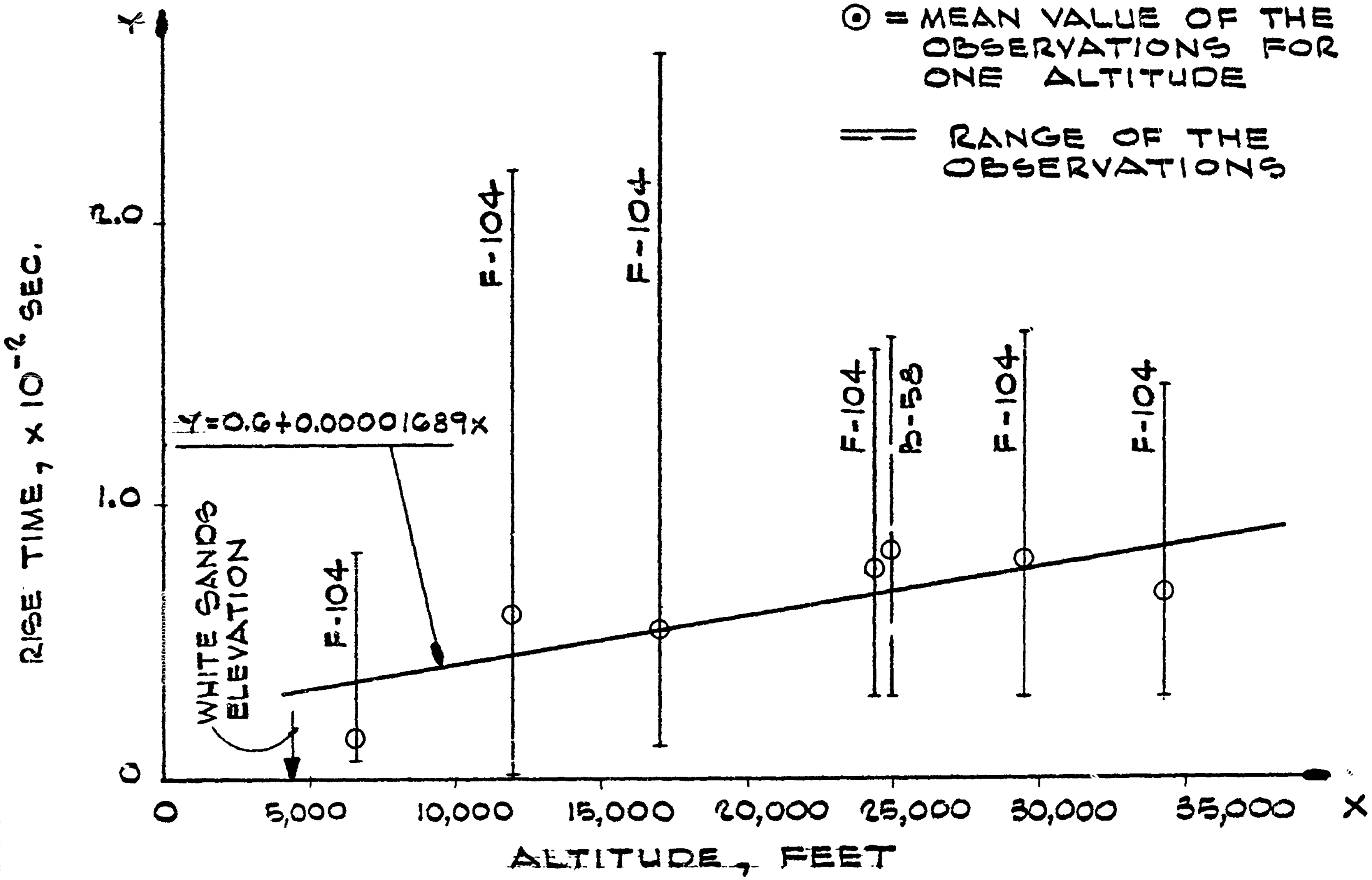


FIG. IV-16 VARIATION OF RISE TIME WITH ALTITUDE design parameters on boom strength have received a lot of attention in the literature[2,4,5,6]. Their general effects are predicted in Eqs. (1) to (5), and are summarized by Power[16]. In general good agreement between data and theory exists[12], but the scatter is so large as to make some investigators unsure of the equations, especially when extrapolating to the larger, yet untested SST type aircraft[6,17].

In examinations of a large amount of data from the Oklahoma City tests[1,3] it was found that one percent of the measured overpressures equalled or exceeded the predicted values from Eqs. (1) and (2) by a factor of about 1.5 to 3.0. The larger factor was associated with the larger distances and with the lower predicted value. NASA also found that one percent of the measured positive impulse values equalled or exceeded the predicted values by a factor of about 1.2 and 2.0. The larger factor again was associated with the larger distances and lower predicted value. This larger deviation at distance was attributed to the predominating winds which shifted the peak pressure from underneath the flight track.

Andrews[3] compared the peak pressure with the wave duration and found essentially no functional relationship even though manipulation of Eqs. (1) and (3) would predict a cube root scaling factor. The theory must be inadequate, but which theory - Eq. (1) or Eq. (3)? Eq. (1) by far has received the most attention by investigators.

The White Sands overpressure data was tested to check the validity of the altitude term in Eqs. (1) and (2). Results are shown in Fig. IV-17. The Mach number variation in the data was accounted for. The theory is slightly high for altitudes greater than 12,000 ft. MSL and slightly low for lower flight altitudes for F-104 data. Considering the large scatter in the data, however, the volume theory in Eq. (1) is accurate within engineering accuracy limits for the F-104. This has been verified within these accuracy limits by many other investigators. Note also that at the low altitude flown by the B-58 (19,500 feet above the ground level) that the volume theory is more accurate than the lift theory. This altitude flown by the B-58 is thought to be the lowest where boom pressures were measured.

The following least squares equation is considered to be adequate for relating overpressure and therefore flight altitude (F-104) to coefficient of variation, C_V.

$$\Delta p = 15.30 - 38.83\ C_V \qquad (7)$$

Fig. IV-18 plots the mean values of wave duration data along with mean values normalized for Mach number and C_a values at 34,500 feet. The data appears to fit a curve whose altitude exponent is closer to -1/8 for the normalized points. This difference would partially account for Andrew's findings that very large regression line slopes through data on graphs of Δ p versus τ must exist.

Comparison of Δ p, τ and I_+ with Mach number were impossible with

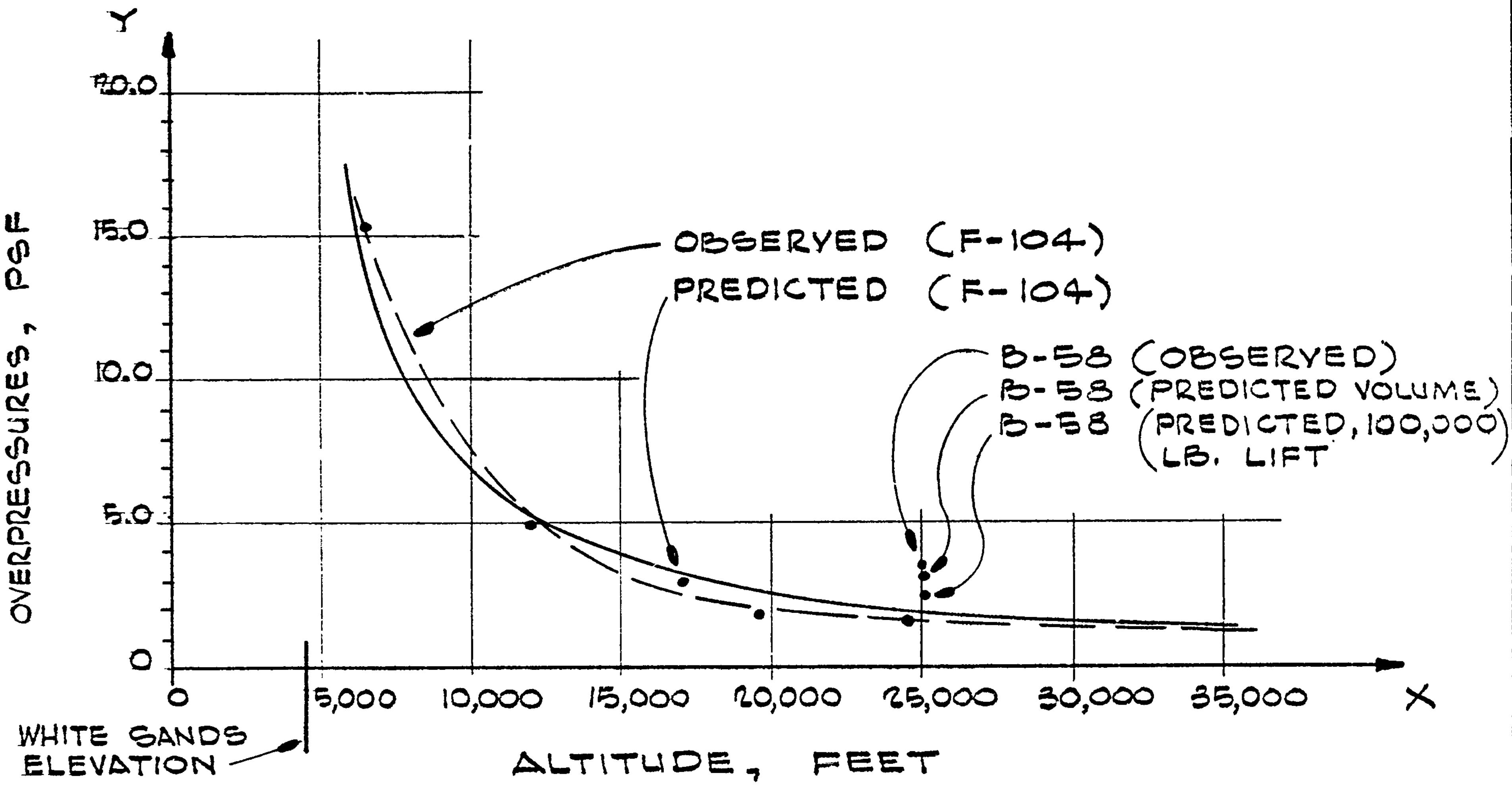


FIG. IV-17 VARIATION OF OVERPRESSURES WITH ALTITUDE

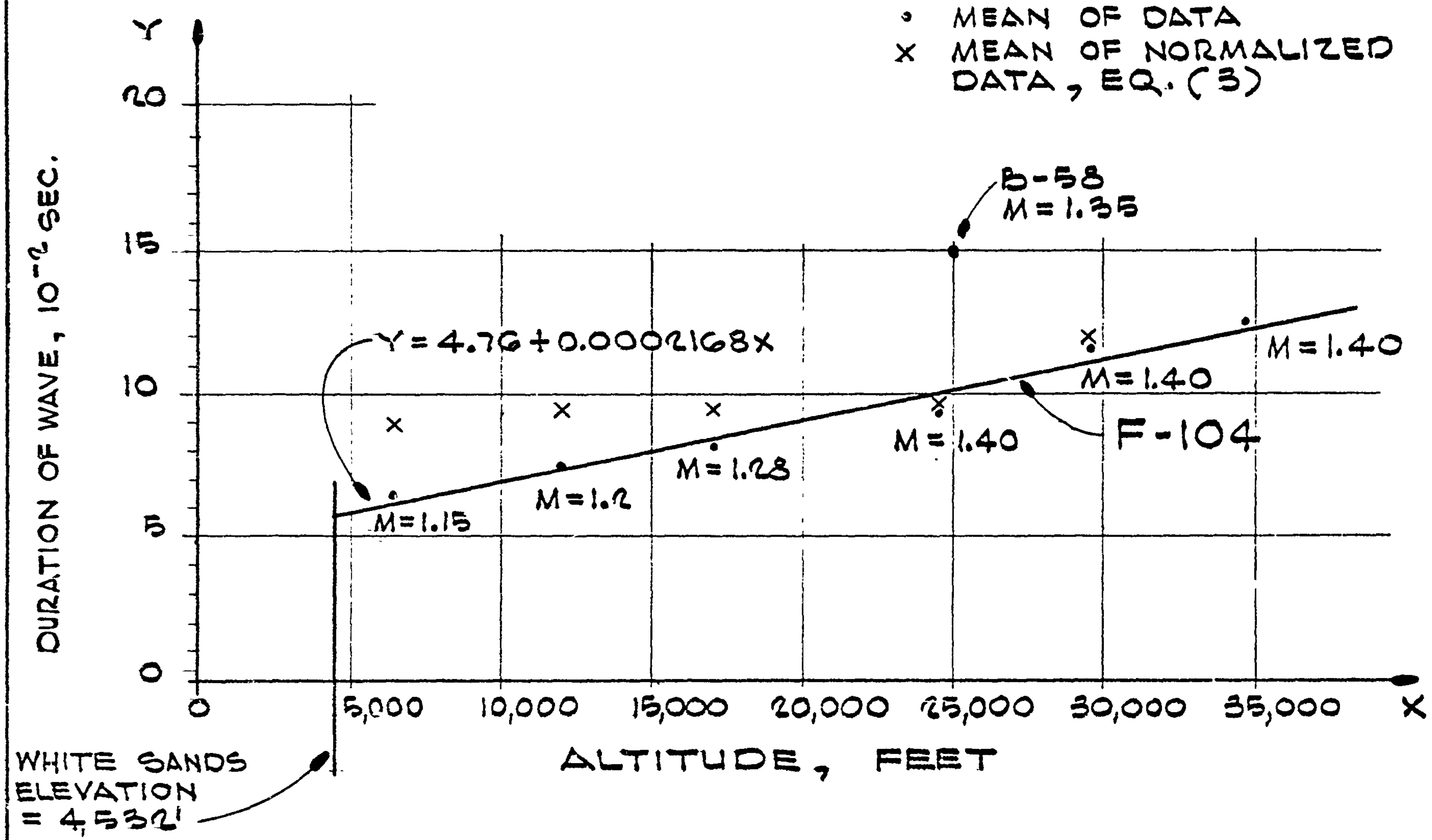


FIG. IV-18 VARIATION OF WAVE DURATION WITH ALTITUDE the data at hand. However, the plot of overpressure with altitude (Fig. IV-17) indicates that the Mach term in Eq. (1) cannot be very far wrong since no large differences are noted. Fig. IV-18 does not identify which of the terms in Eq. (3) is wrong. In the above discussion a smaller exponent for altitude is supposed but the normalizing term for Mach number may be slightly inaccurate as well.

Mean values of positive impulse were plotted versus altitude for the F-104 booms (Fig. IV-19) and compared with theory, Eq. (4). The theory appears to be quite good in the range of altitudes above 17,000 feet, but it is very poor at lower altitudes. This suggests that the error in the positive impulse lies with Eq. (3), assuming Eq. (1) to be correct.

Lansing[18] and Maglieri and Lansing[19] investigated the focusing of booms due to maneuvering aircraft. The results were in good agreement with the theory. Focusing effect was also studied in the White Sands report. No significant effect was noted, not even the coefficient of variation of the maneuver data was greater than the level flight data. The microphones were scattered over a large area, however, so conclusive results about whether or not the phenomenon of focusing can occur can not be made. Any focusing that may occur, however, would be limited to small areas and may be within the standard deviation of level flight data.

F. Lateral Spread:

The variation of overpressure with lateral spread is given theoretically by Kane and Palmer[2]. Maglieri, et al.[12] and Hilton, et al.[1] examine data illustrating it. Hilton found that much of the data taken 5 miles from the flight track was higher than the equation would predict. Kane and Palmer suggest that the shape factor in the equation may vary with lateral spread causing the $[1 + (y/h)^2]^{-3/8}$ normalizing factor to be slightly inaccurate.

White Sands data is plotted in Fig. IV-20 and compared with the theory. This data was taken from booming aircraft flying all vectors over a large period of time. Several stations have fewer data points than others so the spread in the data can not be compared. For the most part the theory appears to be slightly low but is well within the spread of the data.

G. The Effect of Transient Atmospheric Conditions (Turbulence):

The investigation of turbulence and its effect on the shape of the sonic boom wave has been conducted theoretically by several investigators[2,6,7] and experimentally by Hilton, et al.[1] Turbulence basically causes the energy in a boom wave to scatter in time and space. It modifies the N wave shape differently at various points on the ground,

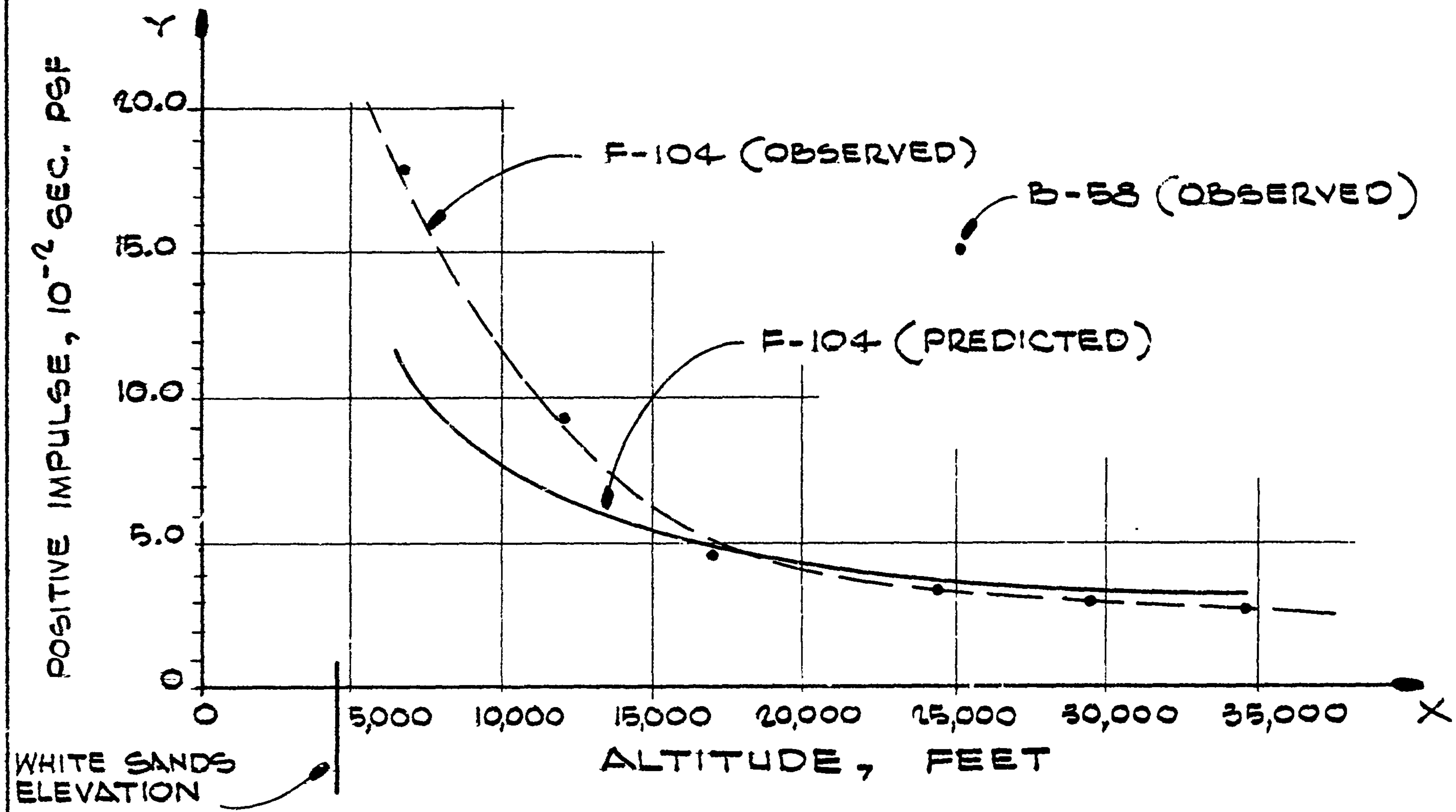


FIG. IV-19 VARIATION OF POSITIVE IMPULSE WITH ALTITUDE

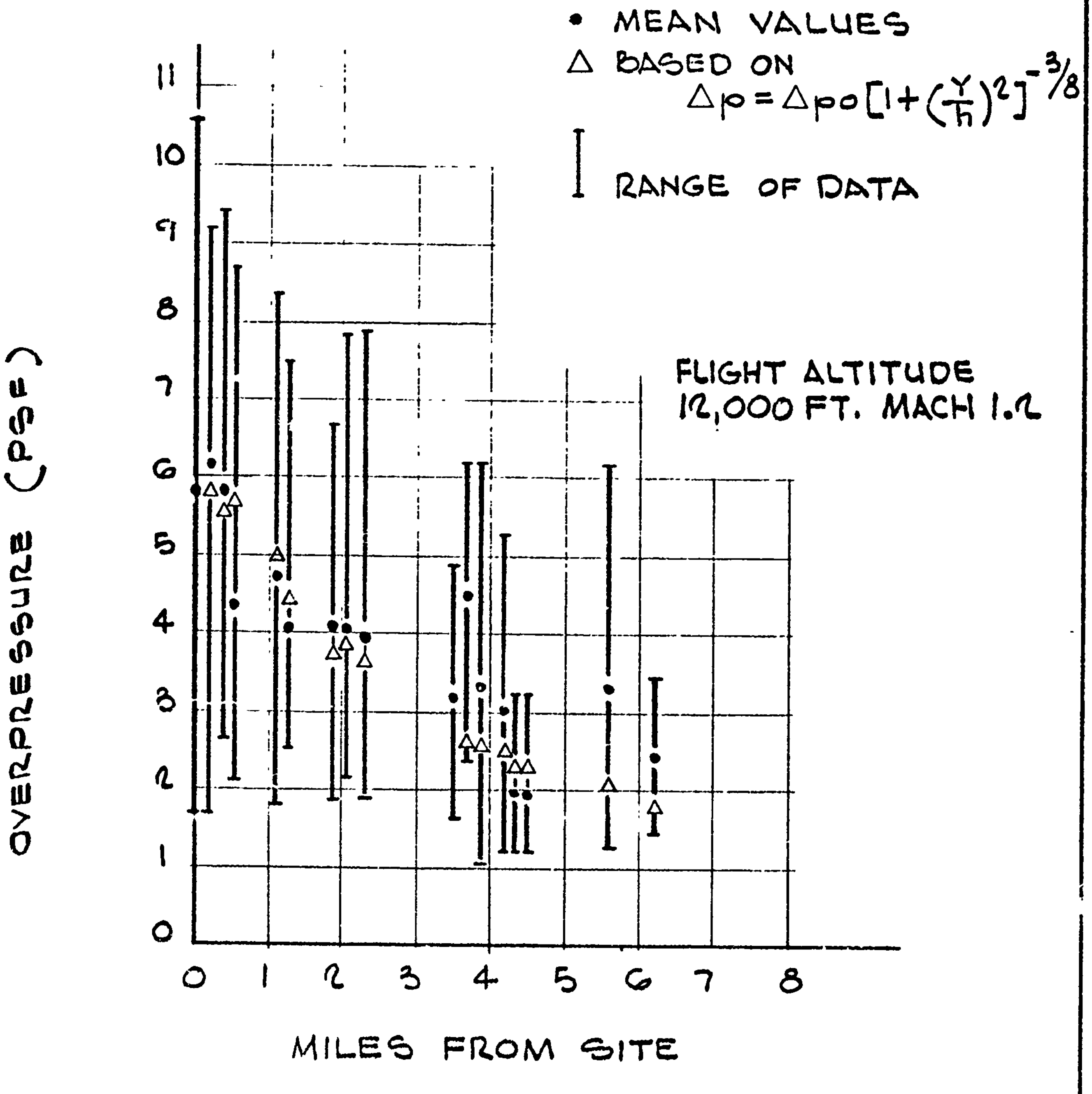


FIG. IV-20 VARIATION OF OVERPRESSURES WITH LATERAL SPREAD in other words. The treatment of turbulence can be made only through statistical concepts.

Hilton shows two examples (Fig. 11, ref. 1) of the spacetime variation in boom wave shapes when only two hundred feet separate the microphones. Only slight variation in shape can be noted in boom waves recorded by five microphones separated from one another by only 8 inches.

Fig. IV-21 shows tracings of records taken by a microphone mounted above the ground. The influence of turbulence on modifying the shapes of the records even at 87 feet above the ground is quite noticeable. The coefficient of variation of the first tower pulse is not necessarily lower than that of the ground recorded overpressure at all values of mean overpressure (Fig. IV-15).

H. Comparison of Theoretical with Observed Mach Angle:

The Mach angle of the wave front as it hits the ground is always larger than the angle of the wave as it leaves the aircraft. This effect has been studied by Maglieri, et al.[12] The disparity between the observed and initial angles also increases with increasing altitude, as expected (Fig. IV-22).

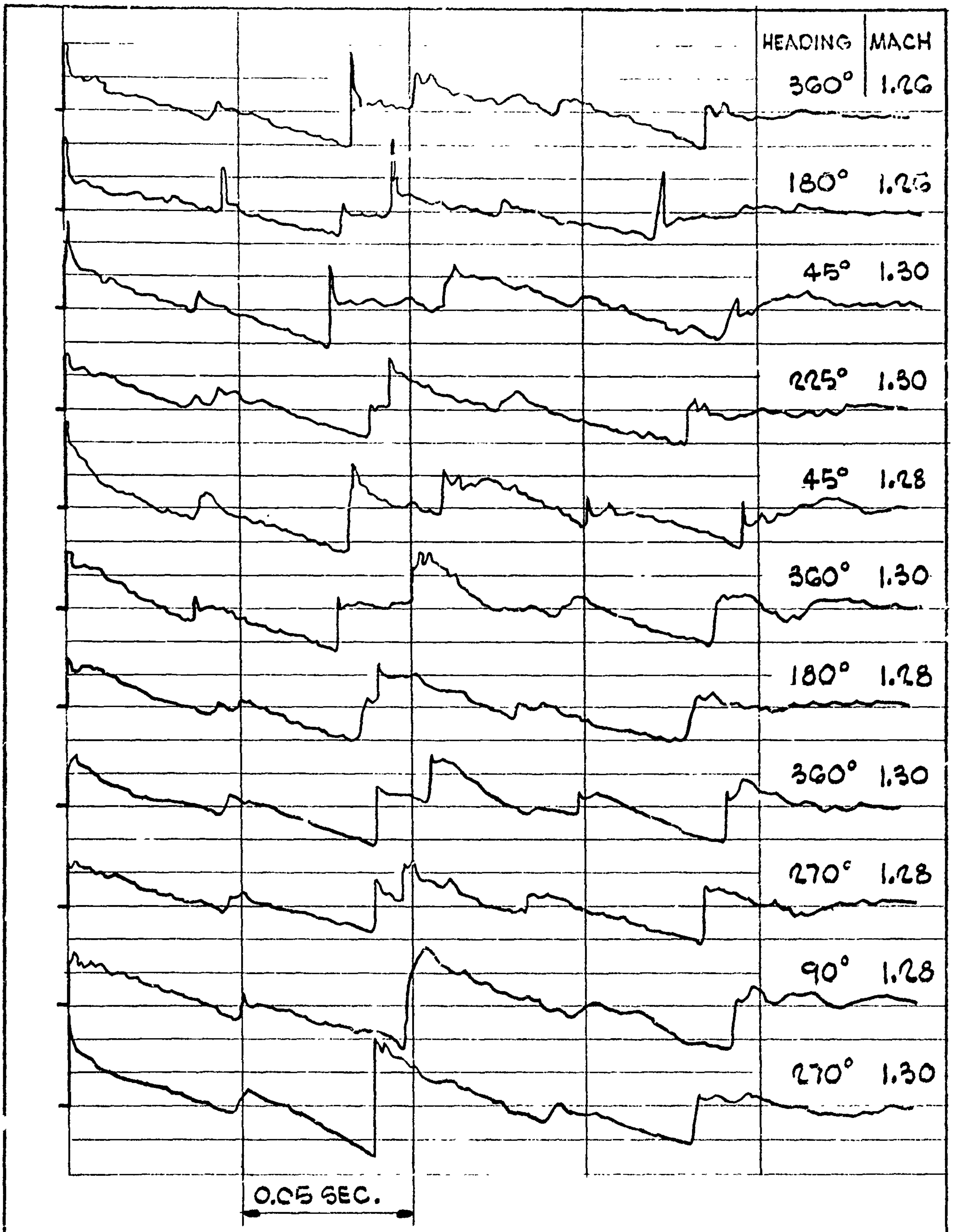


FIG. IV-21 SAMPLE RECORDS TAKEN BY MICROPHONE 87 FT. ABOVE GROUND, 12-12-64. WINDS WERE WESTERLY RANGING FROM 60 KTS AT 17,000' (FLT. ALTITUDE) TO 0 KTS AT GROUND.

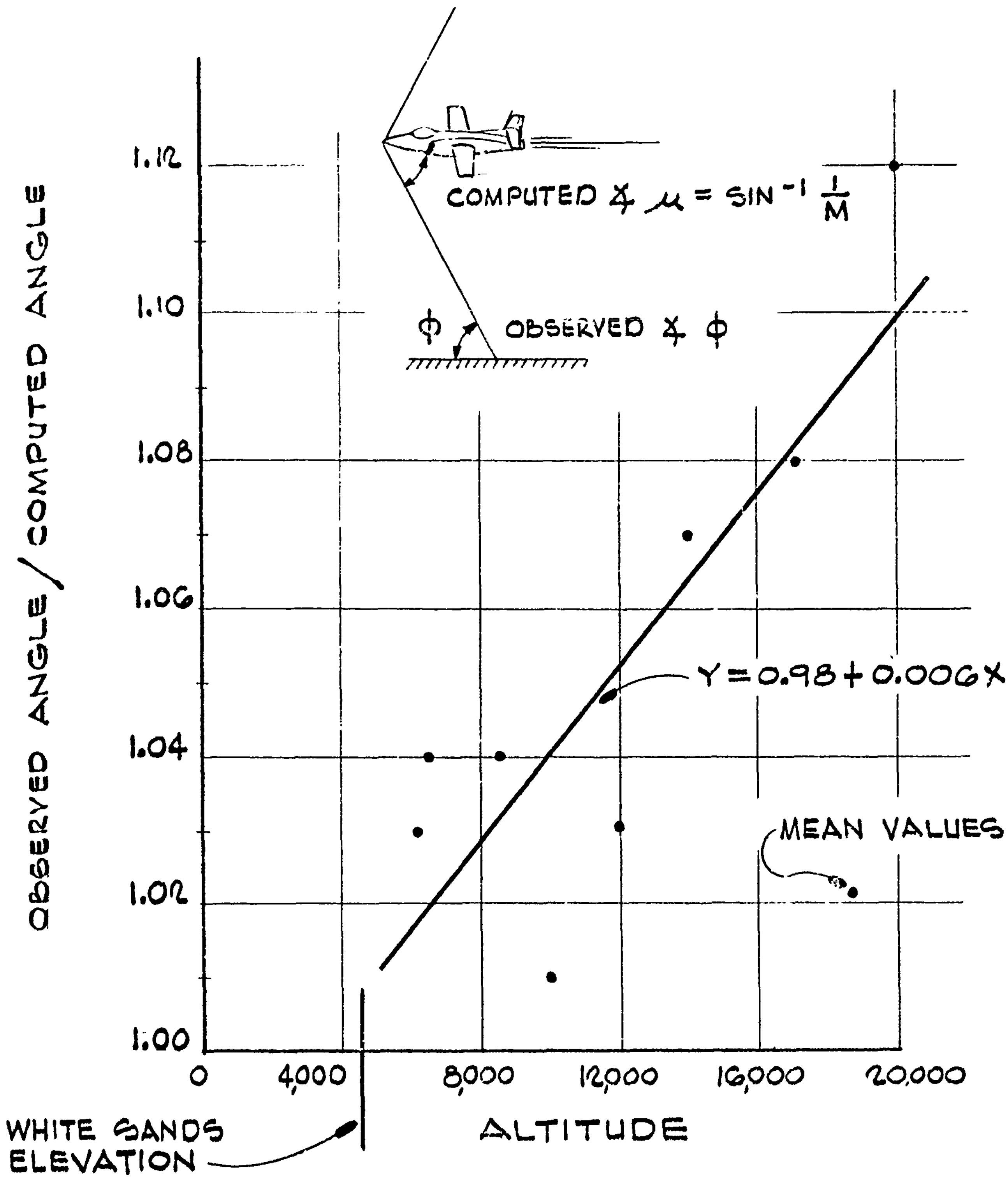


FIG. IV-22 RATIO OF OBSERVED TO COMPUTED ANGLE OF SHOCK WAVE INCREASES WITH ALTITUDE

V. FACTORS AFFECTING THE MAGNITUDE AND TIME VARIATION OF LOADING BOOM WAVES:

A. Introduction:

The foregoing chapter discussed the influence of various parameters controlling a boom wave from point of initiation to the surface of the ground. The wave is modified further as it strikes a structure or adjacent structures. This modification phase is the loading, time history on a wall, window or roof. It is governed by the following major parameters:

1. wall stiffness,
2. reflecting surfaces,
3. height above ground and aircraft speed,
4. net diaphragm action,
5. net racking action,
6. wall distribution, and
7. aircraft vector with regard to loading surface.

The intensity of a sonic boom wave depends on the loading and may be expressed by the following equation,

$$u = \frac{P_{max}\ (DAF)_{f,\beta}}{k} \qquad (1)$$

The strain within a structural element, u, is determined by the peak instantaneous load, P_{max}, the dynamic amplification factor, (DAF), and the effective stiffness, k, of the element loaded. This is a simplified version of a rather complex expression describing the response of distributed mass systems[4]. It serves to indicate the major factors which influence intensity.

The influence of various parameters on peak load has been discussed in the White Sands report. A discussion of stiffness, frequency, f, and damping factor, β, is presented in the following chapter. This section will then be devoted primarily to a discussion of how (DAF) varies with frequency.

B. Statistical Distribution of Loading Data:

Two small boom tests[20,21] and two large tests[3,4] have been conducted wherein boom loading data was gathered and analyzed. Only the White Sands study recorded an adequate number of loading records from which trends may be identified. No distribution analyses of either P_{max} or (DAF)/k have been made in any of the reports.

The maximum pressure data taken on a wall and a roof are plotted on normal distribution probability paper in Figs. V-1 and V-2. The data are well within the one standard deviation control curves; for

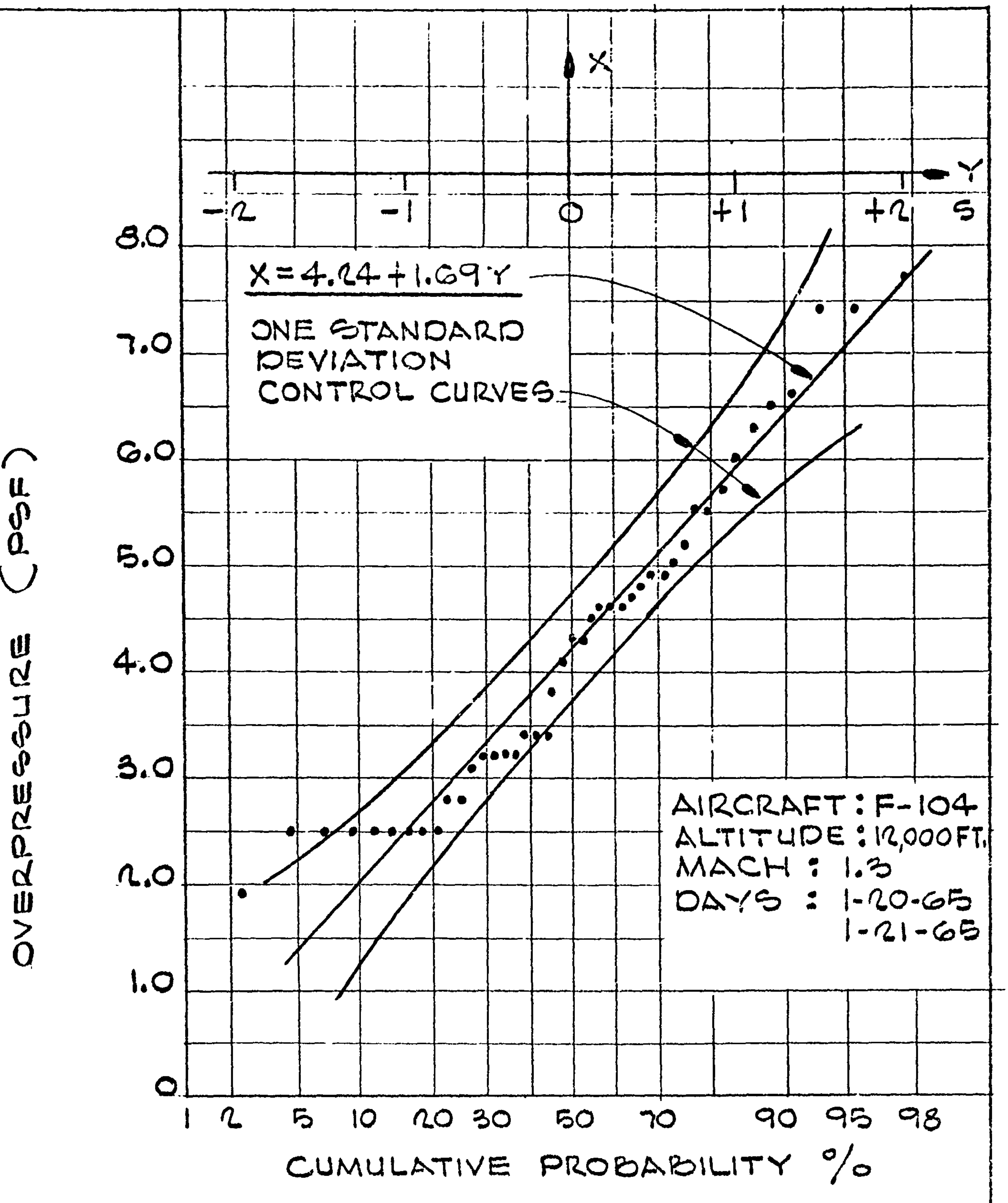


FIG. V-1 PROBABILITY DISTRIBUTION OF THE OVERPRESSURE ON THE N. WALL OF W-4

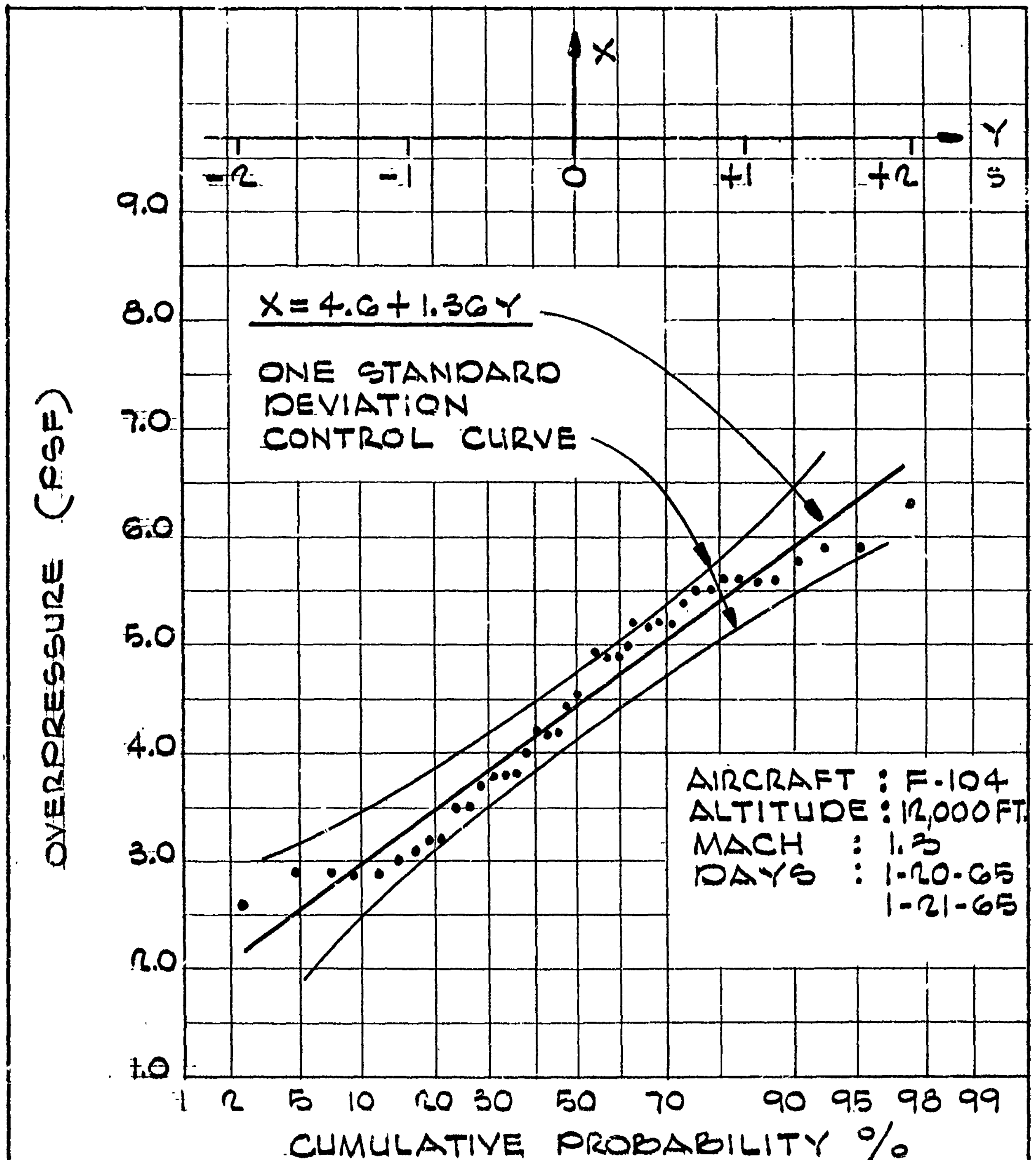


FIG. V-2 PROBABILITY DISTRIBUTION OF THE OVERPRESSURE ON THE W. ROOF OF W-4 practical purposes the peak wall and roof pressures are normally distributed, within three standard deviations.

Figs. V-3 to V-6 plot the effective dynamic amplification factor of wall stud, computed from strain gage and overpressure data taken in Oklahoma City. The peak overpressure used in the expression was not that loading the element of interest but rather the free-field overpressure. The data plots well within the control curves and is therefore judged normally distributed within practical limits.

C. Variation of Free-Field and Loading Dynamic Amplification Factors:

Fig. V-7 shows the upper and lower spectral envelopes of free-field spectra for F-104 booms. Fig. V-8 shows the same envelopes for B-58 booms. The damping factor in each case is conservatively assumed to be zero to expose the scatter in the spectra. Results may be applied to systems with little damping. The reader should note that the spectrum is simply another way of looking at a boom wave with a responding element in mind.

Notice that the spectral envelopes drop off rapidly to zero below 12 cps for F-104 booms and 6 cps for the B-58 booms. The dropoff frequency is determined by, , the boom wave length. The B-58 wave length is about twice that of the F-104 accounting for this difference.

Several major features show up in Figs. V-7 and V-8. Note that the second harmonic of the F-104 spectrum (30 cps) is dominant. Theory would suggest that the second harmonic of an N type wave would peak at about 2.1. This one peaks at about 2.7. The associated minimum is about 1.8. The cause results from a secondary shock wave about half way between the bow and tail shock fronts generated by the air intake and wing of an F-104 (note the first N wave in Fig. IV-21). These spectra were computed from waves generated by aircraft flying at 12,000 feet so that the secondary shock is high. The secondary hump does degenerate somewhat as the aircraft altitude increases but it does not always degenerate.

Note that the first harmonic has a peak amplitude of less than the theoretical value of 2.3 in both the B-58 (6 cps) and the F-104 (12 cps) cases. The cause is probably due to the random noise associated with a boom wave signature. It is not a "clean" N-wave.

The upper limit of the F-104 spectrum for the most part is 2.0 with the exceptions noted. The lower limit is about 1.4. The higher harmonics are excited somewhat more for the B-58 boom waves, probably because it occasionally has ripples just after the bow shock front. Aircraft configuration, which causes these humps, therefore, has some effect on governing the response of elements whose frequencies are higher than the first harmonic.

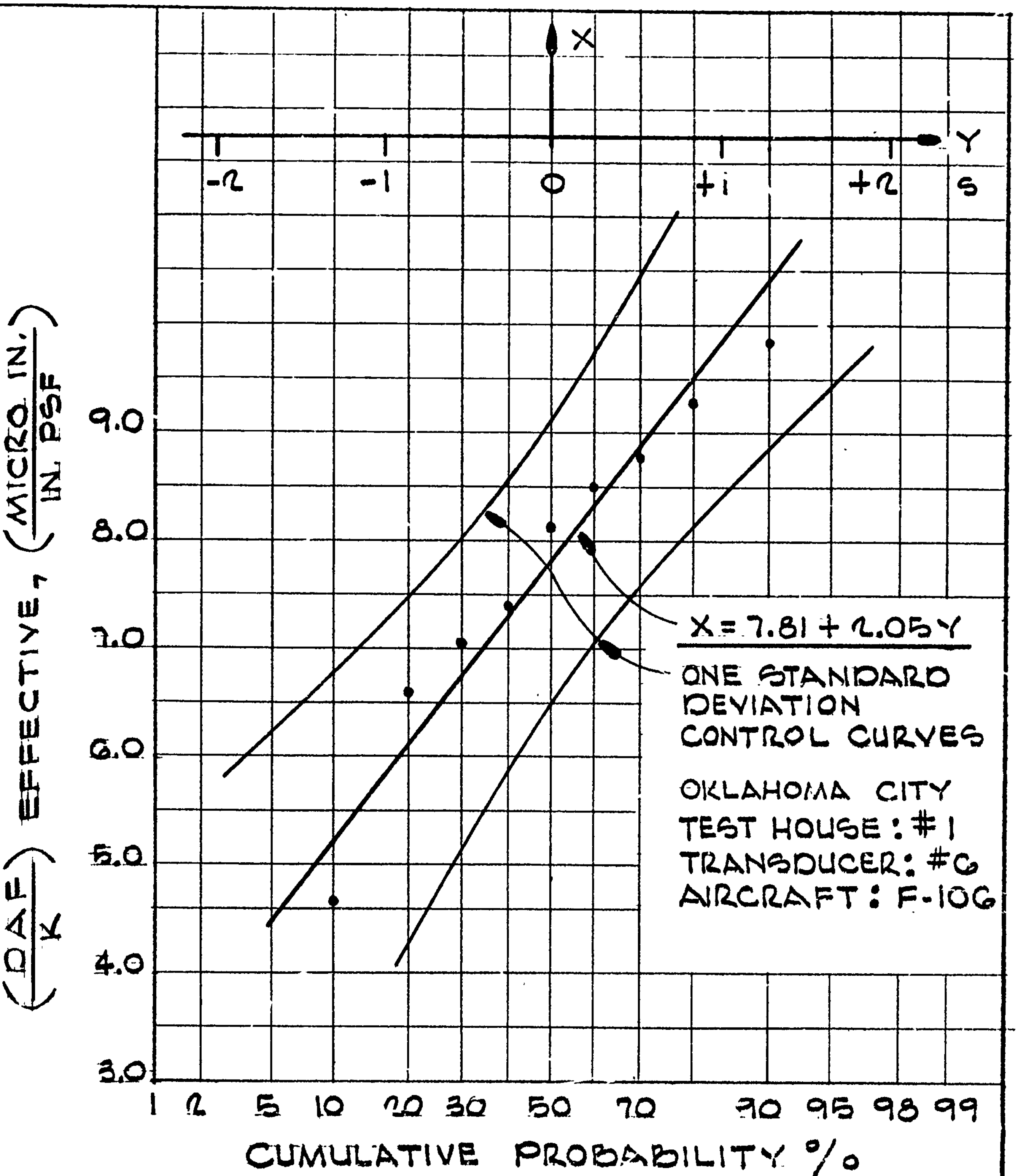


FIG. V-3 PROBABILITY DISTRIBUTION OF $\left(\frac{DAF}{K}\right)$ EFFECTIVE

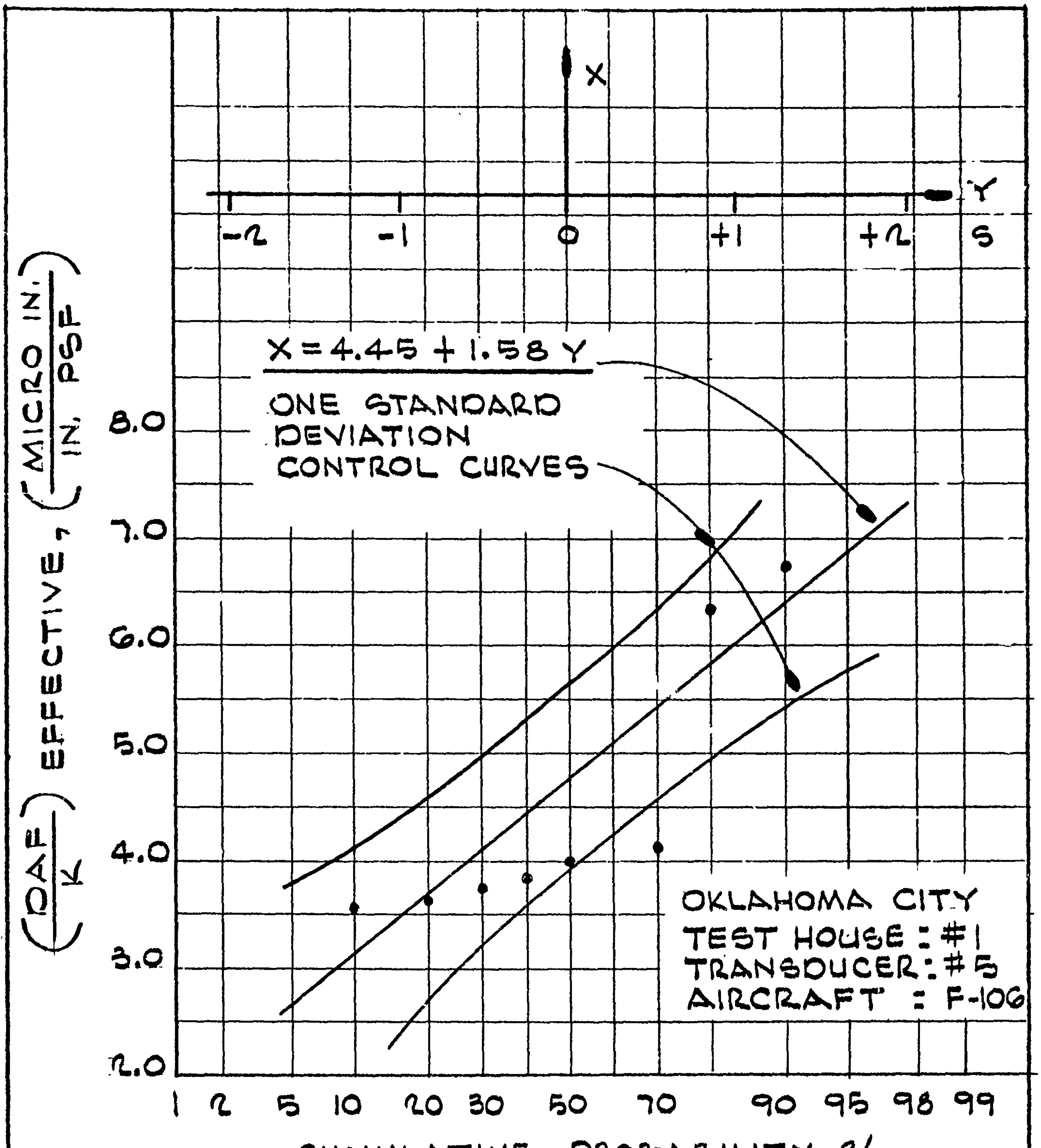


FIG. V-4 PROBABILITY DISTRIBUTION OF $\left(\frac{DAF}{K}\right)$ EFFECTIVE

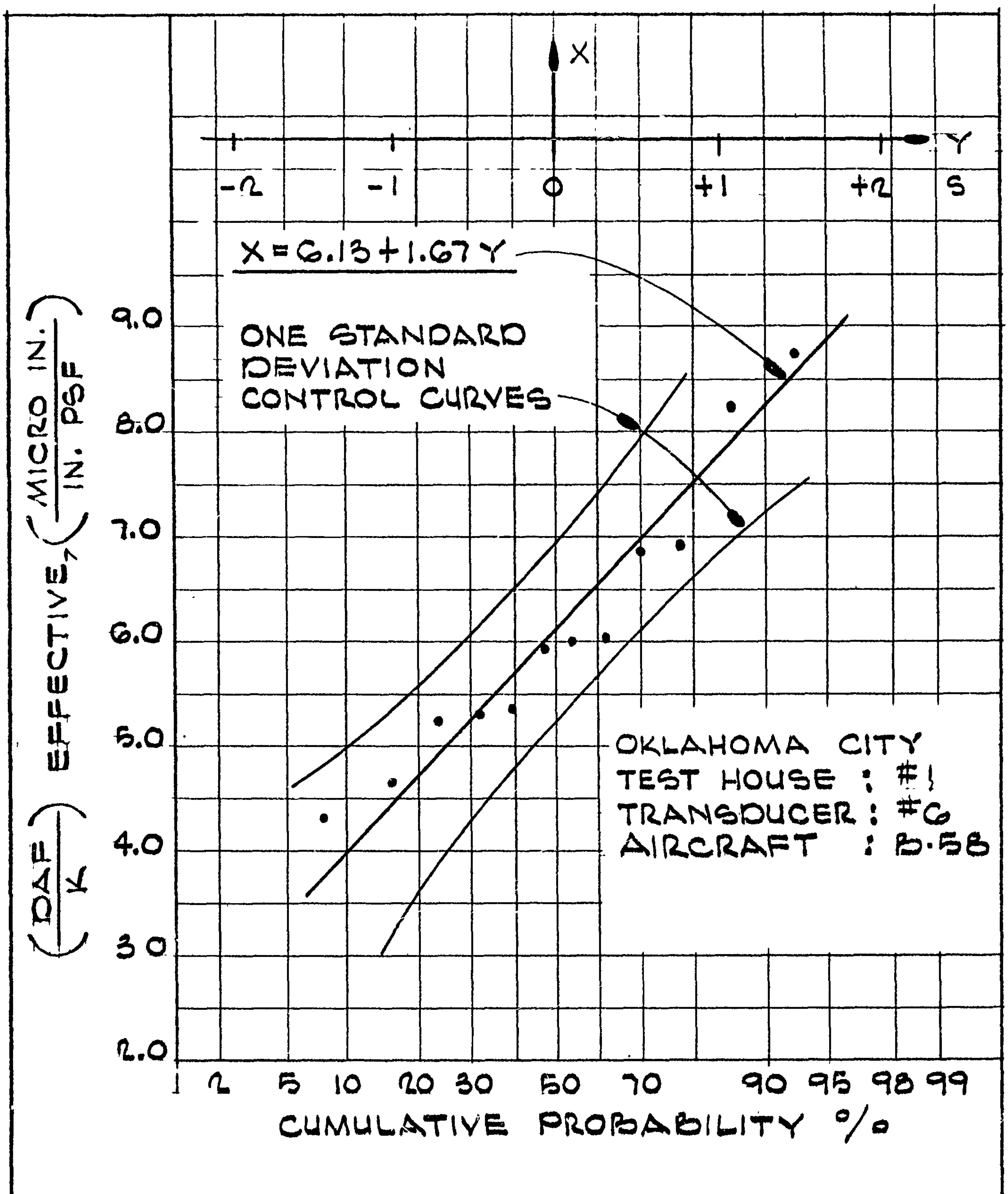


FIG. V-5 PROBABILITY DISTRIBUTION OF $\left(\frac{DAF}{K}\right)$ EFFECTIVE

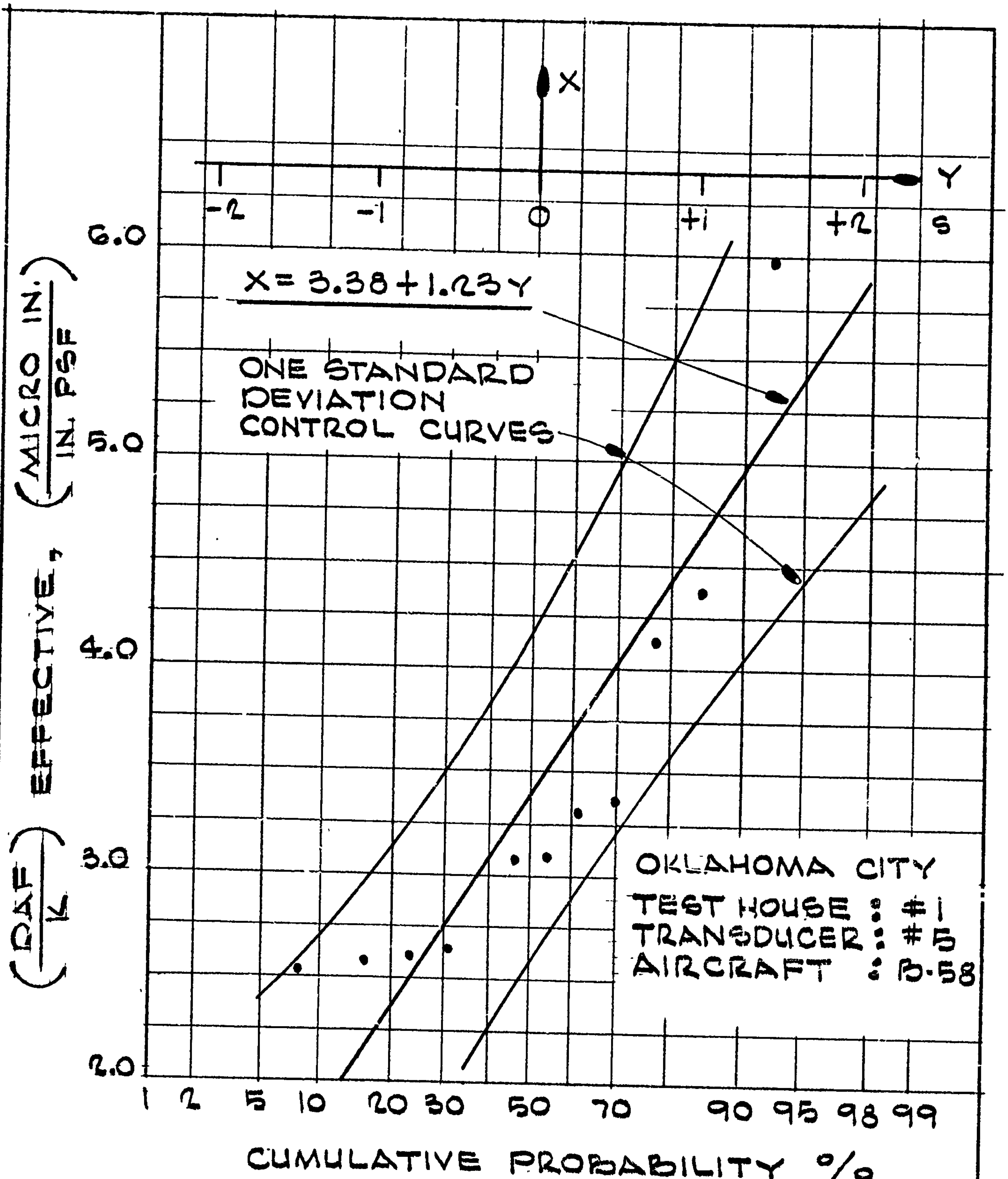


FIG. V-6 PROBABILITY DISTRIBUTION OF $\left(\frac{DAF}{K}\right)$ EFFECTIVE

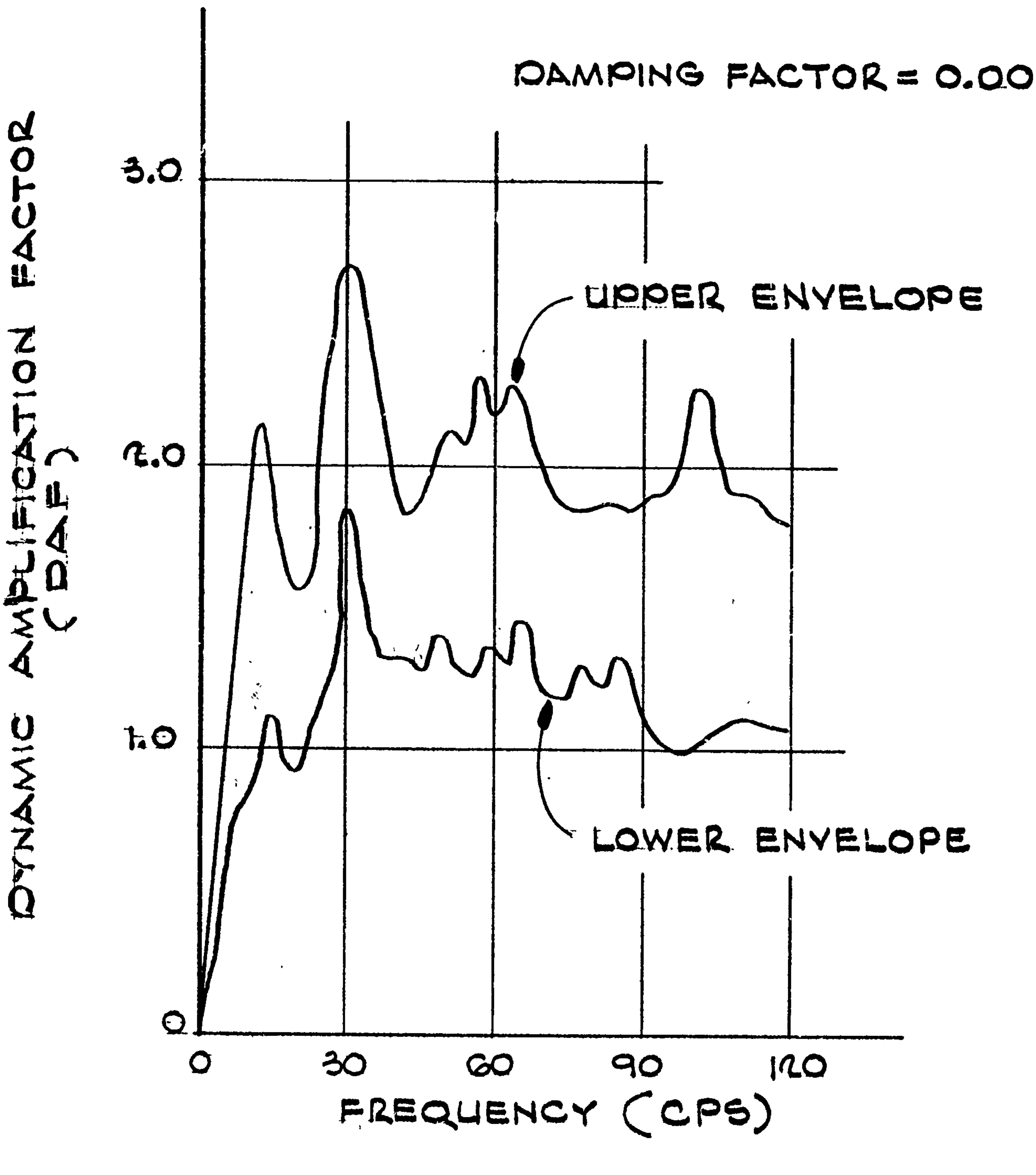


FIG. V-7 UPPER AND LOWER ENVELOPE RESPONSE SPECTRA FOR 90, F-104 GROUND FREE-FIELD RECORDS

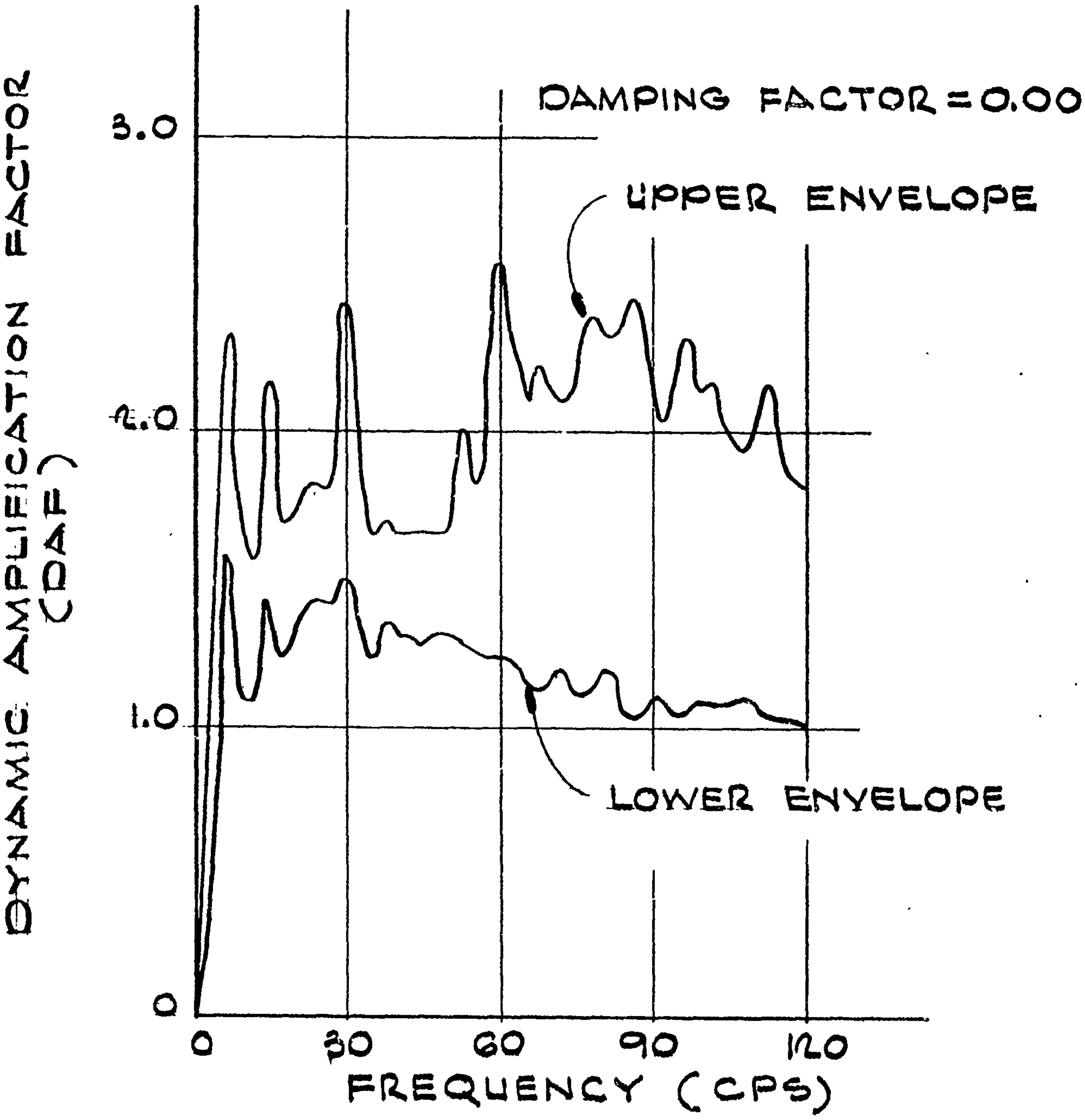


FIG. V-8 UPPER AND LOWER ENVELOPE RESPONSE SPECTRA FOR 15, B-58 GROUND FREE-FIELD RECORDS

One notable feature is absent for boom wave spectra generated by low altitude (12,000 ft.) aircraft. The peak first harmonic response is never 4.0. This is the value predicted for an alternating plus and minus square wave. We can, therefore, predict that a square free-field wave under the flight path of a booming aircraft may not exist. Even if an alternating square wave existed the peak pressure would also be lowered, energy remaining constant, and the effective load, P_{max} (DAF), would remain constant.

Figs. V-9 through V-12 illustrate the upper and lower envelopes of wall loading spectra computed from records made by microphones located 6 ft. above the ground on a wall 10 ft. 6 in. high. (Note the design of building W-4 in Appendix B of the White Sands report.) The peak (DAF) value recorded for each boom wave spectrum was plotted against peak wall pressure for concrete block and frame walls (Fig. V-13). No interrelationship is evident from the figure. But the peak may occur between a frequency bandwidth of 0 to 120 cps. Inspection of the envelopes in the preceding figures reveals that the frequency of maximum may be anywhere.

Two features on the F-104 spectra predominate, the first and second harmonics. These occur within the frequency ranges of 10-14 cps and 28-34 cps in the spectra studied. Fig. V-14 plots the (DAF) of the first harmonic versus the peak pressure computed from records taken on wooden walls. There is a definite functional relationship evident in the figure, the higher the pressure, the lower the (DAF). Inbound vector records are spiked due to reflection against the wall. But the duration of the spikes depends on the height or width of the building[22]. Little energy is present in these peaks which is sympathetic to the first harmonic so that its (DAF) is lowered. On the other hand, the trailing vector waves are rounded. The resulting maximum first harmonic amplification of a sine wave would be 3.2 in this case. Note, however, that the first harmonic (DAF) is always below this value.

It also can be seen that the average pressure on the center of wooden walls is lower than the ground overpressure. Even the inbound vector records are not twice the free-field as would be predicted by theory. On the concrete block wall pressure doubling is seen occasionally.

Fig. V-15 plots the variation of the second harmonic (DAF) with peak wall pressure for F-104 generated waves. Just the opposite case as that presented in Fig. V-14 is shown; the second harmonic increases with pressure. The scatter is greater than that in Fig. V-14, but a definite trend can be identified. On the trailing wall surfaces the

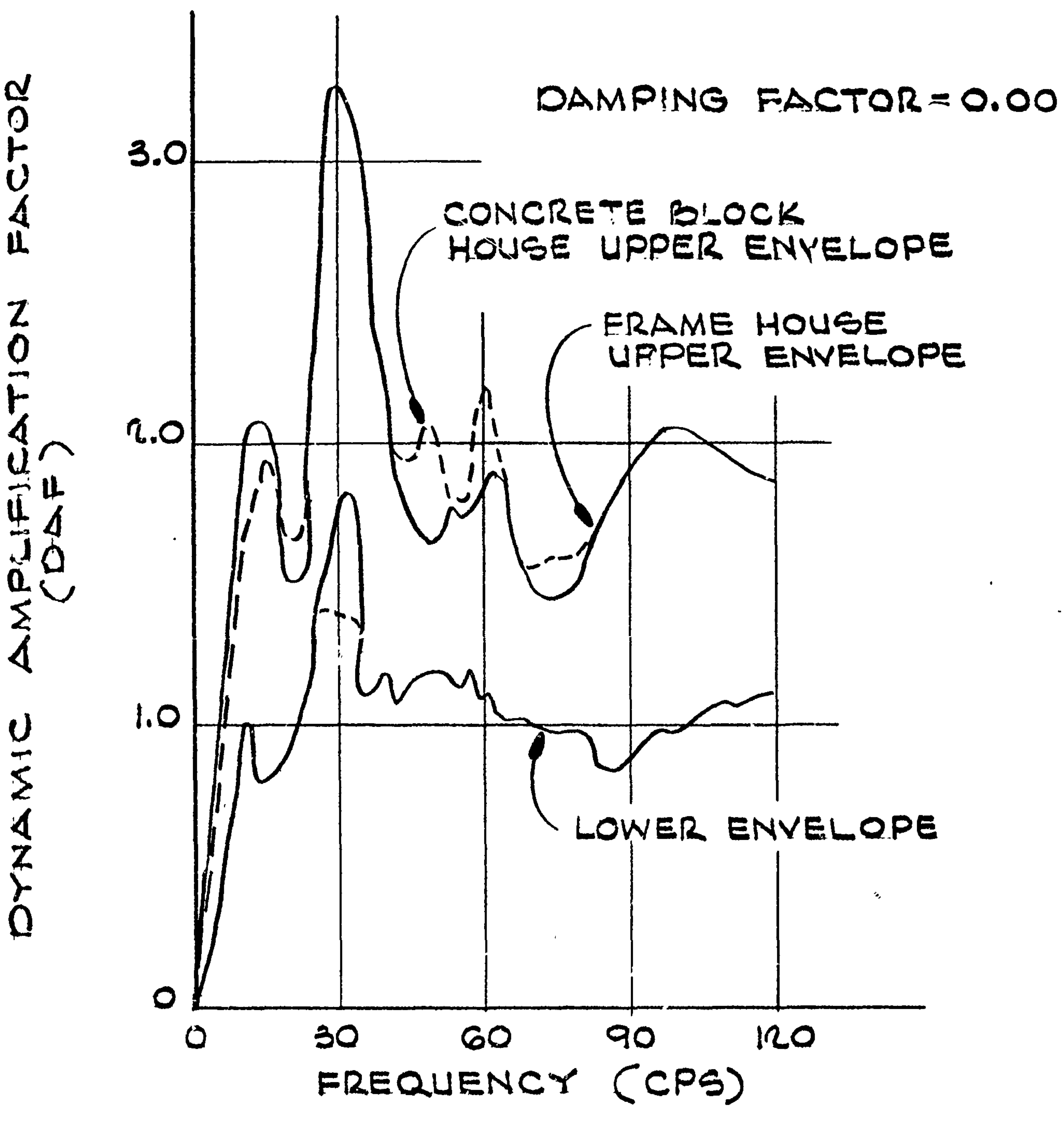


FIG. V-9 UPPER AND LOWER ENVELOPE RESPONSE SPECTRA FOR 24, F-104 INBOUND VECTOR WALL RECORDS

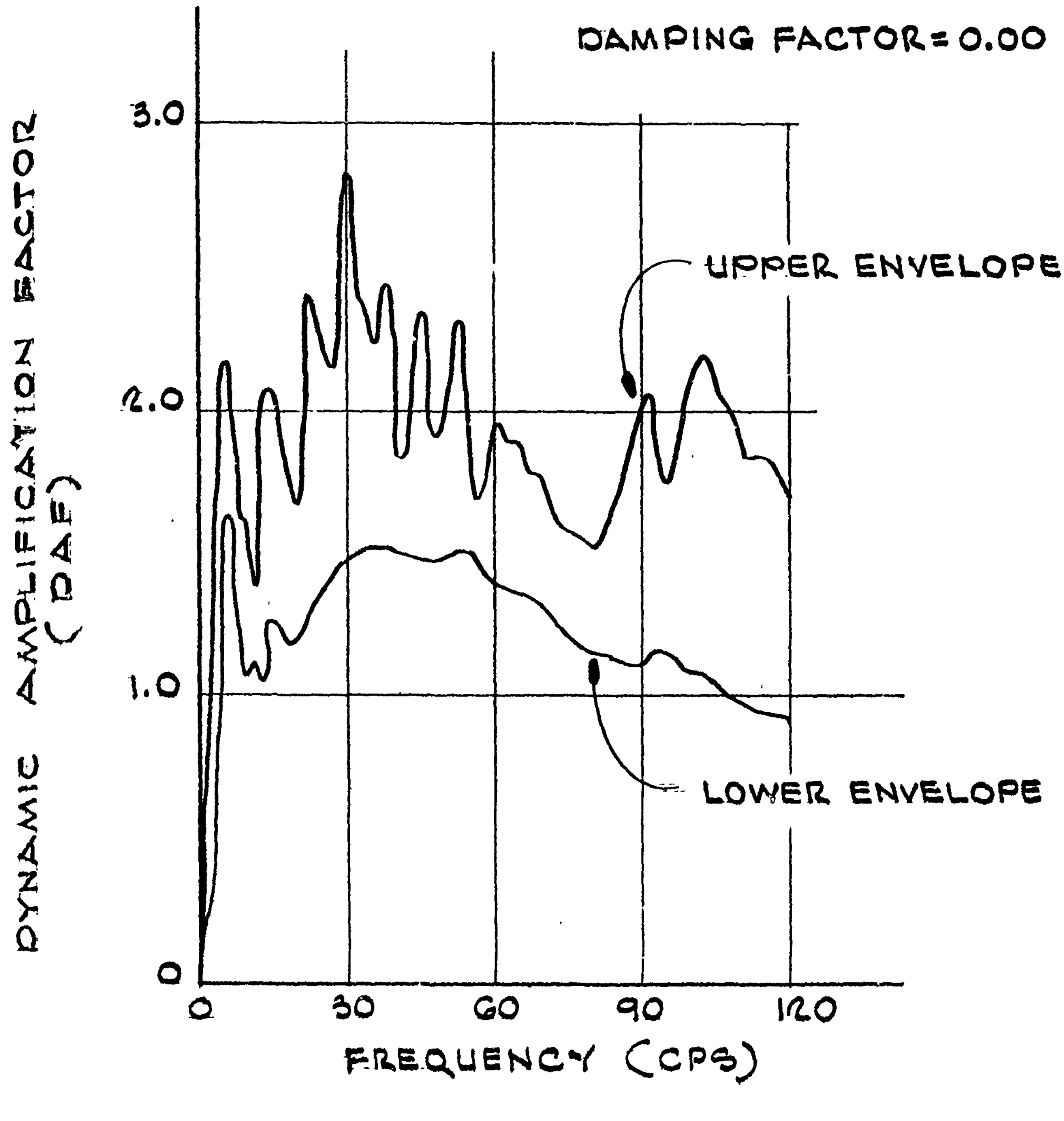


FIG. V-10 UPPER AND LOWER ENVELOPE RESPONSE SPECTRA FOR 5, B-58 INBOUND VECTOR WALL RECORDS

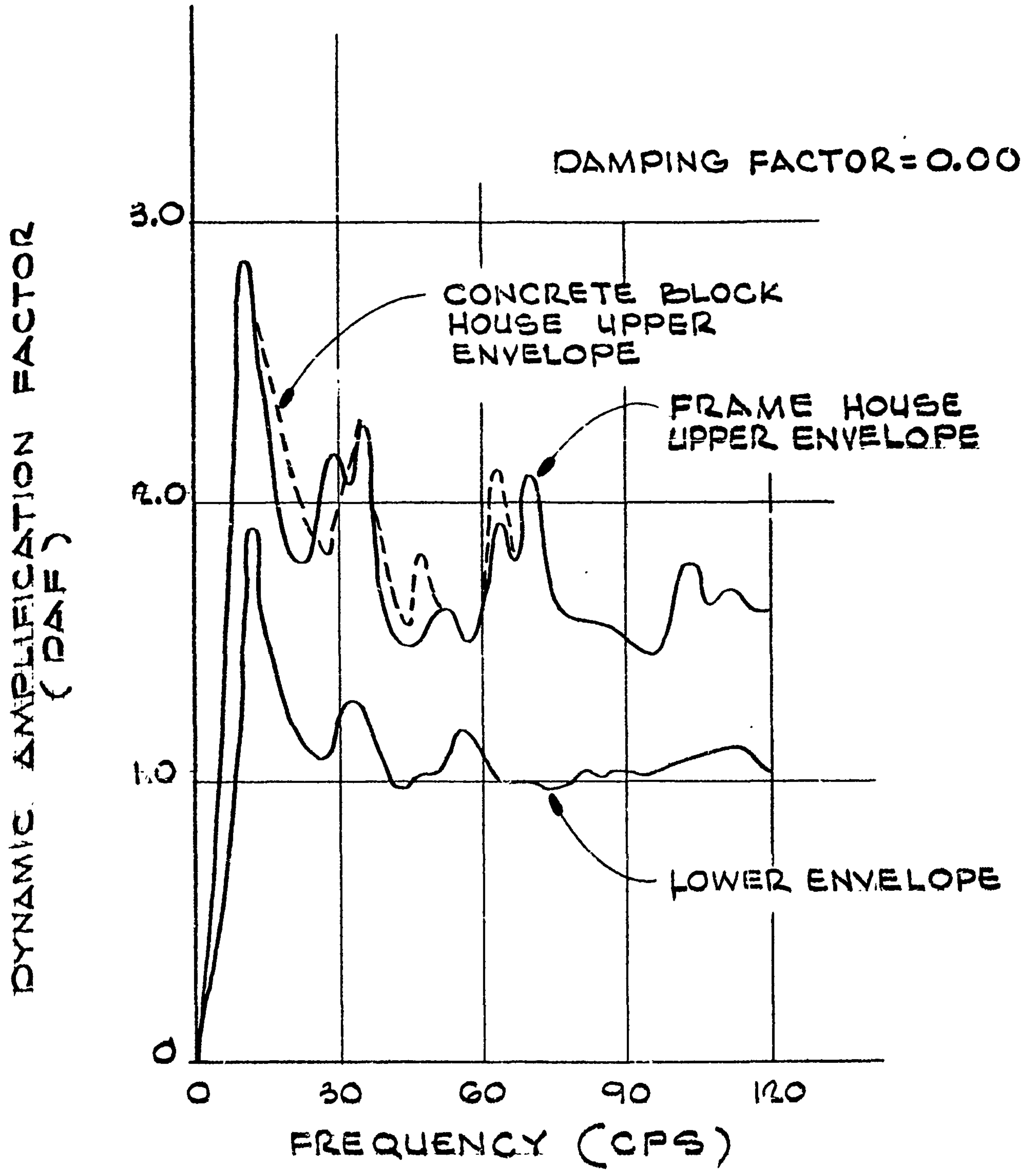


FIG. V-11 UPPER AND LOWER ENVELOPE RESPONSE SPECTRA FOR 22, F-104 TRAILING VECTOR WALL RECORDS

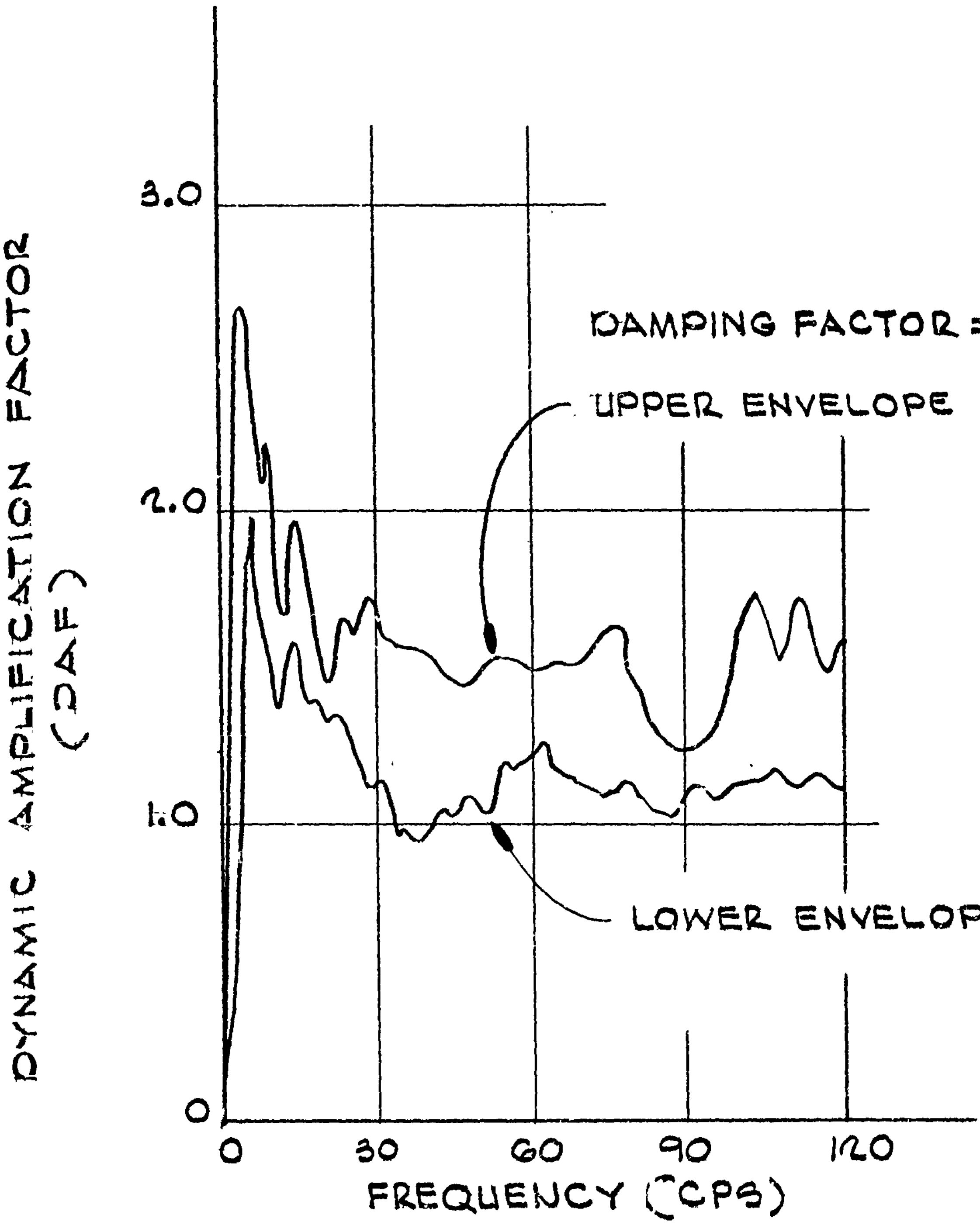


FIG. V-12. UPPER AND LOWER ENVELOPE RESPONSE SPECTRA FOR 5, B-58 TRAILING VECTOR WALL RECORDS

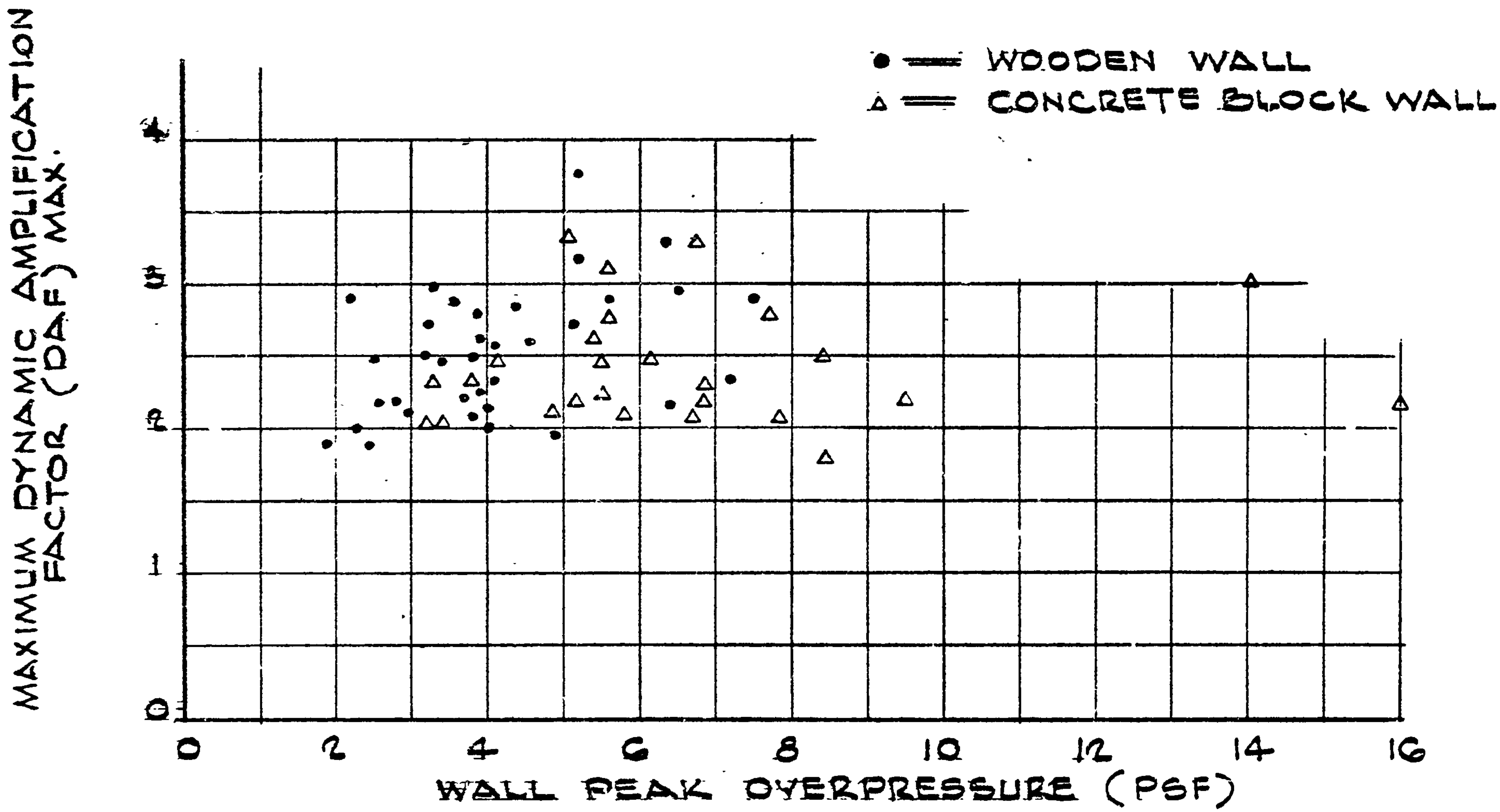


FIG. V-13 MAXIMUM DYNAMIC AMPLIFICATION FACTOR (f=0-120 CPS) IS INDEPENDENT OF PEAK PRESSURE

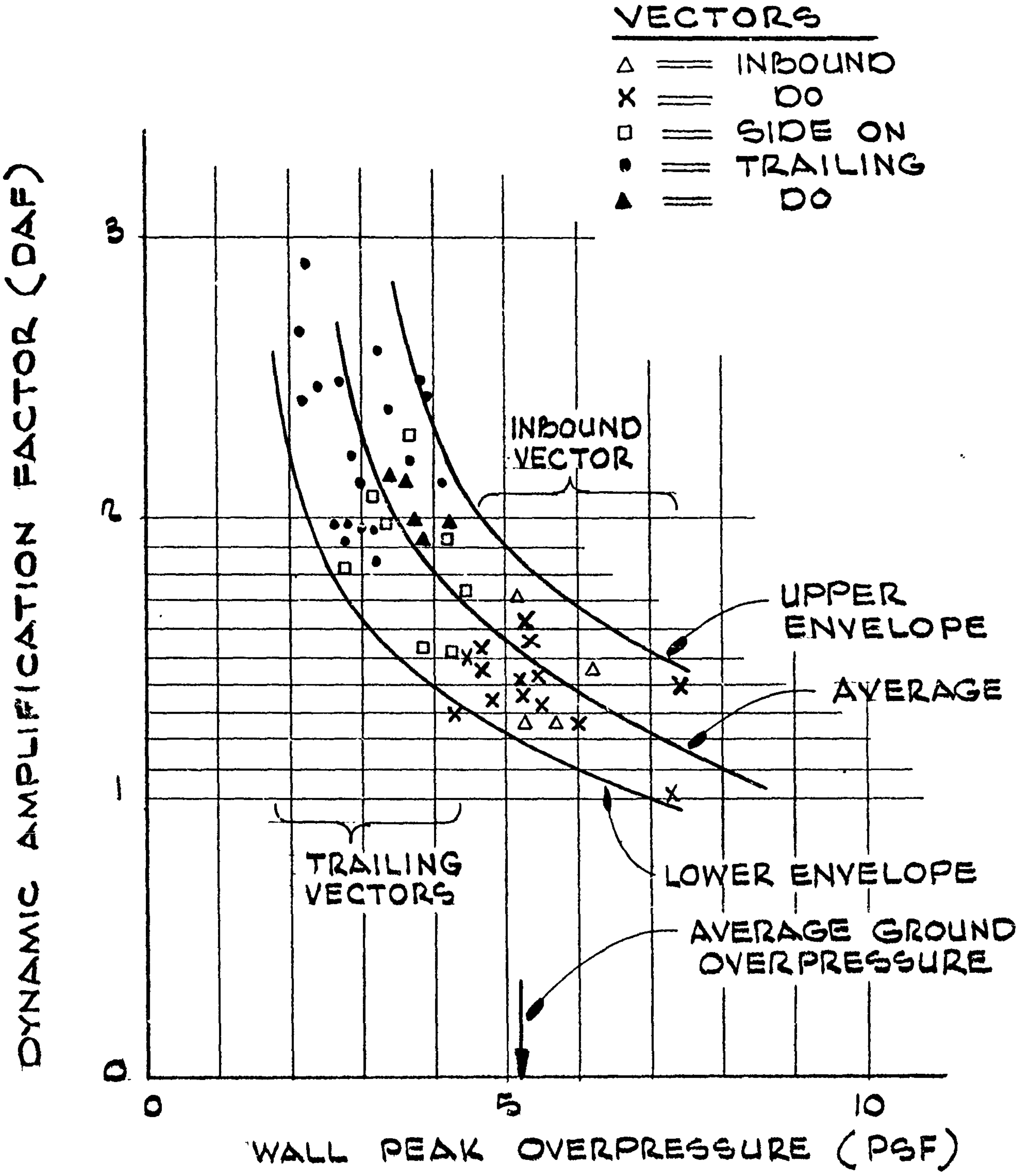


FIG. V-14 MAXIMUM DYNAMIC AMPLIFICATION FACTOR OF FIRST HARMONIC (f = 10-14 CPS) F-104 WALL PRESSURE RECORDS DEPENDS ON VECTOR AND PRESSURE MAGNITUDE

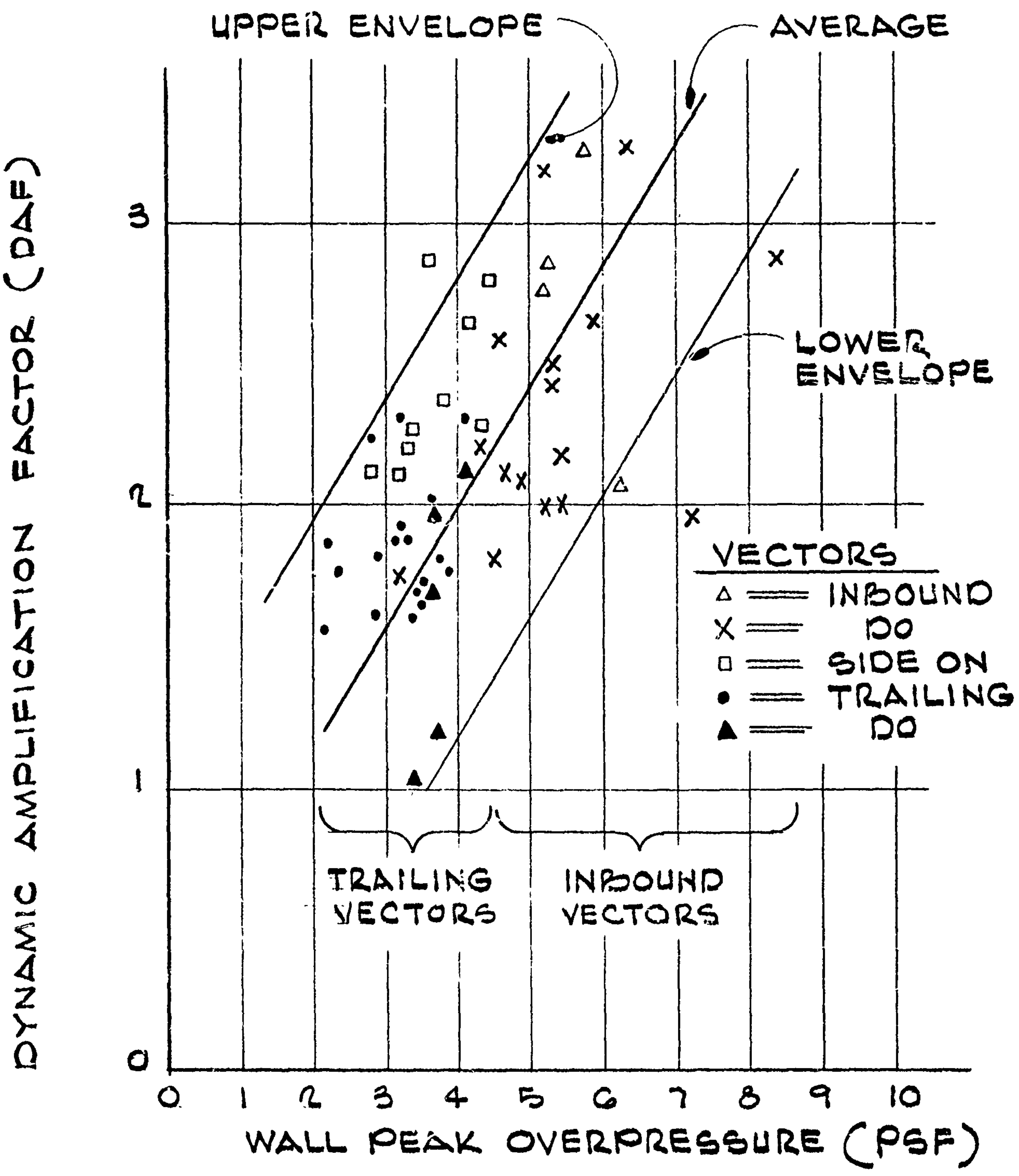


FIG. V-15 MAXIMUM DYNAMIC AMPLIFICATION FACTOR OF SECOND HARMONIC (f=28-34 CPS) F-104 WALL PRESSURE RECORDS DEPENDS ON VECTOR AND PRESSURE MAGNITUDE ripple or second shock caused by intake and wings is smothered. It therefore doesn't add to the excitation of the second harmonic. Records taken on the leading or inbound walls show the opposite effect. Upon visually scanning hundreds of the records it has been noted that if the first peak is large the chances are that the intake-wing boom peak will be large also. This development could cause the second harmonic to be amplified.

Not enough B-58 data was reduced to spectral form to determine any relationship between the first or second harmonics and peak pressure. But, if the reader will again consult Figs. V-10 and V-12, he will note that inbound vectors lower the first harmonic. The second harmonic is relatively unaffected by vector, probably since no secondary booms caused by intake-wing combinations are present midway between the bow and tail wave of a B-58 boom signature.

The higher harmonics of the B-58 inbound boom spectra are accentuated, possibly because of the occasional, almost sinusoidal ripples immediately following the bow wave. An average value of 2.0 for the entire spectrum, especially with some damping added, would be a reasonable average upper bound value for the B-58 or the F-104 on inbound vector runs, for that matter.

D. Influence of Wall Stiffness on (DAF):

In the White Sands report it was shown that the peak pressure recorded on the wall of a concrete block house was slightly higher than that taken on a similar frame house with wood siding (Fig. VI-5, Ref.4). Differences in (DAF) are shown in Figs. V-9 and V-11.

The upper envelope in the vicinity of the first harmonic is somewhat lower for the concrete block wall pressure than that for the wooden wall. The effective load, P_{max} (DAF), for the first harmonic is uninfluenced by wall stiffness. This appears reasonable in light of the discussion about Fig. V-14. The more spiked the data, the lower the (DAF) of the first harmonic. Since the reflection coefficient of a concrete block wall is higher than that for a wooden wall, the tendency for having more and larger spikes than that on the wooden wall on inbound vector booms is larger. The result is a lower upper envelope for the block wall spectra. On trailing vector records (Fig. V-11) no significant differences between first harmonics is evident.

The second harmonic upper and lower envelopes remain unchanged for the two different building spectra. The second harmonic and, for that matter, all of the higher frequencies, probably would have higher effective loads, P_{max} (DAF), on the concrete block house than those on a wooden house resulting from more spikes in the records. High frequencies would be susceptible to spikes having favorable time durations.

In summary, it appears that a stiff, high frequency window within a block wall may be excited slightly more than the same window within a wooden or low stiffness wall. No change should be expected for large, low frequency windows. Fig. VI-28 in the White Sands report, which plots mean movement of a 5' x 10' window in a wooden and a concrete block building, lends support to this observation.

E. The Influence of Near Reflecting Surfaces on Wall Loading:

The White Sands report investigated the effect of near reflecting surfaces on wall peak pressures. Shielding of the wall when billboards were within about 10 feet caused peak pressure on trailing vector runs to increase slightly and decrease slightly on inbound vector runs.

Fig. V-16 shows the variation of mean peak wall pressure at the position noted for other billboard positions. The variation that occurs on all vector runs appears to vary in a predictable manner. That is, booms traveling into corners should be amplified, whereas shielded boom pressures should be lowered. If the reader will consult the billboard plan location with reference to the microphone position, he can verify this observation for about all of the mean data values.

F. The Effect of Height Above Ground on Free-Field Spectra:

The differences between free-field ground spectra and wall spectra have been noted earlier. The size of the first and second harmonics depends on whether or not the data is spiked or rounded. Wide variations in the ground free-field spectra were not observed.

No tall buildings were loaded in the White Sands study, but free-field records were taken at 45 ft. and 90 ft. Inferences about the shapes of wall spectra derived for windows in buildings taller than the residential type can be predicted by studying free-field tower spectra and recalling the discussion about inbound and trailing wall spectra. Figs. V-17 to V-20 present upper and lower spectral envelopes for F-104 and B-58 booms recorded 45 ft. and 90 ft. above the ground.

The form of the tower records can vary significantly (see Fig. IV-21). Time between the bow and tail boom waves, time between the initial and reflected waves, and wave shapes can vary. Figs. V-17 and V-19 indicate that the multiple boom wave can increase the response compared with that in Fig. V-7 by between 25 and 50 percent. But since the maximum pressure is on the average halved, the resultant effective load may be lowered by about 25 percent (1 - (0.5 x 1.5) = 0.25). About the same situation is evident from inspection of Figs. V-8 and V-20 for the B-58 spectra. The harmonics of a single boom wave appear to be accentuated the most while the frequencies with low amplification appear unaffected.

Because the B-58 boom wave is about twice as long as an F-104 wave the heights of the microphones above the ground must be scaled by a

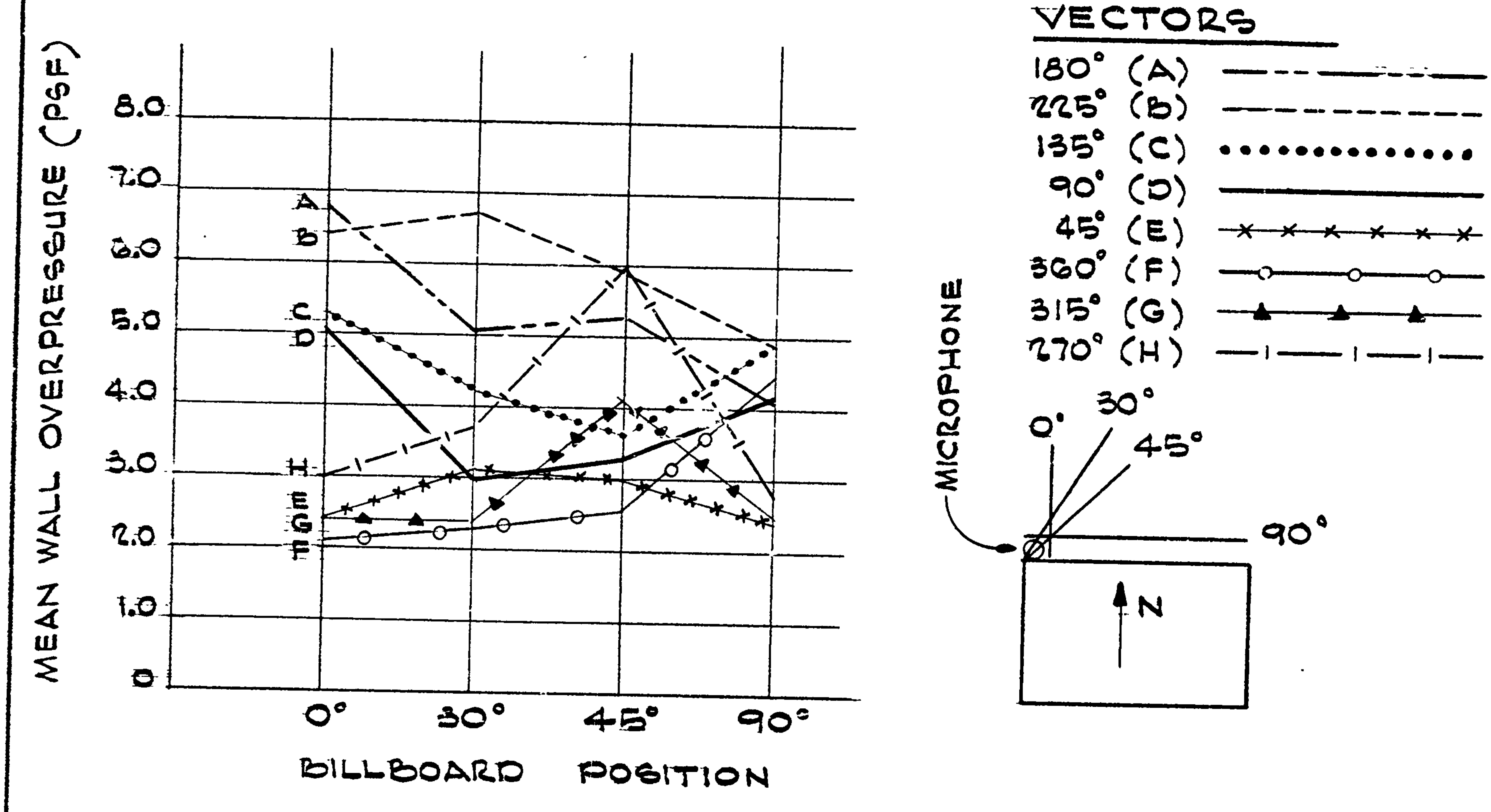


FIG. V-16 EFFECT OF BILLBOARD POSITION ON CORNER OVERPRESSURES

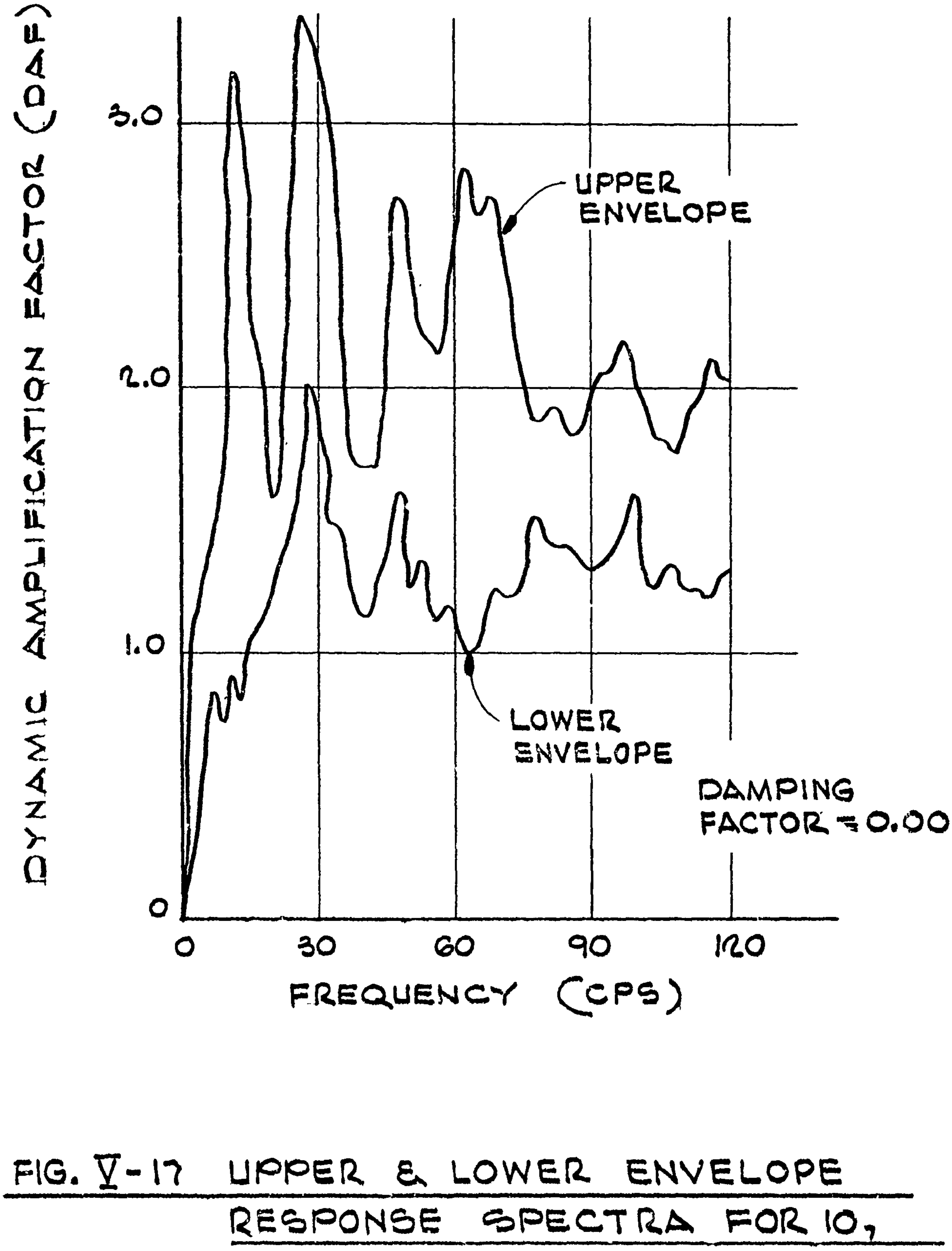


FIG. V-17 UPPER & LOWER ENVELOPE RESPONSE SPECTRA FOR 10, F-104, 45 FT. FREE-FIELD RECORDS

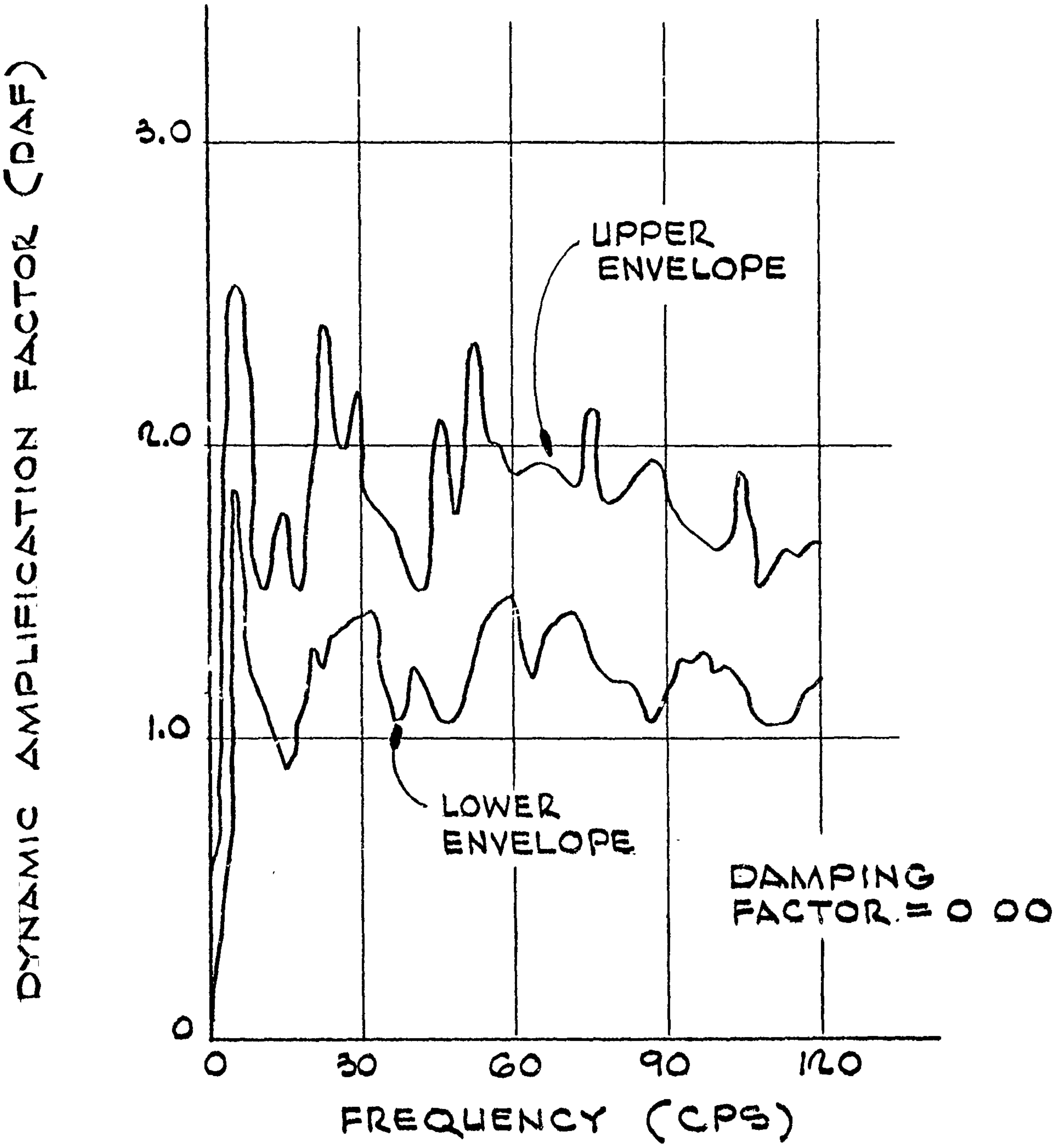


FIG. V-18 UPPER & LOWER ENVELOPE RESPONSE SPECTRA FOR 5, B-58, 45FT. FREE-FIELD RECORDS

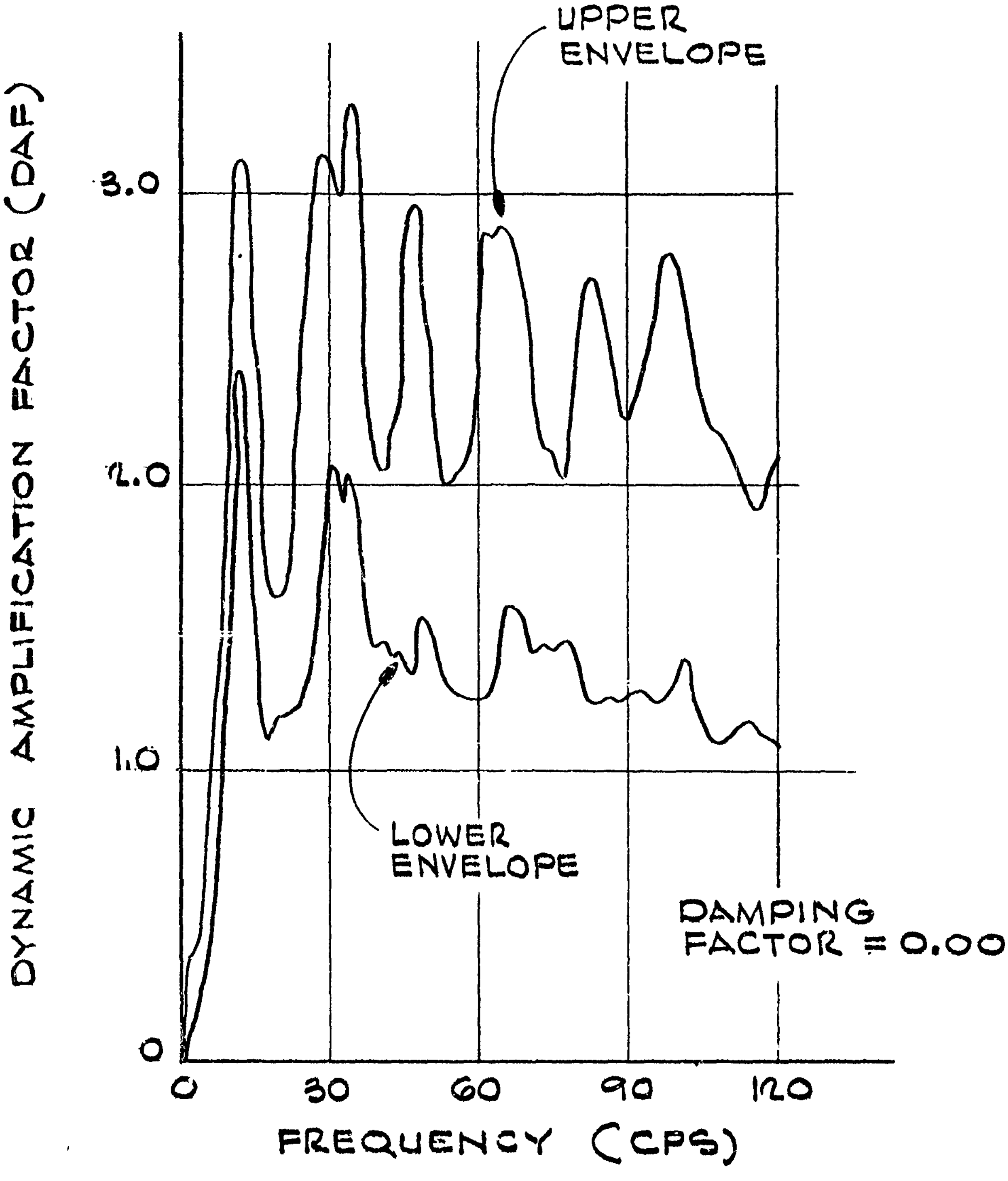


FIG. V-19 UPPER & LOWER ENVELOPE RESPONSE SPECTRA FOR 9, F-104, 90FT. FREE-FIELD RECORDS

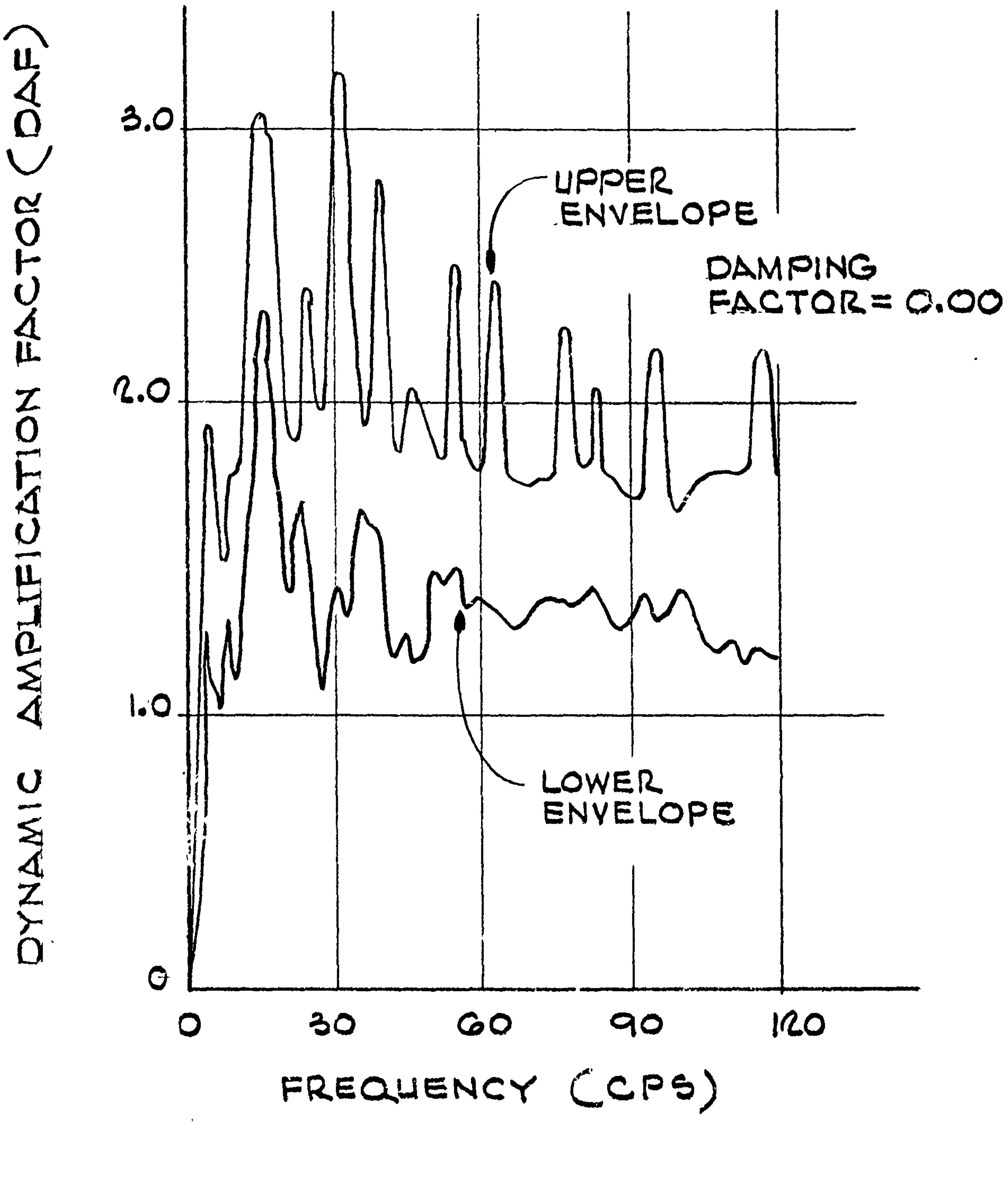


FIG. V-20 UPPER AND LOWER ENVELOPE RESPONSE SPECTRA FOR 5, B-58, 90 FT. FREE-FIELD RECORDS factor of two to get similar envelopes. That is, the B-58 spectra at 90 ft. should look like those for an F-104 at 45 ft. The B-58 spectra at 45 ft. should look like F-104 spectra taken at 22.5 ft. etc. This probably explains the difference between F-104 spectral envelopes at 45 ft. and B-58 envelopes at the same height. No significant increase in the B-58 envelopes at 45 feet compared to those on the ground (Fig. V-8) is obvious. But so, too, at 45 ft., the B-58 peak pressures are not halved, but are reduced by only about 25 percent.

No matter whether the structural element of interest is on the ground or at some height above ground, the effective load is not expected to be higher; its probably lower than that registered on the ground. Of course, some freak condition could exist where dynamic amplification factor may range up to 5 or more at a particular frequency. But so, too, can peak pressure be doubled or trebled over that predicted, as seen in Chapter IV, but the probability of such an occurrence is very low.

G. Diaphragm Loads:

The response spectra discussed up to this point are related to pressure-time histories recorded on only one loading surface. This does not represent the effective load which is determined by the sum of loads acting over an entire element. Pressure is not felt on just the outside of a structure, but some is transferred to the interior by the diaphragm action of the walls, ceilings and windows.

An example of the difference between pressure records and resulting spectra taken outside and inside an 8 ft. x 10 ft. glass window and the net pressure and spectrum is given in Fig. V-21 for a B-58 on an inbound vector boom. The net record does not differ much in appearance from the outside record, but both the positive and negative impulses are lowered. The wave no longer decays linearly as an N-wave but decays in an S shape when the S is on its side.

The outside and net spectra differ greatly from the inside spectrum. Note how the first and second harmonics of the inside spectrum are much greater than the outside or net first and second harmonics. This is probably caused by the rounded shape and the bump in the middle of the inside record.

It is difficult to compare diaphragm spectra with outside spectra and derive meaning about effective load because P_{max} for the net record is not simply the difference of the two outside and inside maximums. Comparison of effective load computed from an outside record and an equivalent net record can be made for the first harmonic, however, to identify a trend (Fig. V-22). Note that on trailing vectors the effective load is about half that computed from the outside loading record only. On the inbound vector runs the net effective load is about the same as the outside effective load for the F-104 and about two-thirds the outside for the B-58. The B-58 boom is transmitted

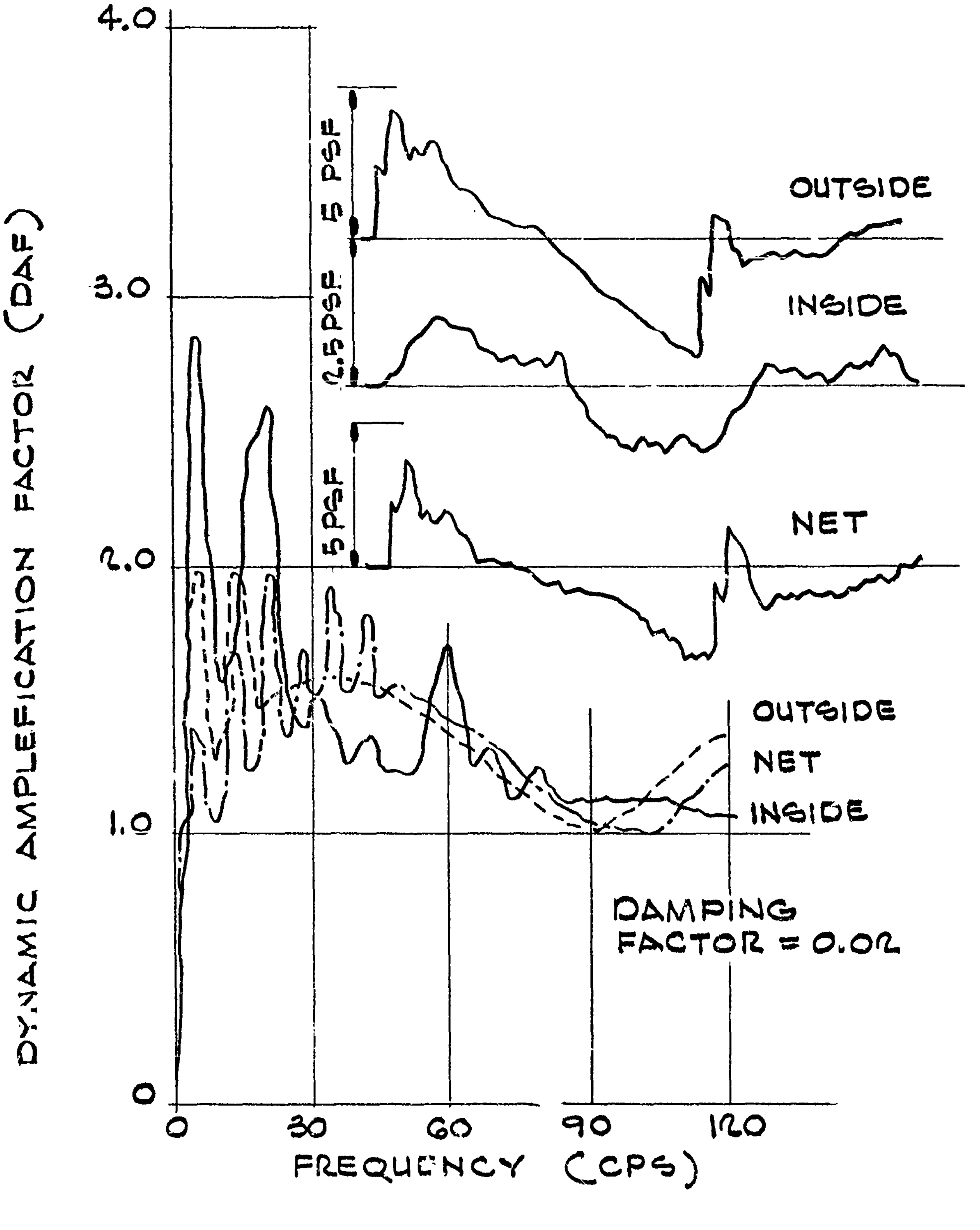


FIG. V-21 COMPARISON OF RECORDS & RESPONSE SPECTRA TAKEN OUTSIDE & INSIDE AN 8'x10' WINDOW ON AN INBOUND BOOM

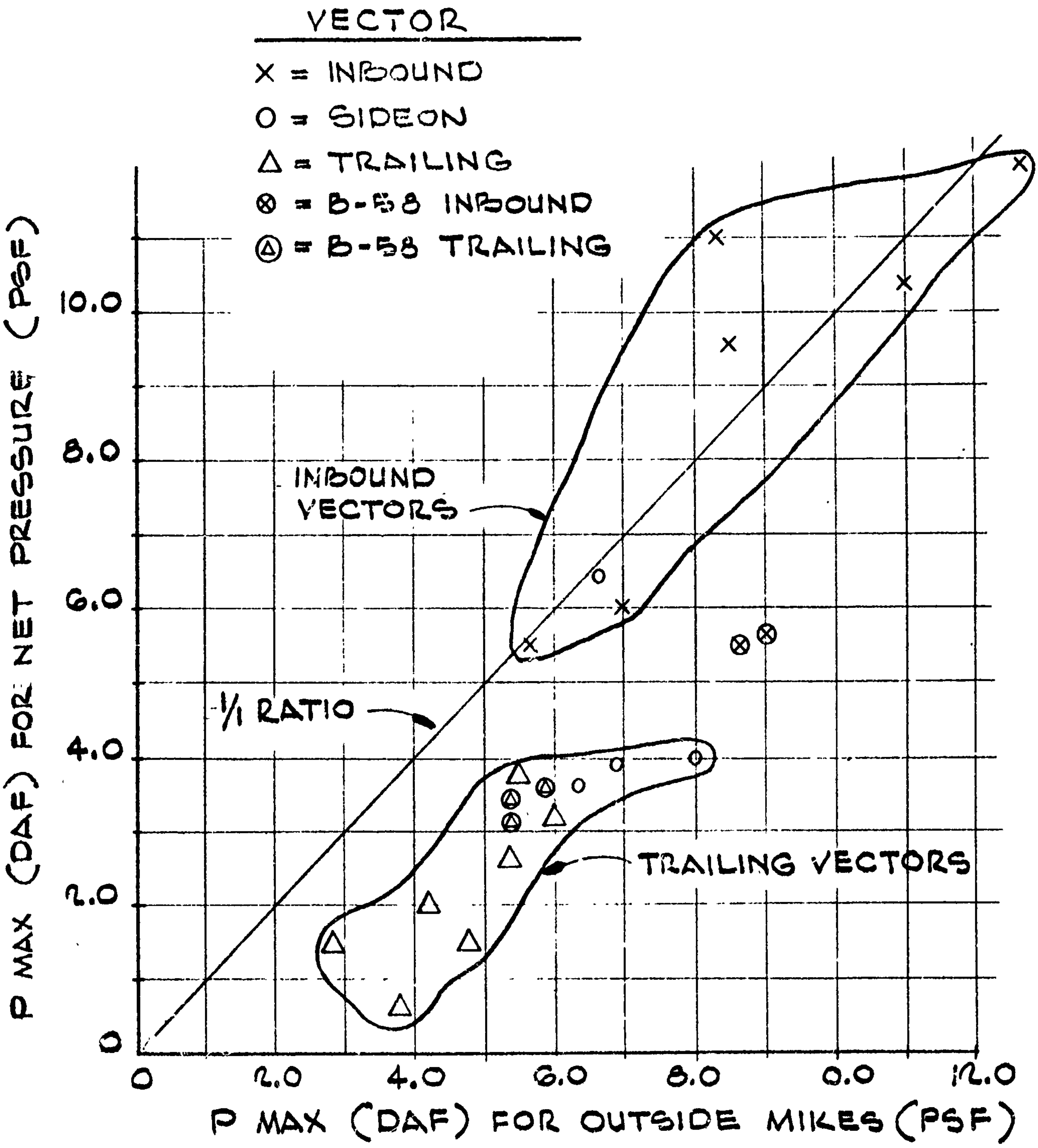


FIG. V-22 EFFECTIVE PRESSURE (OUTSIDE MIKE ONLY) VERSUS NET EFFECTIVE PRESSURE FOR FIRST HARMONIC through walls and windows better than is an F-104 boom (see Fig. VI-33 in the White Sands report and Fig. 15 in Ref. 1). In effect the boom is loading and bracing the window at the same time.

A logical question may arise regarding the validity of using the outside microphone spectra recorded in front of a flexible window in the analysis of stiff windows subjected to boom loads. We have seen earlier that the stiffness of the object loaded slightly affects both the peak pressure and (DAF) in the high frequency range. Both increases are caused by more and larger spikes on the stiff wall records. These spikes in turn contribute more to the response of high frequency items (usually stiff). But since the influence on the (DAF) is only slight, upgrading response by pressure difference only should be accurate enough for practical purposes.

Andrews[3] treated the response of a window as being governed by only the outside pressure record and an equivalent amount of damping. He assumed that the variation of pressure inside a window would not vary significantly and that the outside pressure alone could be used. This is incorrect, as has been seen in Fig. V-21, but it may be possible to equate the damped response of the outside record alone to net response provided it is recognized that different amounts of "effective" damping may be required for different window and room sizes and design stiffnesses.

H. Racking Loads:

The load which causes shear distortion of a building is also different than that recorded on only one wall. The racking net load is the vector sum of loads recorded on two opposite exterior walls. Fig. V-23 shows tracings of inbound and trailing wall pressure records accompanied by net racking loads for various sizes of buildings. The records were actually made on the (10' x 16') face of a (16' x 32') structure. The net records look very similar to the inbound wall record, but their spectra (Fig. V-24) are quite different. There are differences as large as 100 percent between 8 and 50 cps, yet the peak pressure is the same in each case since it is determined by the peak inbound wall pressure.

The dynamic amplification factors for the first harmonic of racking records of various structure lengths are compared in Table V-1. It can be seen that (DAF) and consequently the effective load increases as length of house increases to a maximum at 32 ft. for the inbound and diagonal boom runs. For walls facing sideon the (DAF) increases with wall length.

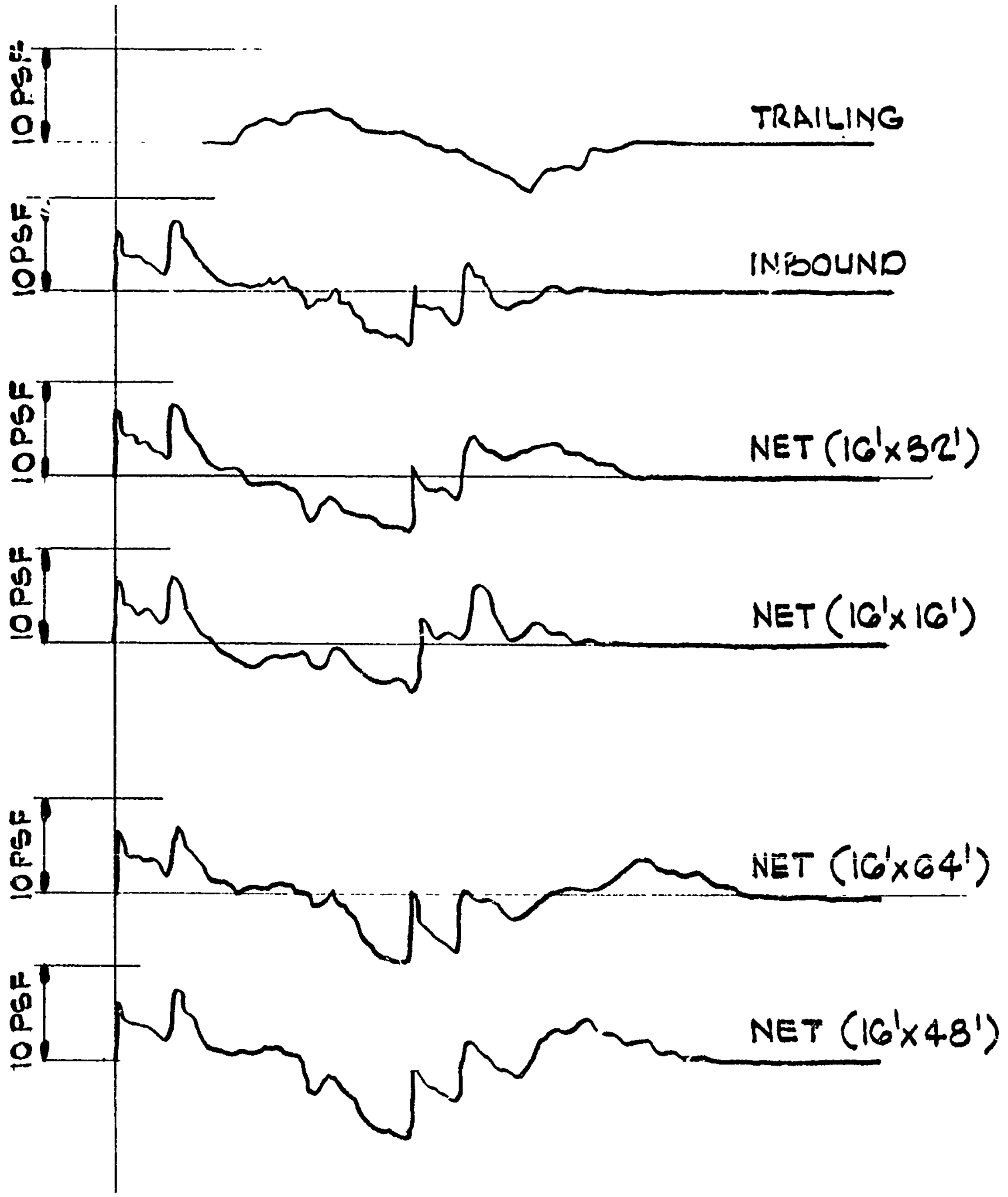


FIG. V-23 PRESSURE RECORDS FOR INBOUND & TRAILING WALLS & NET RACKING PRESSURES FOR VARIOUS BLDG. SIZES

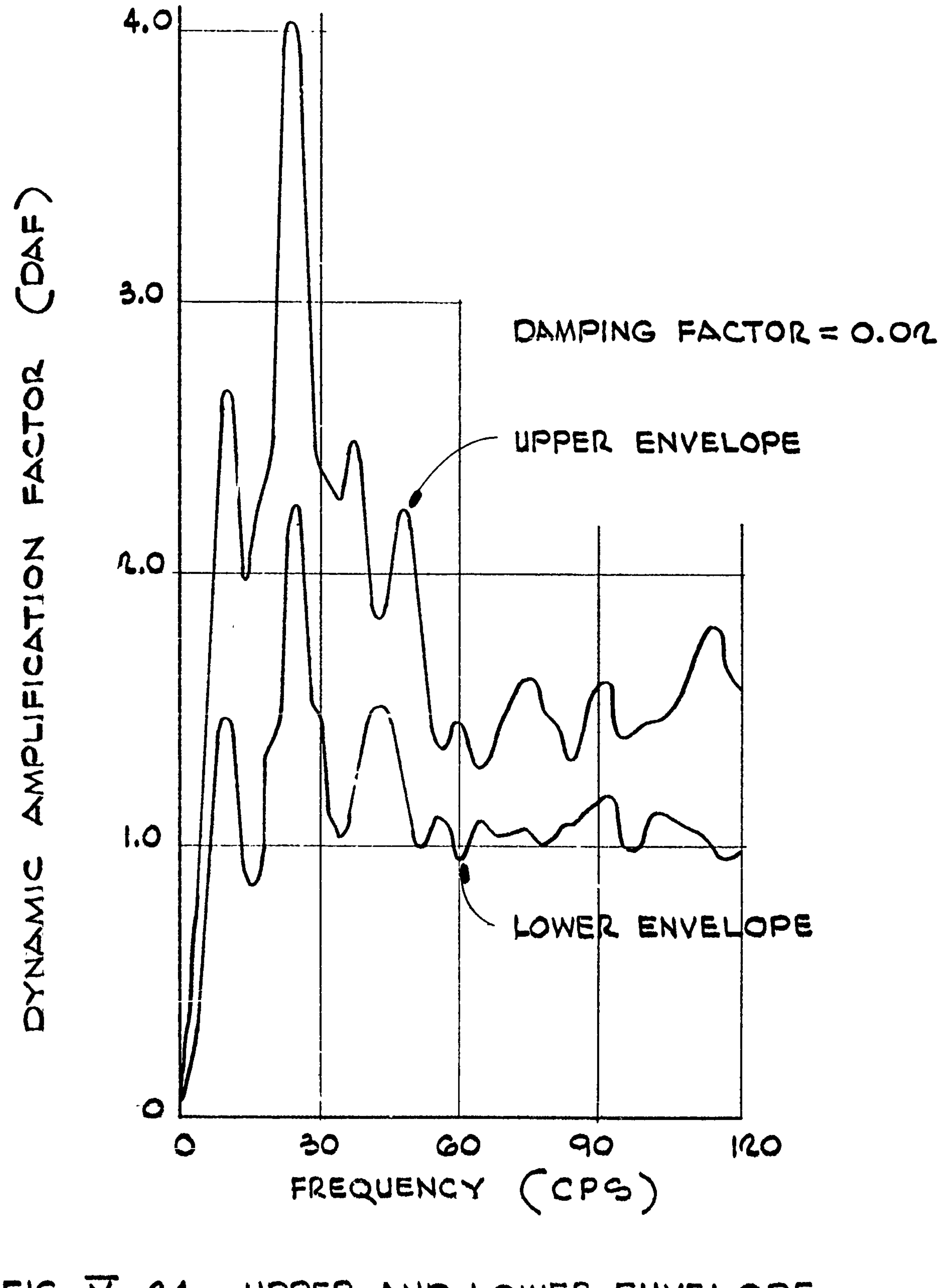


FIG. V-24 UPPER AND LOWER ENVELOPE RACKING SPECTRA COMPUTED FROM RECORDS SIMULATING A 16'x16', 16'x32', 16'x48' & 16'x64' BLDG (INBOUND VECTOR)

TABLE V-1 Dynamic Amplification Factors for the First Harmonic of Racking Records (F-104)

Vector	P_{max}(psf)	$(DAF)_{**}$ (16')	$(DAF)_*$ (16'x16')	$(DAF)_*$ (16'x32')	$(DAF)_*$ (16'x48')	(DAF) (16'x64')
Inbound	3.1	1.5	2.0	2.3	2.7	1.8
"	13.8	1.3	1.8	2.8	1.8	1.5
"	7.4	1.7	2.2	2.4	2.0	2.0
Sideon	2.3	2.1	1.9	1.9	1.7	1.8
"	11.4	1.7	0.5	0.8	1.1	1.1
Diagonal	13.3	1.3	1.5	2.4	2.0	1.5
"	7.0	1.1	1.4	2.2	2.3	2.0
"	2.1	2.0	2.1	2.5	2.5	2.8

*plan dimensions of building. Pressures recorded on 16' face.
**single inbound, diagonal or peak sideon record.

The natural racking frequency of a wall remains nearly constant as length of wall increases. Frequency depends on $(k/m)^{\frac{1}{2}}$, and both stiffness, k, and mass, m, increase linearly with wall length. Distortion, u, however, is inversely proportional to, k, only. For this reason the increase of (DAF) with length does not correspondingly increase the distortion (see Eq. (1)).

The sideon vibration should be zero for a plane wave, since the vector sum of the loads on both sides of the structure is theoretically zero at all times. This is not the case as evidenced by the size of the dynamic amplification factors for the sideon vectors in Table V-1. Since wave fronts generated by supersonic aircraft are not plane but conical and because wave shape and strength may be different for both sideon walls a net load exists. Sideon vibration can be expected and is in fact observed.

In summary, racking spectra can amplify various frequencies differently than one single wall record. The single wall record appears to be a somewhat low and marginally satisfactory approximation for inbound and diagonal booms. It is unsatisfactory for sideon booms. The racking spectrum may be 100 percent higher than the inbound wall spectrum in the 8 to 50 cps frequency range for F-104 booms. A smaller variation is expected for booms from larger aircraft. The equivalent house sizes used in the F-104 racking spectrum analysis would be reduced by a scaling factor of 4 for booms from SST aircraft whose wave duration may be 4 times as long as that from an F-104. The scaled house lengths for loading equivalent to those studied for the F-104 boom would be 4 ft., 8 ft., 12 ft., and 16 ft.. The effective racking load on buildings of this size under F-104 duration waves would be lowered. Likewise, an SST would rack 16 ft., 32 ft., 48 ft., and 64 ft. buildings less than an F-104.

I. Wall Distribution Resulting From Turbulence:

The White Sands report showed that there is little difference between peak pressures recorded at the upper, middle, or lower part of an 8 ft. by 32 ft. wall. The data is scattered because of turbulence, of course, but the mean pressures are relatively the same.

Peak pressure, as has been seen, is only half the influence in determining effective load. Dynamic amplification factor is the other half. Fig. V-25 compares the dynamic amplification factors of the first and second harmonics for records taken on the upper part of a wall with those taken on the lower part of the same wall. The lower wall amplification factors appear to be high for both harmonics. The effective loads, however, are scattered about a 45° or 1/1 ratio line rather evenly, however (Fig. V-26). For all practical purposes and minimum testing expense a single wall microphone located at the center of the wall can represent the net wall load for short buildings. Diagonal vector runs may introduce torsion which can be treated with a single record and some mathematical manipulation, however.

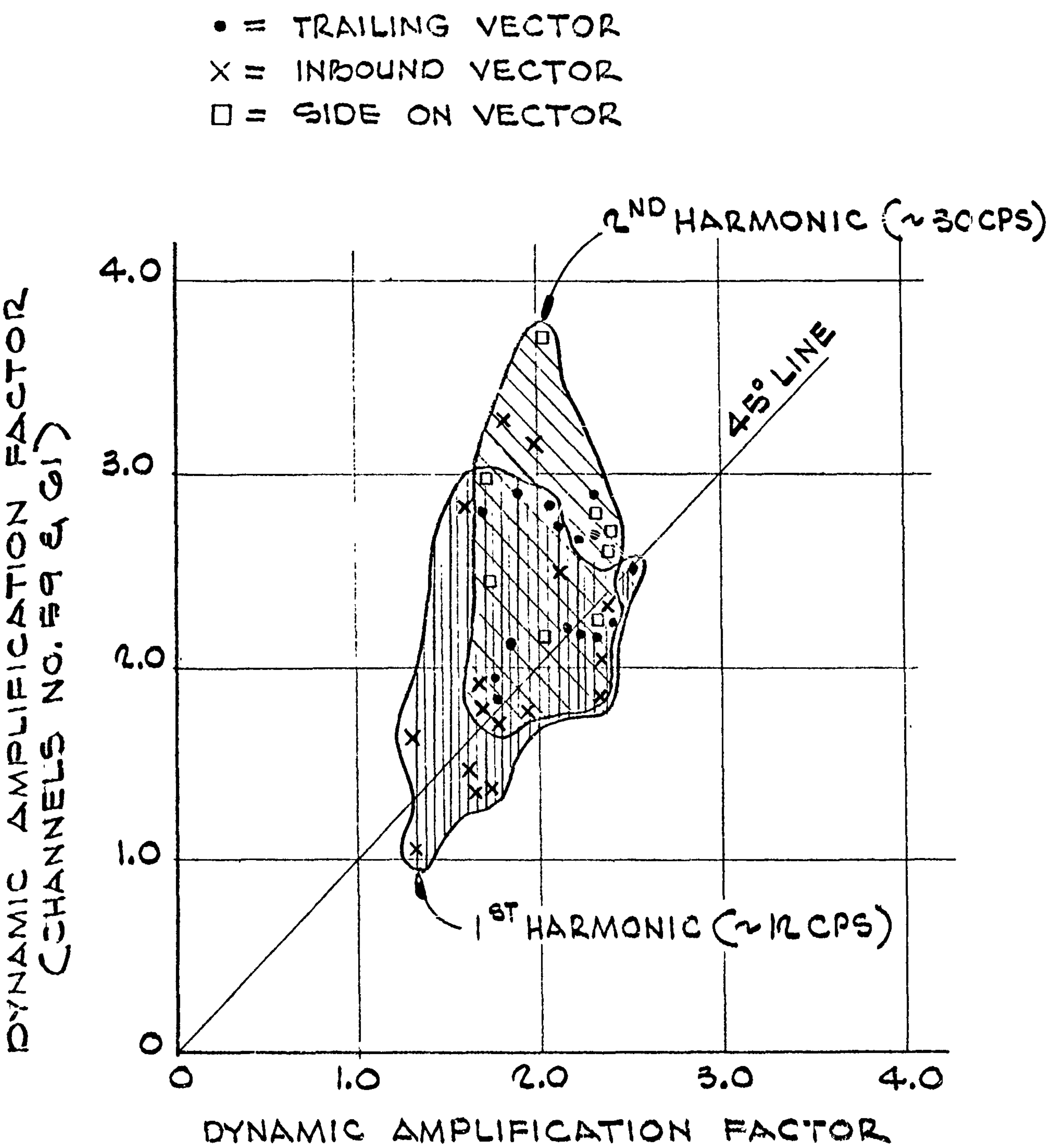


FIG. V-25 DYNAMIC AMPLIFICATION FACTORS AT SELECTED FREQUENCIES OF LOWER WALL RECORDS (CHANNELS NO. 59 & 61) COMPARED WITH AN UPPER WALL RECORD (CHANNEL NO. 58)

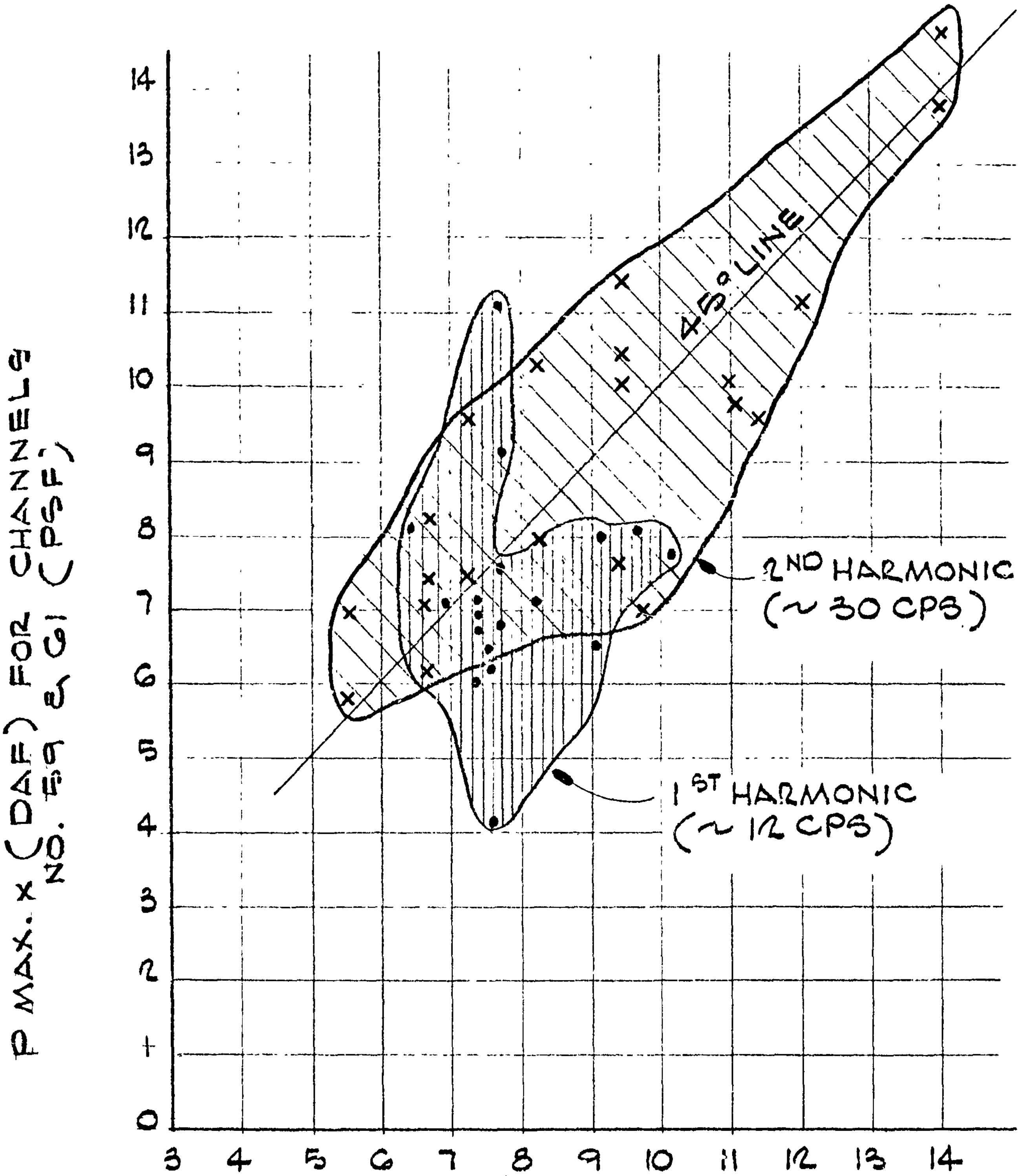


FIG. V-26 EFFECTIVE LOWER WALL LOADS (CHANNELS 59 & 61) COMPARED WITH EFFECTIVE UPPER WALL LOAD (CHANNEL 58) FOR SELECTED FREQUENCIES

VI. RESPONSE OF STRUCTURAL ELEMENTS TO SONIC BOOM LOADS:

A. Introduction:

Response of a pseudo-elastic structural element is simply the strain (differential deflection or deformation) caused by a load. Failure is most closely related to the maximum response, so correlation of this quantity with aircraft design and flight characteristics, as well as the loads generated, is of great importance. After all, man can only control the aircraft design and flight plan so relation of response to these quantities is doubly important.

The White Sands report discussed the maximum response of virtually every type of structural element: walls, windows, roofs, floors, ceilings, and bric-a-brac. Herein, additional analysis explains the maximum response curves obtained. The normality of the distribution of the data is checked first in order to permit statistical testing. Then response of various elements is shown to be dependent on aircraft size and vector. Other studies reveal the variation of natural structure frequency and damping properties and partially explain the large deviation in the maximum response data. The overall movement of large glass panels and Helmholtz resonance effects is discussed to reveal possible failure mechanisms. Finally, response is correlated with actual dynamic loading records.

B. Statistical Distribution of Peak Response Data:

No study on the statistical distribution of response data has been made before. This is now done for two example cases in Figs. VI-1 and VI-2 where the data is shown to lie well within the one standard deviation control curves. Nineteen other distribution studies of free-field (Figs. IV-1 to IV-12) and loading (Figs. V-1 to V-6) data revealed normality of the input. It is concluded that response data is normally distributed within practical limits, say three standard deviations.

C. Effect of Airplane Size and Vector on Response:

The White Sands report concludes that the effect of vector on peak building response is very important. Windows on inbound vectors suffer more than do the same windows on trailing vectors. Houses move in the shear or racking mode much less under sideon vector booms than under inbound vector booms. No variation with vector was noted for ceiling movement. But knowledge of the influence vector has on wall and window response would lend a great deal of assistance to an adjuster who is called upon to judge claims.

Andrews[3] and Blume[4] noted differences in structural response generated by small, as compared with large (B-58), aircraft. The former visually

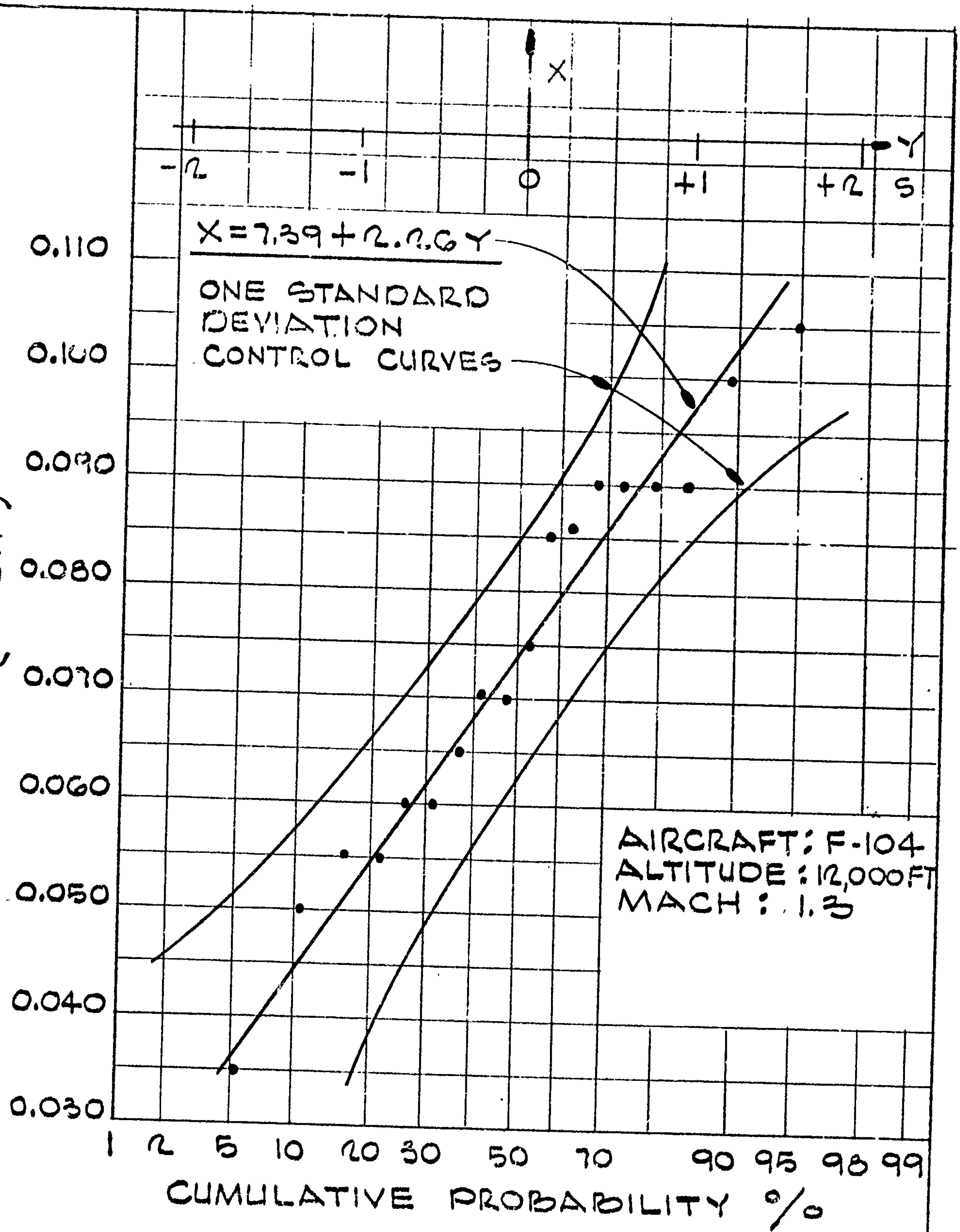


FIG. VI-1 PROBABILITY DISTRIBUTION OF THE PF-6 CEILING DEFLECTION

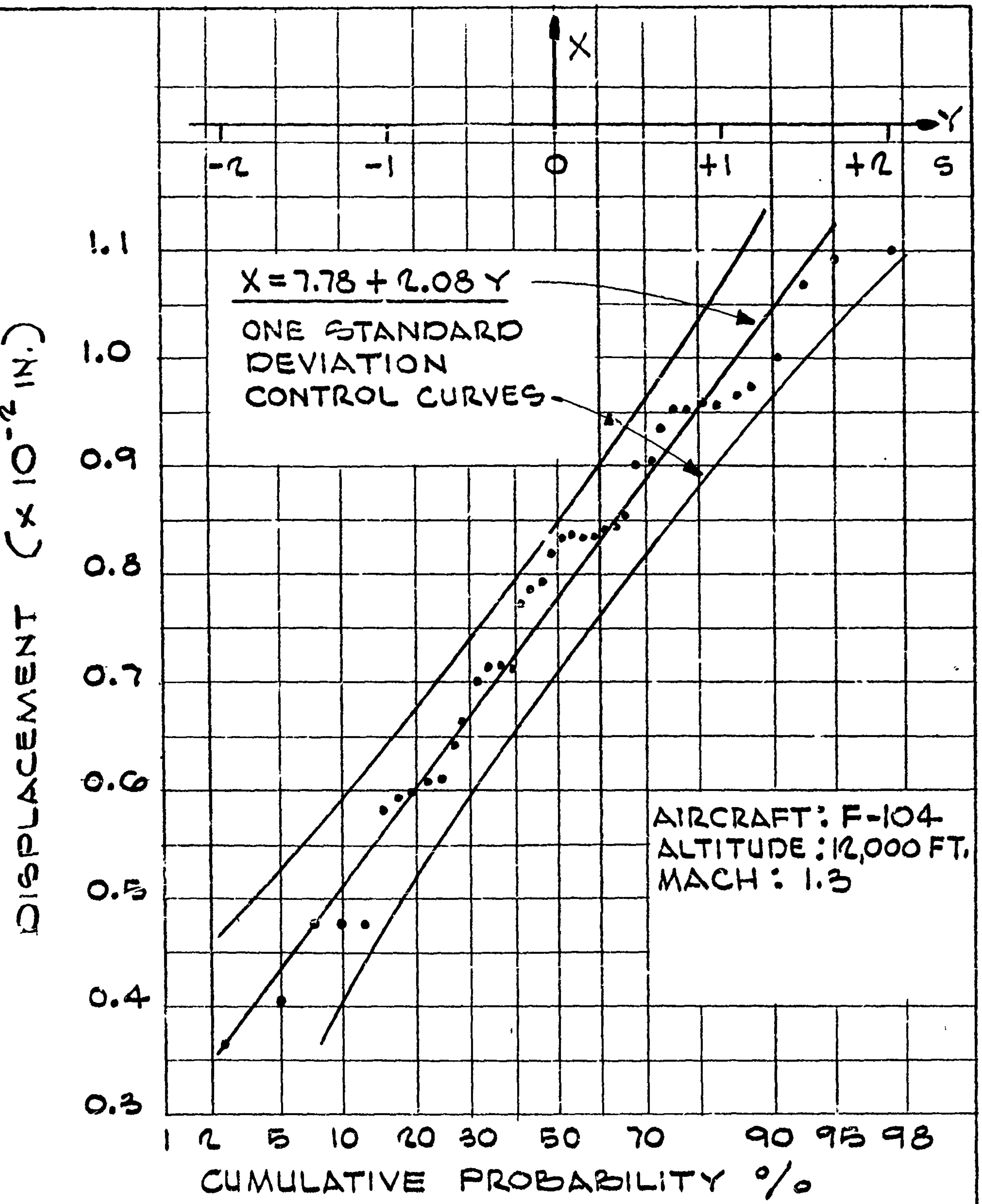


FIG. VI-2 PROBABILITY DISTRIBUTION OF THE W. WALL N. CORNER E.W. DISPLACEMENTS, W-4 noted that an F-106 caused the various strain gages to respond more than a B-58. The latter noted that B-58's caused large, low frequency windows to respond twice as much as F-104's, but no large differences in structural motions were visually observable.

The Oklahoma City data was tested statistically (see Appendix IV-A) to determine whether or not the B-58 in fact vibrated structural members selected at random less than the F-106. Data for Test House No. 1 is presented in Figs. V-3 to V-6, and the results of the tests are listed in Table VI-1:

TABLE VI-1

Means and Standard Deviations of Normalized Response Data Generated by F-106 and B-58 Booms (Vectors are Similar)

Aircraft	Center of Vertical Stud - N. Side (TH #1)		Center of Vertical Stud - W. Side (TH #1)	
	Mean $\frac{(\text{microin/in.})}{\text{psf}}$	Standard Deviation $\frac{(\text{microin/in.})}{\text{psf}}$	Mean $\frac{(\text{microin/in.})}{\text{psf}}$	Standard Deviation $\frac{(\text{microin/in.})}{\text{psf}}$
B-58	3.38	1.01	6.13	1.37
F-106	4.44	1.22	7.81	1.58

Hypothesis: The $(\frac{DAF}{k})_{eff.}$ is greater for the F-106 than the B-58.

Results at 95 percent confidence level:

$$4.44 > 3.38$$

$$7.81 > 6.13$$

Therefore: Hypothesis is true.

We see in Table VI-1 that the F-106 does create a more effective boom for loading the type of wall elements tested than does the B-58. The results from the White Sands, large window tests were obvious, so no testing of the data was necessary (see Fig. VI-3).

In addition to testing Oklahoma City data, tests of randomly selected samples of White Sands B-58 and F-104 data were made. Results of the statistical tests are shown in Table VI-2.

TABLE VI-2

Means and Standard Deviations of Normalized Response Data Generated by F-104 and B-58 Booms (Vectors are Similar)

	Center of Bathroom Wall (PF-6) - Side-On Vectors -		N-S Racking (PF-6) - Inbound Vectors -		Center of Bedroom Wall - Inbound & Trailing Vectors -	
Aircraft	Mean ($x10^{-2}$ in./psf)	Standard Deviation ($x10^{-2}$ in./psf)	Mean ($x10^{-2}$ in./psf)	Standard Deviation ($x10^{-2}$ in./psf)	Mean ($x10^{-2}$ in./psf)	Standard Deviation ($x10^{-2}$ in./psf)
B-58	0.207	0.048	0.035	0.011	0.438	0.229
F-104	0.295	0.086	0.067	0.026	0.398	0.242

Hypothesis: The $(\frac{DAF}{k})_{eff.}$ is greater for the F-104 than the B-58.

Results at 95 percent confidence level:

$$0.295 > 0.207$$

$$0.067 > 0.035$$

$$0.398 = 0.438$$

Therefore: 1) Hypothesis is true for bathroom wall and N-S racking.
2) The data are equal for the bedroom wall.

It is shown that the diaphragm motion caused by a sideon vector, F-104 boom is greater than that generated by a B-58. The racking or shear distortion caused by the F-104 is also greater than that from the B-58. It may be noted further that the B-58 displacement value, 0.00067 in./psf, is significantly larger than that from the F-104, 0.00035 in./psf. As was discussed earlier in Ch. V-H the effective racking loads from large aircraft could be expected to be less than those from smaller aircraft since the effective wave form is not distorted as much. These two observations appear to bear out one another.

The large standard deviation in the bedroom wall data results from both inbound and trailing vector boom data being used. One vector cycle for diaphragm response is 360° (see Fig. VI-3) whereas one vector cycle for shear distortion is only 180°. Separating the inbound from the trailing records for this diaphragm wall, the means and standard deviations are as follows:

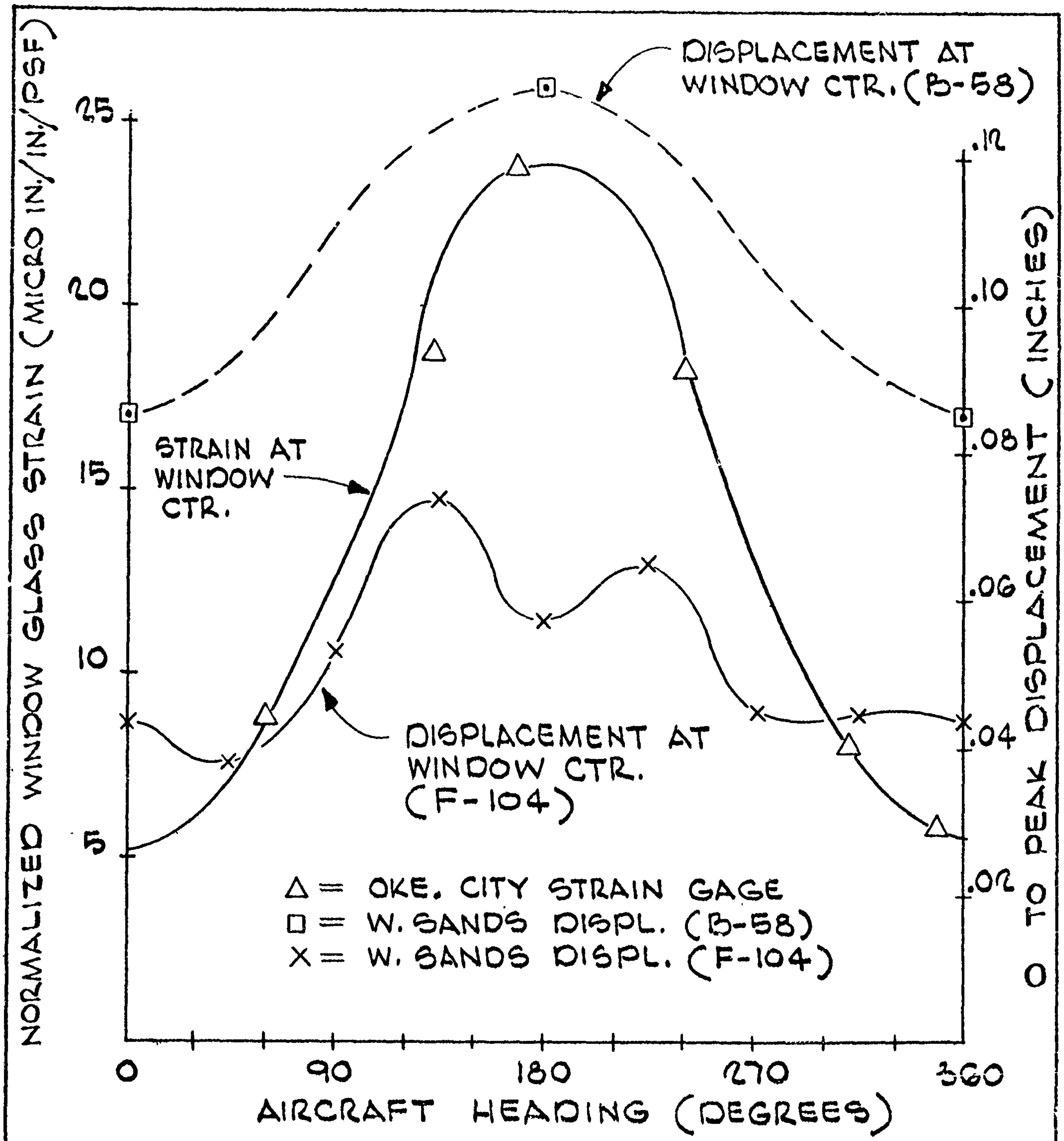


FIG. VI - 3 AVERAGE STRAIN & DISPLACEMENT AT THE CENTER OF LARGE WINDOWS DEPENDS ON VECTOR OF AIRCRAFT WITH RESPECT TO WINDOW

Aircraft	Vector	Mean (x10-2 in./psf)	Standard Deviation (x10-2 in./psf)
B-58	Trailing	0.282	0.116
F-104	Trailing	0.217	0.089
B-58	Inbound	0.613	0.196
F-104	Inbound	0.608	0.178

Even when data are separated by vector, the same result is obtained: that B-58 response is equal to F-104 response for this wall. It is obvious but it was also statistically proved at the 95 percent confidence level that the inbound response in both cases is more than twice as large as the trailing response. Recall in Ch. V-C that dynamic amplification factors of the outside loading depend on vector. Depending on frequency of the wall element, which in this case varied between 10 and 25 cps, the effective load, P_{max} (DAF), is essentially always greater on the inbound runs (see Figs. V-14 and V-15).

The aircraft vector has considerable effect on the motion and strain in a window. Fig. VI-3 presents window response data taken in Oklahoma City at the center of a sliding glass door and in White Sands at the center of a 5'x10' stationary window. The aircraft heading relates to direction of aircraft flight with respect to window. For example, an inbound vector is 180° and a trailing vector 360° or 0°. Note that strains on inbound vectors are 300 percent greater than those on trailing vectors. Displacements are different by only about 50 percent. The peak strain varies in a smooth manner while the displacement is higher on inbound diagonal booms than for headon booms. Reasons for this variation are discussed in Section E to follow.

Means of B-58 window response data are shown to be about twice as great as those for the F-104. Only 180° and 360° vector runs were made by the B-58 at White Sands, so intermediate vector data is unavailable.

D. Variation of Structural Frequency and Damping:

Andrews[3] measured some natural frequencies from strain gage records in the free vibration period. Variations were found to be random, and in general he concluded that any change in frequency "is not a valid measure of the cumulative effects of sonic booms due to the effects of other variables such as temperature, wood moisture content and coupling (of other structural elements)". Small internal members such as a stud or plaster sample do have many frequencies, and temperature and moisture content vary wood properties, but if a boom trend exists it would be unidirectional. A "terrain" correction, as geophysicists refer to it, should be evident, if the variable studied is sensitive enough to the quantity of interest.

By using a lot of data it may be possible to separate the random effects from the boom trend.

The White Sands displacement data taken at the top corner points of house W-4 (plaster-on-wood-lath internal wall finish) was automatically converted to digital form, harmonically analyzed by a digital computer and the frequency of peak displacement read from the spectra for over 300 booms occurring within 18 days. Both E-W and N-S shear wall data were analyzed for a total of over 600 harmonic analyses. Figs. VI-4 and VI-5 present the results. At a 95 percent level of confidence it may be concluded that the data do not vary with day or overpressure strength.

A limited number of the above-mentioned records were also read visually in the free vibration interval. Fig. VI-6 reveals that the means of the natural frequencies read visually do tend to decrease with time as would be expected if booms weakened structures and therefore made them less stiff. But because of the large standard deviation of the data relative to the change of the means and because the structures cracked and weakened overnight during non-boom periods the specific influence of boom on lowering stiffness is not revealed by Fig. VI-6.

Fig. VI-7 reveals at a 95 percent confidence level that frequency is independent of overpressure. If booms weaken structures and therefore lower their natural frequency, the higher strength booms should be more effective in doing so. No evidence of this is present.

At this point a brief word about confidence level is in order. Someone once said that there is no black nor white, only different shades of gray. At a level of confidence (probability of accepting a true hypothesis) of 95 percent we are concluding that very dark gray is in fact black. We could not make this conclusion if a confidence level of 99.99 percent were the criterion for black. But then again, when one deals with a random variable whose standard deviation is large, as is the case for boom, this level of confidence on cumulative effects cannot be achieved without thousands of data points taken over a period of many years. Canada has a ten-year plan for collecting data on snow loads, for example.

At the same time that frequency was visually read from the records the damping factor was also computed. It was derived by measuring the amplitudes of several successive cycles in the free vibration time period and averaging the damping factors computed. Results are shown in Table VI-3.

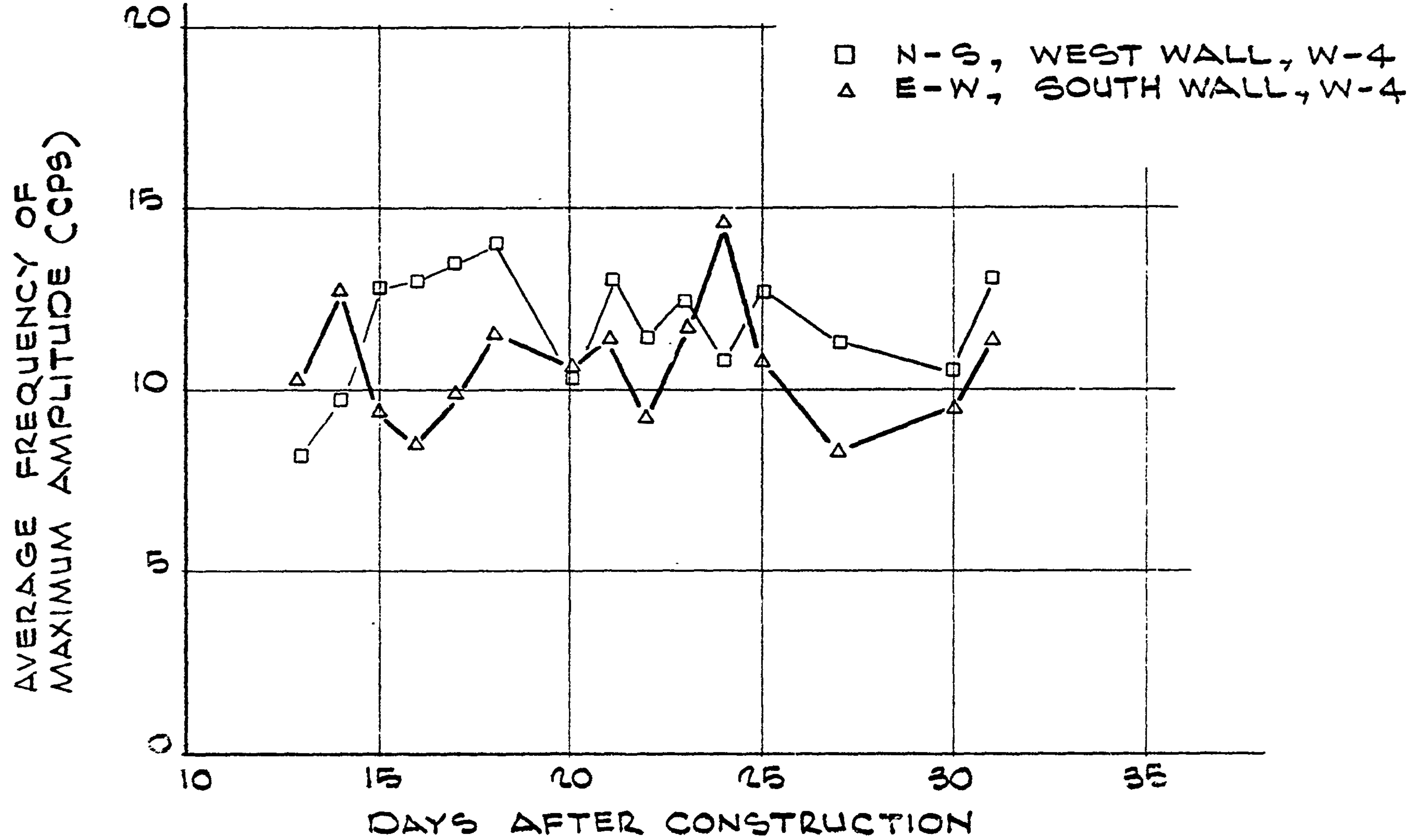


FIG. VI-4 MEAN PEAK FREQUENCY, COMPUTED BY HARMONIC ANALYSIS, VARIES WITH TIME IN A RANDOM MANNER

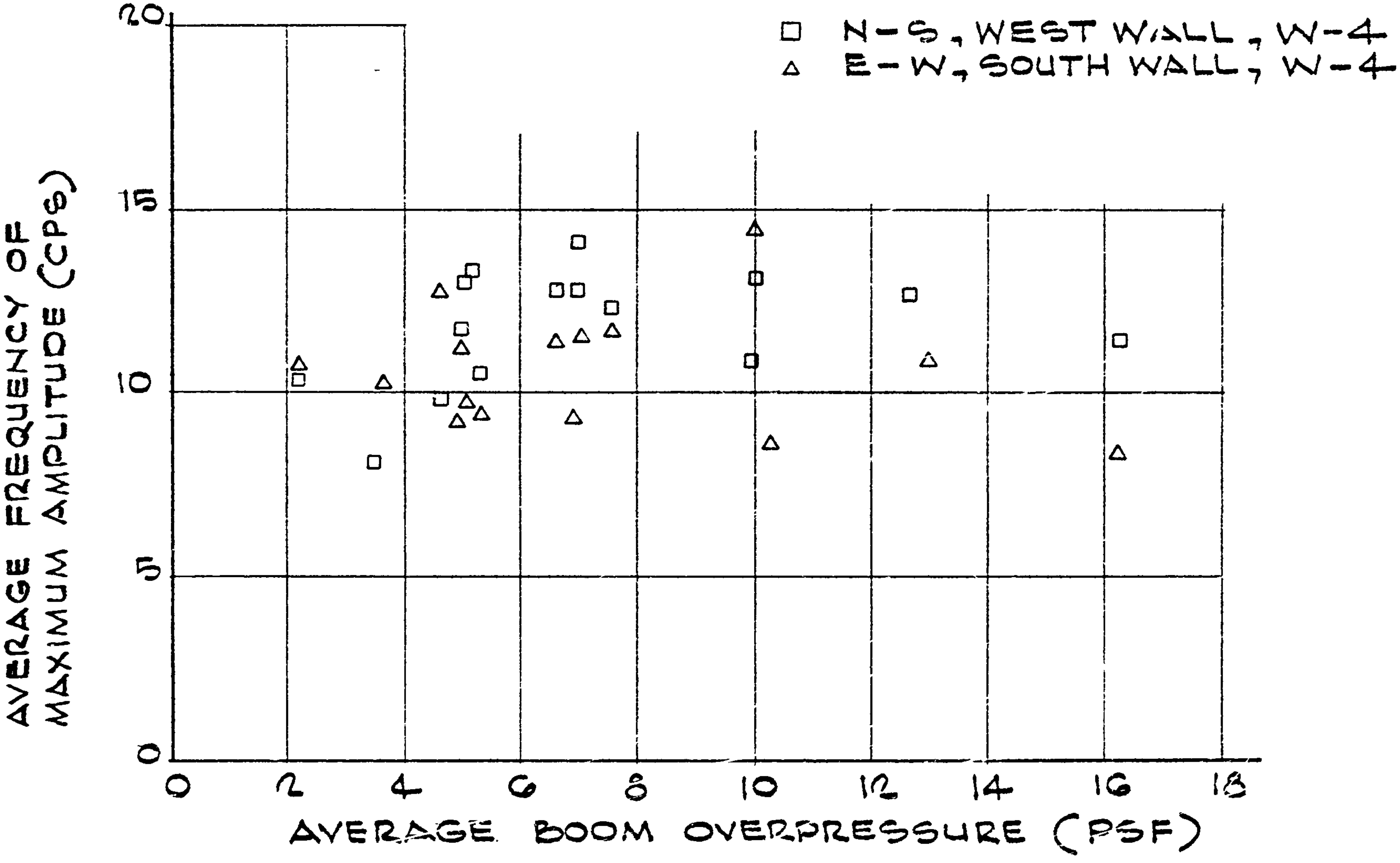


FIG. VI-5 MEAN PEAK FREQUENCY, COMPUTED BY HARMONIC ANALYSIS, DOES NOT VARY WITH AVERAGE DAILY OVERPRESSURE

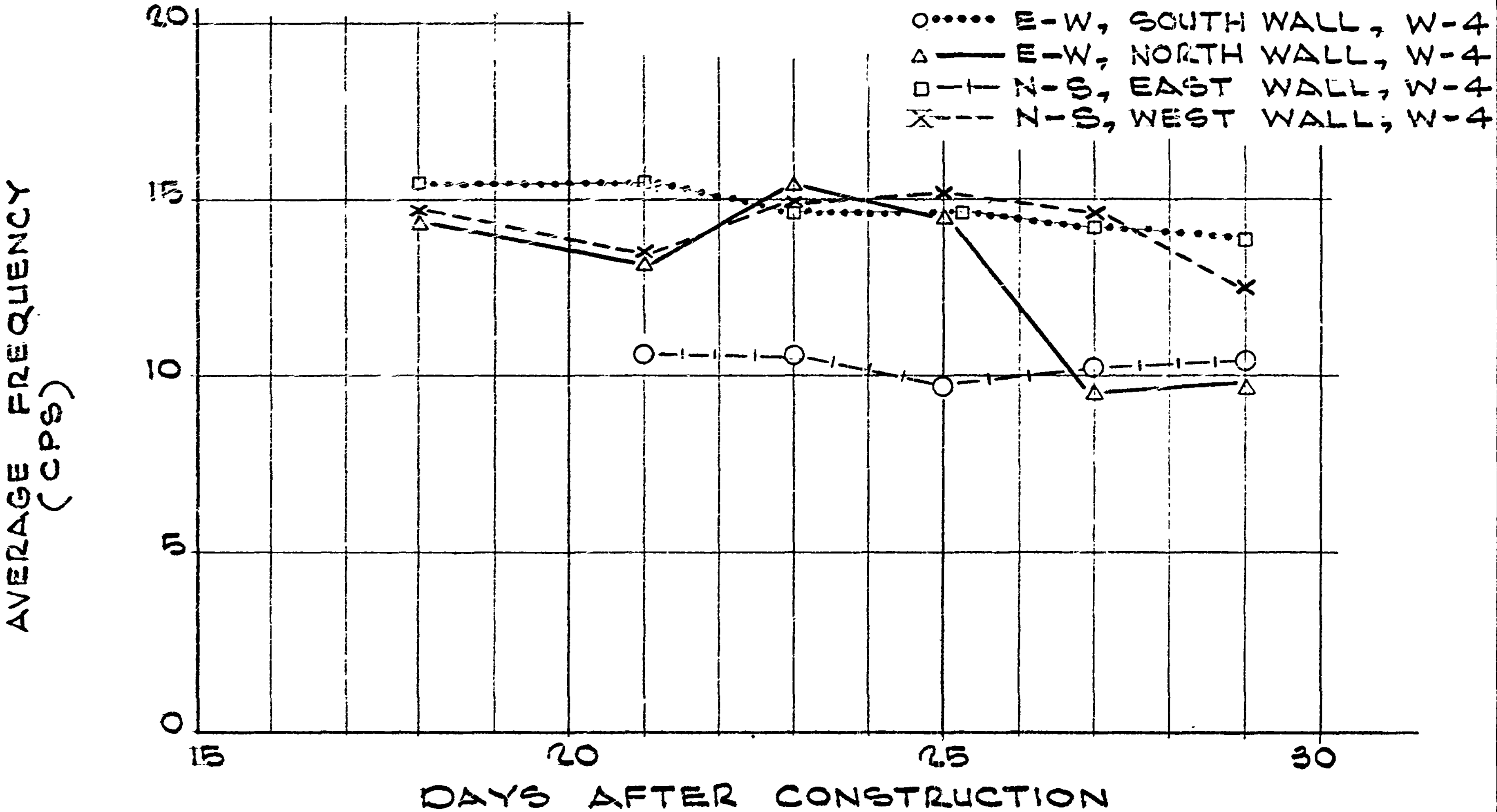


FIG. VI-6 MEAN FREQUENCY, AS READ VISUALLY, APPEARS TO DECREASE WITH TIME

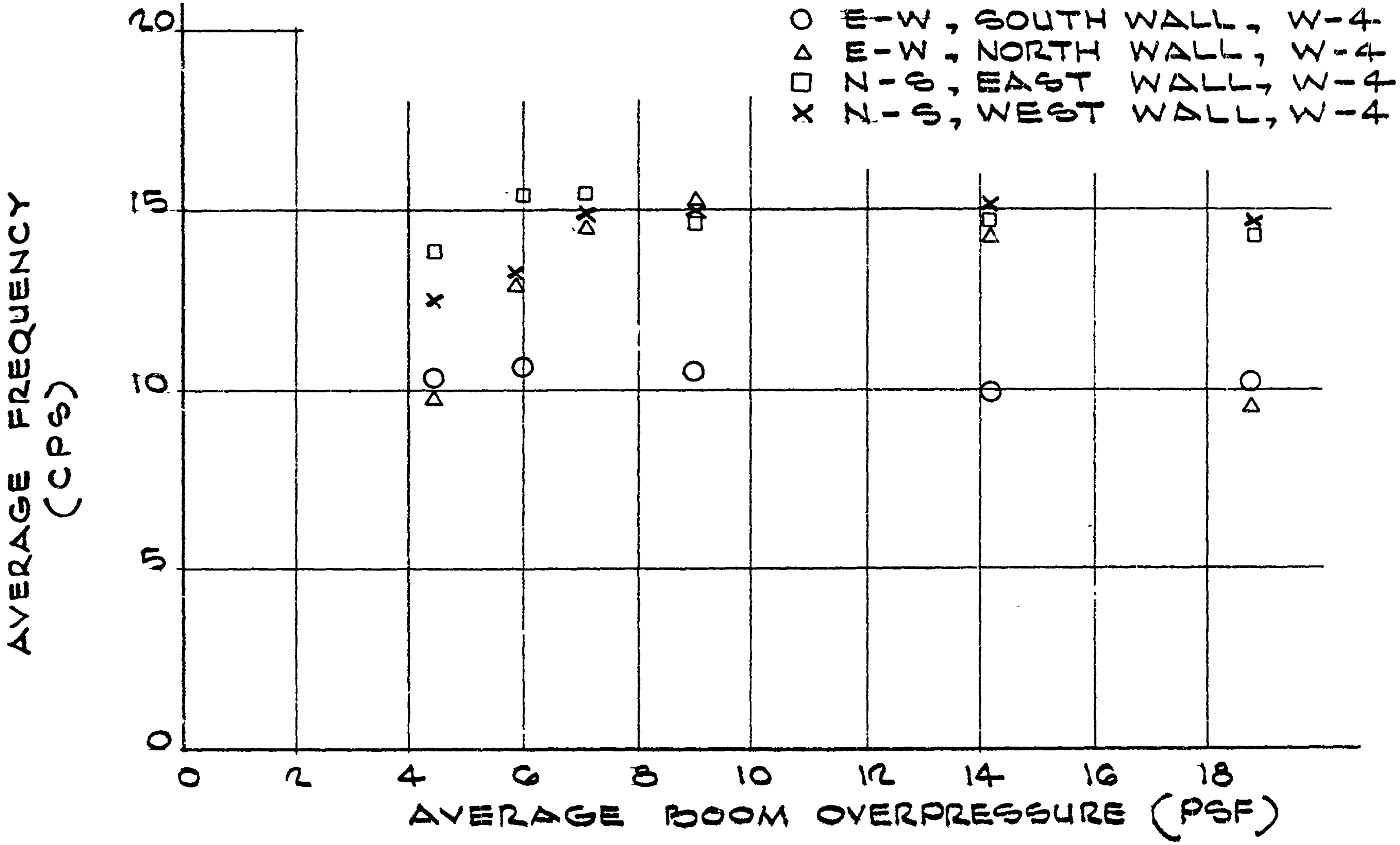


FIG. VI-7 MEAN FREQUENCY, AS READ VISUALLY, IS INDEPENDENT OF BOOM STRENGTH

TABLE VI-3

Mean Damping Factors Read for Various Days During the White Sands Boom Tests

			Damping Factor (%)				
Material	Days After Construction	Free-Field Overpressure (psf)	North Wall	East Wall	South Wall	West Wall	Average
Plaster on Wood Lath	18	7.15	5.83	4.60	4.08	4.03	4.71
	21	5.9	4.57	5.09	5.24	3.58	4.61
	23	8.9	4.73	4.35	5.19	4.50	4.69
	25	14.2	4.76	4.39	5.03	3.56	4.44
	27	18.7	4.86	4.20	4.60	3.81	4.37
	30	4.4	5.04	4.05	5.28	4.88	4.81
			Center Wall	East Wall			
Plaster on Gyp Lath	3	6.8	3.95	3.62			
	5	8.3	4.14	4.23			
	6	6.1	4.00	3.88			
	7	2.2	3.72	3.34			
	9	5.7	4.95	4.97			
	11	4.5	4.53	4.00			

Damping factor varies from day to day and appears to be independent of both time after construction and overpressure. The change in damping factor as well as frequency may be important objective subjects for test to determine cumulative effects. But because the standard deviation of the data is high relative to the change in the means of both frequency and damping and because frequency and damping are probably quite insensitive to small changes caused by minor cracking, the amount of data used in these tests may be insufficient to expose a cumulative damage trend. Cumulative damage has not been defined quantitatively, so no conclusion can be made about it from the above tests.

A method that may prove useful is one which tests the variation of amounts of solid friction present as a function of displacement. And displacement is related to boom strength. There is evidence that solid friction damping is associated with the larger vibrations. But under low vibrations only viscous type damping predominates. Since surface rubbing, as one stud with a plate or internal friction of plaster, causes solid friction, a plot of this quantity versus deflection, and from there to intensity, could give an objective method of determining when a boom caused solid friction and possible cumulative damage.

E. Participation Factors for Large Windows:

During the White Sands tests displacement transducers were placed on several large windows at evenly spaced positions in an attempt to determine how many window modes participated in the motion of glass subjected to boom. Fig. VI-8 shows the location of the gages in one instrument plan and Fig. VI-9 illustrates the records taken on an inbound vector, F-104 boom run. Several observations can be made:

1. Two frequencies predominate, one at about 7.5 to 10 cps and one at about 20 cps.

2. The higher frequencies have their largest participation near the boundaries of the glass.

3. The higher frequency is unimportant at the center.

4. The higher frequency attenuates more rapidly with time than the lower one.

5. The motion is effectively dead after about four cycles of the low frequency.

6. Rise time increases with distance from the window boundaries.

7. The frequencies observed agree better with the modal frequencies of a simply supported beam whose span is the short window dimension (6.35 cps(I)* and 25.4 cps(II)) than one whose span is the long dimension (3.18 cps(I) and 12.7 cps(II)), or a clamped beam (14.4 cps(I) and 39.7 cps(II)).

Fig. VI-10 shows the shape of the window at various times. Both the first and second mode shapes are evident in the short and the long direction. The center point appears either to lag the other positions a little, or the second mode travels back and forth from window edge to window edge like a wave in a rope that is snapped at one end and fixed at the other.

The effect of a trailing vector is shown in Fig. VI-11. Several observations can be made:

1. Only one frequency is evident at about 8.5 cps.

---

*Refers to mode number.

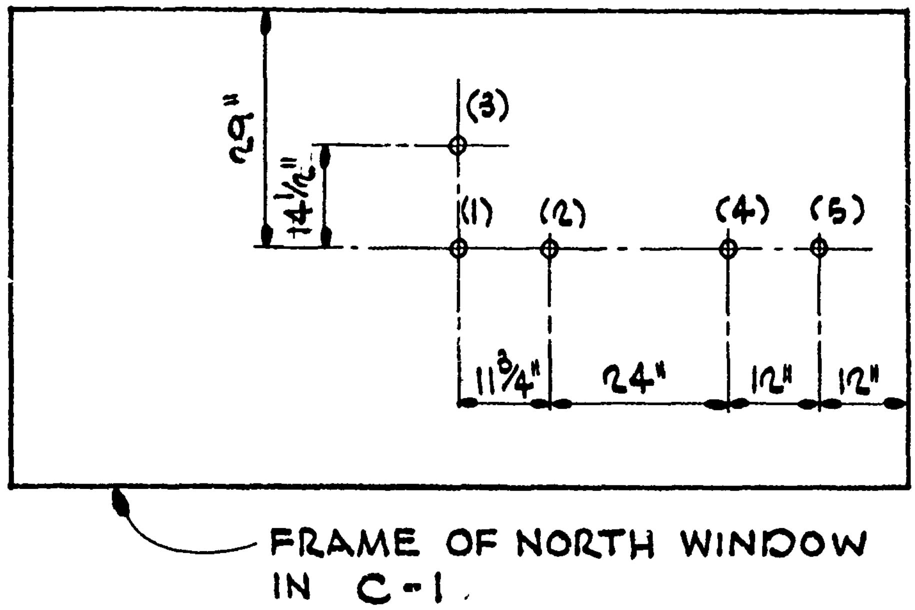


FIG. VI-8 DISPLACEMENT GAGE LOCATIONS ON NORTH 5'x10' WINDOW IN CONCRETE BLOCK BLDG. (C-1)

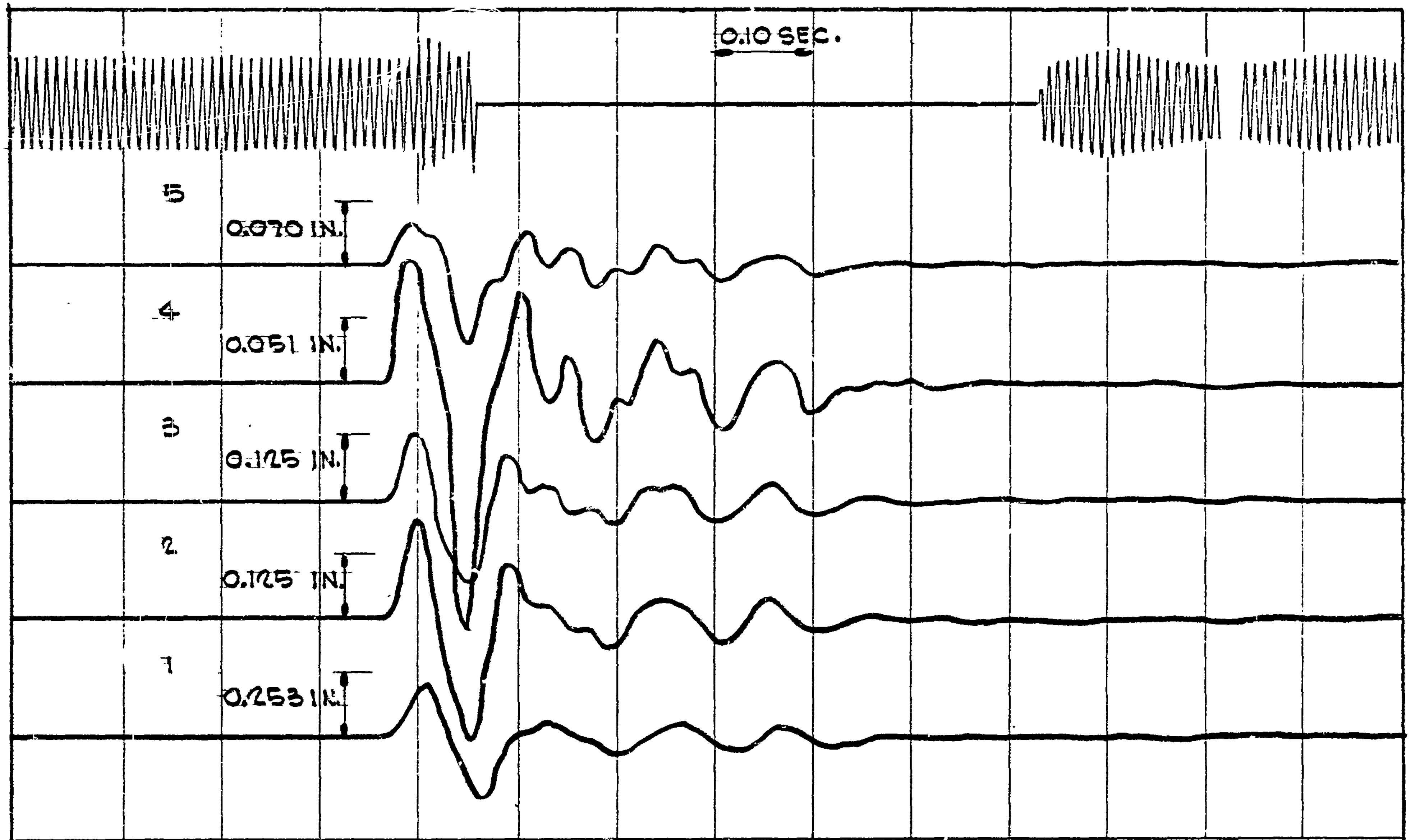


FIG. VI-9 WINDOW DEFLECTIONS AT LOCATIONS (1) TO (5) FOR AN INBOUND VECTOR BOOM.

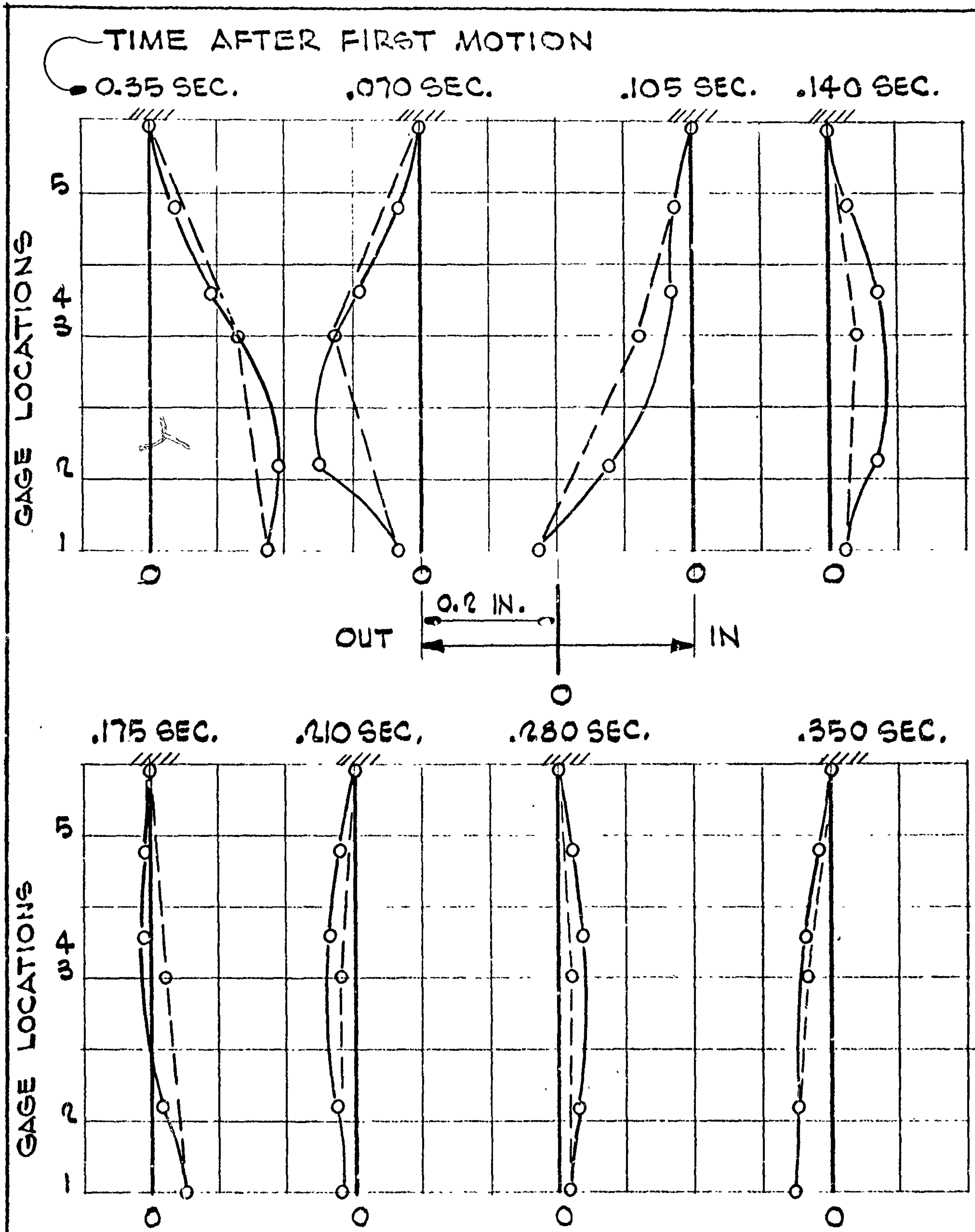


FIG. VI-10 SHAPE OF WINDOW AT VARIOUS TIMES AFTER BOOM ON INBOUND VECTOR BOOM

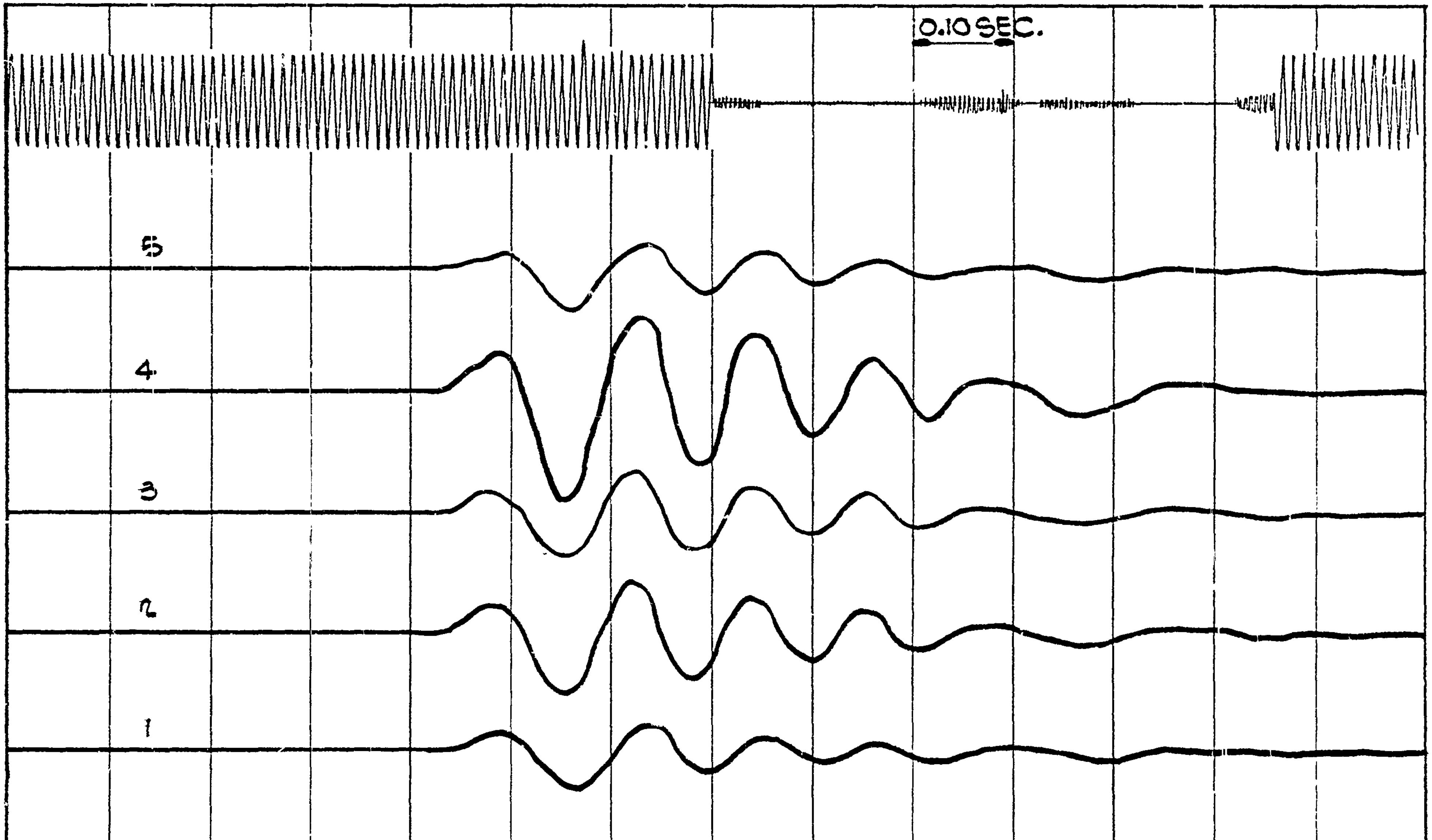


FIG. VI-11 WINDOW DEFLECTIONS AT LOCATIONS (1) TO (5) FOR A TRAILING VECTOR BOOM

2. The motion is effectively dead after about 5 or 6 cycles.

3. The frequency lowers with amplitude,

4. The effective damping factor is about 8 percent.

5. The damping appears to be viscous.

6. The center gage appears to start later than other gages.

The shapes of the window at successive times are shown in Fig. VI-12. The second mode appears to be either present or the center gage starts later than the others for some reason causing the center window position to apparently lag in time. No high frequencies are evident in any of the records. The late start does not appear on the inbound vector runs, however (Fig. VI-9).

The participation of a higher mode in the vibration of glass can account for the large differences noted earlier in Fig. VI-3 between strain and displacement on inbound and trailing vectors. As the higher modes participate a smaller radius of glass curvature and therefore an increase in surface strain can exist. Inbound vectors are about four times as serious as trailing vector runs for large windows because of the participation of the higher modes in the vibration.

The effective damping is higher for the inbound vector runs (4 cycles) than the trailing vector runs (5-6 cycles) even though the initial amplitudes are larger. The air cushion generated by the rapid window movement on inbound vectors discussed in Ch. V probably accounts for the difference.

No comparison of mode shapes for B-58 booms was possible since the gag es were installed after the B-58 series. Because the F-104 boom may excite the higher modes better (no proof available) the stresses in the windows may not be twice those generated by an F-104 even though the center point deflections are twice as large.

F. Helmholtz Resonance:

During the White Sands tests it was noticed that if all windows and doors of the two-story house were closed the vibration of the large 5'x10' windows decayed rapidly as in the closed box case in Figs. VI-9 and VI-11. Fig. VI-13 shows the typical living room, single-story module living room. The two-story house had one of these rooms stacked on the other and interconnected by a large stairwell. If the front door of the two-story house were left open the window vibration would die down to near zero and then begin again but at a lower frequency, about 5.5 cps. This vibration would persist at an amplitude of about 1/20 inch for many cycles. Helmholtz type resonance was evidently taking place as Adnrews[3] suggested. The frequency may be computed by the following equation:

$$f = \frac{1}{2\pi}\sqrt{\frac{KC^2}{Q}} \quad . \tag{1}$$

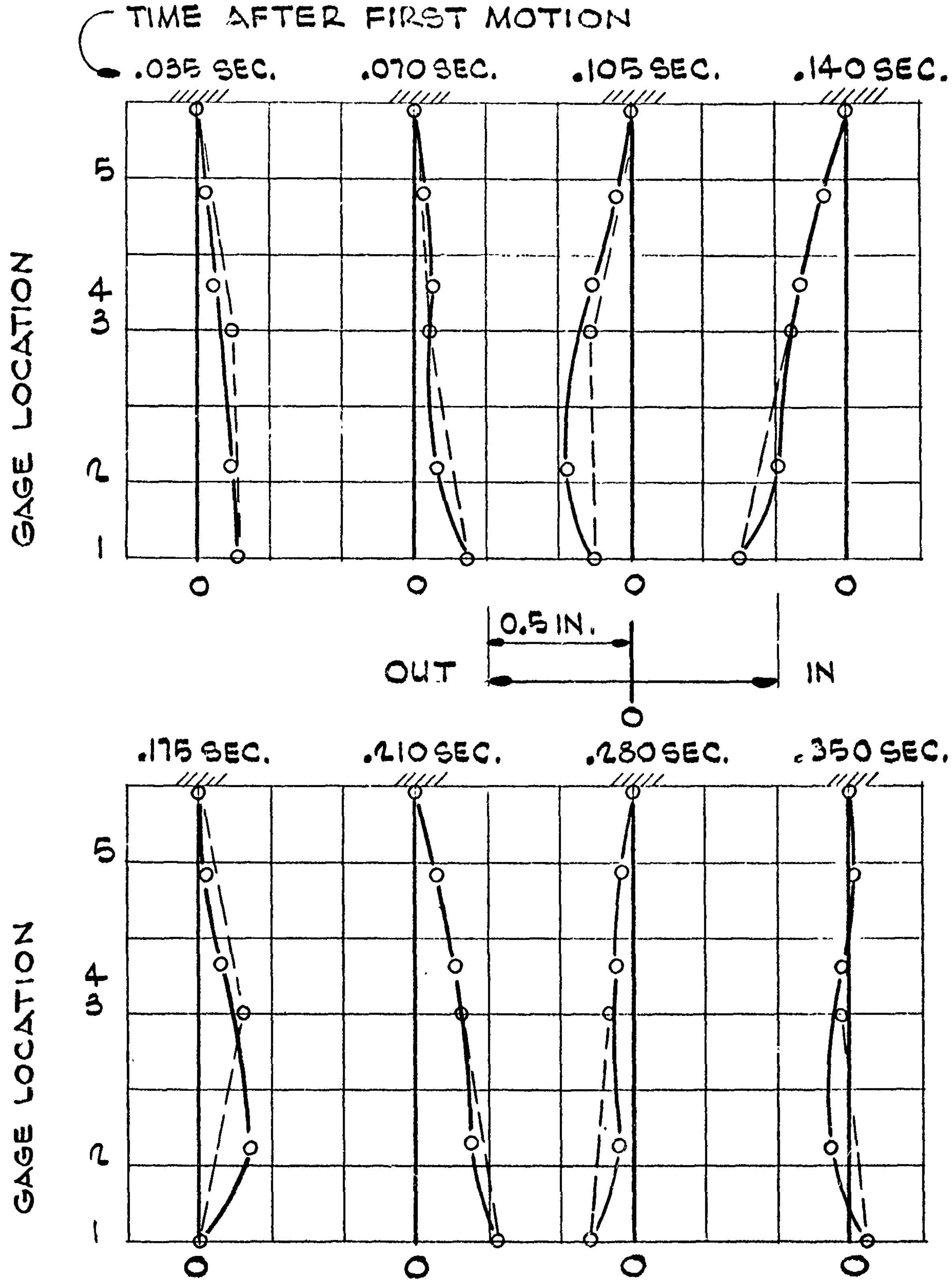


FIG. VI-12 SHAPE OF WINDOW AT VARIES TIMES AFTER BOOM ON TRAILING VECTOR BOOM

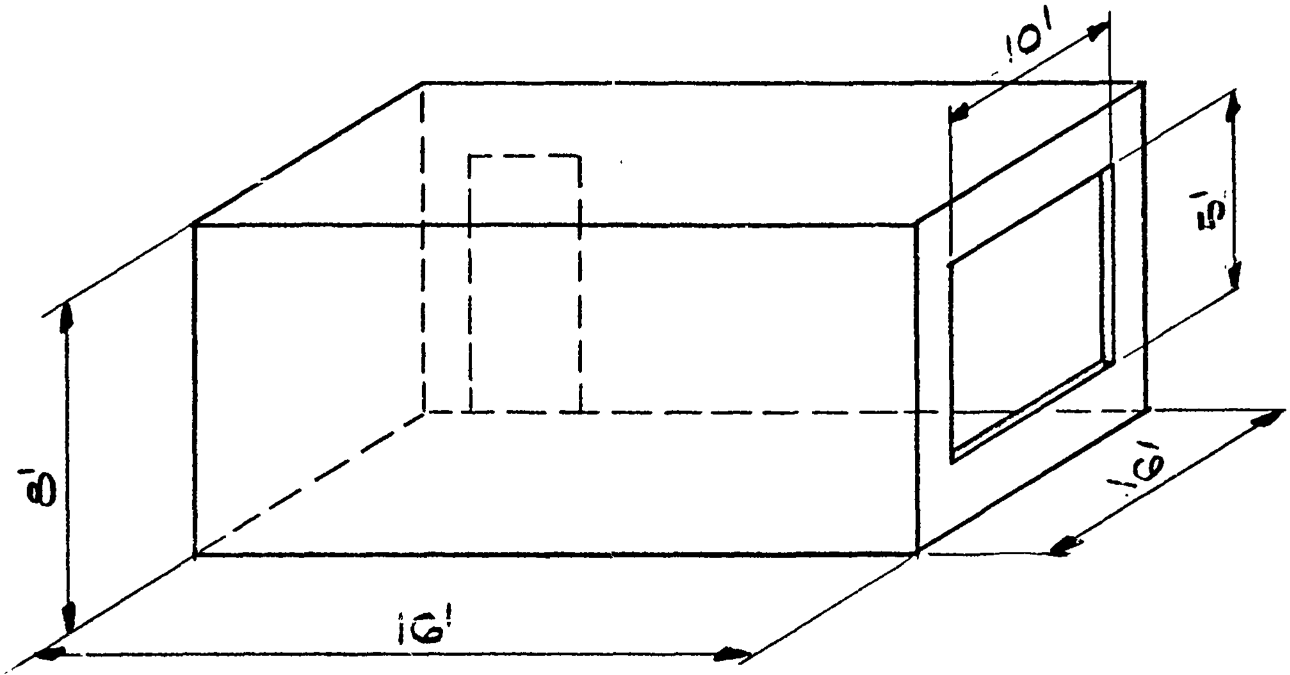


FIG. VI-13 TYPICAL WHITE SANDS LIVING ROOM OMITTING ONE INTERINAL DOOR, EXTERIOR SLIDING GLASS DOOR AND A CASEMENT WINDOW

Where K is about $2\,(A/\pi)^{1/2}$, A is area of the door, C is the speed of sound and Q is the volume of the room. Substituting the appropriate values for the house and door a frequency of 5.83 cps is computed. This is close enough to that observed to support the thought that Helmholtz resonance occurred.

If the frequency of the window agreed with the resonater frequency, would dynamic amplification take place? Can the resonance occur with all doors and windows closed and a large window acting as a diaphragm across the opening?

Let us examine the first question. For Helmholtz resonance to be possible the least diameter of the vessel must considerably exceed the dimensions of the aperture[23], and the wave length of the sound (110 ft. at 10 cps) must considerably exceed the least diameter of the vessel. For the Helmholtz frequency of the room in the house mentioned above to match that of the window the aperture would need to be about $[9/5.83]^4$ or 5.8 times as large as the door. This dimension is about 14.5 ft. which is not considerably smaller than the least dimension of the two-story house (16 ft. assuming both the upper and lower room contribute to the volume).

Frequency of the room could also be increased by halving the volume of the room. This exact condition would exist in the case of the one-story houses on the White Sands tests which were similar in plan to the two-story house. Unfortunately, no window movement was recorded with the door of the one-story buildings open, but the doors were left open on many occasions during non-recording periods without any window breakage. It even visually appeared that the peak motion was less when doors and windows were left open since the pressure on either side of the window could equalize rapidly. Helmholtz resonance may not exist, however, for this door-room size combination since the least diameter of the room (8 ft.) is about the same as the door height and only three times door width.

If the opening were smaller than a door in order to insure volume resonance, the frequency would be lower than the frequency of the existing window. Larger windows could be fitted into this 16"x16" room, but the probability of such a window, room volume combination occurring in practice is low.

There is another factor that would prevent resonance, dissipation. For example, if the amplitude of the window exceeds the initial amplitude caused by the boom pulse the window begins to move air rather than being moved by it and the air then acts as an effective damper. Earlier we found the damping factor of a large window to be 8 percent on trailing vector whereas Andrews found an equivalent value of 10 percent. Window frequency also changes with damping.

In summary, because many parameters such as window size and thickness and room volume and aperture area must agree to cause resonance, because excursions larger than the initial excursions would generate a damping effect and because windows did not break under booms when a resonance condition existed at White Sands the probability of Helmholtz resonance being a critical parameter is considered to be low.

The second question of volume resonance existing even with all doors closed requires formulation of a different frequency equation. This may be done by following Lamb's procedure of determining the frequency of an air "piston" within a tube connected to a vessel[23]. A very approximate expression for the frequency, f, of such a window-room combination would be:

$$f \cong \frac{1}{2\pi} \sqrt{\frac{\rho c^2}{Q \rho^1} \frac{A}{h}} \quad , \qquad (2)$$

where, ρ = density of glass, and h = glass thickness.

Assuming C = 1100 ft./sec. and $\rho^1 = 2000 \rho$, Eq. (2) becomes

$$f \cong 3.9 \sqrt{\frac{A}{Q\, h}} \quad , \qquad (3)$$

where all values are in feet.

If the window area and thickness values in the two-story house were used ($A = 50 ft.^2$ and h = 1/48 ft.) a frequency of about 3 cps is derived. This is lower than the 8-9 cps window frequency. Window frequency varies directly with thickness and inversely with window area,

$$f \cong 2x10^4 \frac{h}{A} \quad , \qquad (4)$$

where both h and A are in feet and the window length to breadth ratio is 2/1.

The equation resulting upon combining Eqs. (3) and (4) is,

$$f^3 = \frac{1.18 \times 10^6}{Q} \quad , \qquad (5)$$

where Q is in cubic feet. For an 8"x16" window the associated volume must be 1.47×10^5 $ft.^3$ or a 24 ft. cube. This volume and diameter are not considered to be either a probable room-window size combination or an acceptable diameter to window dimension requirement for resonance. It is considered highly improbable that a room-window combination exists where the condition of window dimension $\ll$ vessel diameter is met.

G. Comparison of Actual Response with that Predicted from Load:

Response computed from microphone pressure records has been assumed to represent actual response. This is not entirely accurate for the microphone does not record loads introduced by structural elements adjacent to the element in question, nor does it integrate over the loaded surface. But if the damping and principal frequency were known, could one approximately predict response with the P_{max} $(DAF)_{f,\beta}$ technique?

Fig. VI-14 plots several quantities for comparison. The line represents the displacement of an 8"x10" window under a static load computed by beam theory using the least window dimension. As we saw earlier this theory appeared to be most adequate for prediction of frequency for a large window. The circles plot the peak outside pressure with recorded peak window displacement, the triangles plot the effective load using only the outside pressure record and recorded displacements and the crosses plot net load versus displacement. A frequency value of 2.5 cps was measured for the window and a damping factor of 2 percent was assumed.

The net load agrees best with the assumed theory, and the standard deviation of a line passed through each set of points and the origin is least for the net load data. Some degree of correlation is therefore achieved even though a simplified set of assumptions for window behavior were used.

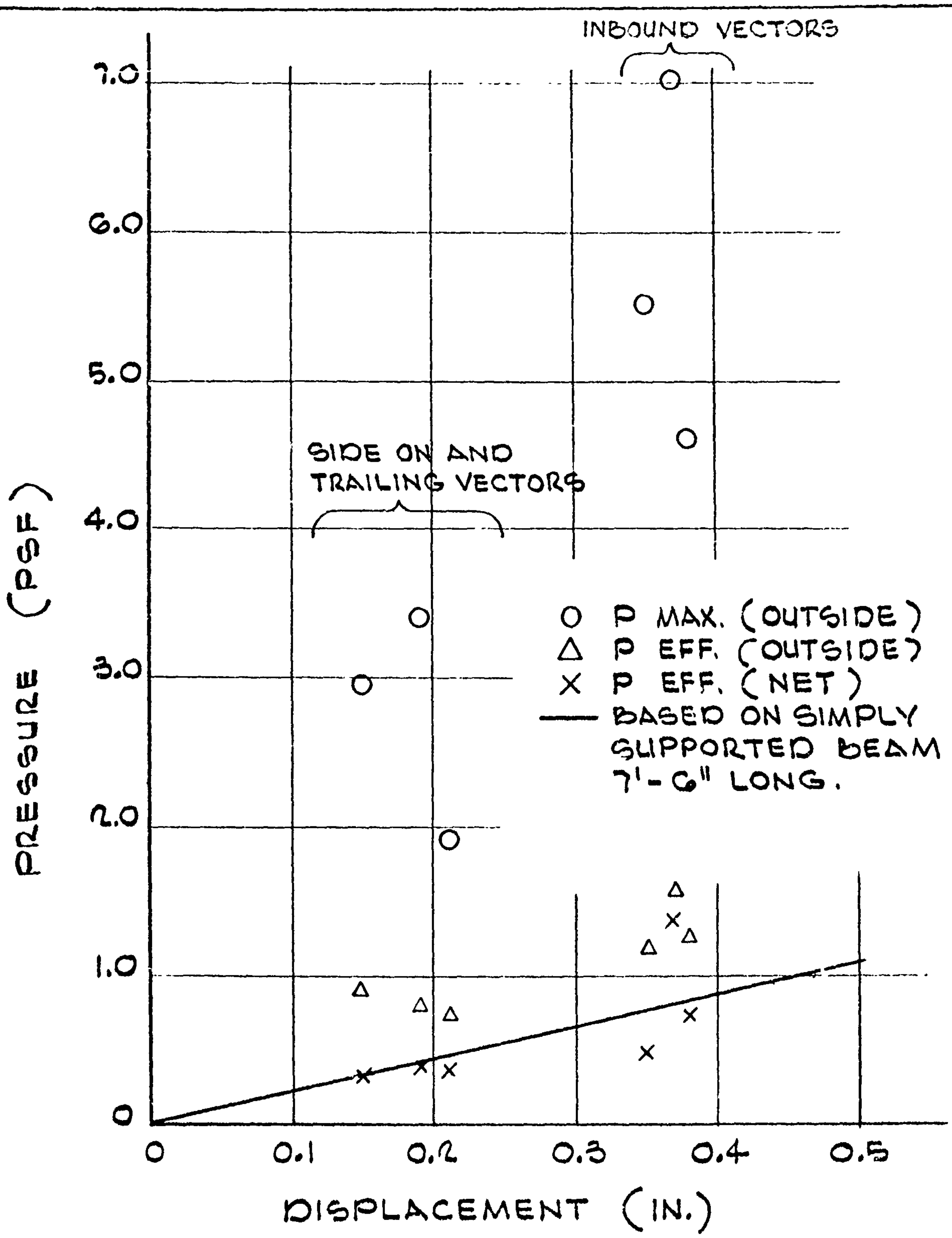


FIG. VI-14 EFFECTIVE LOAD COMPUTED FROM A NET RECORD AND PLOTTED WITH OBSERVED DISPLACEMENT AGREES WELL WITH BEAM THEORY FOR 8'x 10' WINDOW

VII. FACTORS GOVERNING THE INTENSITY* OF SONIC BOOM:

A. Introduction:

The response of structures to sonic booms is determined by the peak pressure, the time character of the effective boom load on the object, and the impedance of the object in question. In examining free-field boom waves Andrews[3] and others have suggested that simple quantities such as positive impulse, negative pressure, etc., with response to determine which of them appear to govern response the best. Another objective is to discuss the evolution of thinking on intensity in general.

At this point it is important to know why correlation of one variable (load dependent) with another (response dependent) is even the subject of an investigation such as this. It is needed for:

1. understanding boom response,
2. monitoring and damage analysis during regular SST flights,
3. input to aircraft design and flight plan considerations, and
4. input to future building design codes in the SST age.

As an hypothetical example, the peak boom pressure ten miles from the flight track of a supersonic airplane may be one half that directly under the flight track. But, because of atmospheric dispersion effects, the duration of the wave may be twice as long. In turn, low frequency windows may respond more at ten miles than they would when situated directly under the flight path even though the peak pressure is halved. (DAF) may be increased by two or more in other words. A monitoring gage should be designed to better record the effect of duration than peak pressure, if such were the case.

Regarding aircraft design, if it were found that the spacing of secondary bumps on a boom wave caused a random and therefore a possible decrease of critical bandwidth response by 30%, it may be cheaper to modify the aircraft configuration than it would be to fly supersonic at an altitude 59% higher ($p_o \sim y^{-3/4}$) to achieve the same effect.

B. Factors Governing Intensity Values:

We have mentioned that intensity from a dynamic load such as boom is governed by the effective or equivalent static load and the effective stiffness. Response is,

$$u = \frac{P_{max}(DAF)_{f,\beta}}{k} . \qquad (1)$$

---

* Intensity refers to peak structural response.

Let us discuss some of the difficulties that exist in determining u from the above load quantities (P_{max} and DAF) and structure properties (f, , and k).

1. If only a single microphone record is used in analysis, an approximation of the load on only one surface is available. As has been seen, two records, inside outside in the case of a diaphragm and front and back for shear distortion, are the minimum requirements. Even then, load varies from point to point on a structure because of turbulence and a non-normal wave front with respect to the surface of interest. Walls, ceilings, roofs, and floors are coupled with each other. The effective load is therefore not only the vector sum of external loads but also the foundation motion resulting from motions of the other elements. An effective loading record can be considerably different from that from a single microphone placed on a wall or other element.

2. There is no single natural frequency of a distributed mass system. Effective frequency approximations are usually assumed or computed. Earlier in Chapter VI it was shown that the predominant frequencies of the shear walls of the 16' x 32' houses tested at White Sands were about 10.5 cps for the 16' wall and 14.7 cps for the 32' wall. Since these frequencies varied by $\pm$15 percent a considerable difference in response under F-104 booms could be expected. Many higher modes of vibration are unlikely to participate in the response of elements under sonic boom loading, which is short rather than long duration loading, but perhaps two to three may be present depending on the load. Figs. VI-9 and VI-11 differ a great deal from one another, for example.

3. Damping determined from response records varies from boom to boom and day to day. Response, u, will also vary. Fig. VII-1 shows an example of the influence of damping factor in controlling the response of oscillators subjected to earth motion from a nuclear explosion. A damping factor variation of from 0 to 10 percent may cause a response variation of up to 300 percent. This wide a divergence is not expected for boom type loads.

4. Effective stiffness must vary since frequency does. The change is probably brought about by temperature, humidity, and aging conditions altering composite wood-plaster structures, as well as change in participation factors.

It is easier to predict static than dynamic response since only the static stiffness and maximum load are the variables. When the load varies in time and when dynamic structural properties enter the determination of response, more scatter and less correlation between simple quantities such as peak pressure or impulse and response are to be expected.

C. Background:

Intensity has been the subject of investigation and a point of controversy for many years. Two major areas have contributed the most

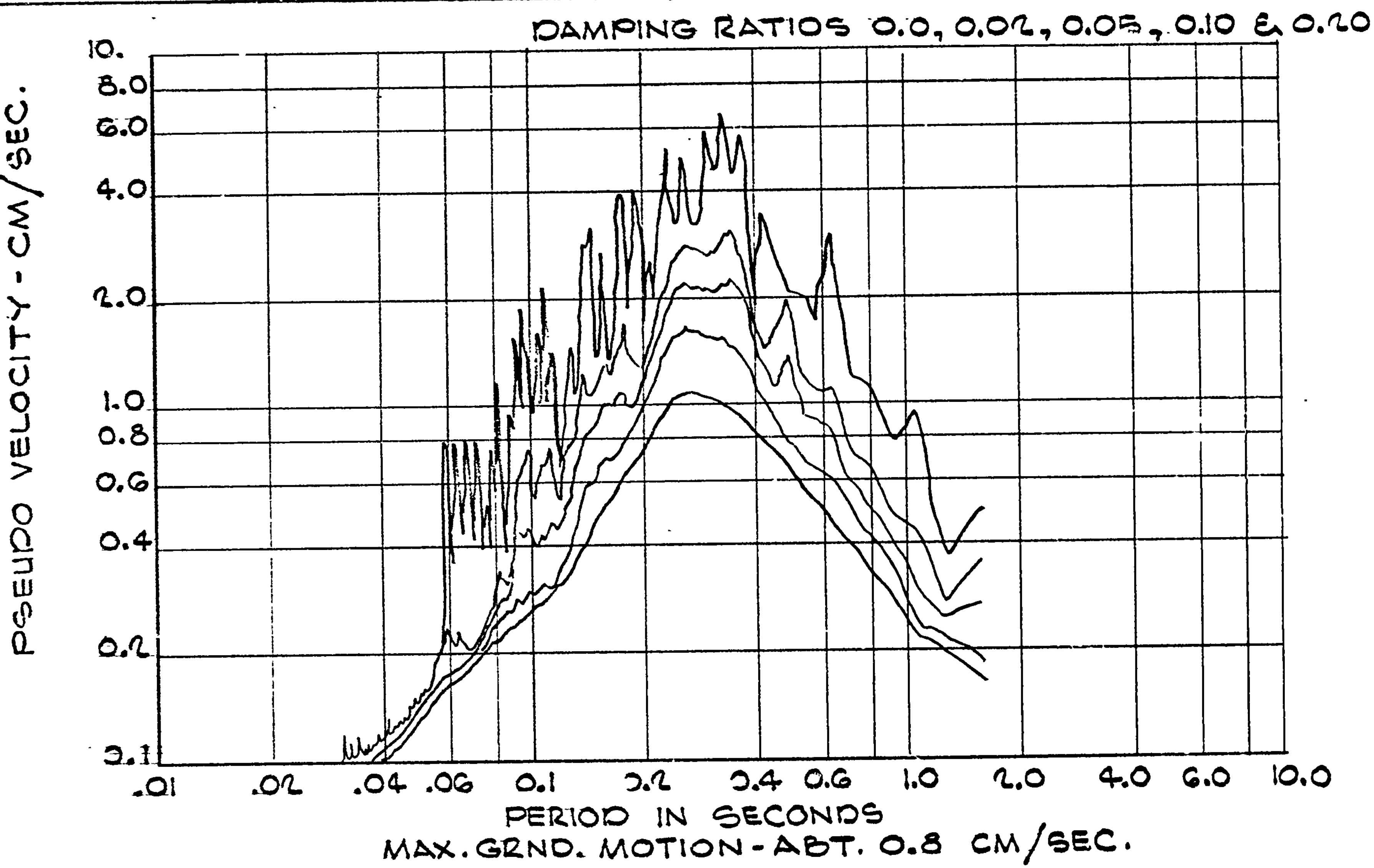


FIG. VII-1 RESPONSE SPECTRUM FROM A NUCLEAR EXPLOSION insight into the problem, earthquake and blast. A brief review of experience in these fields follows.

1. The Intensity of Earthquakes:

Transient earth waves generated by blast, earthquake, pile drivers, railroad trains, trucks, etc., have received a great deal of attention since about 1930. The subjective modified Mercalli intensity scale[24] was the first attempt to classify types of reaction, both human and structural, to earthquake action. It is a useless scale in both analysis and design since no physical properties of the motion are included in the scale.

The first attempt to define earth motion intensity physically was one using maximum particle acceleration as an index. This seemed logical since acceleration is proportional to dynamic load (force equals mass times acceleration for a particle) and response can be calculated directly from load. Peak boom pressure in air would be analogous to the peak acceleration of ground. However, it was noticed from a number of test blasts and earthquakes that no good correlation existed. Crandell[25] thought that maximum particle velocity was a better measure of intensity.

Yet another measure of earthquake intensity was postulated by Housner[26] and confirmed by Wiggins[27] wherein the area under a response spectrum in the bandwidth of the structural period population was the best general measure of intensity (Fig. VII-2). This is a better method for computing intensity since all the properties of the motion and structure are included. However, the selection of the bandwidth is very important (see reference 27).

Because of the extreme difficulty in computing the spectrum and integrating under it within a given bandwidth earthquake engineers have selected the simple scratch gage, nicknamed the "seismoscope" as an inexpensive meter of intensity. The natural period selected for the instrument is 0.75 sec.. This would be good for a 5- to 10-story building but not for bigger or smaller buildings. It is an obvious compromise.

Within frequency regions where a spectrum line parallels lines of equal motion properties the property itself can be used as an intensity measure. Take Fig. VII-1 for example. Within the period region 0.04 sec. to 0.2 sec. the spectra slope NE-SW. These diagonals happen to be lines of equal particle acceleration. If, then, response spectra of various magnitudes always appeared to parallel lines of equal acceleration within this period band, intensity would be proportional to peak acceleration. The same observation would be true in the region 0.35 sec. to 2.0 sec. where the spectral lines slope NW-SE. These diagonals parallel lines of equal displacement. Maximum particle displacement relates to intensity for oscillators whose periods lie within this bandwidth. Spectral lines within the remaining bandwidth, 0.2 to 0.35 sec., roughly parallel the velocity quantity. If the spectra would shift either left or right as magnitude of disturbance is increased, the useful bandwidth for either of the simple quantities would be diminished by the amount of the shift.

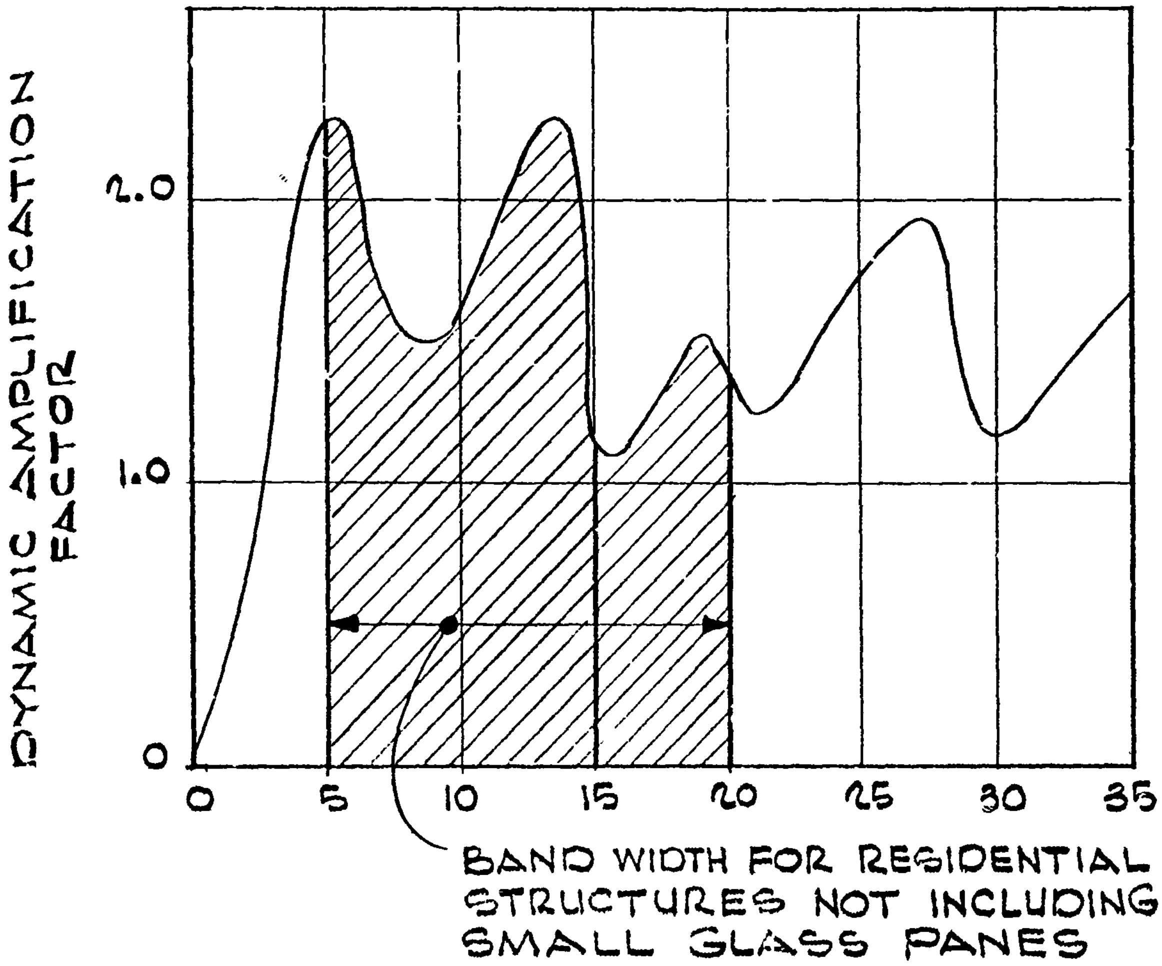


FIG. VII-2 AREA UNDER THE RESPONSE SPECTRUM WITHIN STRUCTURAL FREQUENCY POPULATION INDICATES INTENSITY

2. <u>The Intensity of Air-Borne Pulses</u>:

Most of the work on defining intensity of air-borne vibrations has been done with explosion pulses. The large interest in explosion pulses was stimulated by nuclear weapons effects investigations since 1945.

For purposes of discussion the bomb explosion wave influences structural response in the same way as a triangular pulse whose impulse is all positive. The reason for this approximation results because the negative impulse portion of the blast pulse is so long and has such a low peak amplitude that peak structural response is never governed by it.

We can gain an appreciation for the properties determining response to blast pulses in the low pressure range by studying the response of oscillators to the simple triangular pulses shown in Fig. VIII-3. The maximum value of the peak response computed in the rise time, decay, or residual vibration period is plotted as a function of oscillator period. The spectrum, thus calculated, is shown in Fig. VII-3.

Blast response experts recognized upon glancing at this response spectrum that within certain τ/T regions various quantities govern amplification factor. For example, for τ/T less than 0.4, impulse governs. That is, $P_{eff} = 2.9P_m \tau/T$ (where P_{eff} = effective static pressure and P_m = peak dynamic pressure). For $\sigma = 0$ and $\tau/T > 2$ peak pressure governs and $P_{eff} = 2P_m$.

Rise time is also an important quantity influencing response. Fig. VII-3 shows that $P_{eff} = P_m$ for oscillators whose natural period is equal to or less than the rise time.

In the foregoing the quantity τ/T has been mentioned continually. A natural time quantity of both the load and the responder determine the impedance or dynamic amplification factor for certain load-structure combinations. One can not be divorced from the other.

3. <u>The Intensity of Boom Pulses</u>:

Free-field boom pulses are unlike free-field bomb pulses in two major respects:

a. Both negative and positive impulses are present.
b. Pulse duration is primarily a function of airplane length and not distance from the source to responder. For the same airplane, duration is almost invariant.

The first difference causes the response spectrum within a certain τ/T range to differ from a triangular pulse spectrum. The second variation makes the analysis of response to boom easier than that to bomb since τ/T remains relatively constant, independent of distance from plane to source.

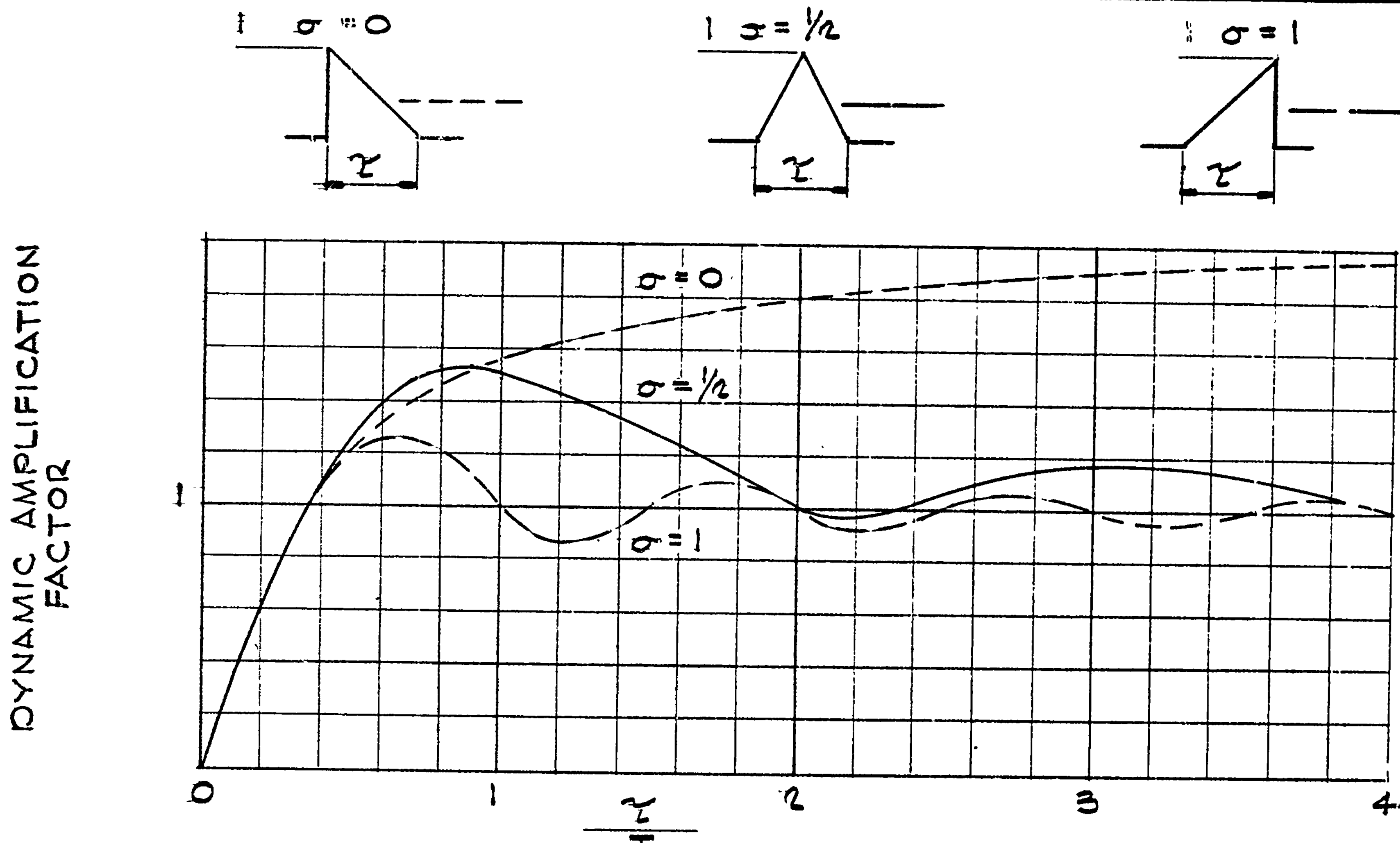


FIG. VII-3 RESPONSE SPECTRA OF TRANGULAR PULSES HAVING VARIOUS SLOPES (AFTER JACOBSEN)

Fig. VII-4 shows the response spectra for an ideal and simply modified free-field boom wave and a triangular pulse having a similar peak pressure and duration. The information on spike height and duration was derived from F-104 free-field data, but may be provisionally applied as noted in the figure. The discussion pertains to F-104 booms but may be applied to B-58 and SST booms by substituting frequencies noted in Fig. VII-4. Free-field is not loading, so the following is intended simply to give guidance in interpreting boom response spectra.

a. Positive impulse governs structural response below 5 cps for an F-104 boom wave. $P_{eff} = 1.43P_m \tau/T$, where $P_m \tau/2$ = positive impulse. The triangular pulse shown would cause the oscillators to vibrate twice as much. ($P_{eff} = 2.86P_m \tau/T$) as would the boom wave. Since τ varies little for the same airplane response is effectively P_m sensitive for specified responder frequencies.

b. Pressure, P_m (not spike pressure P_s), governs oscillator response from about 23 cps and higher. Note that in this region $P_{eff} = 2P_m$. With damping added the coefficient, two, would be less.

c. Between 5 cps and 23 cps, the natural frequency range of most structural elements, the amplification factor varies widely from an amplification factor of 0.7 to 2.3. With only a slight change in structural period response could change markedly. Peak pressure alone would not be a good, constant determinant of intensity within this frequency region for an F-104 boom wave. But no better physical determinant of intensity is known at this time. A scratch gage whose natural frequency is $\frac{(23 \text{ cps} + 5 \text{ cps})}{2}$ = 14 would have a peak error of $\pm$ 64 percent.

d. Spikes would have no appreciable contribution to structural response below natural frequencies of 90 cps. Between 90 cps and 350 cps response is spike sensitive and P_{eff} would have a maximum value of about $2.7P_m$.

e. Rise time lowers amplification factor for oscillator periods shorter than 0.0028 cps above the corresponding frequency levels $P_{eff} = P_m$. This frequency range is not important to structures, however.

It must be emphasized that the above examination refers only to the ideal free-field cases presented in the figure. Loading waves differ from free-field in the manner presented in Chapter V. It can be used as a guide or standard for understanding loading spectra and response under boom conditions, however.

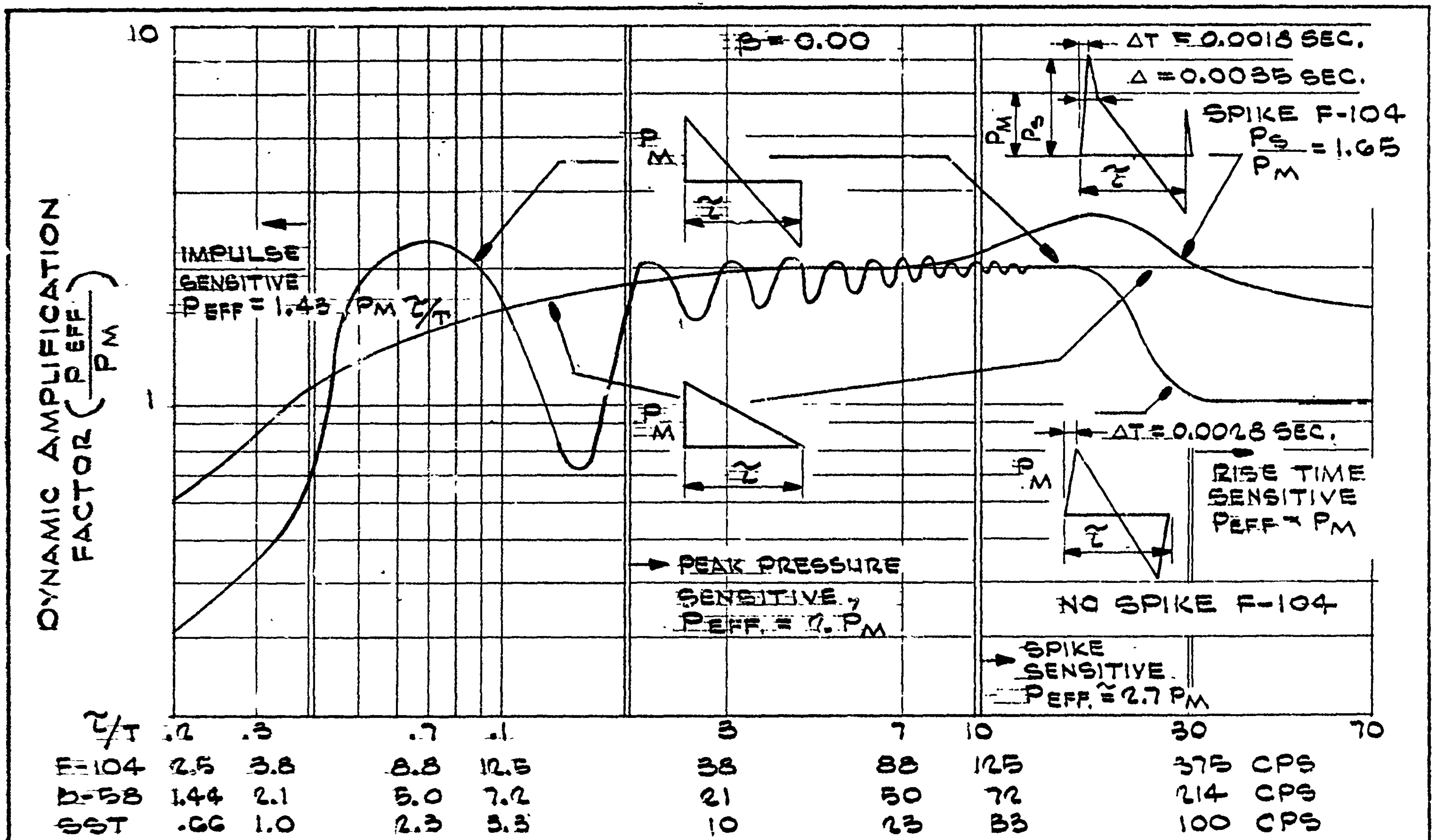


FIG. VII-4 RESPONSE SPECTRUM FOR A GROUND FREE-FIELD BOOM WAVE SHOWING INFLUENCE OF RISE TIME, IMPULSE, & SPIKE SENSITIVITY.
(SPIKE & RISE TIME CURVES FOR ONLY F-104. MOVE TO RIGHT 1.75 x FOR B-58, 3.75 x FOR SST)

D. Correlation of Response with Simple Loading Quantities:

The following quantities were compared with maximum response of some selected structural elements:

1. P_s, peak pressure including spike,
2. P_m, projected peak pressure,
3. P_b, peak tail wave pressure,
4. I_+, positive impulse, and
5. P_i, peak pressure inside building.

The coefficients of variation of R/Q = (DAF), where Q is one of the quantities listed above and R is the response quantity of interest were computed for each (DAF). Both free-field, loading, and modified free-field pressures (internal peak pressures) were used in the correlation.

Results of the study are shown in Table VII-1. The free-field data used were 180° and 360° vector flights for three days. Other vectors were not used so that the F-104 numbers could be used for direct reference with B-58 values (B-58's flew only these vectors). About ten randomly selected samples were used in the computation of each coefficient of variation.

The reader can make his own conclusions from the results of coefficient of variation studies summarized in Table VII-1. No single simple quantity appears to be better than another for correlating response with an effective load quantity with one notable exception. The large Storefront window response correlates best with the impulse quantity computed from records of a microphone located directly outside the window. The low natural frequency of the window, 2.5 cps, puts it squarely in the impulse sensitive range (Fig. VII-4) for both F-104 and B-58 booms. The (DAF), variation does not appear to be very different using free-field or loading pressures.

The wide variation associated with all simple (DAF) parameters results from the variations in all the quantities listed earlier in section B. The true loading that the wall or window experience is difficult to determine.

A better method of comparing (DAF) quantities than that attempted (coefficient of variation) would probably be to compute and compare correlation coefficients. But, the merit of going further in a study such as this where so many parameters are involved is questionable. Because boom targets are loaded by diffraction and not by drag forces peak free-field pressure is analogous to peak free-field ground particle velocity, which is most often used as a simple intensity quantity by blasting vibrations engineers.

In light of the discussion in section C and the above observations it is suggested that peak projected free-field overpressure, P_m, along with an appropriate coefficient of variation represent an effective boom intensity. In this manner one can compute a statistical response expectancy for each boom. For example, if the average pressure of a boom

TABLE VII-1

Coefficients of Variation *For Varicus Simple Dynamic Amplificati on Quantities

(DAF)	Free-Field N-S West Wall W-4		Free-Field E-W North Wall W-4		Loading N-S West Wall W-4		Loading E-W North Wall W-4		Loading Scratch Gage Pane E Storefront		Modified Free-Field N-S West Wall W-4		Modified Free-Field E-W North Wall W-4		Modified Free-Field Scratch Gage Pane E Storefront	
Effective	F-104	B-58	F-104	B-58	F-104	B-58	F-104	B-58	F-104	B-58	F-104	B-58	F-104	B-58	F-104	B-58
R/P_s	0.16	0.50	0.44	0.24	0.29	0.67	0.45	0.20	0.68	0.26						
R/P_m	0.16	0.50	0.44	0.21	0.29	0.65	0.43	0.20	0.60	0.26						
R/P_{-}	0.19	0.40	0.48	0.20	0.21	0.51	0.37	0.23	0.65	0.28						
R/I_+	0.22	0.48	0.43	0.25	0.30	0.65	0.53	0.27	0.54	0.15						
R/P_i											0.56	0.43	0.20	0.23	0.26	0.26

*Coefficient of Variation $(\frac{s}{\bar{x}})$

recorded over an area were 2.0 psf a related mean response of a particular structural element exists. With a coefficient of variation one could determine the expectancy of having the response being 50, 100, or even 200 percent greater or less than the mean. So all intensity data points are valid in relation to response, but with each is also associated a probability value.

E. Reflection on Intensity Philosophy:

The basic misconception for intensity stemmed from the idea that energy content governs. This is only half the problem. Impedance of structure to the energy includes the second half. The second problem involved with predicting response from load is that the true load is known only to a first approximation. Discussion in Chapters IV and V bears out the many factors affecting the space-time variation of free-field and load pulses.

It is desirable to predict response and therefore damage from intensity measured during a sonic boom by appropriate gages, however. We predict that the best monitoring gage is a calibrated structure itself. Figure VII-5 shows the correlation of shear response of one building motion with another building motion. Both gages are located at top corner points of walls of different buildings about 200 feet apart but which are oriented similarly. Even the scatter in data comparing shear response of end walls for the same building can be large, however, as shown in Figure VII-6. The data used in the figures were taken for the same booms. Wall stiffnesses and therefore frequencies are different, as the differences in the slopes of both curves illustrate. Both the south wall of W-4 and the north wall of PF-6 are stiffer than the north wall of W-4. Nevertheless, it may be identified from the data that response of one element compares well with that of a similar element since both are sensing effective racking loads. The calibrated building is acting much like the earthquake engineer's "Seismoscope".

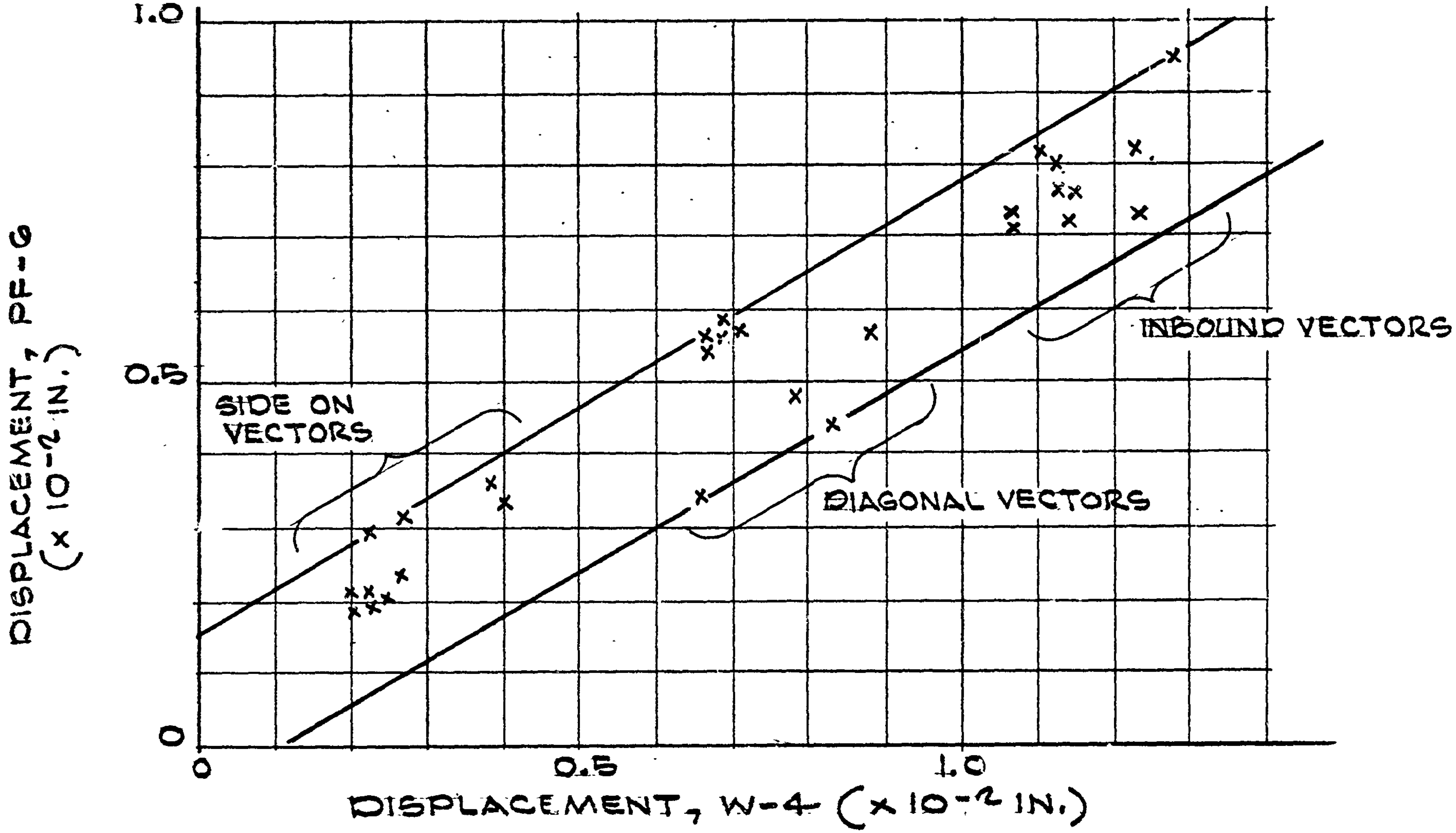


FIG. VII-5 E-W DISPLACEMENT OF THE SOUTH WALL OF PF-6 COMPARED WITH THAT OF THE NORTH WALL OF W-4 FOR SIMILAR BOOMS, 194 FT. SEPARATE THE WALLS.

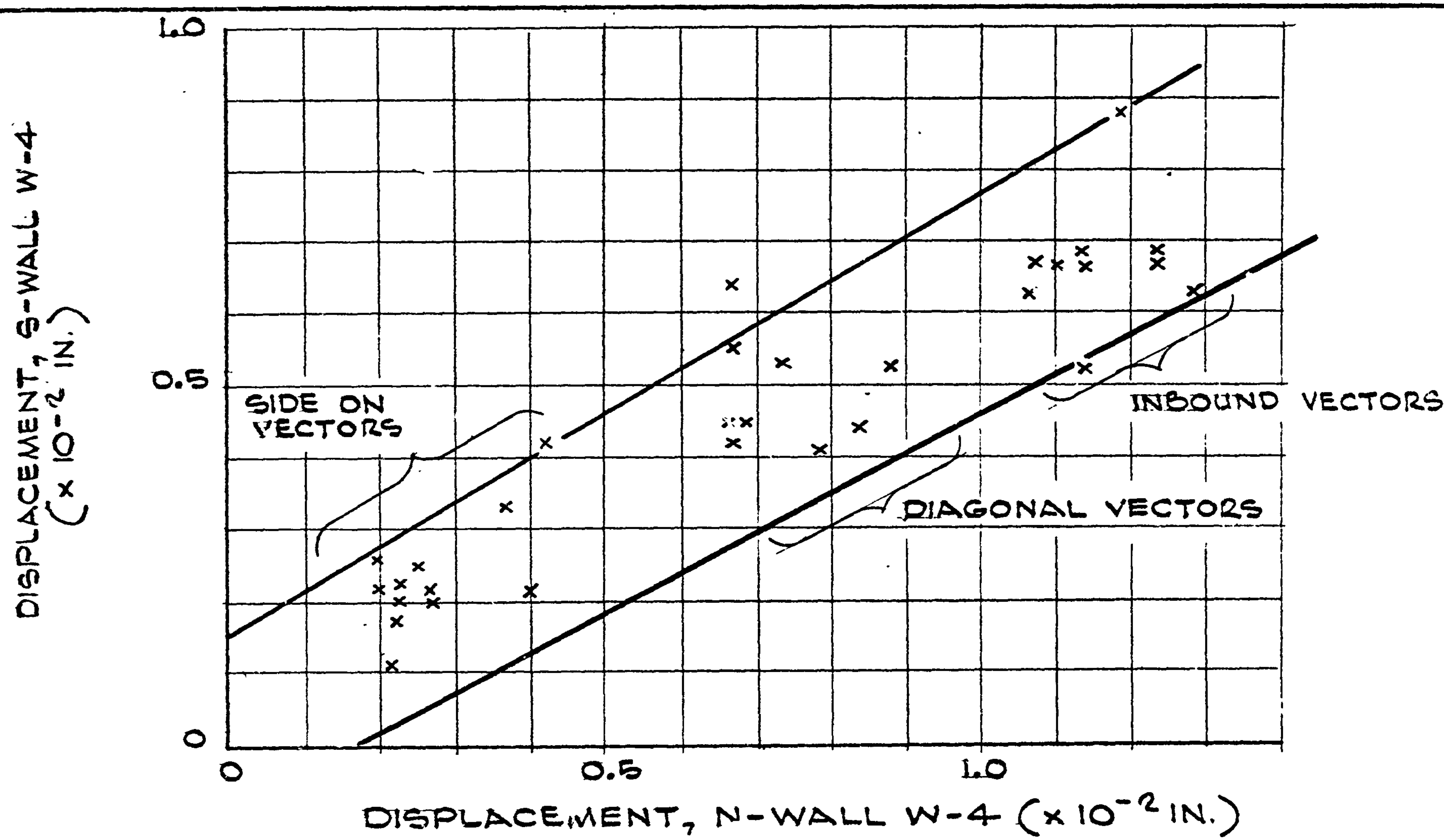


FIG. VII-6 E-W DISPLACEMENT OF NORTH WALL OF W-4 COMPARED WITH THAT OF THE SOUTH WALL OF W-4 FOR SIMILAR BOOMS, 32 FT. SEPARATE THE WALLS.

VIII. BOOM DAMAGE ANALYSIS AND PREDICTION:

A. Introduction:

This section analyzes and discusses further the observer data collected during the Federal Aviation Agency sonic boom tests and the limitations associated with the data collected by observers. Boom damage itself is identified and the characteristics of such damage listed. Because response and loads and not necessarily damage observation are the only objective measurements taken during boom tests, correlation of these quantities with damage is done. Finally, from correlation of damage reported by others in quarry blast experiments as well as boom test experiments, the statistical probability for damage to common structural elements is given.

Factors which influence the objectivity of damage analysis are also discussed. Some of these include the natural conditions existing at time of boom; the subjectivity of observer data; the limitations on methods of cumulative damage data analysis; and the wide variety of structural types and conditions, materials and stiffnesses that may exist in practice.

B. Parameters Influencing Cracking:

Structures crack under boom and non-boom conditions. The relative influence of boom compared with other factors in causing permanent relative expansion (and resultant cracking) of wall and ceiling elements has not been quantified. This probably results from the large number of natural parameters which influence, and therefore tend to mask, boom effects. Basic causative forces of differential expansion of the material result from thermal, humidity, settlement and moisture driving conditions. These may result from:

1. Ratio of inside to outside surface temperature.
2. Range of inside and outside humidity.
3. Range of inside and outside air temperature.
4. Wind conditions.
5. Duration of wind loading.
6. Differential settlement.
7. Room volume.
8. Wall and ceiling area.
9. Orientation of walls to solar gain.
10. Type of skin, frame and exterior materials.
11. Type of finish material.
12. History of patching.

Shrinkage occurs due to the drying out of the initial water content of materials such as mortar and concrete. Unseasoned or improperly conditioned materials such as timber also tend to dry out and shrink. Long-term shrinkage occurs in materials such as Portland cement. The chemical setting of materials or the subsequent chemical reactions (e.g., corrosion of steel) can cause voids and therefore increase residual stresses and cracking.

Reversible movements of materials can occur due to variation in moisture content. Most building materials exhibit these movements, but particularly timber and masonry or Portland cement products. Timber, for example, can have a two percent change in dimension for a moisture content change of 10 percent. Temperature variations can also cause cracks to open and close, depending on the coefficient of thermal expansion of the various materials used in the composite product (a wall for example). Irreversible expansion of ceramic products results upon the absorption of moisture. Settlement is not a unidirectional process. For example, depending upon the moisture variation in the ground underlying a structure, clays can expand or contract. Continuous expansion and contraction tends to work and actually grind cracks open in a fatiguing process.

Figs. VIII-1 and VIII-2 present examples of the variation of floor movement. Letters A, B, and C refer to floor measurements taken as shown in the figures. The terms NE, NW, SE, and SW refer to the vertical movements of the foundation corners. Note that movement takes place in a random manner.

Table VIII-1 lists crack length readings taken at various times of the day during the White Sands program. There is no directly evident reason for the crack length changes shown with regard to the boom strength during the day of observation. The length variations of the three cracks recorded on house W-3, plotted in Fig. VIII-3, indicate only that temperature variations probably cause the change. On the last three days shown the temperature was generally lower and the sky overcast. These conditions caused the cracks to remain open and permitted little variation.

The effect of temperature on crack number is further illustrated in Tables VIII-2 through VIII-5. On January 16, 1965, the heat went off in the structures. A large number of preboom cracks resulted. Four hours after the preboom inspection and refiring the heaters about 90% of the new preboom cracks had disappeared.

During November 24, 1964, no boom runs were made. Observations, however, were made at the same time intervals during the day in structures C-1, W-2, and W-4. No large differences in crack recordings between boom and nonboom conditions were noted.

Data taken during Part B (Tables VIII-4 and VIII-5), on the whole, show that preboom time crack rate is greater than boom time rate. The interval of inspection was greater between preboom time and boom time inspections by a factor of three, but between three to ten times as many inspections were made during boom time. It is our opinion that the larger number of preboom time cracks recorded at 0830 hours were caused by the cooler overnight temperatures.

The influence of shrinkage stresses in causing cracks is shown in Fig. VIII-4. This sample of plaster-on-wood lath was fabricated at the

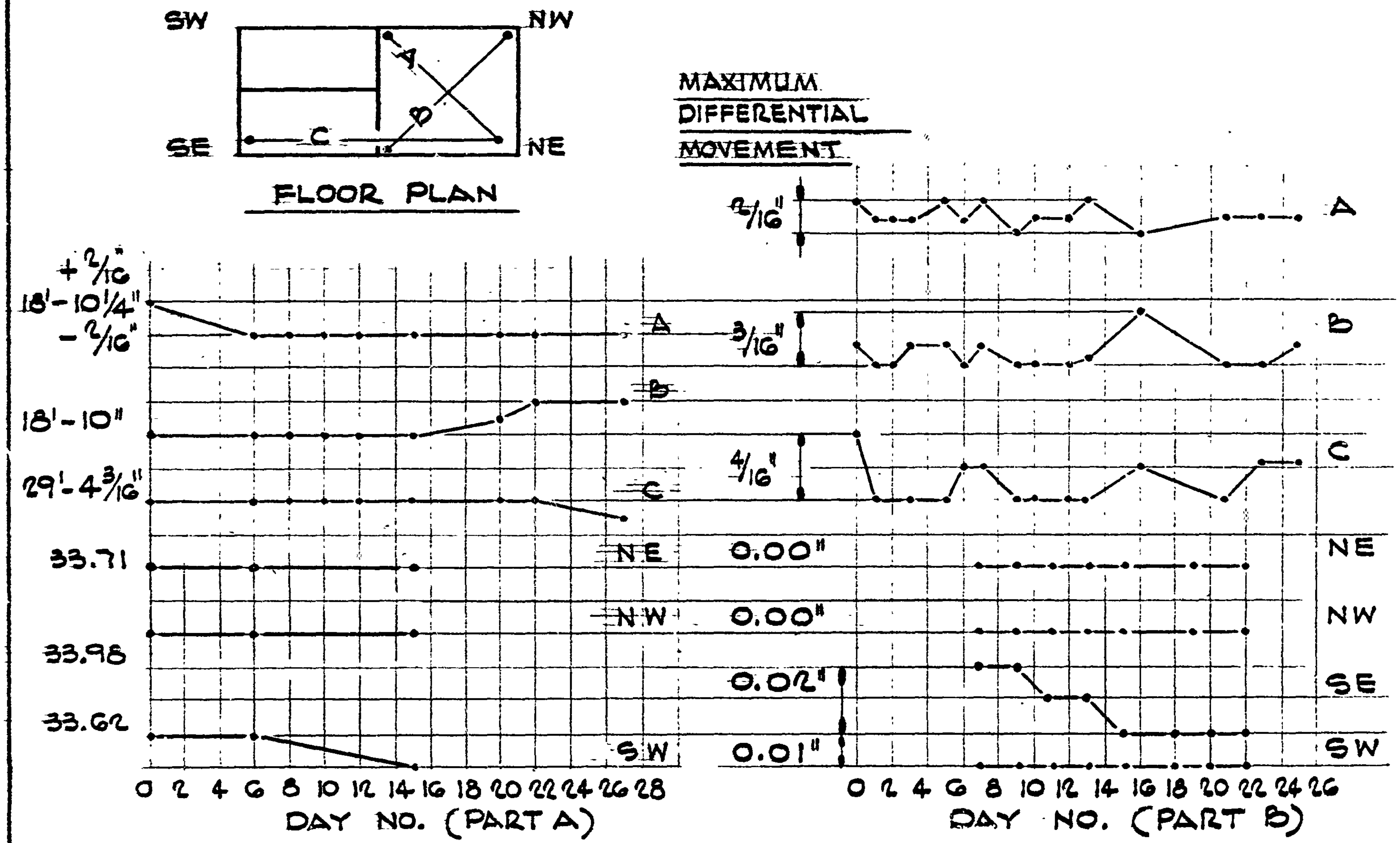


FIG. VIII - 1 DIFFERENTIAL MOVEMENT OF FLOORS CAUSED BY SETTLEMENT, MOISTURE & TEMP. CHANGES IN HOUSE W-3

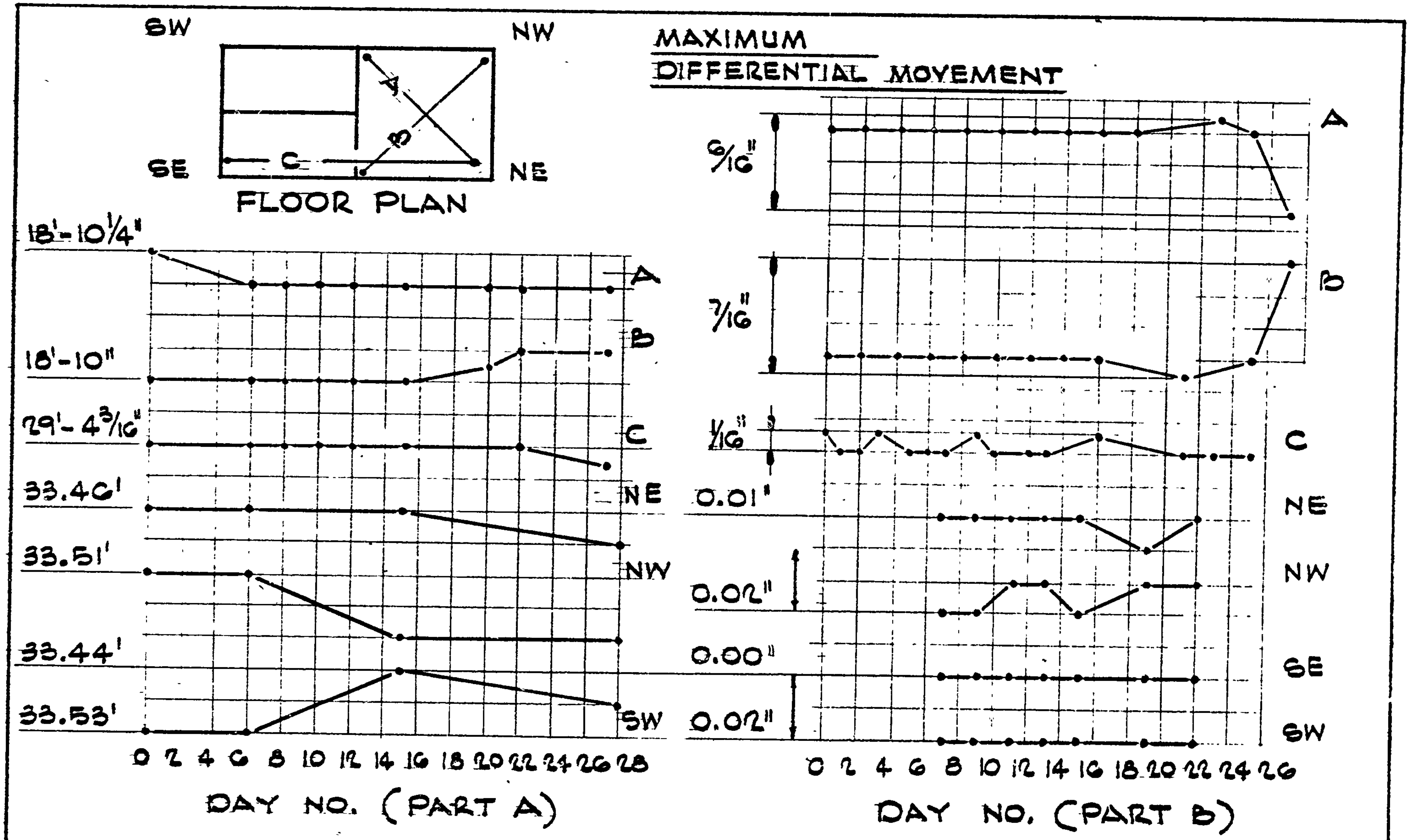


FIG. VIII - 2 DIFFERENTIAL MOVEMENT OF FLOORS CAUSED BY SETTLEMENT, MOISTURE & TEMP. CHANGES IN HOUSE W-4

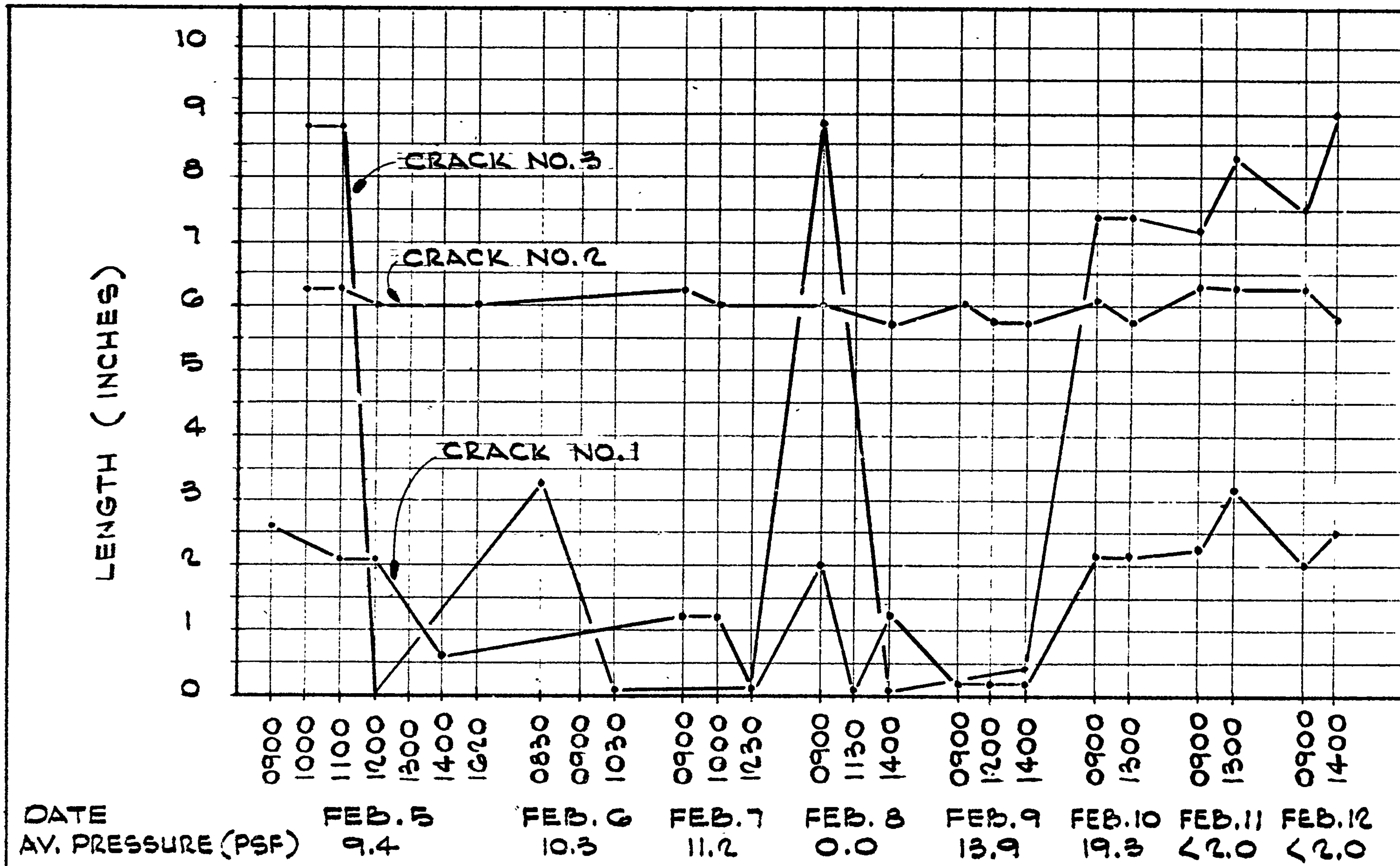


FIG. VIII - 3 CRACK LENGTH CHANGE WITH TIME FOR HOUSE W - 3

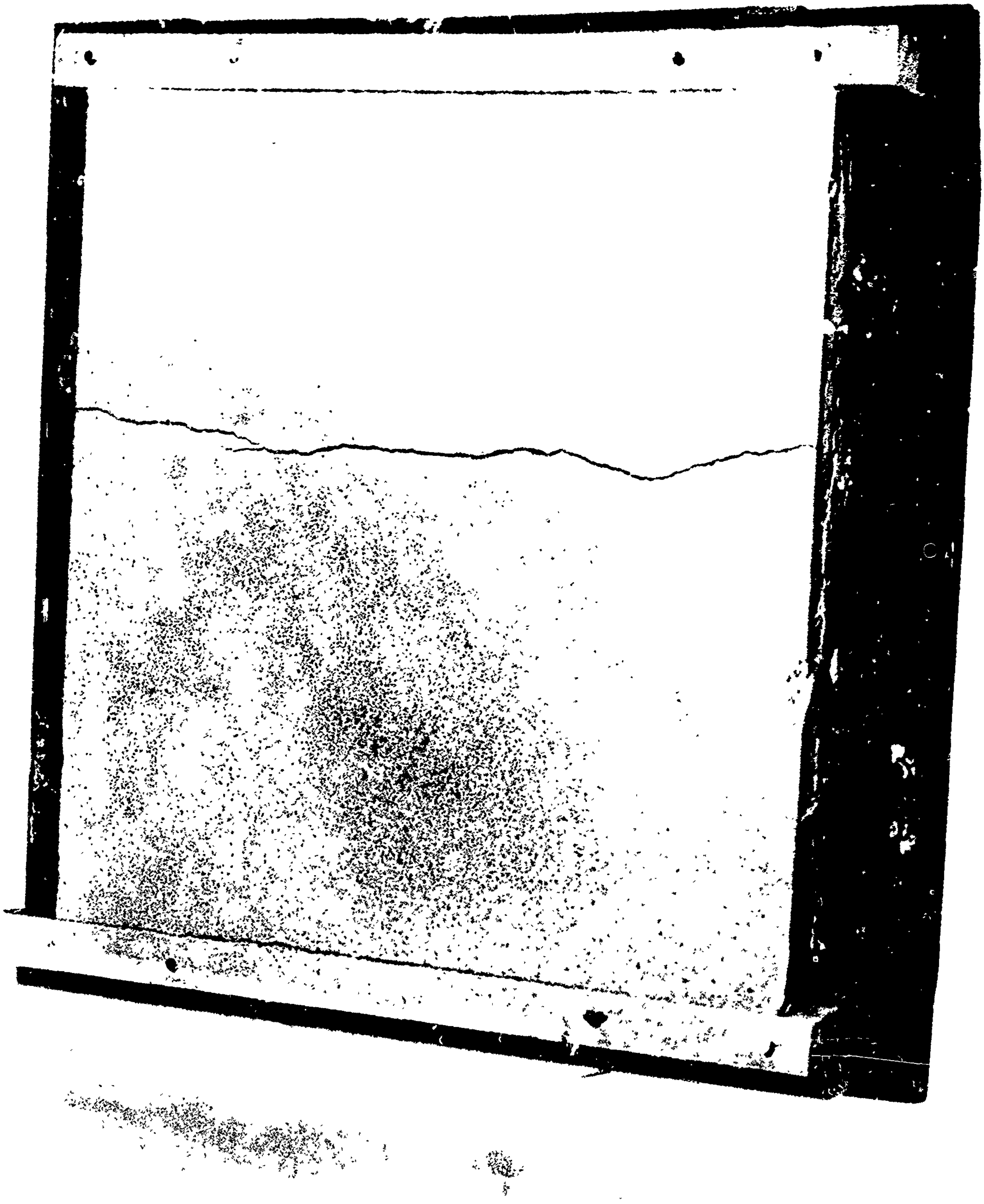


Fig. VIII-4 Expansion Crack of Plaster-on-Wood Lath Sample Occurred Outside of Boom Area.

TABLE VIII-1 CRACK LENGTH MEASUREMENTS

Date	Average ΔP	Bldg. C-1 Crack No.							Bldg. W-2 Crack No.		Bldg. W-3 Crack No.			Bldg. W-4 Crack No.	Time
	(psf)	1	2	3	4	5	6	7	1	2	1	2	3	1*	
2-5	9.4	-	8¼	12¼	12¼	10½	-	-	-	-	2½	-	-	-	0900
		-	-	-	-	-	-	-	-	-	-	6¼	9	4½ (min)	1000
		-	-	-	-	-	-	-	-	-	2¼	6¼	8½	-	1100
		-	-	-	-	-	-	-	-	-	2¼	6	0	12 (max)	1200
		-	-	-	-	-	-	-	-	-	-	6	-	-	1300
		-	-	-	-	-	-	-	-	-	½		6	-	1400
		-	8¼	12¼	12¼	9½	23	28	-	-	-	-	-	-	1500
			0	0	12¼	9½	18	23¼	-	-	-	6	-	-	1600
2-6	10.3	-	0	0	0	4	2½	0	-	-	-	-	3¼	11¼ (min)	0830
		-	-	-	-	-	-	-	-	-	-	-	-	16 (max)	0900
		-	-	-	-	-	-	-	-	-	-	-	0	-	1000
2-7	8.7	-	0	0	12¼	6½	-	-	16½	16	1¼	6¼	0	-	0900
		-	-	-	-	-	-	-	-	-	1¼	6	0	6 (min)	1000
		-	-	-	-	-	-	-	13½	3¼	-	6	0	15½ (max)	1230
		-	0	0	12¼	6½	-	-	10	2¼	-	-	-	-	1300
2-8	0.0	-	0	0	10	4	5¼	0	16½	16	2	6	8½	16½ (min)	0930
		-	5½	9¼	11	8½	6	1½	-	-	-	-	-	16½ (max)	1100
		-	5½	10	12	8½	9	7	-	16	0	-	-	-	1200
		-	5	10	12	8½	7	3½	16½	16	1¼	6	0	-	1400
2-9	13.9	16	0	10	12¼	8½	3½	6½	16	9½	0	6	0	-	0900
		18	7	11	11½	10	3½	1½	14½	9	0	6	0	16½ (min)	1200
		16	8	11	12	10	1½	1¼	13½	8	0	6	0	16½ (max)	1500
2-10	19.3	15½	7½	9	10½	9	23	29¼	17¼	16	2	6	7½	-	0900
		-	-	-	-	-	-	-	17¼	16	2	6	7	16½ (min)	1300
		18	7½	12	12	10¼	20¼	22	17¼	16	-	-	-	16½ (max)	1430
2-11	2.0	16	7½	10	12	10	23	37¼	17	16	2¼	6¼	7	-	0900
		18	7½	10	12	9	30	40	17	16	3	6¼	9	-	1300
2-12	2.0	18	7	10	12	9	30	40	17	16	2	6¼	7½	-	0900
		19½	9½	2½	2½	9	1½	0	19	16	2½	6	9	-	1400
2-13	2.0	-	-	-	-	-	-	-	20	16	-	-	-	-	0900
		-	-	-	-	-	-	-	19½	16	-	-	-	-	1400

* Times do not apply to these readings

TABLE VIII-2 CRACK TABULATIONS-BOOM TIME

READINGS (WHITE SANDS-PART A)

Date	Average ΔP(psf)	C-1		W-2		W-3		W-4		2S-5, 1st		2S-5, 2nd		PF-6	
		No.	L*	No.	L*	No.	L*	No.	L*	No.	L*	No.	L*	No.	L*
11-18	1.9	0	0	7	115	5	190	2	23	-	-	-	-	0	0
19	No Boom	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20	1.8	4	296	5	90	0	0	12	159	-	-	-	-	1	15
21	1.6	1	38	0	0	0	0	2	2	11	168	7	68	3	192
22	2.2	0	0	11	128	13	242	7	105	10	111	5	89	32	387
23	2.1	0	0	0	0	7	34	1	10	4	33	3	12	8	134
24	No Boom	3	16	3	95	5	31	4	25	-	-	-	-	8	50
25	2.8	-	-	-	-	-	-	0	0	-	-	-	-	-	-
26	4.5	2	27	2	48	6	20	15	74	15	427	9	53	0	0
27	3.6	0	0	1	33	2	9	4	14	4	29	6	50	5	25
28	4.7	0	0	0	0	4	13	4	10	3	33	1	24	0	0
29	6.9	0	0	3	12	0	0	15	63	5	47	3	24	1	10
30	10.2	0	0	0	0	-	-	3	51	6	67	26	169	1	5
12-1	4.9	1	8	0	0	-	-	12	37	6	112	24	103	0	0
2	7.1	0	0	0	0	-	-	1	2	1	10	6	62	0	0
3	No Boom	0	0	-	-	-	-	9	38	-	-	-	-	-	-
4	2.1	1	9	0	0	0	0	2	8	12	57	7	18	0	0
5	4.9	3	23	0	0	0	0	11	67	2	9	13	82	0	0
6	4.9	0	0	0	0	0	0	3	52	11	23	30	84	0	0
7	7.6	3	25	-	-	0	0	-	-	3	8	0	0	-	-
8	10.0	0	0	0	0	-	-	14	61	6	34	3	16	8	58
9	12.6	0	0	0	0	12	10	1	1	10	17	12	25	6	20
10	13.7	0	0	0	0	2	2	3	19	2	5	11	36	7	12
11	16.3	0	0	6	23	3	7	2	3	1	1	8	19	0	0
12	2.8	2	74	0	0	0	0	0	0	0	0	0	0	0	0
13	2.6	0	0	0	0	3	30	0	0	3	6	6	25	0	0
14	5.3	0	0	11	363	3	20	3	8	2	9	0	0	0	0

* L is in inches

TABLE VIII-3 CRACK TABULATIONS -

NON BOOM TIME READINGS (WHITE SANDS-PART A)

Date	C-1		W-2		W-3		W-4		2S-5, 1st		2S-5, 2nd		PF-6	
	No.	L*	No.	L*	No.	L*	No.	L*	No.	L*	No.	L*	No.	L*
11-18	3	288	-	-	-	-	-	-	-	-	-	-	-	-
19	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20	-	-	-	-	37	430	25	-	-	-	-	-	-	-
21	-	-	-	-	-	-	0	-	-	-	-	-	0	0
22	-	-	-	-	4	191	20	417	28	210	39	207	7	343
23	3	69	0	0	8	520	2	96	-	-	1	12	10	318
24	2	12	0	0	5	63	-	-	-	-	-	-	16	159
25	-	-	-	-	-	-	1	16	-	-	-	-	-	-
26	5	60	0	0	16	91	15	121	10	159	3	26	2	20
27	0	0	4	50	4	34	2	13	11	96	2	42	9	43
28	0	0	0	0	3	30	9	67	3	111	1	24	0	0
29	0	0	4	17	0	0	0	0	1	2	0	0	3	8
30	10	103	0	0	-	-	6	15	4	70	11	24	2	18
12-1	0	0	3	21	-	-	4	8	11	153	7	83	2	5
2	0	0	2	30	-	-	2	29	2	13	17	38	4	5
3	-	-					-	-						
4	3	29	0	0	2	3	13	65	8	35	1	9	0	0
5	4	22	0	0	0	0	6	25	13	135	24	305	1	19
6	0	0	0	0	0	0	4	13	12	30	21	97	1	4
7	15	56	0	0			2	9	2	13	7	29	-	-
8	0	0	0	0	-	-	39	133	2	2	9	22	0	0
9	2	3	0	0	5	38	1	17	3	6	34	114	10	27
10	0	0	0	0	24	252	3	14	2	26	3	2	-	-
11	0	0	0	0	0	0	0	0	2	13	10	16	0	0
12	6	76	1	12	11	71	1	4	2	2	4	14	0	0
13	0	0	1	13	12	96	2	2	3	16	3	10	0	0
14	0	0	7	141	3	6	2	11	1	15	4	10	1	10

*L is in inches

TABLE VIII-4 CRACK TABULATIONS-BOOM TIME READINGS (WHITE SANDS-PART B)

Date	Average	C-1		W-2		W-3		W-4		2S-5, 1st		2S-5, 2nd		PF-6	
	ΔP(psf)	No.	L*	No.	L*	No.	L*	No.	L*	No.	L*	No.	L*	No.	L*
1-15	6.8	3	31	12	317	8	23	0	0	0	0	1	38	2	114
16	4.5	0	0	0	0	3	4	2	5	0	0	0	0	7	74
17	8.3	3	13	2	18	5	10	1	8	0	0	0	0	1	3
18	6.1	0	0	3	91	0	0	0	0	0	0	0	0	0	0
19	2.2	0	0	0	0	0	0	0	0	1	24	0	0	0	0
20	4.5	0	0	0	0	0	0	0	0	0	0	0	0	2	14
21	5.7	0	0	0	0	0	0	0	0	3	42	0	0	2	14
22	4.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	4.5	0	0	0	0	0	0	3	15	0	0	0	0	0	0
24	4.8	1	84	0	0	0	0	5	212	1	23	0	0	0	0
25	4.2	0	0	0	0	0	0	0	0	4	55	2	25	0	0
26	5.1	0	0	-	-	0	0	0	0	0	0	0	0	0	0
27	5.1	0	0	0	0	0	0	0	0	1	4	0	0	0	0
28	4.9	0	0	0	0	0	0	1	4	0	0	0	0	0	0
29	5.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	4.4	1	20	3	67	0	0	0	0	1	0	0	0	0	0
31	4.6	0	0	0	0	0	0	1	9	0	0	0	0	0	0
2-1	4.7	2	11	1	11	0	0	2	11	0	0	0	0	0	0
2	4.3	1	4	3	31	0	0	1	1	0	0	0	0	-	-
3	4.6	0	0	0	0	0	0	0	0	0	0	0	0	3	6
4	5.8	0	0	0	0	0	0	1	9	0	0	0	0	2	2
5	9.4	4	193	-	-	0	0	3	3	0	0	0	0	1	54
6	10.3	0	0	1	36	0	0	2	6	0	0	0	0	2	16
7	11.22	0	0	0	0	3	48	0	0	4	108	5	72	0	0
8	No Boom	-	-	-	-	-	-	-	-	-	-	-	-	-	-
9	13.9	0	0	0	0	0	0	0	0	2	19	1	3	0	0
10	19.3	3	114	0	0	0	0	2	7	2	19	4	40	0	0
3-1	No Boom	-	-	19	343	3	23	5	27	11	272	2	74	3	112
5-20	No Boom	-	-	47	847	24	457	22	518	24	719	45	1211	20	305

*L is in inches

TABLE VIII-5 CRACK TABULATIONS -

NON BOOM TIME READINGS (WHITE SANDS-PART B)

Date	C-1		W-2		W-3		W-4		2S-5, 1st		2S-5, 2nd		PF-6	
	No.	L*	No.	L*	No.	L*	No.	L*	No.	L*	No.	L*	No.	L*
1-15	7	193	0	0	7	27	1	9	2	59	3	26	5	214
16	6	399	1	22	1	1	2	60	26	790	12	399	6	407
17	14	201	6	80	1	5	6	92	3	51	4	40	1	4
18	0	0	3	91	3	3	2	104	0	0	5	79	3	13
19	0	0	0	0	0	0	0	0	4	42	1	4	0	0
20	0	0	0	0	0	0	0	0	3	116	4	45	1	24
21	2	147	0	0	0	0	1	15	1	7	0	0	0	0
22	3	20	0	0	0	0	0	0	1	8	0	0	0	0
23	8	104	0	0	9	68	2	25	2	77	2	7	2	5
24	5	54	0	0	12	508	0	0	9	189	10	148	0	0
25	4	51	3	195	9	503	1	44	0	0	0	0	0	0
26	0	0	1	13	0	0	1	47	2	14	2	15	0	0
27	0	0	0	0	2	50	4	193	5	46	1	9	0	0
28	0	0	0	0	6	120	2	17	2	10	1	11	0	0
29	7	132	0	0	0	0	2	29	16	151	3	84	0	0
30	0	0	6	97	0	0	0	0	13	58	0	0	3	34
31	3	6	2	9	2	41	6	76	12	60	8	34	1	10
2-1	0	0	1	1	4	84	1	14	2	48	1	1	0	0
2	3	13	-	4	4	34	9	49	3	81	1	33	-	-
3	4	58	6	363	1	4	2	8	2	29	2	54	5	166
4	0	0	32	870	0	0	0	0	8	31	4	66	4	34
5	7	87	-	-	0	0	5	9	6	52	4	58	2	37
6	0	0	9	134	0	0	3	3	1	11	1	8	0	0
7	0	0	0	0	1	1	2	10	6	43	1	30	2	100
8	-	-	-	-	-	-	-	-	-	-	-	-	-	-
9	0	0	3	14	0	0	1	4	4	36	3	11	0	0
10	3	76	0	0	0	0	0	0	0	0	0	0	1	128

*L is in inches

same time as the plaster was applied in house W-4. The sample was then taken to a materials testing laboratory in El Paso, Texas, and maintained at room conditions throughout the program.

It is important, therefore, to know that these normal conditions exist during any test period wherein crack observations are made. Methods must be devised to expose the relative importance of boom, while at the same time able to cancel the effects of these other causes.

C. Factors Influencing Crack Observation and Recording:

Due to the fact that cracking of plaster and other masonry products occurs in time and is therefore a cumulative process, the use of discrete data points taken by observers must be treated with care. The observer himself is not as objective as a strain gage or a pressure transducer (even these are not very objective) and is subject to his ability to read the structures and his knowledge of structures.

Some of the factors that must be considered when analyzing observer data are discussed below.

1. Frequency of Observation:

Frequency of observation affects the number of cracks recorded. For example, if an observer examined a structure ten times during a recording period he is more likely to find cracks than if he examined it only once. Secondly, cracks open and close during the day due to thermal and humidity changes.

As an experiment one observer during the White Sands study examined various buildings for cracks immediately after it was read by another observer. From 25 to 100 percent more defects were found by the second observer, depending on the house studied.

2. Objectivity of Observers:

During non boom inspection periods observers were prone to miss cracks. They simply assumed that few cracks would be present during nonboom times. Education of the observer as to the meaning and significance of a program is therefore quite important. This is very difficult to do in light of the fact that looking at cracks in structures can be an extremely boring task.

3. Maintenance of the Same Observers Throughout a Program:

From time to time observers during the White Sands test were necessarily called back to their home office which necessitated using others in their place. This caused a rather heterogeneous sample of crack data since up to twelve different people were used to record cracks throughout the program. Therefore, the observers used at the start of any future program should be continued throughout the program.

4. Rotation of Observers to Randomize their Effect:

It is desirable to rotate each observer from building to building and then calibrate them in order to remove his influence from the data, if differences in house behavior is a study requirement.

5. Positive Crack Recording:

Only positive cracks should be recorded since cracks can expand and contract. Recording the net value (plus and minus) can be an extremely tedious job and is virtually an impossible one. (See Table VIII-1). For this reason only positive cracks should be read.

6. Analysis of Length Times Crack Number Data:

If only the number of cracks are read during equal intervals of time the true extent of damage is not determined. For example, one might have ten one inch cracks and one two hundred inch crack in the same period of time. The two hundred inch crack is probably more important than the ten, one inchers. For this reason it is deemed best to record both the length and number of cracks and analyze data resulting from their product.

7. Relation of Boom Time Cracking with Preboom Time Cracking:

In order to determine the effects of boom one must also have a control sample of data, unaffected by boom. Because of the variability of structures, reading a control set of structures out of a boom area and comparing it with those in a boom area would only introduce more parameters caused by workmanship, etc., and would tend to mask and confuse the results. For this reason it is suggested that the same structures be observed during preboom time. The time for observation should be as close to the same time as that during which booms occur. Reading structures during boom period and after boom periods tends to cause the effect of climate, settlement, shrinkage etc., to enter the problem more than if preboom cracks were measured at or near the same time of day as the booms.

Fig. VIII-5 shows the effect of observer on crack number recorded. The numbers in the figure were computed by normalizing the observer rate for each house story with the average rate and adding normalized rates for each house. Only these seven observers were chosen for test since all read the same buildings.

Note the differences between observers. Observer A recorded about 10.4 cracks per day whereas observer G recorded 2.5 cracks per day. Observers A through D were civil engineers who were well acquainted with the behavior of masonry products. Observers E through G were engineers who were unacquainted with the behavior of materials. Observer G, further, was uninterested in the job of crack recording.

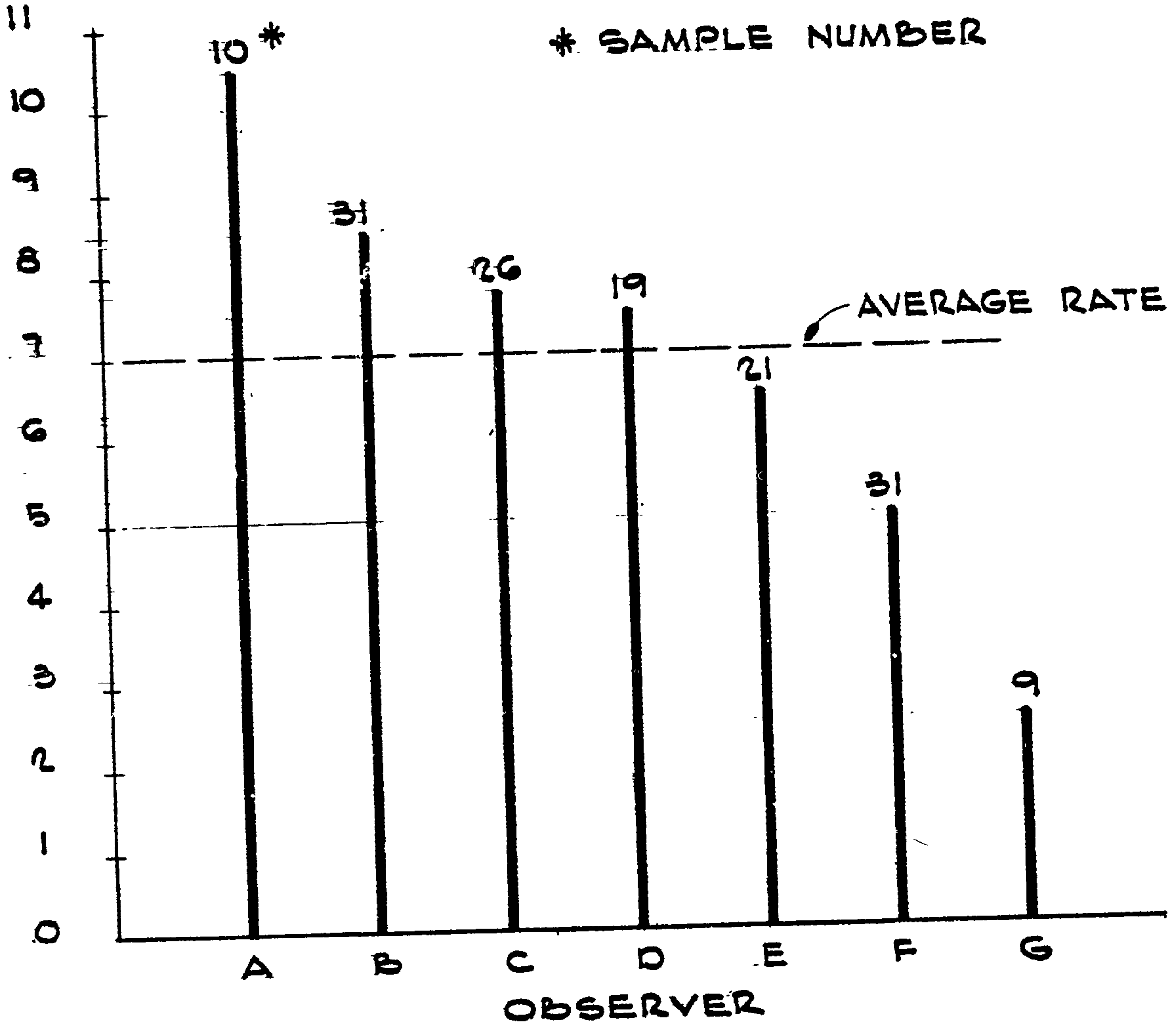


FIG. VIII - 5 NORMALIZED CRACKING RATE REPORTED BY SEVEN OBSERVERS, A THROUGH G

D. Analysis of Crack Data Taken During Boom Tests:

In the White Sands report a method was developed using observer crack data to expose a minimum damage, pressure index level. It simply compares the ratio of cracking rate under boom conditions to that under nonboom conditions with average overpressure. The validity of using this method to determine cumulative damage index level is based on the conditions that:

1. Preboom time crack recordings are controls that may be compared with boom time recordings.
2. Number of observations and time duration between observations can be effectively normalized.
3. Observers are regularly shifted from building to building to randomize the effect of observer technique.
4. Standard forms are used and buildings are architecturally designed similarly.

All preboom crack recordings were made once each morning at approximately nine o'clock. Boom time cracks were read at various times throughout the day. Only one preboom observation was made per day whereas from three to ten observations per day were made during boom time. Approximately 18 hours elapsed between the last boom time crack recording and the preboom recording made the next morning. Boom times were approximately six hours in duration. Because the time interval between boom and preboom time recording was greater by a factor of three and the frequency of boom time recording was greater than preboom by a factor of from three to ten, the raw data were normalized by an assumed factor of one and then used in analyzing ratios.

This method of comparing rate ratios against average daily overpressure is the same as that used in comparing the slopes of cumulative damage index curves of boom and preboom data where time is plotted on the abscissa. Average overpressure varied from day to day.

The analysis technique appears reasonable in view of the fact that cracking is a stochastic process. This was demonstrated in the White Sands report. However, in view of the suggestion that the meaningful data point should be the product of crack number and length, a new analysis of this quantity has been conducted. Tables VIII-2 through VIII-5 present the data.

Least square lines of slope ratios versus average daily overpressure is plotted in Fig. VIII-6. Using the 45 degree line as a criterion minimum cumulative damage index levels for the houses are, in order:

W-3	11.5 psf
W-4	13.2 psf
W-2	14.7 psf
2S-5 (1st floor)	15.2 psf
2S-5 (2nd floor)	16.7 psf
PF-6	16.7 psf
C-1	21.5 psf

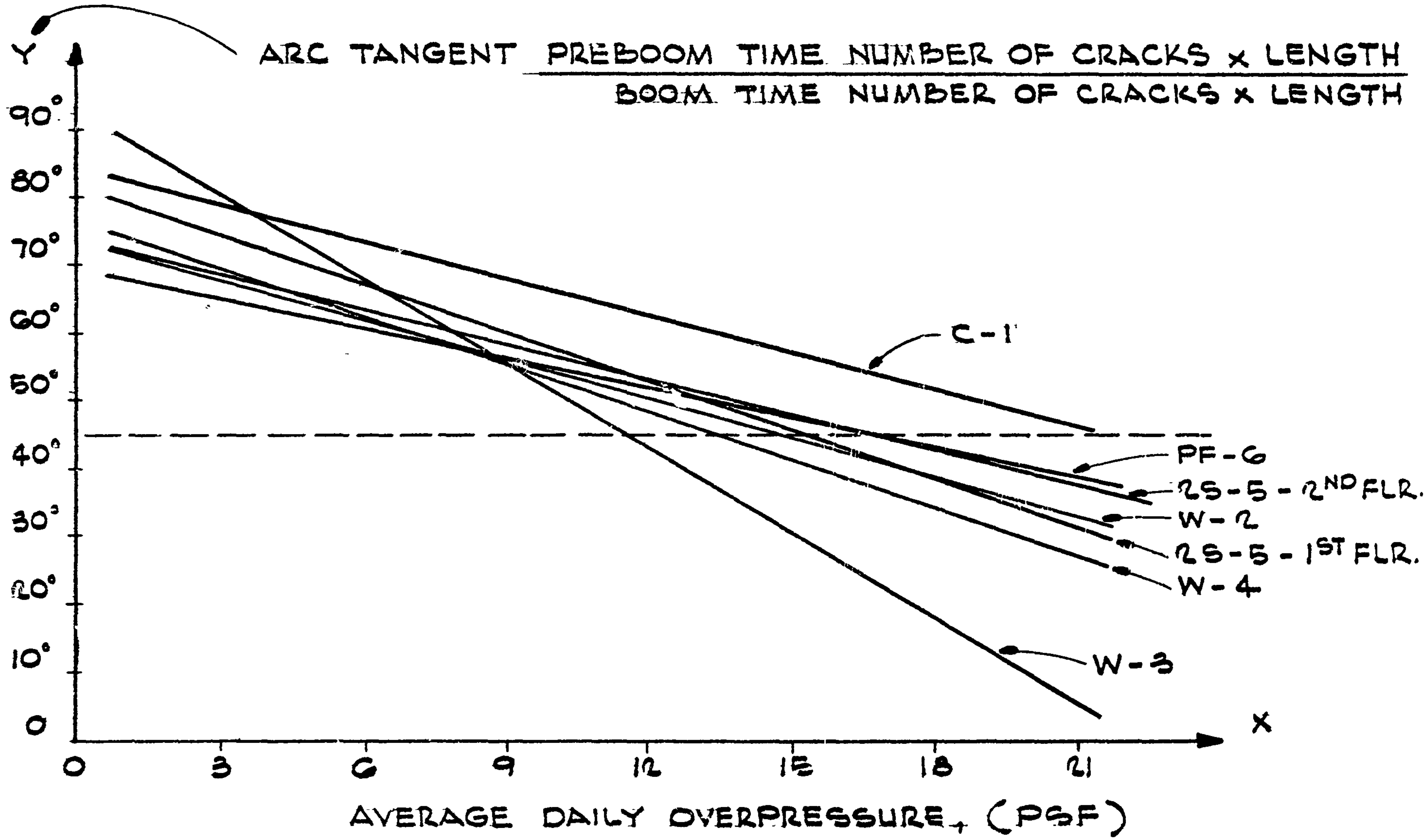


FIG. VIII-6 SLOPE RATIO VERSUS AVERAGE OVERPRESSURE FOR ALL OF WHITE SANDS TEST HOUSES USING ALL DATA

The high values of overpressure are controlled mainly by the data collected during Part B of the White Sands Tests. During Part B shrinkage had, for the most part, ceased. The plaster was stronger and the heat inside the house maintained at a higher and more uniform temperature.

About the only real conclusion that can be made, based on inference and not statistical tests of the data, is that a minimum cumulative damage index level for these buildings exists since the slope of all the lines is negative. Since the index levels for new plaster (5 psf) computed by the above method but with the new data are lower than those for older plaster there is the further inference that cracking from normal shrinkage processes are accelerated by booms.

Tables VIII-2 through VIII-5 list daily summaries of crack number and length recorded during the White Sands Program. Some 19 and 99 days after the last cracks were recorded the structures were re-read. The daily crack rate computed was 52.5 inches per day on March 1, 1965 and 59.1 inches per day on May 20, 1965. These rates compare well with boom time readings, but are much less than preboom time readings. The average temperature was warmer on both post boom days, however.

No conclusions about the meaning of these readings will be made in light of the discussion in Section C above. No obvious deviation in the data may be noted, however, because of the obviously large standard deviation.

The Oklahoma City crack data* can also be analyzed in view of the discussion in Section C. Total interior defects reported during boom and post boom periods for Test Houses 1-11 are shown in Table VIII-6.

This table lists the total interior defects noted as well as the readings per week, weeks when readings were taken, and a resulting normalizing factor. The number of defects per reading is then calculated.

The Boom/Post-Boom ratio is listed in the last column. More weight should probably be given to the ratios from test houses one to four since more data is available. Even so the defect ratio data shows no abnormal deviation. Adding rate ratios for test houses one to four and dividing by four the average is 0.91. This is close enough to one (1), in view of the large standard deviation, to indicate no change due to booms. If houses five through eleven were included one might conclude by inference that booms cause structures not to crack. This obviously, is an erroneous conclusion resulting from the questionable data (see Section C) and method of analysis (inference).

The nail pop data can be normalized similarly (Table VIII-7). All of these Boom/Post-Boom rate ratios are less than one. The average is 0.55. The low average probably results from the 7/3 reading rate

---

* pg. 67, 68, 69, 70 and 72 in the Oklahoma City report.

TABLE VIII-6 RAW INTERIOR DEFECT DATA AND NORMALIZED DATA TAKEN IN THE TEST HOUSES 1-11 (OKLAHOMA CITY)

Test House	Boom Period					Post Boom Period					Boom
	Raw Data	Readings Per Week	Weeks Read	Mult. Factor	Defects Per Reading	Raw Data	Readings Per Week	Weeks Read	Factor	Defects Per Reading	Post-Boom Ratio
1	282	7	26	0.0055	1.55	99	3	13	0.0256	2.54	0.61
2	261	7	26	0.0055	1.44	56	3	13	0.0256	1.43	1.00
3	432	7	26	0.0055	2.37	77	3	13	0.0256	1.97	1.20
4	509	7	26	0.0055	2.79	134	3	13	0.0256	3.43	0.81
5	70	7	4	0.0358	2.50	300	3	13	0.0256	7.70	0.33
6	3	3	6	0.0556	0.17	34	3	13	0.0256	0.87	0.20
7	5	3	6	0.0556	0.28	18	3	13	0.0256	0.46	0.61
8	6	3	6	0.0556	0.33	43	3	13	0.0256	1.10	0.30
9	2	3	6	0.0556	0.11	39	3	13	0.0256	0.98	0.11
10	6	3	6	0.0556	0.33	180	3	13	0.0256	4.60	0.07
11	0	3	6	0.0556	0.00	29	3	13	0.0256	0.74	0.00

TABLE VIII-7 RAW NAIL POP DATA AND NORMALIZED DATA TAKEN IN TEST HOUSES 1-4 (OKLAHOMA CITY)

Test House	Boom Period					Post Boom Period					Boom
	Raw Data	Readings Per Week	Weeks Read	Mult. Factor	Defects Per Reading	Raw Data	Readings Per Week	Weeks Read	Factor	Defects Per Reading	Post-Boom Ratio
1	149	7	26	0.0055	0.82	73	3	13	0.0256	1.87	0.44
2	12	7	26	0.0055	0.07	10	3	13	0.0256	0.26	0.27
3	178	7	26	0.0055	0.98	50	3	13	0.0256	1.28	0.76
4	346	7	26	0.0055	1.90	104	3	13	0.0256	2.65	0.72

normalizing factor being higher than necessary for nail pop data. This deduction assumes that a nail does not unpop and is easily spotted. Further, it would be reasonable to assume that nail popping rate should diminish with time since there are a finite number of nails in a house.

In summary, the large standard deviation of the data, the use of different time periods for reading cracks under boom and nonboom conditions, the questionable, statistical validity in the methods of analysis, and the variable observer techniques makes the results of the analysis doubtful. The only definite conclusion that can be made is that no cumulative effect can be positively established from the Oklahoma City and White Sands observer data. Inference suggest that an effect exists above 5 psf for new plaster and 10 psf for cured materials.

To determine whether booms cause cracks to propagate more rapidly, development of criteria by laboratory testing under controlled conditions is necessary. Too many natural conditions affect field test data to easily expose boom effect.

E. Identification and Description of Boom Damage:

The White Sands Report listed damage done to various building materials at the minimum pressure levels. Exact boom intensity levels at which specific damage was done was not recorded in many instances, because of the cumulative nature of damage and because an observer was not necessarily present at the exact time of damage. Up to 45 boom runs per day were made over the structures. For the most part three detailed examinations of the structures were made per day. Table VIII-8 summarizes all of the White Sands damage findings and lists the exact pressure recorded at time of damage (if known) as well as the average and range of pressure for the day of damage. It is our opinion that most of the damage reported was caused by the higher boom intensities for the day recorded.

During the White Sands tests brittle sealing wax was placed over existing diagonal cracks starting from corners of doors and windows and over lateral cracks parallel and perpendicular to the underlying wood lath. Only the wax on the diagonal cracks broke. The lateral cracks, affected mostly by diaphragm action, did not break on any boom runs. Assuming brittle sealing wax to have the same modulus and strength characteristics as plaster, this test is important for indicating the load and deflection at which plaster on wood lath can be expected to break. The Oklahoma City displacement meters placed across cracks also showed displacements across cracks to be below 0.001 inch.

No damage was observed by the Oklahoma City observers to be caused by the booms. Nails were seen to pop when an observer walked in the attic, but none were reportedly seen during the 1256 booms.

Observers actually saw cracks extend during the planned booms only three times. This occurred during the White Sands Tests:

TABLE VIII-8 Sum Total of Damage Caused or Probably Caused by F-104 Booms During White Sands Tests

Motion Induced Fall and/or Breakage

Item No.	Item and Description	Mecha-** nism	Bldg	Intensity (psf) Boom	Min	Max	Av.
1	loose paint fell (one fleck)	T	H	6.0*	--	--	2.1
2	loose grout fell (one fleck)	T	H	--	3.0	5.4	4.5
3	precarious screen toppled	T	H	--	2.4	7.6	4.7
4	picture and glass fell	S	H	--	6.4	12.1	10.2
5	loose grout fell	T	H	38	--	--	--
6	picture fell off nail	S	PF-6	38	--	--	--
7	ash tray fell off sill	S	H	38	--	--	--
8	tea cup fell	S	W-3	38	--	--	--
9	picture and 2 figurines fell	S	PF-6	--	8.2	22.4	13.7
10	glasses moved	S	PF-6	--	11.0	21.6	16.3
11	window screens toppled	T	H	--	11.0	21.6	16.3
12	figurines moved	S	PF-6	--	7.0	12.2	9.4
13	venetian blinds fell	S	H	--	7.0	12.2	9.4
14	glasses moved	S	PF-6	--	7.6	13.1	10.3
15	figurine fill off sill	S	PF-6	23.4	11.8	23.4	19.3
16	relay switch covers moved	S	Comm.	--	11.0	21.6	16.3

Plaster & Ceramic Tile Cracking & Nail Popping

Item No.	Item and Description	Mecha-** nism	Bldg	Boom	Min	Max	Av.
1	jacking crack ext. (2 in.)	R	W-4	--	4.8	7.4	5.9
2	stucco cracks hairline ext. (1 in.)	D	W-3	--	4.6	12.5	7.6
3	old gypboard ceiling crack ext. (1 in.)	D	H	--	4.5	11.0	6.9
4	crack ext. in bathroom tile (8 in.)	R	H	--	4.4	11.0	6.9
5	possible nail popping	R&D	PF-6	--	6.4	12.1	10.2
6	crack ext. in tile (2 - 3 ft.)	R	H	38	--	--	--
7	new hairline stucco cracks (1 in.)	R	W-3	38	--	--	--
8	nail popping	R&D	PF-6	--	8.7	11.7	10.0
9	nail popping	R&D	H	--	8.7	11.7	10.0
10	ceiling crack ext. (1/2 in.)	D	H	--	8.7	11.7	10.0
11	nail popping	R&D	PF-6	--	8.2	22.4	13.7
12	ceiling crack ext. (1/2 in.)	D	H	--	8.2	22.4	13.7
13	jacking crack ext. (2 in.)	R	W-4	--	2.4	7.6	4.7
14	damaged suspended ceiling spalled at joint	D	366TAC	--	1.6	11.6	4.2
15	cracks spalled, ceiling (2 in.)	D	H	--	7.0	12.2	9.4
16	ceramic tile in shower moved (1/2 in.)	R	H	--	7.6	13.1	10.3
17	nail popping	D	H	--	8.7	14.0	11.2
18	paint spalling	D	H	--	8.7	14.0	11.2

*By calibrated sound level intensity meter
T - toppling and falling
S - sliding and falling
R - racking action
D - diaphragm action
I - impact action
P - pressure caused failure

** large variations in peak pressure are due to large deviation flight altitude during day of recording.

TABLE VIII-8 (Continued)

Plaster and Ceramic Tile Damage

Item No.	Item and Description	Mecha-nism	Bldg	Intensity (psf) Boom	Min	Max	Av.
1	ceiling (8' x 8' section) fell	D	W-4	12.1	6.4	12.1	10.2
2	piece of ceramic tile fell in shower	R	H	--	10.6	20.2	13.9

Glass Damage

Item No.	Item and Description	Mecha-nism	Bldg	Intensity (psf) Boom	Min	Max	Av.
1	crack in 16" x 24" x 0.085" glass at nail holding	I	GH	12.1	6.4	12.1	10.2
2	14" x 18" x 0.085" glass crack extended	P	H	38	--	--	--
3	16 panes (average 16" x 24" x 0.085") broke or cracked	I	GH	38	-	--	--
4	12" x 42" x 0.085" trailer window broken	I	OT	38	--	--	--
5	2, 8' x 10' x 0.229" store front windows	P	SF	38	--	--	--
6	16" x 24" x 0.085" panes cracked further	I-P	GH	--	8.7	11.7	10.0
7	3 panes, 16" x 32" x 0.085" and 16" x 24"	I-P	GH	--	8.8	17.7	12.6
8	32, 3/4" x 48½" x 0.115" casement window shattered	I	C-1	21.6	11.0	21.6	16.3
9	3 panes, 16" x 24" x 0.085" broken	I-P	GH	--	11.0	21.6	16.3
10	32, 3/4" x 48½" x 0.115" precracked glass cracked further	P	W-4	--	3.8	11.0	6.8
11	6 panes, 16" x 32" to 16" x 24" (t= 0.085") broken	I-P	GH	23.4	11.8	23.4	19.3
12	16" x 24" glass dislodged and fell (t= 0.085")	I-P	GH	--	4.6	12.5	7.6

Miscellaneous Damage

Item No.	Item and Description	Mecha-nism	Bldg	Intensity (psf) Boom	Min	Max	Av.
1	3 bricks loosened below window	D	2S-5	38	--	--	--
2	molding popped off 5' x 10' window	D	W-2	38	--	--	--
3	glass door loosened when screw fell	D	2S-5	38	--	--	--
4	mullions twisted on store front windows	D	SF	--	8.2	22.4	13.7

1. Hairline stucco cracks were seen to extend about one-half inch under 7.6 psf booms. After the booms the cracks continued to extend under natural conditions. (Table VIII-8, item 2).
2. The existing cracks in the ceiling of the barracks building and bathroom extended about an inch under 6.9 psf booms. Further extension of these specific cracks did not occur even under the "Big Boom" pressure of about 38 psf. (Table VIII-8, item 3).
3. The head of a hairline crack caused by artificial settlement extended about two inches after 20 booms having a 5.2 psf designed overpressure. Jumping on the floor near the wall with the crack caused further crack extension. (Table VIII-8, item 1).

These and other cracks, which were not observed directly but could positively be identified as boom caused, were hairline in size and could barely be seen with the naked eye. This indicates that the buildings oscillated near elastically under boom loads. The sealing wax cracks could also be barely seen since they, too, were essentially closed.

This observation appears to be borne out upon review of the "Big Boom" damage survey (Appendix VIII-A). No cracking different from normal was identified in the structures. A copy of one observer's critical survey of the minimum house, W-4 (wood lath), is included for information (Fig. VIII-7). Cracks may have occurred in this house under the "Big Boom", but none could be seen. They were closed if they were there. This again illustrates that little to no permanent set under boom loads occurs since boom cracks are not discernible or are hairline in size.

Glass breakage for the most part was cuased by impact of glass against a stress raiser, as in the case of the greenhouse glass being battered by the boom against a nail. The "Big Boom" pressure did break the big store front windows, and boom pressure broke glass that was already cracked.

Bric-a-brac may be broken by toppling or sliding action. This action is provided by base (wall, table, etc.) vibration and not by boom pressure directly. A series of high pressure booms can "walk" bric-a-brac to the edge of a table, say, so that it falls if not precariously placed.

In summary, it appears that boom damage is either obvious (ceiling falling, window breaking dramatically at stress raisers, bric-a-brac falling) or unobvious (one or two hairline cracks). Large cracks in brick, stucco, plaster, concrete, etc., could not be caused by booms since large amounts of permanent set even at high pressures is virtually impossible.

F. <u>Discussion and Summary of Loading-Response-Damage Knowledge</u>:

Two minor studies [20,21] and two major studies (Oklahoma City[3] and

JOHN A. BLUME & ASSOCIATES RESEARCH DIVISION

612 HOWARD STREET • SAN FRANCISCO, CALIFORNIA 94105

JOB NO ____ JOB Structural Reaction Program, Sonic Boom Study BY TWR DATE ____

CLIENT ____ SUBJECT Visual Inspection Chart CHK'D ____ DATE ____

DATE 12/3/64 HOUSE: W-4

TIME 11:00

RUN.

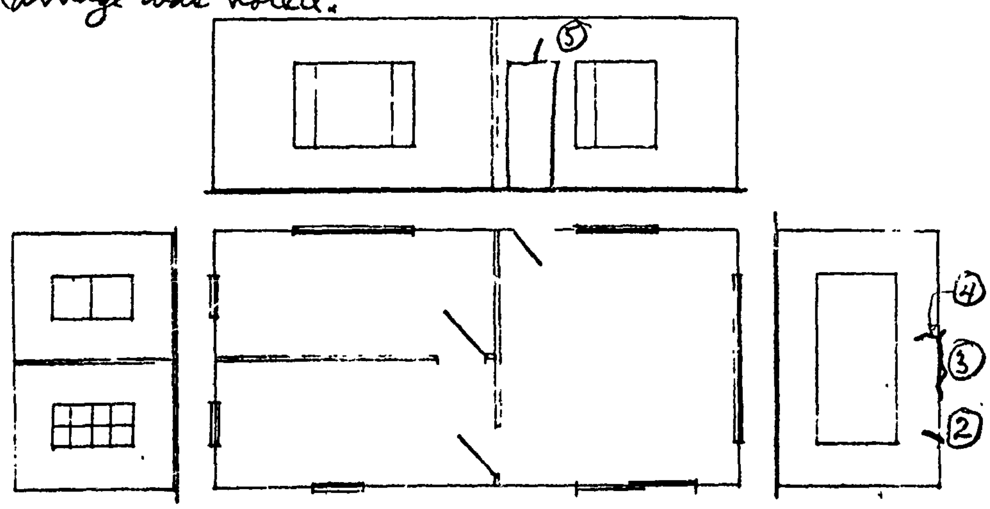
B = Broken

C = Ch…

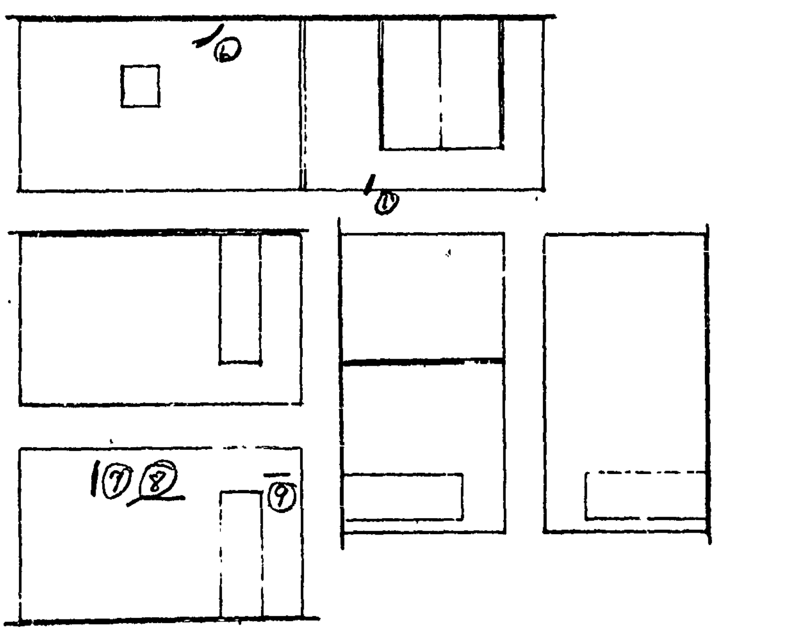
[illegible]

Post Mortem

Most amazing thing is that no positive boom damage was noted.



Results of A Fine Tooth Exam.



1. $1\frac{1}{2}$" Extension
2. $1\frac{1}{2}$" Extension
3. 14" New - wall-ceiling joint
4. $1\frac{1}{2}$" Ext.
5. $3\frac{1}{2}$" New
6. 4" Ext.
7. 2" New.
8. $10\frac{1}{2}$" New
9. $1\frac{1}{2}$" Ext.

All cracks were minor and some were probably missed previously.

SHEET NO.

Fig. VIII-7. Survey of Damage in Building W-4 after the White Sands 38psf "Big Boom".

White Sands[4]) constitute the structural response studies conducted under sonic boom loads of varying intensities. Only the White Sands Report discusses damage criteria. The damage noted during that study was slight except for the glass breakage which occurred during an unscheduled 38 psf boom and the falling ceiling under a 12.1 psf boom.

Programmed research into the effects of blast vibrations on structural damage has continued since 1935. Of the many papers on blasting since that time only three publications [28,29,30] examine damage data from blasts and attempt to correlate it with displacement and frequency. Even a large portion of the damage data points that are used in criteria development were not caused by blast but by destructive testing with a machine. In USBM Bulletin 442, for example, only two cracks were caused by blasting. (The other 160 or so data points were obtained with the machine.)

It is interesting to examine the story behind the blast damage and to compare it with boom-crack observations. The blast cracks appeared in plaster ceilings of a two-story structure situated directly over a mine shaft some 70 feet deep. The blasts naturally caused predominantly vertical motion which diaphragmed the ceilings. Minor, hairline cracks were observed in the first and second floor ceilings at 0.08 inch displacement. One hairline crack was new and one was a 14 inch hairline extension. Further blasts with larger charges giving rise to response of up to 0.3 inch caused no further damage. The locked-in stresses were evidently relieved by the first damage so that larger vibrations were ineffective. This agrees with boom experience. The ceiling in the barracks building during the White Sands tests showed crack extensions under 8 psf booms. However, even under the 38 psf boom further extension did not occur in this particular ceiling.

Bulletin 442's definition of plaster damage (the U. S. Bureau of Mines' minimum damage index material) from blasts can be compared with that resulting from booms. "Visually the indication of damage was when dust fell from the sides of cracks as they rubbed together. As the severity of vibration is increased fine new cracks are formed, and the plaster may flake or spall slightly or the surface or putty coat separate from the brown coat beneath. A further increase of vibration causes extension of the new cracks and finally causes large areas to separate from the lath and fall. In this report the term 'damage' refers to falling plaster unless otherwise stated." This agrees with the White Sands observations that the three levels of damage, increasing in severity, are characterized by flakes from old cracks, hairline crack extensions and falling plaster.

Other than the 16 day old plaster ceiling, which fell on a 12.1 psf boom, a piece of ceramic tile which fell on 14 psf booms, and glass breakage only very short hairlike extensions and some spalling were observed in old drywall, stucco, and plaster under booms of up to 38 psf in strength. The ceiling damage cited above can be compared with the one incident of plaster separation from a ceiling reported by Bulletin 442. Therein the authors record that in Ceiling C plaster, already loose from the lath, fell at 0.15 inch forced vibration at 11.6 cps, the ceiling's natural frequency. Extrapolating the upper response envelope of Figure VI-34 in the White Sands Report to 0.15 inch displacement the value of 11.8 psf is obtained. This agrees well with the 12.1 psf figure recorded during the test lending credence to the hypothesis made in the White Sands report that the plaster was loose from the lath before the damage occurred.

In both Bulletin 442 and the White Sands report no conclusive evidence of cumulative damage resulting from fatigue of plaster or some other unknown creep mechanism has been advanced. Since little to no permanent set occurs under booms of the magnitudes tested the creep hypothesis may be eliminated as a cumulative mechanism. One ceiling was vibrated by Thoenen and Windes at resonance for 44,000 cycles at 0.023 inch displacement without damage. This displacement would correspond to a peak, upper bound pressure of about 3.5 psf. The limited amount of fatigue information cannot be used to judge the cumulative damage behavior of a ceiling category, however.

As a result of the studies dealing with blast damage various types of criteria have been suggested. The first criterion considered peak acceleration as an intensity index (Bulletin 442). Later, Crandell[25] suggested that "energy ratio", defined as the square of the maximum acceleration in feet per second divided by the square of the frequency in cycles per second, was a better criterion. As a result of this and other studies New Jersey, Massachusetts, the New York State Power Authority and the U. S. Corps of Engineers adopted an enery ratio of 1 as a criterion for damage. Pennsylvania adopted a displacement of 0.03 inches as a safe blasting limit. Later analysis of all the data in 1962 indicated that peak particle velocity was a better criterion. (Fig. VIII-8)

Duvall and Fogelson[31] indicate that a particle velocity of 2.0 inches/second was a safe limit since it included 94 percent of the damage data. This corresponds to the Pennsylvania limit of 0.03 inches when read at 10 cps on the abscissa of Fig. VIII-8. Using an energy ratio of 1, adopted by the states mentioned above, an equivalent particle velocity of 1.81 inches/second is computed.

Looking deeper into the claims problem of vibrations effects and related claims, Fig. VIII-9 shows the relationship of human beings' sensitivity to vibration. That which is severe to persons is one-third the popular 2.0 inch/second criterion. People, unaccustomed to vibrations and within the sanctuary of their private home, could very easily associate damage gone unnoticed with an event that was troublesome or severe to their body response. Human body "gages", as shown in Fig. VIII-9, are not good damage assessors, therefore. But this factor cannot be overlooked in the overall claims problem.

In view of the foregoing discussion, discussion about boom damage and cumulative damage, and information presented in Chapter VII on intensity, Table VIII-9 lists damage index levels for various materials using White Sands and U. S. Bureau of Mines data and predicted peak overpressure as a criterion.

Table VIII-9 was constructed by the following reasoning:

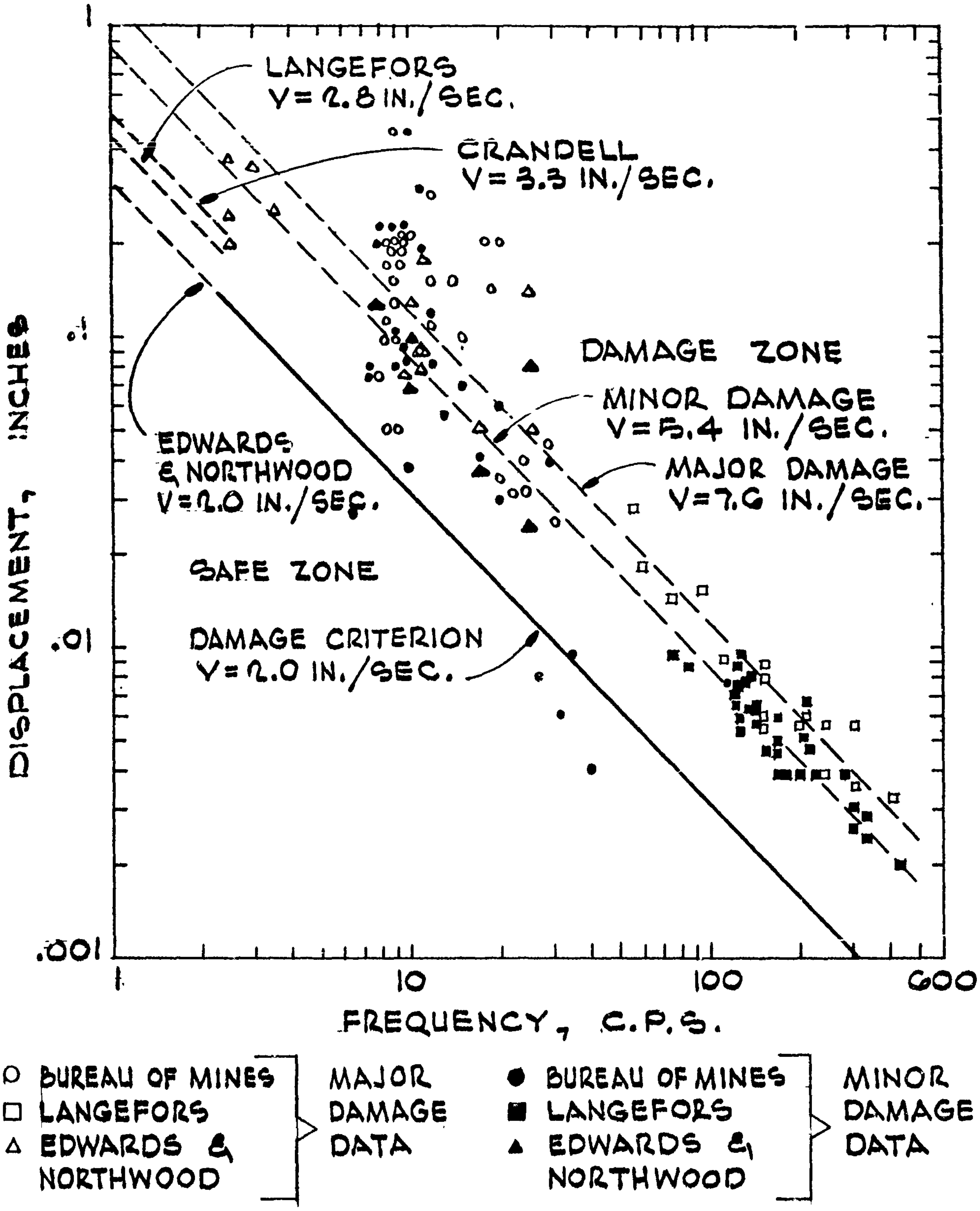


FIG. VIII-8 U.S. BUREAU OF MINES CRITERION FOR DAMAGE FROM BLAST VIBRATIONS (RI 5968)

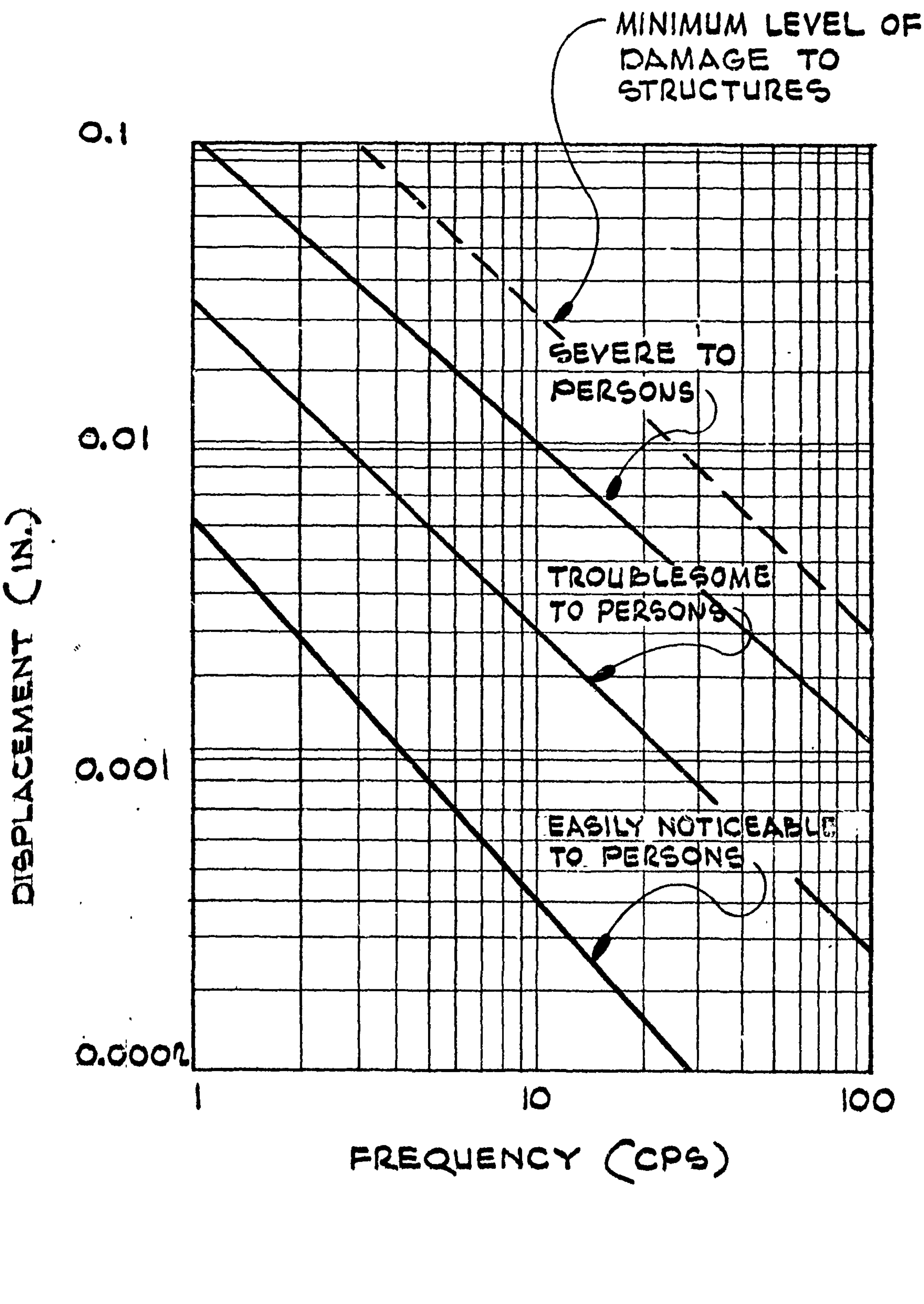


FIG. VIII-9 VIBRATION SENSITIVITY OF HUMAN BEINGS (AFTER CRANDELL) COMPARED WITH U.S.B.M. DAMAGE CRITERION

TABLE VIII-9 Maximum Safe[1] Predicted Peak Overpressure for Representative Building Materials and Bric-a-brac Other than Glass

Material	White Sands		USBM	
	Minor[2]	Major[3]	Minor[2]	Major[3]
Interior Walls and Ceilings				
1. plaster on wood lath	3.3	5.6	5.5	NA[4]
2. plaster on gyplath	7.5	16.	NA	NA
3. plaster on expanded metal lath	16.	16.	NA	NA
4. plaster on concrete block	16	16.	NA	NA
5. gypsum board (new)	16	16.	6.0	NA
6. gypsum board (old)	4.5	16.	6.0	NA
7. nail popping (new)	5.4	16.	NA	NA
8. bathroom tile (old)	4.5	8.5	NA	NA
9. damaged suspended ceiling (new)	4.0	16	NA	NA
10. stucco (new)	5.0	16		
Bric-a-brac				
1. extremely precariously placed or unstable items	NA	3.1	NA	NA
2. normally stable or placed items	NA	5.6	NA	NA
Miscellaneous				
1. brick cracked	19	--	NA	NA
2. glass door loosened	19	--	NA	NA
3. twisted mullions	9	--	NA	NA
4. popped molding	19	--	NA	NA

1. Less than one chance in 10,000 when within five miles of flight track. This value corresponds to a 99.99 percent confidence that damage will not occur.

2. Small (less than three inches) hairline cracks extensions or pre-damaged paint chipping or spalling.

3. Falling plaster, tile, bric-a-brac etc.

4. Not applicable.

1. The average of the maximum and average peak pressure reading for the minimum damage level for the material of interest is divided by two. For example, crack extensions in the gypboard ceiling were noted at five separate pressure levels. The minimum value was used. Justification for using an average of the maximum and average pressure as a starting criterion stems from the judgement that the higher pressure booms on the day of recording caused the damage. The use of the value two (2) as a divisor is justified by using a confidence level of three standard deviations from the predicted or average overpressure (1.3 chances in 1000) and an average coefficient of variation of 0.33. This is considered to be conservative for the F-104 at the altitudes necessary to generate the pressures listed. It may be more in line with B-58 and SST variations, however.

2. The pressures given are the average of those recorded during a series of boom runs or the value calculated knowing aircraft flight altitude and speed and theoretical peak pressure versus altitude curves.

3. Minor damage is defined as hairline crack extensions. These are not distributed extensively in a building.

4. Major damage, where applicable, refers to falling plaster, etc. A falling piece of bric-a-brac is assumed to break.

5. Safe refers to an expectancy of less than one chance in 10,000, or a 99.99 percent confidence that damage will not occur. This expectancy derives from the use of three standard deviations and the judgement that 20 booms in a day were required to cause the damage. Combining these the resultant probability is 1.3/1000 x 1/20 = 1.3 chance in 20,000 boom-samples. The coefficient of variation of 0.33 is also considered conservative at the mean pressures indicated.

Since 94 percent of the damage data lies within the U. S. Bureau of Mines curves the safe term for their data is 6/100 x 1.3/1000 is about 1/10,000.

Fig. VIII-10 was prepared from Pittsburg Plate Glass Company's Technical Service Report No. 101 in combination with the reasoning that follows.

1. Chart no. 1 in report 101 was used as the basis for glass damage prediction.
2. The abscissa pressure values of chart no. 1 are multiplied by a coefficient of 0.187. This coefficient is derived by multiplying the effects of the following conditions:

a) strain rate - 1.5
b) 3 standard deviations - 0.5
c) dynamic amplification factor - 0.5
d) impact - 0.5

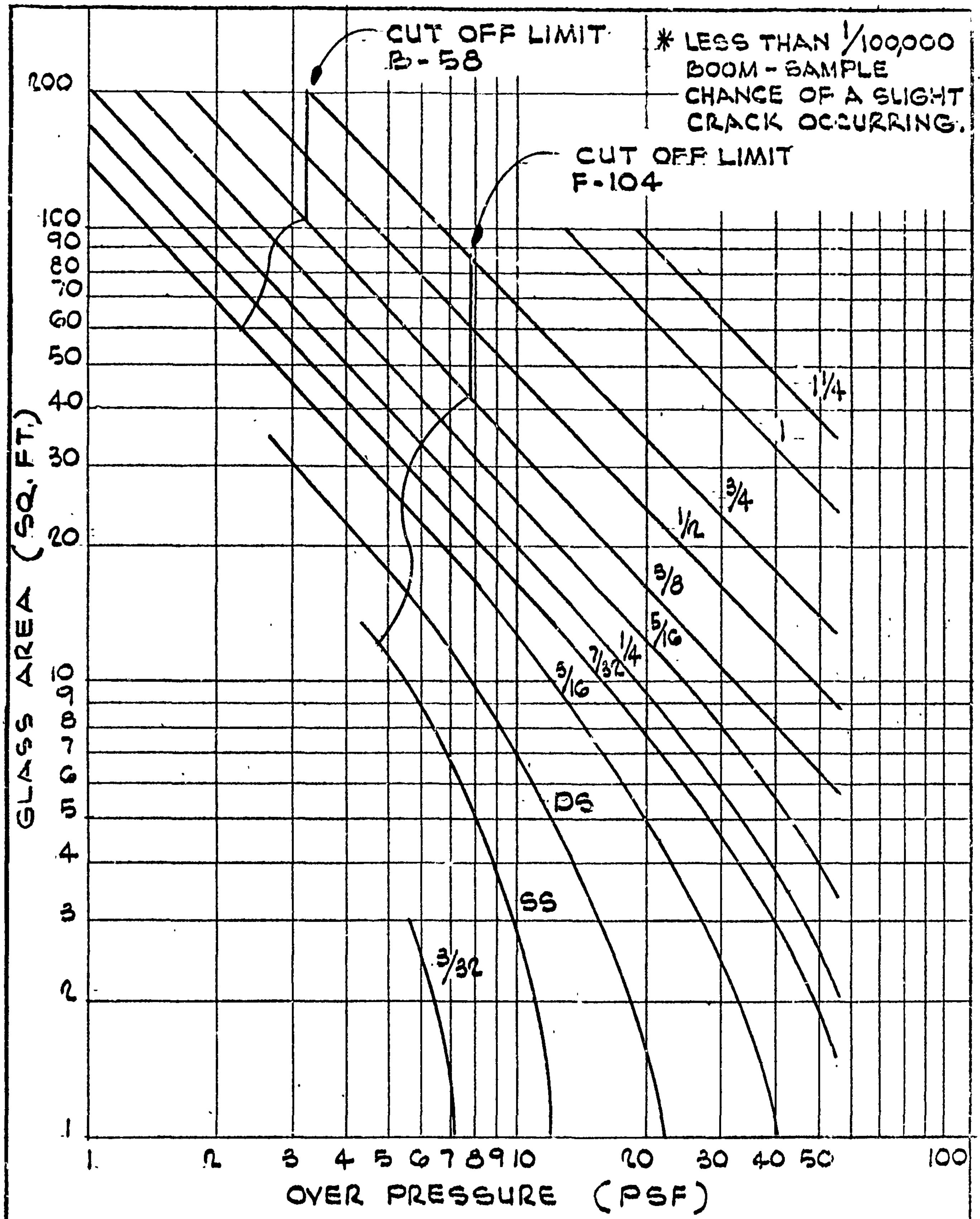


FIG. VIII-10 MAXIMUM SAFE PREDICTED OR MEASURED AVERAGE GROUND OVER-PRESSURE FOR PL & WINDOW GLASS

3. The cutoff limits, beyond which boom from a given aircraft is ineffective, are determined by use of the fact that dynamic amplification factor decreases almost linearly to zero for panes having natural frequencies below the fundamental. This fundamental frequency is about 12 cps for an F-104 at 5 psf and 5-6 cps for a B-58 at 3.5 psf. The natural pane frequencies were calculated by assuming an l/d ratio (l = length, d = width) of 2/1.
4. The overpressures are safe by a factor smaller than 1/100,000. This is found by recognizing that the glass curves were fabricated with an expectancy of breakage less than 8/1000. The standard deviation of boom pressure has a confidence expectancy of 1.3/1000. The resultant boom-sample confidence is the product of these two or 1.04/100,000. Even this is conservative since the average (DAF) value of 2 is large and only inbound vectors are assumed. However, the value of ½ used for impact at a stress raiser is okay.
5. The type of damage to be expected at these limits is simply a modest crack or two. No shattering should occur.

Let us compare the observed damage with the chart. The lowest average pressure at which precracked greenhouse glass was dislodged and slid down (cracks were not extended) was 7.6 psf. The chart indicates that there was a 1/100,000 chance that this could happen on a 6 psf day (3/32" glass with an area of 2.67 feet). The double strength 11 ft.^{2} glass in C-1 which broke on an inbound vector on a 16.3 psf day would be predicted to break with a 1/100,000 chance at 7.5 psf. Therefore, the chart appears to be quite conservative for severe glass breakage. It also allows for the effect of a larger impulse from the B-58 for large windows.

Let us examine the well documented case of an F-100 which caused a boom over Cedar City, Utah. The aircraft altitude was probably 500 ft. above the town. Claims were filed for damage only within 2000 feet of the flight path. Of the 97 claims filed (324 damage cases were reported) the following were found:

1. glass - 88
2. plaster - 13

Miscellaneous other claims were made.

The peak pressure caused by the aircraft was probably about 18 psf as analyzed by the ARDE report[22]. The distance from the flight path beyond which no damage was claimed (2000 feet) experienced a theoretical overpressure of about 5.7 psf. On the glass damage chart the minimum theoretical glass damage level for the F-104 (similar to an F-100) is governed by 12 ft.^{2} single strength glass at 4.8 psf. These figures agree very well with one another.

IX. A PROVISIONAL GUIDE FOR SONIC BOOM CLAIMS ADJUSTERS:

A. Introduction:

The purpose of this Guide is to provide interim data to assist adjusters in handling claims for damages allegedly caused by sonic booms. In no sense is it meant to be a technical treatise, nor is it intended to make structural dynamicists of adjusters.

With the advent of the supersonic transport and supersonic Air Force operations over populated areas, more and more boom claims have been and will be reported. Yet comprehensive studies by the Federal Aviation Agency indicate that properly designed and controlled supersonic overflights have essentially a zero probability of damaging structures and structural elements. Every adjuster who wants to make a proper evaluation of the claims he is called upon to adjust should be familiar with these studies and the statistical implications of the results.

B. Identification of Boom Damage:

Damage to plaster and gypsum board caused by boom can be broken down into three categories increasing in severity:

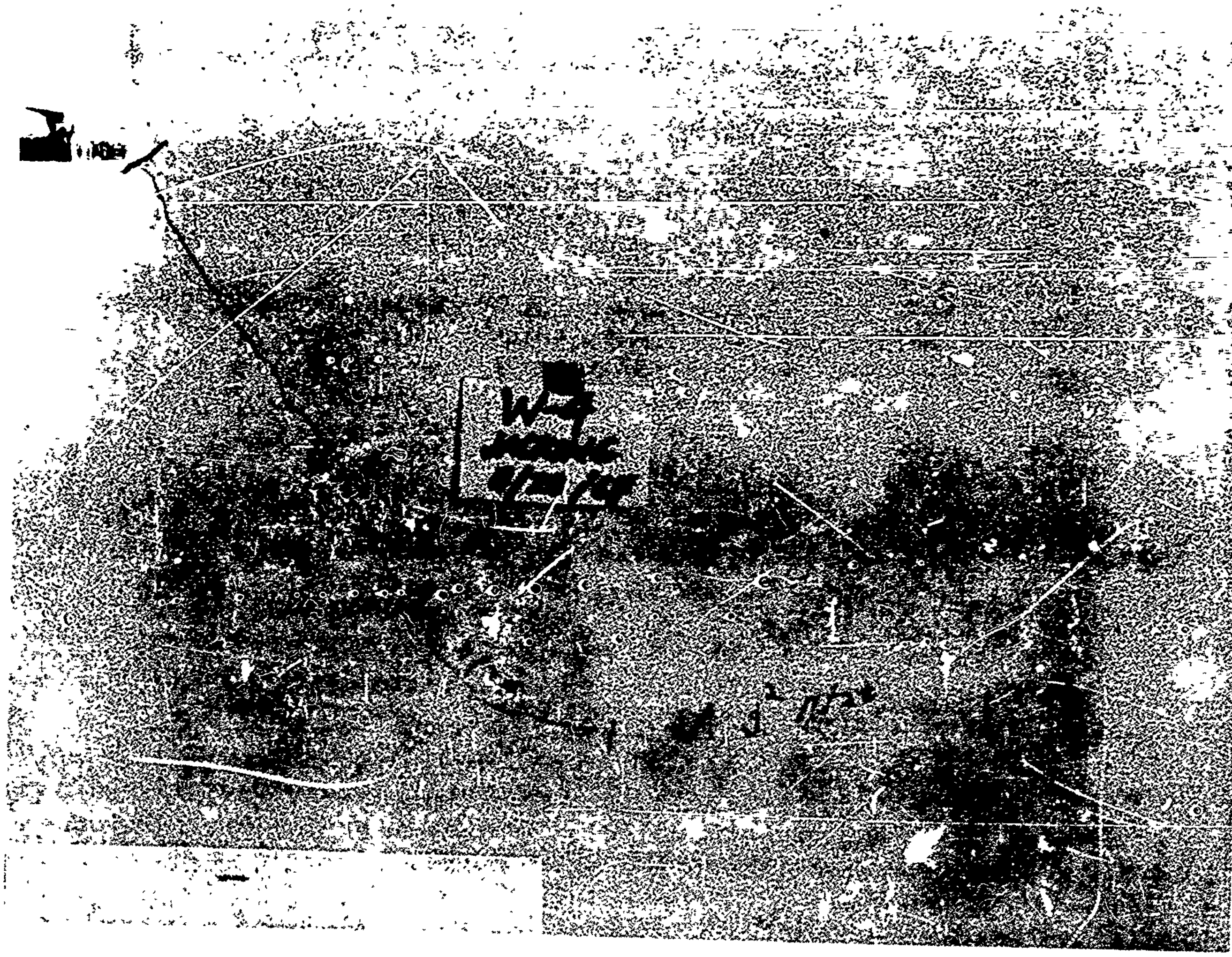
1. Slight spalling of old cracks. A little dust will fall from an existing crack that can be seen by a very observant person or a trained observer.

2. Fine or hairline cracks will extend from old ones. Extension is usually less than about 4 inches and can be detected only upon very close examination.

3. Plaster falls. Part of a ceiling or a loose piece of wall plaster may fall to the floor.

Examples of these types of damage, determined from Federal Aviation Agency tests, are shown in Figs. IX-1 to IX-5.

The crack in Fig. IX-1 shown emanating from the corner of a window was formed in three stages. A jack placed under the corner of the area shown was raised an eighth of an inch. This caused the first diagonal crack noted as AJ 11/28. Three 5.2 psf designed overpressure booms hit the structure, not one of which caused further extension. The corner of the building was raised another eighth of an inch causing the extension marked AJ^2 11/28. A boom caused extension (damage "type 2") occurred at the head of this crack after 20 booms of 5.2 psf overpressure. It was about 2 inches long and could be identified easily only with a magnifying glass. This extension lies within the interval identified



as 11/28. About 7 other artificial settlement cracks emanated from other parts of the window shown but these did not extend under the booms.

Fig. IX-2 shows a fleck of old, water damaged paint which fell under booms of 2.1 psf designed pressure. Since this type of flaking occurred from time to time under non-boom conditions and considering the condition of the paint, this is not regarded as boom damage. The purpose of the figure is to show the difficulty in identifying what is and what is not boom damage in old, run down buildings. The paint shown is in extremely poor condition resulting from neglect. Gravity as well as boom could be the final straw to dislodge dangling paint, some of which still hangs and has not fallen under the booms. But the boom did not cause the cracking on the wall. This was done by water before the booms. The adjuster must bear this example in mind when looking at old extensive damage such as this which can not be caused by boom.

Since bathroom ceramic tile is brittle, it too may be subject to boom damage. Fig. IX-3 shows what damage "type 2" might look like. The crack shown extended about 5 inches under 7.9 psf designed booms. The crack was so fine that carbon paper black had to be rubbed on the surface for it to show in the photograph. Boom caused crack extensions are very fine and can barely be seen with the naked eye.

Fig. IX-4 shows the only plaster damage "type 3" to occur during 1494 booms ranging up to 38 psf in strength. This damage occurred under a 12.1 psf boom on a day of runs when the designed overpressure was 10.4 psf. This ceiling was diaphragmed by the boom and failed in tension on the attic side of the ceiling. No cracking or warning could be seen prior to the damaging boom.

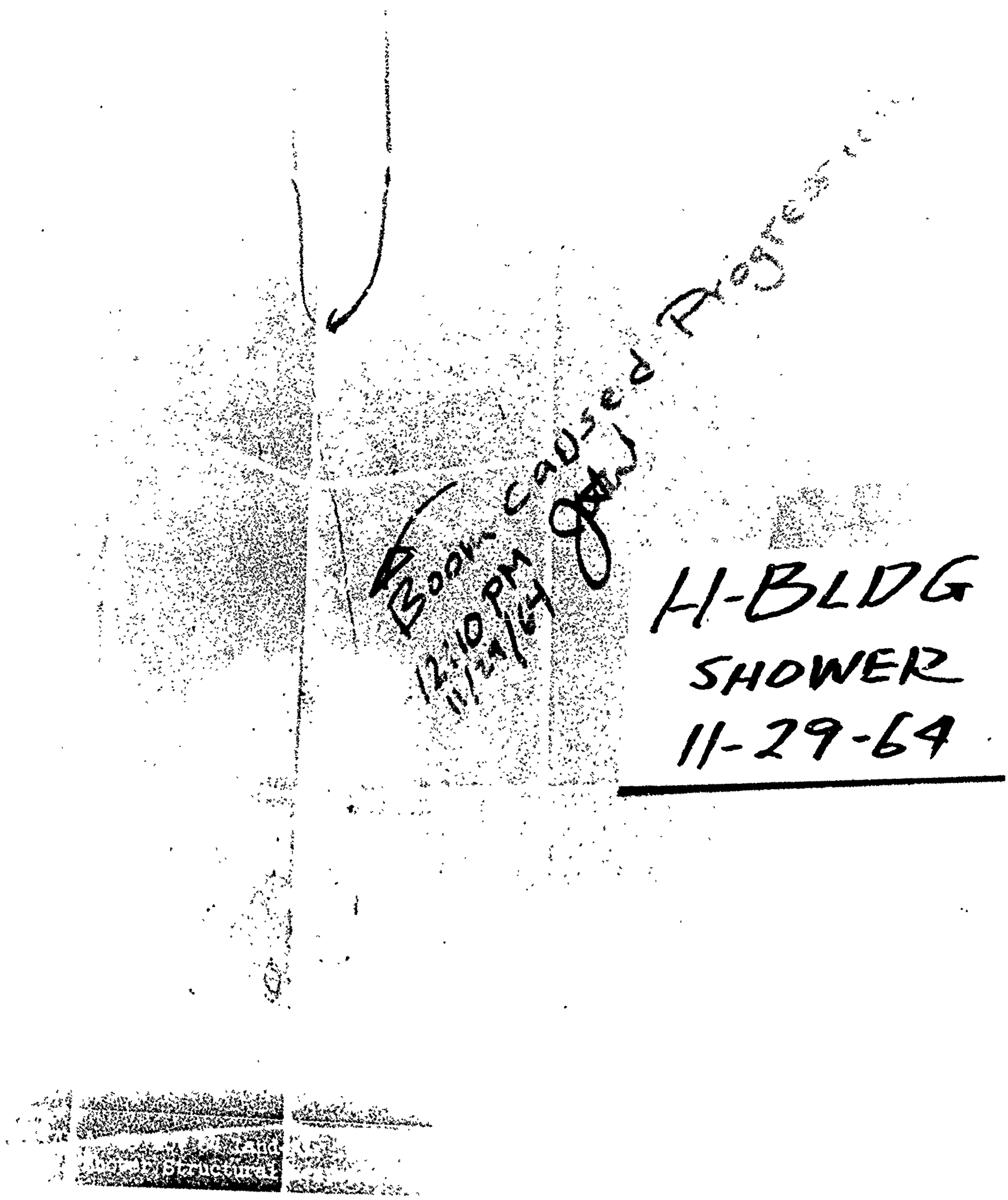
The plaster in this ceiling was, however, very weak and poorly bonded to the lath. The strength of the ceiling was considered to be below that of the usual old plaster-on-wood-lath buildings. One 40-year old plaster-on-wood-lath ceiling subjected to the same booms did not exhibit damage "type 1" under 12.5 psf designed boom overpressures.

Damage "type 3" is also shown in Fig. IX-5. Over 1000 booms, 153 of which were over 10 psf designed overpressure, loaded this old shower prior to the dislodgement of the tile by 15 psf designed booms.

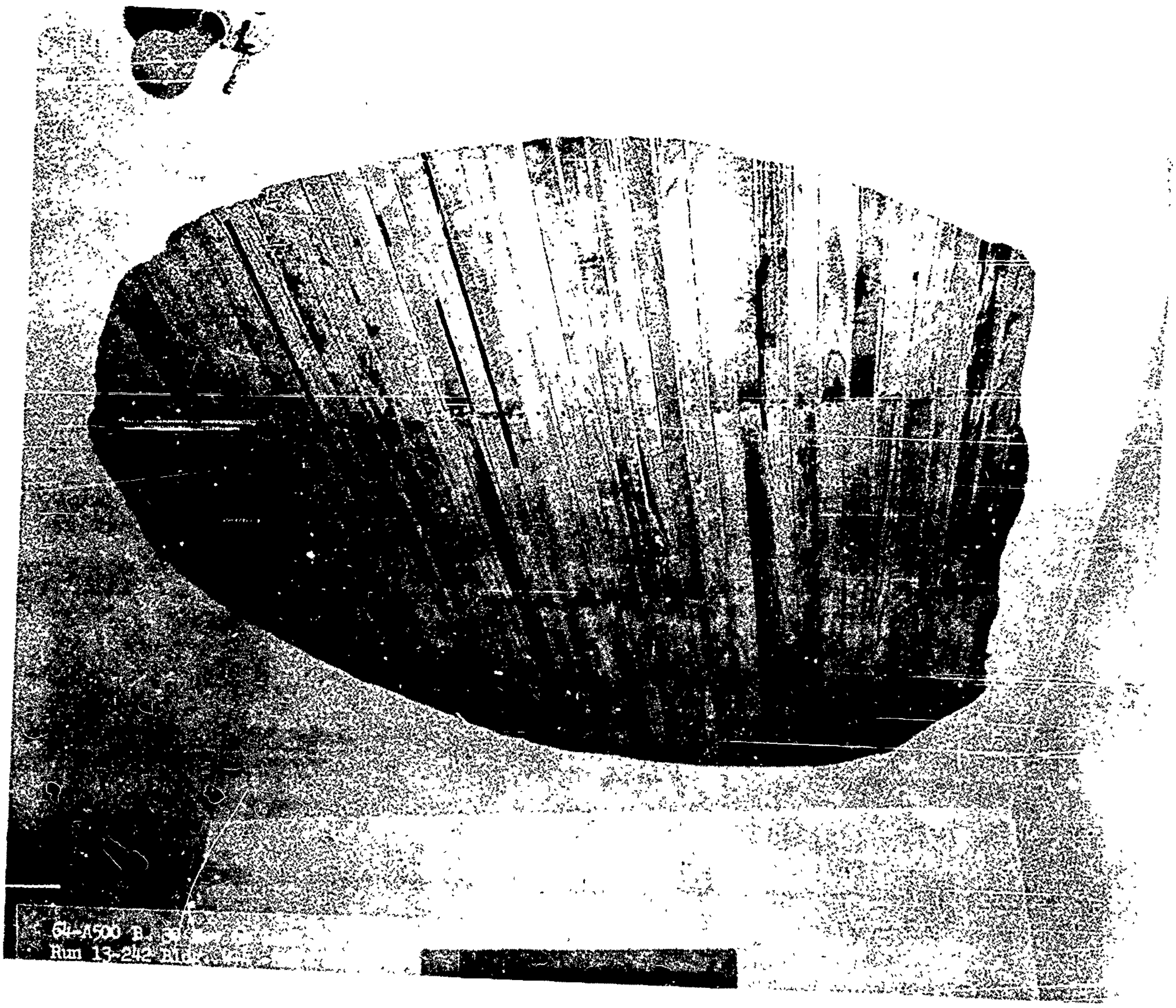
Glass is a stronger material than one normally thinks it to be. For example, a 38 psf boom directed into a 5'x10'x¼" window (critical vector) deflected up to 1.5 inches at the center causing the molding to pop off (Fig. IX-6). It did not break. Eleven similar windows did not break as well.

Fig. IX-7 shows breakage of a 32½"x48½"x0.115" window on an inbound (critical) vector boom run. It broke at 21.5 psf on a run designed to be 16.3 psf. Five other similar windows did not break. A prior 38 psf boom did not break this window because the boom was directed sideon. This indicates the importance of aircraft direction (vector) in relation


ORIG. CRACKS
IN PEELINGS
H-BLDG
11/22
6 Land-Air
Uncl.



Boom caused Progression
12:10 PM
11/29/64
H-BLDG
SHOWER
11-29-64


64-A500 B.
Run 13-242

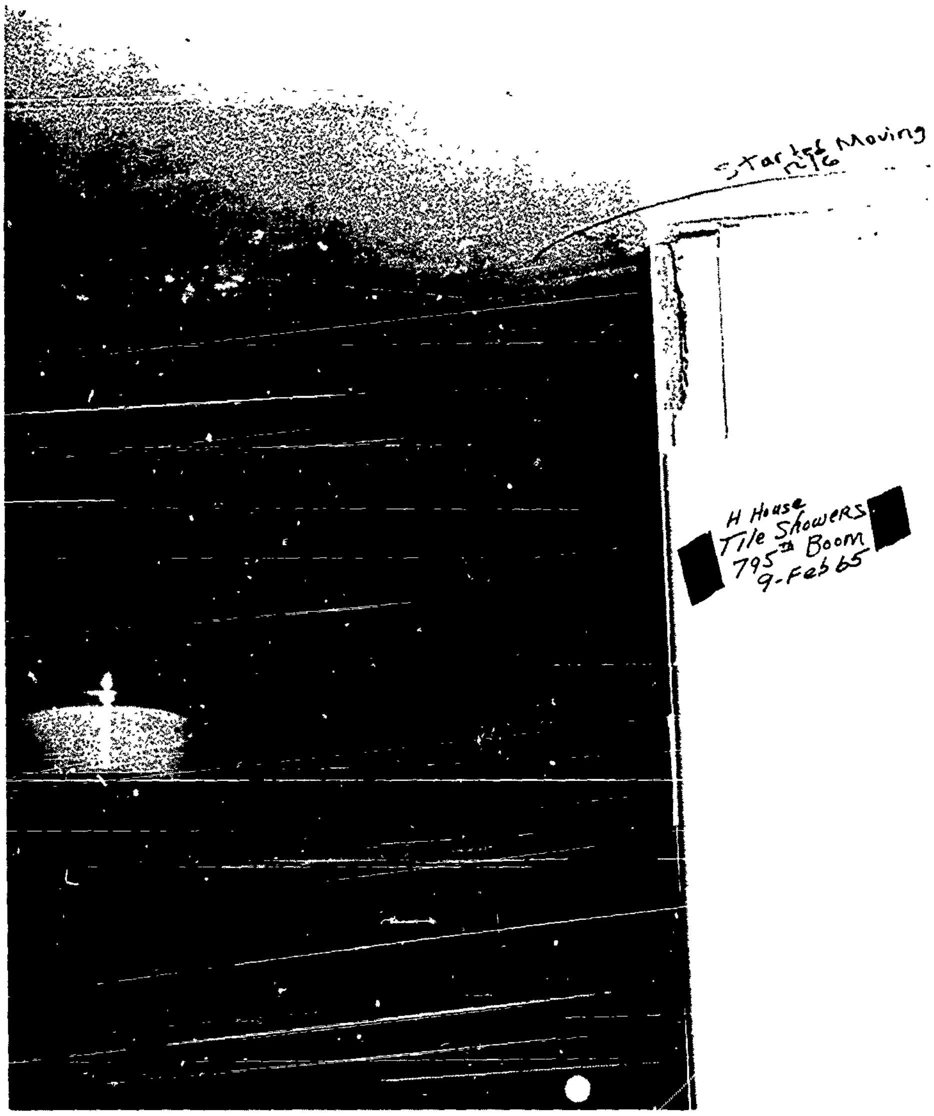


Fig. IX-5 One piece of old Bathroom Tile Worked Loose After Repeated Booming at Designed Overpressures of 15.0 psf. This Building had been subjected to a 38 psf Boom Prior to Damage.

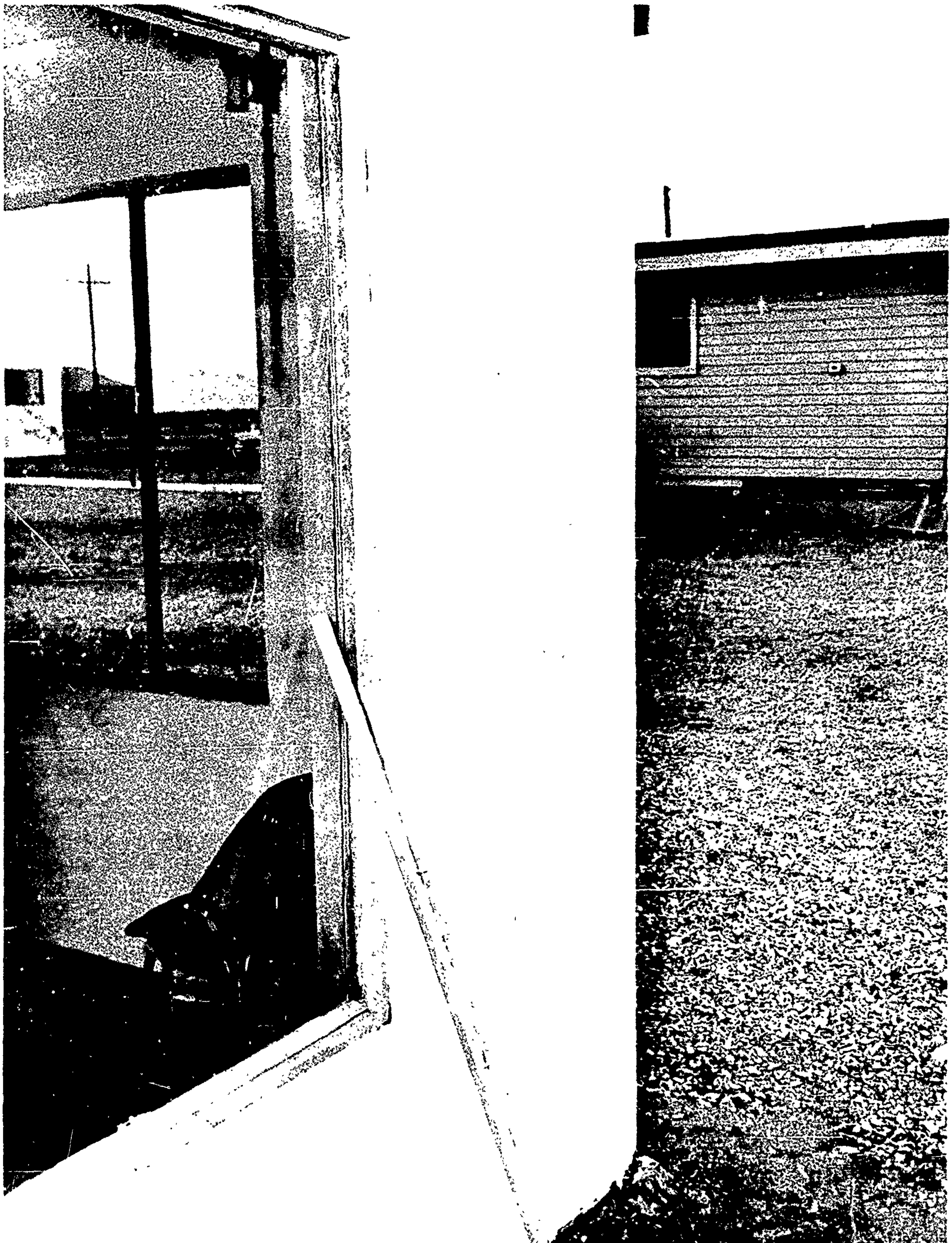


Fig. IX-6 Molding on 5' x 10' x 1/4" Window Popped off During a 38 psf Boom. Note that Only One Nail Held the Molding and that the Window Did Not Break. None of 12 Windows of this Size Broke on this Critical Vector Boom.


11 Dec

to glass damage. Note in Fig. IX-7 that the glass cracks started from the edge of the glass where the casement window latches are located. This indicates that new damage initiates at points of weakness or concentrated stress.

The above two examples of either glass breakage or damage associated with glass movement relate to normally mounted glass. Fig. IX-8 shows the type of damage that might be expected in poorly mounted glass. A chip of glass was caused by a 12.1 psf boom on a 10.4 psf designed overpressure boom run. This was the only damage done (at this designed overpressure) to glass in a greenhouse having more than 100 similarly mounted panes.

On a 38 psf boom 12 panes were broken and 4 panes cracked in this same greenhouse (Fig. IX-9). This illustrates that on even very high overpressure booms extensive glass damage can not be expected.

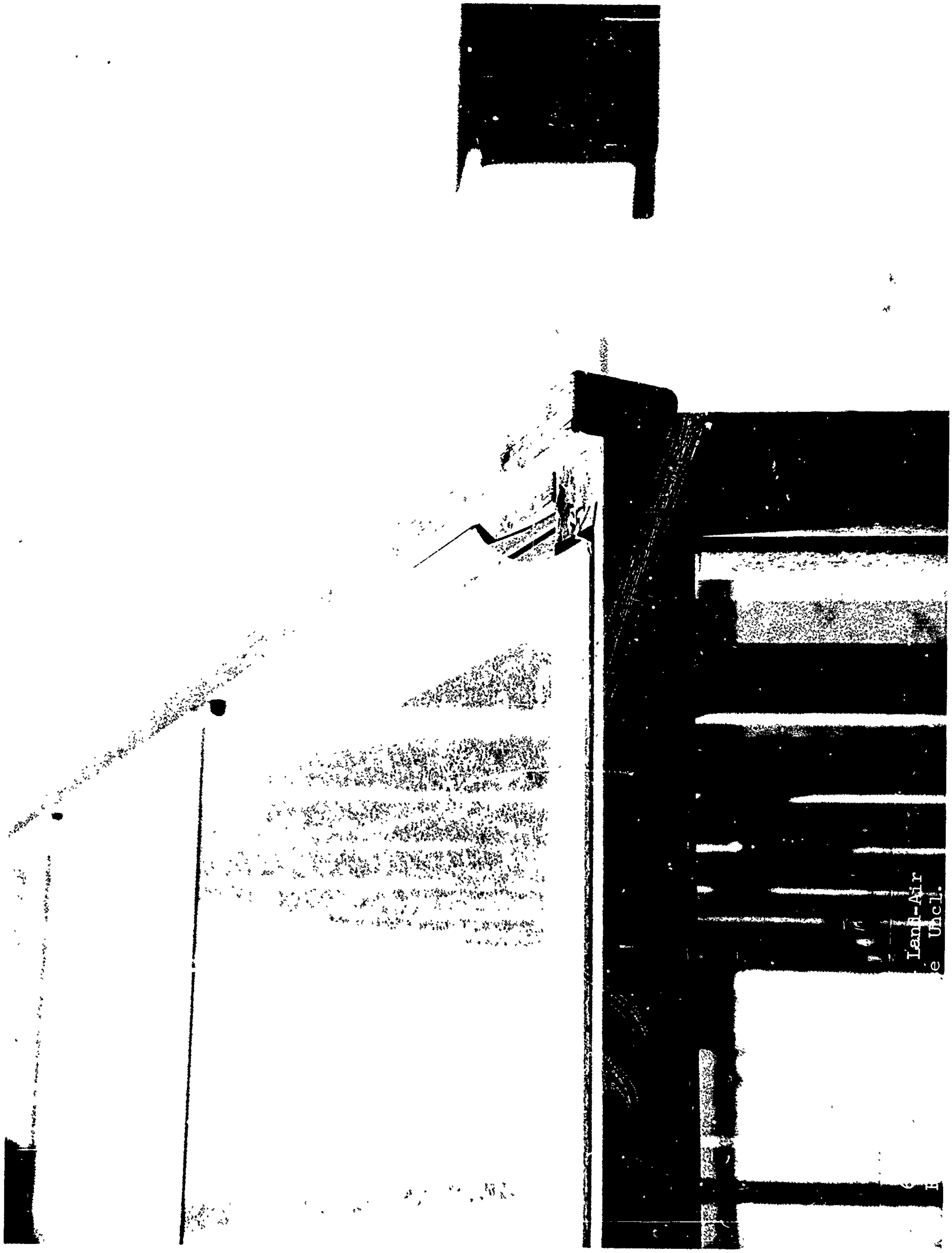
The term critical vector has been mentioned from time to time. This means that the window is oriented perpendicular to the direction of flight, and the airplane is flying toward the side of the house with the window of interest. For example, if a window were on the north side of the house the critical aircraft vector is from north to south. It has been found that the orientation of a window with respect to the direction of aircraft flight is quite important in determining glass breakage. A window on a trailing vector, south side of the house in the above example, would experience about one-fourth to one-half the boom intensity as one on the north side. This is an extremely important point to note when judging whether or not a boom caused glass damage.

Bric-a-brac, objects situated within a house, are motion sensitive. That is, they will slide or topple as the result of motion at their support. It is impossible to tell whether bric-a-brac damage is caused by a boom or not without an eye witness report. However, bric-a-brac mounted on a table attached to a slab floor can not fall because slab floors do not move under boom loads.

Miscellaneous building materials such as foundations, concrete driveways, brick facing or concrete block have not been noted to crack even at very high boom overpressures. These materials virtually do not move under sonic booms of 10 psf say, and therefore do not crack.

Table IX-1 presents minimum damage index levels for plaster, bric-a-brac, etc.. Fig. IX-10 shows charts for predicting the minimum damage index level for various thicknesses and sizes of glass on critical vector runs. If the adjuster knows the vector orientation of the window in question he can double the values given on the abscissa in Fig. IX-10 for trailing vector (180°) booms and interpolate for vectors between 0 and 180°.

This table and chart list "safe" limits. Since we are working with probability of occurrence in everything that happens the term "safe" for the table means a chance of less than 1/10,000 of the type of damage



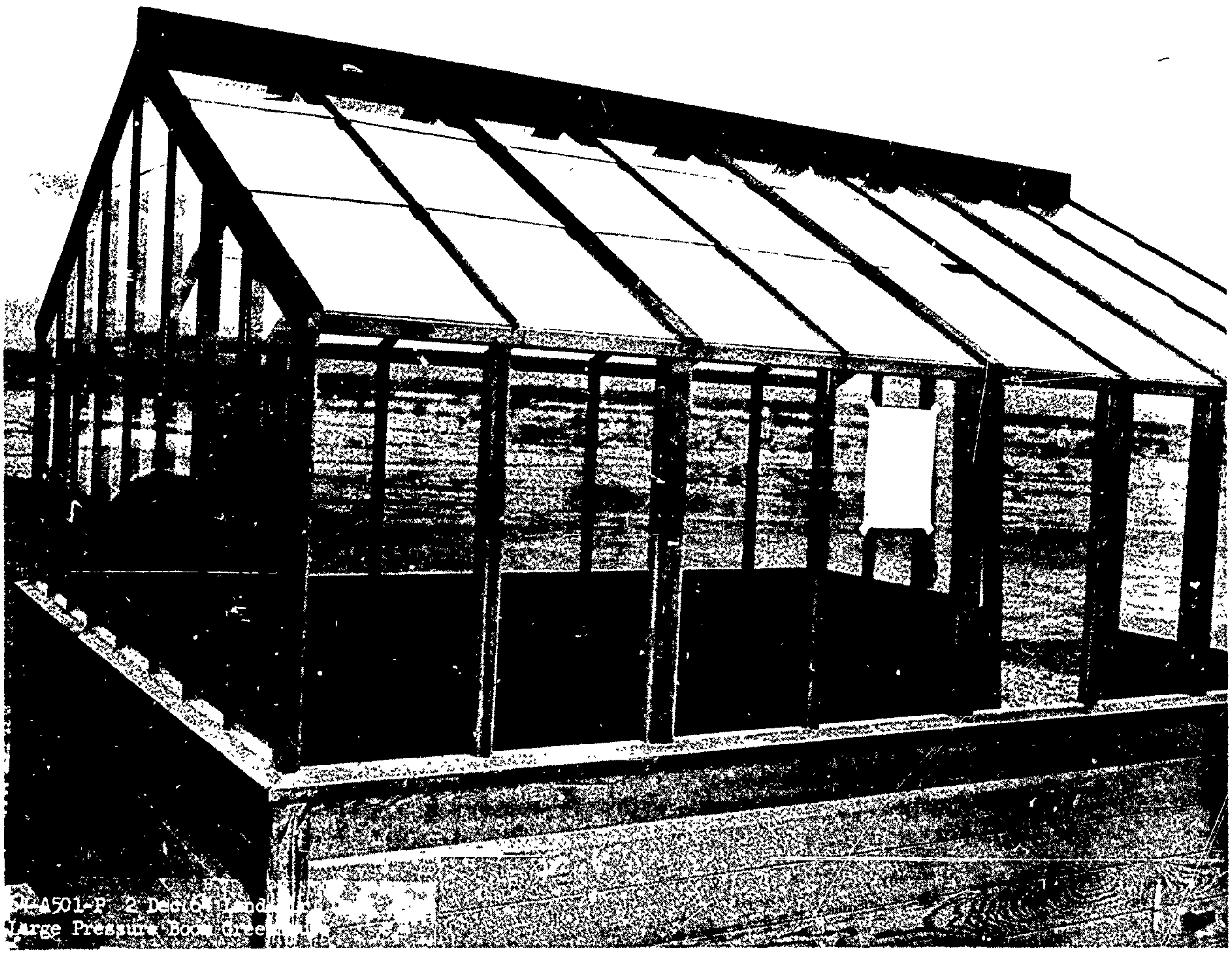


Fig. IX-9 A 38 psf Boom Broke 12 and Cracked 4 0.085-inch thick Panes in a Greenhouse Having More than 100 Such Panes. The Cracks Originated at Nail Holding Points.

TABLE IX-I Maximum Safe[1] Predicted or Recorded Peak Overpressure for Representative Building Materials and Bric-a-brac Other Than Glass

Material	White Sands Minor[2]	White Sands Major[3]	USBM Minor[2]	USBM Major[3]
Interior Walls and Ceilings				
1. plaster on wood lath	3.3	5.6	5.5	NA[4]
2. plaster on gyplath	7.5	16.	NA	NA
3. plaster on expanded metal lath	16.	16.	NA	NA
4. plaster on concrete block	16	16.	NA	NA
5. gypsum board (new)	16	16.	6.0	NA
6. gypsum board (old)	4.5	16.	6.0	NA
7. nail popping (new)	5.4	16.	NA	NA
8. bathroom tile (old)	4.5	8.5	NA	NA
9. damaged suspended ceiling (new)	4.0	16	NA	NA
10. stucco (new)	5.0	16		
Bric-a-brac				
1. extremely precariously placed or unstable items	NA	3.1	NA	NA
2. normally stable or placed items	NA	5.6	NA	NA
Miscellaneous				
1. brick cracked	19	--	NA	NA
2. glass door loosened	19	--	NA	NA
3. twisted mullions	9	--	NA	NA
4. popped molding	19	--	NA	NA

1. Less than one chance in 10,000 when within five miles of flight track. This value corresponds to a 99.99 percent confidence that damage will not occur.

2. Small (less than three inches) hairline cracks extensions or pre-damaged paint chipping or spalling.

3. Falling plaster or tile etc.

4. Not applicable.

noted happening under the designed overpressure. In the case of glass breakage the "safe" limit of expectancy is 1 chance in 100,000. For example, if the designed or theoretical overpressure of one booming airplane is 3.3 psf there is a chance of less than 1 in 10,000 that one, two or three-inch hairline crack extensions can occur to the house claiming damage. Out of 10,000 similar houses under the booming airplane one claim for a two-inch crack extension may be valid.

The chart for glass may be used in the following manner. Say a 4 ft. by 4 ft. double strength window is claimed to be damaged by a boom. If the adjuster knows the theoretical or designed boom overpressure but not the aircraft vector in relation to the direction the claimed window faces, he must be conservative and use the chart as is. If on the other hand he knows the window faces 90^{o} or sideon to the direction of flight he may increase pressure values by 50 percent. The indicated safe overpressure for the window is (5.5 psf x 1.5 = 8.25 psf). This is the tolerable pressure for a B-58 or F-104 boom or for a boom created by any aircraft, for that matter.

The overpressure generated by a supersonic airplane is governed primarily by design of aircraft (weight, length, diameter) altitude and speed, called Mach number. One such chart (Fig. IX-11) shows the relationship between altitude, speed, and overpressure for an F-104 generated boom. With the chart, and knowing the altitude and speed of a boom generating F-104, the adjuster may calculate the boom strength. For example, if the airplane was known to be traveling at Mach 1.4 (40 percent faster than the speed of sound) 20,000 feet above the ground the expected strength under the flight path would be 2.0 psf. The 4 ft. x 4 ft. window investigated above would be safe by a factor of 8.25/2.0 = 4.13. If the booming aircraft is other than an F-104 a different chart must be obtained from the Air Force.

Fig. IX-11 shows two overpressure cut-off limits, one for the B-58 and one for the F-104. Beyond these limits windows of greater area suffer no more. The B-58 limit is lower than the F-104 limit because of the lower frequency boom generated. Limits for airplanes intermediate in size between the F-104 and B-58 will lie within the two shown.

When adjusting a boom damage claim the adjuster must be aware of two factors that influence a claimant's opinion. First, he will be influenced by the sound of booms and automatically relate it to damage. Tests have shown that the human ear is a very poor gage of boom strength. Even calibrated sound level intensity meters, which have about the same frequency response range as the human ear, correlate very poorly with the response of a structure under boom loads. Second, one cannot tell whether or not damage occurs by feeling or seeing a vibration, such as a moving window. What may be large to the eye may be small to the window. For example, twelve 5 ft. x 10 ft. x ¼" windows deflected a total of 3.0 inches in and out without breaking. It has also been shown that vibration levels registered to be severe to human beings are one-third that of the safe level for blasting damage. Therefore, use caution when judging the validity of eye witness claims.

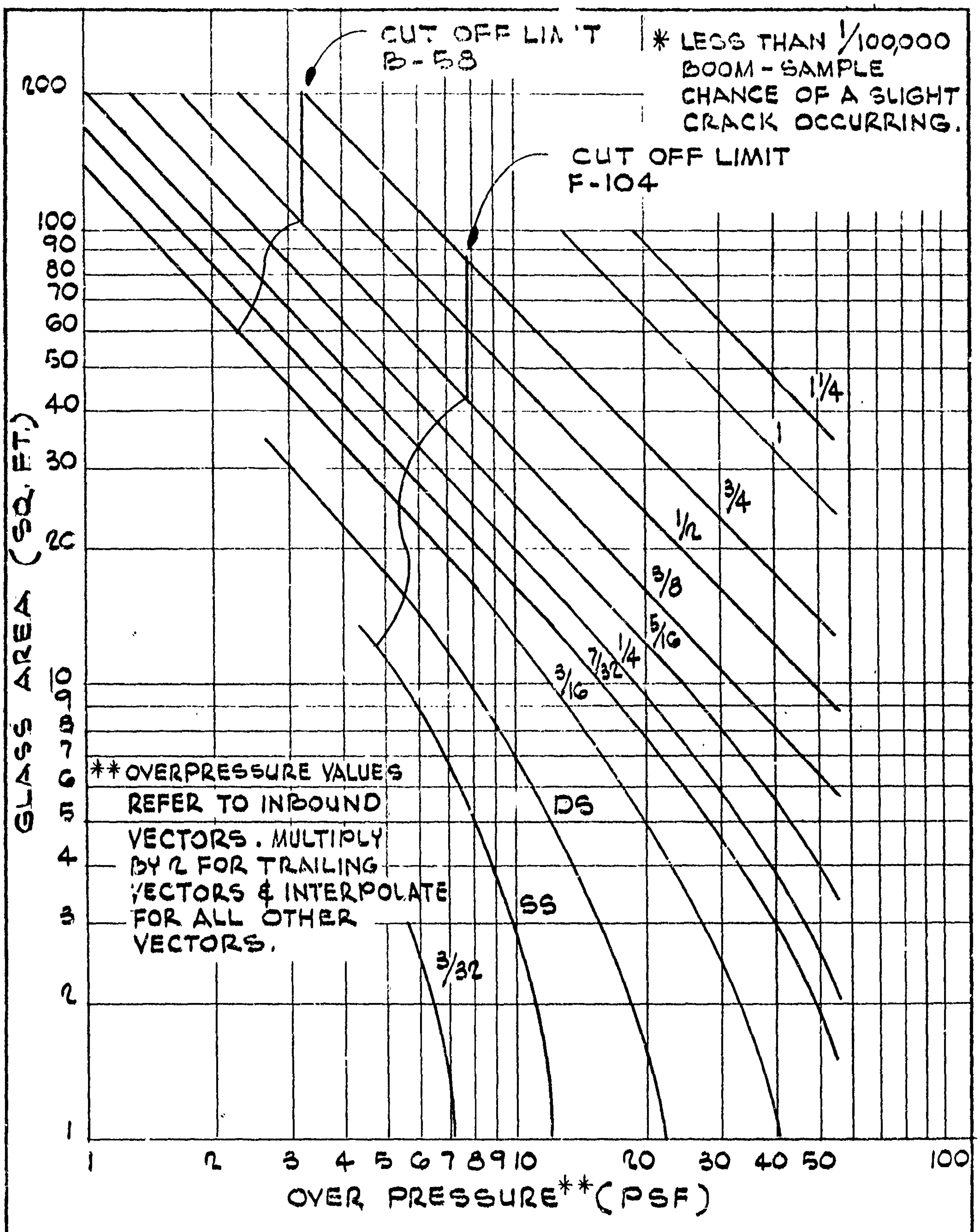


FIG. IX-10 MAXIMUM SAFE* PREDICTED OR MEASURED AVERAGE GROUND OVER-PRESSURE FOR PL & WINDOW GLASS

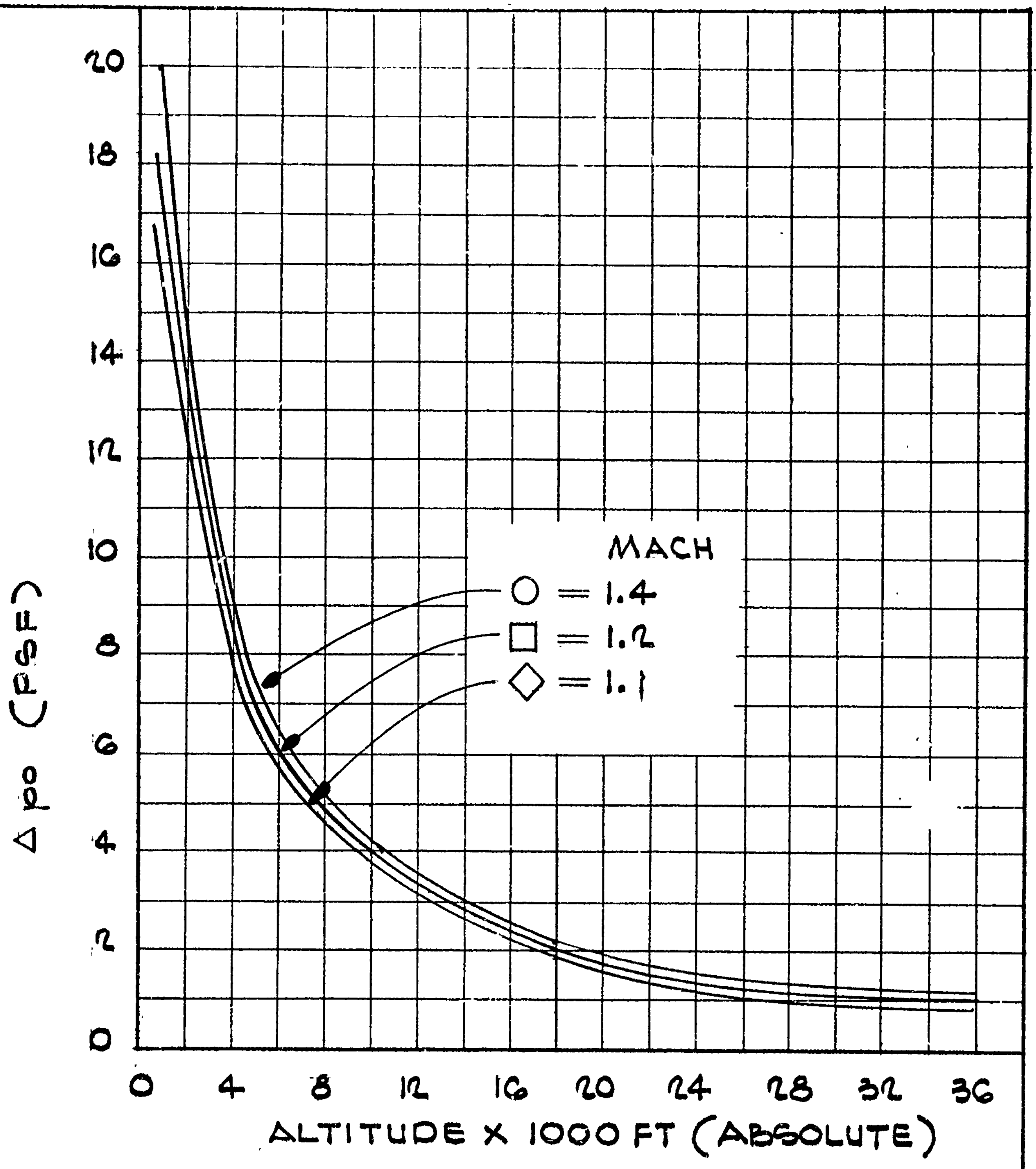


FIG. IX-11 SONIC BOOM OVERPRESSURE GENERATED BY AN F-104 AT VARIOUS ALTITUDES & SPEEDS

C. Other Causes of Cracks and Glass Breakage:

One of the principal causes of the cracking of plaster in residential construction is the shrinkage and expansion of lumber as the atmospheric humidity and temperature change over a period of time. Humidity changes cause appreciable movement across the grain of the lumber, and rigid materials (such as plaster) that are attached to the lumber will inevitably crack when it moves. Temperature differentials can cause cracking in virtually all directions.

The cracking appears first at or near the points of expansion or contraction. Cracks over doors and windows are the most common, because of the expansion of the headers that carry the loads over such openings. Cracks at the junction of ceilings and walls are also common, because of the expansion and contraction of the plates on top of the wall studding.

The cross-grain movement may result in unevenness in the floors, misalignment of all the partitions and even cracks in the ceiling. This is particularly true of houses that have a heavy wood beam extending the length of the basement, for as this beam expands and contracts with changes in the humidity, it lifts the whole center of the house up and down.

Another cause of plaster cracking is the settling of the foundation. Although foundation cracks are commonly thought to be caused by vibration, they are usually the result of the wall's inability to withstand the earth pressure caused by the weight of the structure without deflection. And when deflection occurs, cracks are bound to appear. If it were not for the lateral support that the floor joists give to the wall, the whole wall would lean in without cracking. But with this support in place, the wall must bend between its base and top. And this bending inevitably results in horizontal cracking.

A third cause of plaster cracking is water leaking from interior pipes or through windows, roofs, walls or foundations.

The Architect's Small House Service Bureau of United States[1] lists 40 reasons why the three natural force sources above can be effective in damaging structures. These reasons lead to structural weakness through poor design or inferior workmanship or construction practice. They are as follows:

1. Building a house on a fill.

2. Failure to make the footings wide enough.

3. Failure to carry the footings below the frost line.

---

[1] The Architect's Small House Service Bureau of United States, "The Small Home", Vol. 4, No. 8 (1925).

4. Width of footings not made proportional to the loads they carry.

5. The posts in the basement not provided with separate footings.

6. Failure to provide a base raised above the basement floor line for the setting of wooden posts.

7. Not enough cement used in the concrete.

8. Dirty sand or gravel used in the concrete.

9. Failure to protect beams and sills from rotting through dampness.

10. Setting floor joists one end on masonry and the other on wood.

11. Wooden beams used to support masonry over openings.

12. Mortar, plaster or concrete work allowed to freeze before setting.

13. Braces omitted in wooden walls.

14. Sheathing omitted in wooden walls (except in "back plastered" construction).

15. Drainage water from roof not carried away from the foundations.

16. Floor joists too light.

17. Floor joists not bridged.

18. Supporting posts too small.

19. Cross beams too light.

20. Subflooring omitted.

21. Wooden walls not framed so as to equalize shrinkage.

22. Poor materials used in plaster.

23. Plaster applied too thin.

24. Lath placed too close together.

25. Lath run behind studs at corners.

26. Metal reinforcement omitted in plaster at corners.

27. Metal reinforcement omitted where wooden walls join masonry.

28. Metal lath omitted on wide expanses of ceiling.

29. Plaster applied directly on masonry at chimney stack.

30. Plaster applied on lath that are too dry.

31. Too much cement in stucco.

32. Stucco not kept wet until set.

33. Subsoil drainage not carried away from walls.

34. First coat of plaster not properly keyed to backing.

35. Wood beams spanned too long between posts.

36. Failure to use double joists under unsupported partitions.

37. Floor joists placed too far apart.

38. Too few nails used.

39. Rafters too light or too far apart.

40. Failure to erect trusses over wide wooden openings.

The adjuster is referred to the reference "Blasting Claims, A Guide for Adjusters" prepared by National Board of Fire Underwriters and Association of Casualty and Surety Companies for a description of common cracks caused by natural causes.

Common causes of glass breakage are projectiles or an external force generated by wind or some other pressure. Projectiles usually cause holes in the glass or cracks radiating from the point of impact. Booms cannot cause this type of damage. Steady or boom loads usually cause cracks which originate from some point of weakness at the support such as a mounting clip or some other type of stress raiser. It is virtually impossible to determine the source of force when these types of cracks are identified without the eyewitness report of a trained and unprejudiced observer.

The adjuster must be aware that commonly caused forces are at work continually during a booming interval. For this reason he must use caution in determining what is and what is not boom caused damage.

D. Suggested Procedure for Adjusters:

In dealing with any claim for alleged damage, the first step is always to determine the cause of the damage. The noise of a boom may cause many people in the vicinity to believe that their property has been damaged, and once they begin to look around they are almost sure to discover cracks and foundation failures they have never noticed before. So immediately they file a claim either against the Air Force, the Federal Aviation Agency, or the property owner's insurance company. But the matter never stops there, for one claim always leads to another. And before long, everyone is filing a claim. A booming operation rarely produces a single claim--it produces none at all, or many.

Clearly, then, the crucial moment in investigating a situation of this sort is when the adjuster admits or denies liability for the first claim. If faulty judgment leads him to admit liability when he should not, he establishes a pattern that will make it difficult to handle properly similar claims that arise out of the situation.

So determining the cause of the damage is the key to the whole situation. But just how is the adjuster to go about this?

The first step is to inspect the property and itemize the damage. In itemizing alleged boom damage many adjusters find that making a quick on-the-spot sketch gives them a handy record later on.

Then the adjuster should inspect neighboring property to determine whether or not new damage was caused by the same booms. Examination of other effects such as bric-a-brac damage may give a clue as to whether the booms caused the reported damage.

Next the adjuster should contact the Air Force or Federal Aviation Agency monitoring team and his liability carrier. The Air Force maintains a detailed log of their operations showing the dates, flight times and flight altitudes, aircraft types and possibly even boom intensities recorded.

After the adjuster has learned all he can from the Air Force log, he should make an estimate of the boom intensity from Fig. IX-11 or one like it for the airplane used, if not recorded. With this information, the adjuster should be able to decide whether the claim is probably, not possibly, caused by the booms.

Often the adjuster will find that experts engaged by the Air Force or Federal Aviation Agency recorded boom intensities during operations to determine boom results or probable effects. If such tests have been made, the adjuster should make every attempt to secure the information they have revealed. Occasionally the Air Force will have made preboom surveys to determine the condition of buildings in the potential area of damage before any booming occurs. Again, the adjuster will find such information of great value.

If at this point the adjuster is still in doubt about the exact cause of the damage, he should not hesitate to suggest to the company he represents that a sonic boom, structural dynamics expert be retained for consultation. Too many adjusters fail to search out expert advice even when the situation clearly indicates that it is called for.

Vibration is a highly specialized field of study, and vibration experts are scientists or engineers who have made a specialty of the causes and effects of shock waves on structural resistance. They differ from building contractors, who are qualified to estimate the cost of repairs but generally are not expert in discovering the cause that made those repairs necessary.

If possible, inspection of the damage should be made jointly by adjusters representing the liability carriers and property insurers. The adjusters should always make a point of telling the property owner who the company representatives are, what companies they represent, and what the purpose of the visit is.

If the casualty interests agree that liability exists, they may be willing to take over the adjustment. But if the direct property adjuster is convinced that the booms did not cause the damage, his company may wish to consult and cooperate in the investigation of the claim with the Air Force.

In those cases where adjustment is concluded by property insurance carriers, the company may wish to ascertain from counsel whether the booms took place in an absolute liability state, or whether it is necessary to prove negligence before the Air Force can be held liable.

Whenever an adjuster is investigating claims for damage alleged to be caused by booms, he should always find out whether the Air Force was operating under any written contract, or under the authority of any permit or license granted by the city. If there is any such arrangement, the adjuster should always be sure to examine all the documents involved to determine whether the Air Force has agreed to pay for damage caused by them regardless of fault. The adjuster should report the text of this agreement to his company.

A Check List for Adjusters:

1. Inspect the property.
2. Itemize the damage.
3. Make an on-the-spot sketch of the damage.
4. Examine the Air Force log.
5. Estimate boom intensity.
6. Study boom intensity reports, if available.
7. Compare intensities with damage table and chart.
8. Study pre-boom surveys or nearby buildings, if available.
9. Study neighbors' property, if possible.
10. Examine any permit containing agreement by Air Force to pay for damage.
11. Consult company regarding expert advice if cause is still not clear.

BIBLIOGRAPHY

1. Hilton, D.A., et al., Sonic Boom Exposures During FAA Community-Response Studies Over A 6-Month Period in the Oklahoma City Area, NASA Technical Note, NASA TND-2539 (Dec. 1964).

2. Kane, E.J., and Palmer, T.Y., Meteorological Aspects of the Sonic Boom, Federal Aviation Agency, SRDS Report No. RD64-160 (Sept. 1964).

3. Andrews Associates, et al., Structural Response to Sonic Booms, Federal Aviation Agency, Vols. 1, AD610822 and 2, AD610823 (Feb. 1965).

4. John A. Blume and Associates Research Division, National Sonic Boom Study, Structural Reaction Program, Federal Aviation Agency Report No. SST-65-15, Vols. 1 and 2 (April 1965).

5. Sonic Boom Bibliography, Office of Deputy Administrator for Supersonic Transport Development, Federal Aviation Agency (Sept. 1964).

6. Reed, Jack W., Microbaragraph Measurements and Interpretations of B-58 Sonic Booms, Project Big Boom, Sandia Corporation, Report No. SC-4634(RR)(Dec. 1961).

7. Warren, C.H.E., The Effect of Meteorological Variations on the Statistical Spread in the Intensity of Bangs at Large Distances from the Source, Royal Aircraft Establishment (Farnborough), TN No. Structures 334 (May 1963).

8. Gumbel, E.J., Statistics of Extremes, Columbia University (1958).

9. Gumbel, E.J., Statistical Theory of Extreme Values And Some Practical Applications, Nat. Bur. Std., Appl. Matl. Ser., No. 33.

10. Hald, A., Statistical Theory with Engineering Applications, John Wiley and Sons, New York (1962). Note pp. 160-163.

11. Maglieri, D., et al., Ground Measurements of the Shock-Wave Noise from Airplanes in Level Flight At Mach Numbers to 1.4 and at Altitudes to 45,000 Feet, NASA TN D-48 (Sept. 1959).

12. Maglieri, D.J., et al., Lateral-Spread Sonic-Boom Ground-Pressure Measurements from Air Planes at Altitudes to 75,000 Feet and at Mach Numbers to 2.0, NASA Tech. Note, NASA TN D-2021 (Nov. 1963).

13. Cox, E.F., and Reed, J.W., Long Distance Blast Predictions, Microbarographic Measurements, General Report on Weapons Tests.

14. Reed, J.W., et al., Ground Level Microbarographic Pressure Measurements from a High-Altitude Shot, Operation Teapot, Sandia Corporation, WT-1103 (1956).

15. Wilton, C., et al., Study of Channeling of Air Blast Waves, prepared for DASA by United Research Services, Burlingame, California (June 1963).

16. Power, J.K., Some Considerations of Sonic Boom, Federal Aviation Agency, Office of Plans (May 1961).

17. Sigalla, A., "Lift Produced by a Sonic Boom," Journal, Aeronautical Society, Vol. 67 (Dec. 1963).

18. Lansing, D.L., Application of Acoustic Theory to Prediction of Sonic Boom Ground Patterns from Maneuvering Aircraft, NASA Technical Note, NASA TN D-1860.

19. Maglieri, D.J., and Lansing, D.L., "Sonic Booms from Aircraft in Maneuvers," Sound, Vol. 2, No. 2, pp. 39042 (Mar.-Apr. 1963).

20. Mayes, W.H., and Edge, P.M., Jr., "Effects of Sonic Boom and Other Shock Waves on Structures," Materials Research and Standards, 588-594 (Nov. 1964).

21. Newberry, C.W., "Measuring the Sonic Boom and Its Effect on Buildings," Materials Research and Standards, 601-612 (Nov. 1964).

22. ARDE Associates, Response of Structures to Aircraft Generated Shock Waves, WADC Tech. Rept. 58-169 (April 1959).

23. Lamb, H., The Dynamical Theory of Sound, Dover Publications (1960) (first published 1925).

24. Wood, H.O., "Modified Mercalli Intensity Scale of 1931," Bull. Seis. Soc. Am., 277-283 (Dec. 1931).

25. Crandell, F.J., "Ground Vibration Due to Blasting and Its Effect Upon Structures," Journal Bost. Soc. Civil Engineering, 222-245 (April 1949).

26. Housner, G.W., "Behaviour of Structures During Earthquakes," Proc. Am. Soc. Civ. Eng., EMD, 109-131 (Oct. 1959).

27. Wiggins, J.H., "Construction of Strong Motion Response Spectra from Magnitude and Distance Data, Bull. Seis. Soc. Am.,Vol. 54, pp. 1257-1269 (Oct. 1964).

28. Thoenen, J.R., and Windes, S.L., Seismic Effects of Quarry Blasting, Bureau of Mines Bull. 442 (1942).

29. Langfors, Ulf, et al., "Ground Vibrations in Blasting," Water Power, 335-338, 390-395, 421-424 (February 1958).

30. Edward, A.T., and Northwood, T.D., "Experimental Studies of the Effects of Blasting on Structures," The Engineer, 538-546 (Sept. 30, 1960).

31. Duvall, W.I., and Fogelson, D.E., Review of Criteria for Estimating Damage to Residences from Blasting Vibrations, U.S. Bureau of Mines Report of Investigation 5968 (1962).

GLOSSARY OF TERMS

Symbols:

A = area of Helmholtz aperture,

c_a = speed of sound at flight altitude,

c = speed of sound,

c_v = coefficient of variation,

d = diameter of airplane,

(DAF) = dynamic amplification factor,

f = frequency,

h = glass thickness,

I_+ = positive impulse,

k = stiffness

K = $2(A/\pi)^{\frac{1}{2}}$,

K_1 = reflection coefficient,

K_2 = shape factor (0.54 - 0.81),

K_3 = shape factor (lift),

l = length of aircraft,

L_3 = effective wing length,

m = mass,

M = Mach number,

Δp = theoretical peak boom pressure,

P_a = atmospheric pressure at flight altitude,

P_b = peak tail wave pressure,

P_i = peak pressure inside a building,

P_m = peak projected pressure (without spike or rounding),

P_{max} = maximum pressure,

P_o = atmospheric pressure at ground level,

P_s = peak spike pressure,

Q = volume,

r = distance from plane to ground observer,

s = standard deviation,

T = period,

u = differential displacement (strain),

w = airplane gross weight,

$\bar{x}$ = mean value,

β = damping factor (of critical),

ρ = density of air,

ρ_1 = density of glass,

σ_n = normal standard deviation,

τ = duration of N wave.

Definitions:

Critical Vector	That flight direction which causes the maximum response of a given element.
Dynamic Amplification Factor	The ratio of equivalent static load to peak dynamic load.
DAF Spectrum	A plot of dynamic amplification factor versus element frequency.
Effective (Equivalent Static) Load	The static load which when applied to an element causes the same maximum response as the dynamic load.
Free-Field	The region within the atmosphere that is uninfluenced by reflecting surfaces other than the ground.
Harmonic	That frequency which is an integer multiple of the fundamental frequency.
Helmholtz Resonance	A phenomenon where the gas in a vessel has resonant properties similar to those of a single degree of freedom, spring-mass system.
Impedance	The motion resistance capacity of a system to an applied dynamic force.

Inbound Vector	The direction of an airplane traveling into the element in question.
Intensity	The maximum strain within an element produced by a dynamic load.
Lift Theory	This theory modifies volume theory by accounting for aircraft altitude under lift conditions.
Loading	The forces imparted to a structure by boom pressures.
Net Load	The sum of the forces acting on a structural element.
Normal Distribution	A normally distributed random variable may have a value ranging from minus to plus infinity.
Outside Load	The external loading on an element.
Positive Impulse	The positive area under a pressure-time curve.
Racking Load	The net load determined by the sum of external loads acting on opposite walls of a building.
Reflectivity Coefficient	The ratio of the peak pressure at ground level to that which is unaffected by a reflected wave.
Response	The movement or strain of an element under load.
Rise Time	The time difference between onset of pressure and peak pressure.
Secondary Pulses	Shock waves appearing within the wave duration.
Sideon Vector	Aircraft vector perpendicular to element in question.
Standard Deviation	A mathematical ratio expressing the degree of randomness of a variable.
Stochastic Process	The statistical variation of a phenomenon in time.

Trailing Vector	The vector with respect to an element facing the same direction as the vector.
Vector	The direction of an aircraft.
Volume Theory	The theory which predicts boom strength based solely on the volume and shape of the supersonic object.
Wave Duration	The time between the positive shock (bow) wave and negative (tail) wave.

Appendix IV-A

STATISTICAL PROCEDURES

The use of statistical procedures provides a degree of confidence to conclusions made from analysis of data. Tests of hypotheses are statistical methods most often used in the analysis of the sonic boom data.

The sample mean ($\bar{x}$) is a measure of central tendency corresponding to the center of gravity in a mechanical system. It is mathematically expressed as,

$$\bar{x} = \frac{\sum^{n} X_i}{n} , \qquad (1)$$

where X_i is the i^{th} observation in a sample of size n.

The sample standard deviation, a measure of the spread or dispersion of the observations about the mean, corresponds to, in a mechanical system, the radius of gyration measured from the center of gravity. The mathematical expression of the sample standard deviation is,

$$s = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}} . \qquad (2)$$

The sample mean and the sample standard deviation have the same units as the observations.

Another measure of the spread of the data is the sample coefficient of variation. This is a dimensionless quantity defined as the ratio of the sample standard deviation to the sample mean:

$$c_v = \frac{s}{\bar{x}} . \qquad (3)$$

When comparing two normally distributed random variables, the sample mean and the sample standard deviation can be used as estimates of the theoretical mean and of the theoretical standard deviation. To test the hypothesis of equality of means against the alternate hypothesis of one mean being greater than the other, we use the following t statistic when the theoretical mean and the theoretical standard deviation are unknown:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}} . \tag{4}$$

When $t \leq t_{\alpha,p}$, the means are equal; when $t > t_{\alpha,p}$, $\bar{x}_1$ is greater than $\bar{x}_2$. The confidence level, or reliability of a test, is $(1 - \alpha)$ 100% and p is the degrees of freedom given by,

$$\frac{\left(\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}\right)^2}{\frac{(S_1^2/n_1)^2}{n_1+1} + \frac{(S_2^2/n_2)^2}{n_2+2}} . \tag{5}$$

To test the equality of a normally distributed random variable to a constant (μ_o) the following t statistic is used if the theoretical mean and the theoretical standard deviation are unknown:

$$t = \frac{(\bar{X} - \mu_0)\sqrt{n}}{S} \tag{6}$$

When $t \leq t_{\alpha,n}$, the mean is equal to μ_o; when $t > t_{\alpha,n}$, $\bar{x}$ is greater than μ_o. The confidence level is $(1 - \alpha)$ 100% and n, the sample size, is the degrees of freedom.

Assuming that x and y are two normally distributed random variables and that y is a function of x, then the line $y = a + bx$ is called a regression line. The equation of the line can be written as,

$$y = \bar{y} + b\,(x - \bar{x}), \tag{7}$$

where $\bar{y}$ is the mean of the y_i observations, $\bar{x}$ is the mean of the x_i observations, and b is the slope of the line given by,

$$b = \frac{\sum_{i=1}^{n} (y_i - \bar{y})(x_i - \bar{x})}{\sum_{i=1}^{n} (x_i - \bar{x})^2} . \tag{8}$$

To test the equality of the slopes of two lines we used the following t statistic:

$$t = \frac{b_1 - b_2}{\sqrt{\dfrac{s_1^2}{\sum_{i=1}^{n_1} (x_i - \bar{x})_1^2} + \dfrac{s_2^2}{\sum_{i=1}^{n_2} (x_i - \bar{x})_2^2}}}, \tag{9}$$

where s^2 is given by,

$$s^2 = \frac{\sum_{i=1}^{n} (y_i - \bar{y})^2 - \dfrac{\left[\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})\right]^2}{\sum_{i=1}^{n} (x_i - \bar{x})^2}}{n - 2}. \tag{10}$$

Again if $t \leq t_{\alpha,f}$, b_1 is equal to b_2; if $t > t_{\alpha,f}$, b_1 is greater than b_2. The confidence level is $(1 = \alpha)$ 100% and f is the degrees of freedom given by $n_1 + n_2 - 4$.

All these tests are developed for normally distributed random variables and are used only with observations satisfying this requirement. In a regression analysis there is also a condition of functional relationship.

References

Bowker, Albert H., and Liberman, Gerald J., Engineering Statistics. New Jersey: Prentice Hall, 1963 (Fifth Printing).

Cramer, Harald, Mathematical Methods of Statistics. Princeton: Princeton University Press, 1961.

Hald, A., Statistical Theory with Engineering Applications. New York: John Wiley & Sons, Inc., 1962 (Fifth Printing).

Mood, Alexander M., and Graybill, Franklin A., Introduction to the Theory of Statistics. Second Edition. New York: McGraw-Hill, 1963.

Appendix VIII-A

CONDITION SURVEY OF THE STRUCTURES SUBJECTED TO THE "BIG BOOM"; December 2, 1964

C-1: Observation: No new cracks have been observed.

Opinion: It appears that the crack width around the window frame on the south window (S.W. room) has increased. This joint is formed by dissimilar materials (wood, concrete block and mortar). The observer reports the building to be in good condition.

W-2: Observation: Minor cracking on large wall areas were observed. Very few extensions were noted on walls in small rooms. Minor cracking observed on stucco. Direction of crack indicates racking mechanism prevailed. Seams between door moldings and plaster appear to have widened somewhat. The molding around the north bay window (held by one nail) had popped off. The remaining molding appeared to be loosened.

Opinion. The structure is in about the same condition as was observed before the "Big Boom".

W-3: Observation: Two nails holding plaster board to ceiling joists and one nail above the bay window had popped slightly. A tea cup on shelf located on west wall fell and broke. Outside stucco cracked at intersection of top plate on all four corners.

Opinion: Racking mechanism predominated.

W-4: Observation: No positive "Big Boom" damage was observed. Some minor cracking may be present but observer is unsure. Top frame of sliding door appears to have bent permanently to a small degree. An inner door sticks slightly now, possibly indicating slight permanent set due to racking.

Opinion: Amazingly good condition considering single "Big Boom" strength. This indicates that repeat loading due to booming is important failure mechanism in view of failure caused at lower overpressures.

2S-5: Observation: Sliding glass door has jarred loose due to improper number of screws. This is a common installation method in many residences, however. No extra damage was observed in ceilings or walls after the "Big Boom". Damage was confined to shaking the paint film between sliding door. Three bricks on outside sill of picture window had been loosened. The paint had cracked around the top of the west window in the large lower room.

Opinion: Loading primarily came from the side or at a grazing incidence. The lack of cracking in this minimum structure also indicates that repetitive loading of composite structural elements is also a bigger factor in damage than is a single "Big Boom".

PF-6: Observation: Interior corners show hairline crack extensions at joints. Several nails had popped out of dry wall slightly. The 8"x10" picture frame had fallen.

Opinion: The house is still in good condition.

Greenhouse:

Observation: 12 panes broken, 4 panes cracked. No glass broken on south wall.

Opinion: All glass broken or cracked at nail holding points. Transverse pressure alone did not cause breakage. The fact that no glass broke on south wall indicates directional nature of boom wave (aircraft flew from north to south). Further, glass was broken by motion impact at nail holdings.

Storefront:

Observation: Two 8'x10' panels under the overhald were completely broken. The east window did not shatter while the west window did. Some glass samples in rear room were broken.

Opinion: Boom pressure broke the glass.

FAA Trailer:

Observation: One window pane 12"x42" was broken. It was partially open at time of "Big Boom".

Opinion: Impact of glass against trailer in combination with boom pressure failed the window.

H-Bldg.:

Observation: Tile shower had grout loosened and cracks extended. Crack in latrine window extended.

No other buildings had cracks extended or were damaged in any observable way. Guard shack and communications building personnel about 3,500 feet to the east and west of the t est structures heard no "Big Boom", indicating narrow boom path.

Total number of glass panes broken or cracked was 19. Total glass area subjected to "Big Boom" was 2,345 square feet. Total area of glass broken or cracked was 204.9 square feet. (Without 8'x10' storefront windows area would be reduced to 44.9 square feet.) This represents less than 9 percent of glass broken or cracked.