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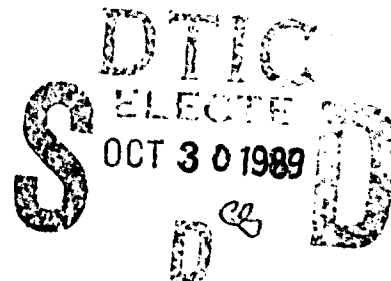
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# NOISE AND SONIC BOOM IMPACT TECHNOLOGY

## Effects of Aircraft Noise and Sonic Booms on Structures: An Assessment of the Current State-of-Knowledge

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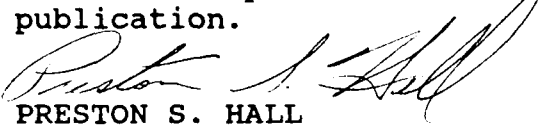
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## EXECUTIVE SUMMARY

A literature search was performed to develop a database of pertinent references regarding the effects of aircraft noise and sonic boom on structures. These references are cited in the Citation Database.

Abstracts were prepared for particularly significant citations. For the most pertinent and most controversial articles, critical reviews were prepared and included in the citation in order to define the position taken in the article, the strengths and weaknesses of the positions expressed, and the pertinence to the environmental planner. To assure that efforts to abstract and review articles were optimally allocated among the broad body of available literature, the BBN Assessment System for Aircraft Noise (ASAN) Citation Index Database development plan (prepared under Task 0003 of this contract) was used as a guideline.

During this process, approximately 2,500 candidate citations were initially identified. Of these, 635 were chosen to be included in the Citation Index Database, abstracts were entered for 144 citations, and critical reviews were prepared for solicitation. The major topics treated in the literature are as follows:

- o Sonic Boom Effects on Conventional Structures
- o Sonic Boom Effects on Unconventional Structures
- o Sonic Boom Effects on Terrain Structures
- o Low Frequency Noise Effects

The literature on sonic boom effects on conventional structures treats direct single exposure sonic boom damage; cumulative damage from multiple booms; and unusual circumstances, such as, particularly weak structural elements or enhanced loads resulting from metastructural effects.

The following is a synopsis of the technology gaps identified:

- o An appropriate characterization of the effective strength reduction associated with glass which has stress raisers is needed; a similar understanding of the effective strength of very new, very old or partially damaged plaster is needed.
- o A statistical description of the frequency of occurrence of these weakened elements is needed.
- o A statistical description of the variation in effective loading due to topographical effects is needed.
- o Cumulative damage from repeated sonic booms is not well understood. Further investigations are necessary to determine if the effect is real and the relationship of cumulative damage to stress raisers.
- o At present, no systematic approach exists for defining types of unconventional structures nor for defining vulnerable elements and damage algorithms for these elements. Isolated examples of sonic boom tests and analyses of particular structures exist in the literature.
- o While ground vibrations normally produced by sonic booms are not sufficient to cause damage in structures, it is possible that geological conditions exist which would be of concern. This possibly must be investigated.
- o It is currently unknown under what conditions a sonic boom can trigger an avalanche or a landslide.

- o The effects of low frequency noise are qualitatively but not quantitatively understood.

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EFFECTS OF AIRCRAFT NOISE AND SONIC BOOMS  
ON STRUCTURES: AN ASSESSMENT OF THE  
CURRENT STATE-OF-KNOWLEDGE

1. INTRODUCTION

1.1 Objective

Public Law 96-588, the National Environmental Policy Act of 1969 (NEPA), requires the U.S. Air Force (USAF) to conduct environmental assessments of its flight activities. NEPA and other regulations apply not only to flight operations near air bases, but also to operations in about 350 Military Operating Areas (MOAs), and Restricted Areas (RAs), and along 400-odd Military Training Routes (MTRs), encompassing roughly one-half million square miles of domestic airspace. Compliance with statutory and regulatory environmental requirements is not a simple task for the USAF. These requirements poses technical and practical challenges to providing a complete assessment of the potential consequences of these operations and to responding to the public concerns about possible consequences.

Task 0010 of Contract F33615-86-C-0530 addresses these needs by developing a comprehensive database of the literature related to the sonic effects of aircraft operations on structures, and developing a White Paper summarizing the current state of knowledge and technology gaps. The data are to be incorporated into the Noise Environmental Planning Aid database developed as part of an automated environmental planning aid (Assessment System for Aircraft Noise (ASAN) partially developed under Task 0003.

## 1.2 Background

At present, a U.S. Air Force environmental planner charged with assessing the environmental effects of aircraft operations has no well-defined method for performing this assessment. Moreover, as a consequence of the USAF procedure of rotating assignments, the planner may have little opportunity to develop personal knowledge and experience to assist him in this task. To address these needs, Noise and Sonic Boom Impact Technology (NSBIT) has funded the development of a planning aid, the ASAN. A key component of ASAN will be a database (the Citation Index Database) characterizing the current state of knowledge as reflected in pertinent studies, reports, and data sets. In addition, this database will provide a means of integrating and organizing the results of research addressing sonic boom propagation and effects.

While the ASAN system will provide a planner with the means for directly assessing the impacts of aircraft operations on structures, it is important that the planner be able to address unusual situations or points of view that may not be reflected in the basic ASAN modules. By identifying primary sources of information, the database will enable the planner to investigate alternatives. In addition, the database will assist the planner in responding to comments and objections raised during public hearings, scoping meetings, claims hearings, and litigation.

To meet this need, a broad list of pertinent literature is required. For the most pertinent and the most controversial articles, abstracts were prepared to define clearly the position taken in the articles; analytical or empirical bases and reviews were generated to identify the strengths and weaknesses of the positions expressed. Figure 1-1 outlines the procedure used for this purpose.

During the initial literature search, approximately 2,500 documents were identified for review to rate their suitability for ASAN. Of these documents, 635 were selected to be included in the Citation Index Database. Among the documents included, 144 abstracts were entered on the database, and 40 documents were critically reviewed. The topics of the reviewed articles include: conventional structures, cumulative damage effects, terrain effects, metastructural effects, unconventional structures, and low frequency noise effects. In addition, four articles that were rated as controversial were each critiqued by three reviewers. All of the reviews are included in the database.

### 1.3 Scope: Definition of Structures and Loads

An environmental planner must be able to assess the effects of aircraft operations on a wide variety of "structures." In this context the meaning of the word structures is extended to include not only modern man-made structures such as residences, offices, and manufacturing facilities, but also historical, archaeological, and other unconventional man-made structures, such as delicately or critically aligned equipment. In a much broader sense, the word structures is defined to include terrain that may enhance the hazards of the airborne waves through focusing or ground coupling (primarily in connection with Rayleigh waves) and terrain features that may be triggered to act as a secondary hazard (e.g., avalanche or landslide).

The sonic effects of interest include damage to a structure or its contents as well as structural response that has an adverse effect on other structures or their occupants. Thus, the planner is concerned not only with damage to a structure, but also how the structural response may annoy the building's occupants or enhance the loads to which another structure may be subjected.

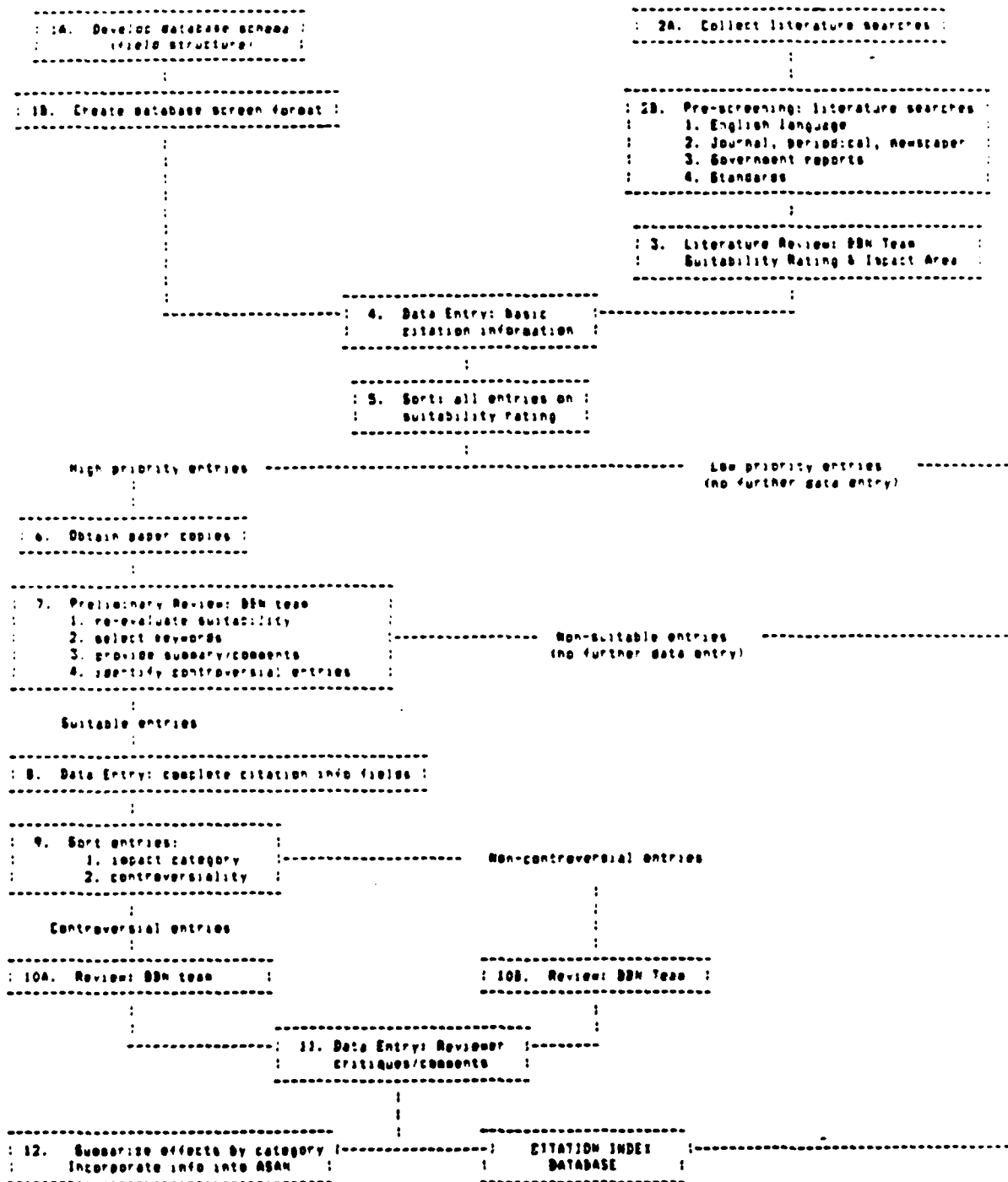


Figure 1-1. Development Procedure: Citation Index Database

From the planner's perspective, the loads of interest are the airborne sonic booms generated by supersonic aircraft, low frequency airborne noise generated by subsonic aircraft, and the seismic signals imparted into the earth by the two types of airborne waveforms. When significant sonic booms are generated by an operation, they may be expected to dominate the other effects under most situations.

While for some combinations of structural types and loading conditions, ample data are found in the literature, in other instances, data are sparse or nonexistent. To supplement the aircraft noise and sonic boom effects literature, it is useful to consider other analogous loads, such as blast, wind, and thunder. To make use of these other loading conditions, it is necessary to consider their differences from the loading waveforms of interest and identify procedures for reconciling these differences.

Sonic booms, blast waves, and thunder are all impulsive loading forms. The amplitudes and waveforms, however, may differ significantly. Moreover, while normally the sonic boom is an airborne waveform, a significant amount of blast energy may be transmitted from the source to the receptor through the ground. In addition, we may argue that the waveform incidence angle, with respect to a structure, will be different for sonic boom than for blast waves because of the location of the source. In the case of wind loading, many analyses are based on a constant load as opposed to an impulsive load.

The just-cited issues have varying degrees of significance in assessing the applicability of articles regarding these loading waveforms to aircraft noise effects. The following explanation outlines the approach used for each issue:

- o Waveform differences: a comparative analysis of the maximum dynamic load factors (DLF) for sonic boom waves and blast waves shows that a sonic boom wave-forcing function generally produces a larger DLF than a blast wave of equivalent peak pressure and duration. Figure 1-2 illustrates the variation in the peak structural responses in terms of the DLF for different waveforms. Figure 1-3 shows an example of a graph of resultant peak stress versus wave peak pressure which can be developed to correlate the responses produced by different waveforms.
  
- o Airborne versus Seismic Waves: in contrast to sonic boom, in some cases a significant portion of the energy from an explosion is imparted into the ground. As a consequence of the difference of wave propagation speeds in the air and in the ground, the airborne blast wave normally arrives later than the groundborne wave. This response data may allow separation of the effects of the two loads when adequate data have been gathered by the investigator.

However, full damping of the structural response from the seismic waves may (depending on the specific conditions) not have occurred before the arrival of the airborne blast waves. Thus, empirical papers on blast loadings must be carefully examined to determine whether or not the air blast load effects can be isolated. In contrast to this determination, theoretical papers on blast loading would normally identify the type of loads being modeled and so facilitate judging their applicability. To draw any useful conclusions out of ground wave-generated

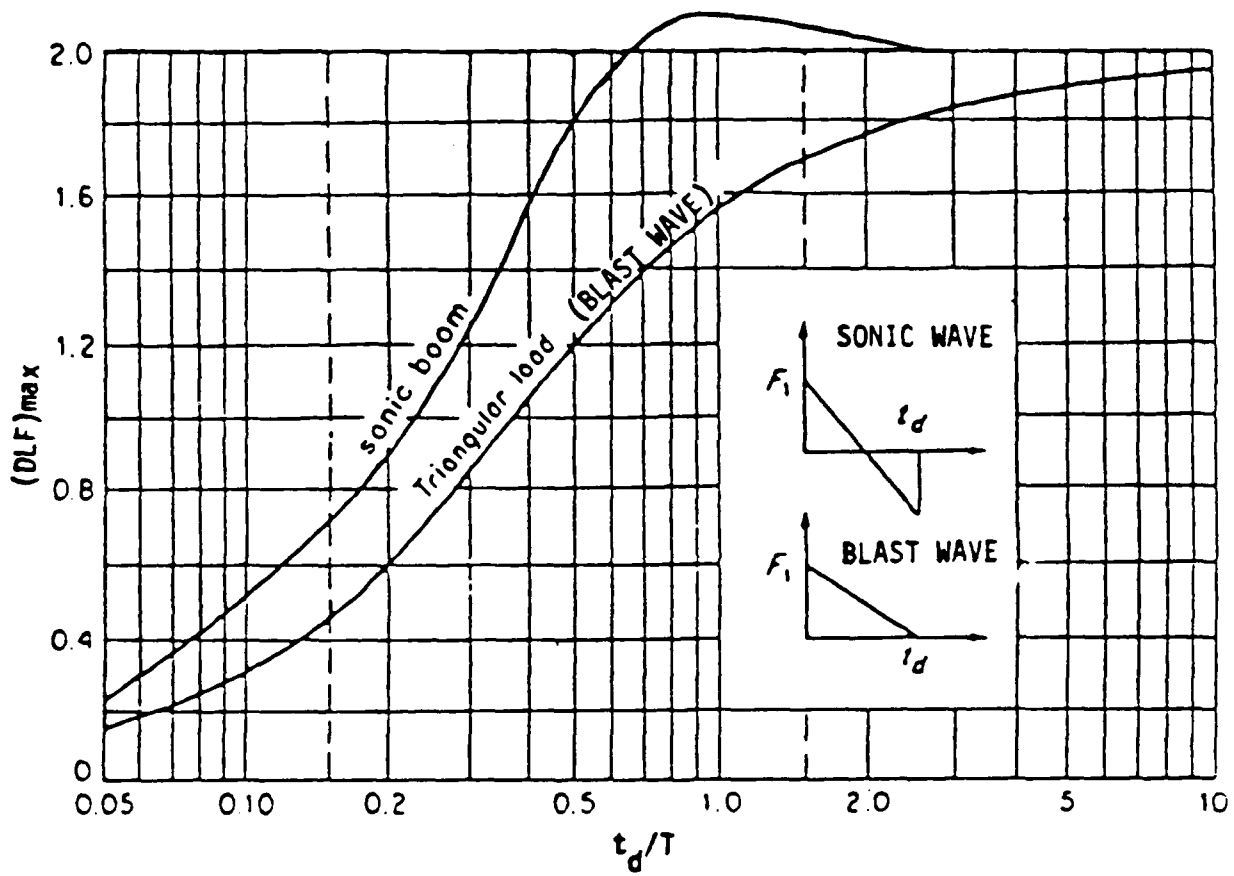


Figure 1-2. Variation of  $(DLF)_{max}$  with Different Wave Forms

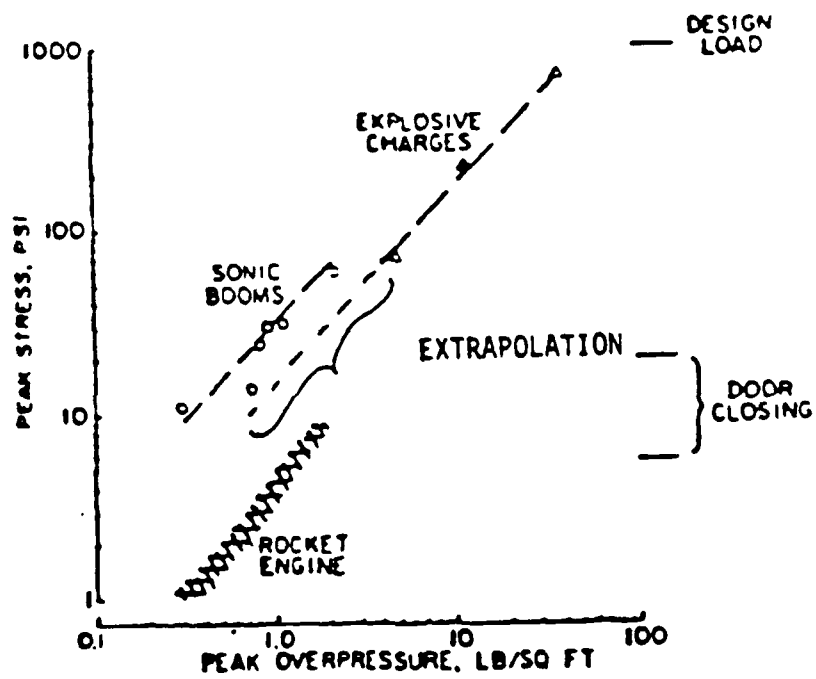


Figure 1-3. Variation of Peak Stress Due to Different Wave Forms at Various Peak Over-Pressures (W.H. Mayes and P.M. Edge, Jr., "Effects of Sonic Boom and Other Shock Waves on Buildings," Mater. Res Stand. 4, 588-593 (1964))

structural response data, one has to bear in mind that the ground wave-forcing function magnitude should be comparable to that due to sonic booms.

- o Wave incidence angle: the angle of incidence of the wave on a structure will affect the load that the structure will see. At typical sonic boom overpressures, the load applied by a normally incident wave is twice that applied by a grazing wave. When analyzing a specific source of energy and a specific structure, the distinction between an elevated source (sonic boom) and one at the surface (blast) may be significant. However, the planner must consider many structures, aircraft, and flight paths. This distinction results in a distribution of incidence angles. Moreover, while one might argue that the distinction between an elevated and surface source will affect this distribution, the magnitude of this effect is more than offset by the uncertainty in the particular air traffic patterns which may occur, approximations which must be made in characterizing the structural environment at risk, and the need to omit or drastically simplify the effects of meteorology on sonic boom propagation.
  
- o Wind Loading: an analyst can convert a dynamic impulsive problem to an equivalent static problem through the use of the properly defined load factor and mode participation factor. Thus, the response to wind loads may be useful in understanding the response to low-level, low-frequency loads; in understanding the response of selected building elements (notably windows) to sonic booms; and particularly for unconventional structures, in establishing that ambient

or design loads may be comparable to or exceed sonic boom loads.

Data from blast tests and other impulsive loads analogous to sonic booms can be used as supplementary information. However, the data must be used judiciously due to the differences in the waveforms and other effects not discussed. In developing the summaries of the current state of the knowledge, data were drawn from the available sonic boom literature and from literature on other applicable load conditions.

## 2. CURRENT STATE OF KNOWLEDGE

Research into the field of sonic booms began in the mid 1950s when aircraft began flying at speeds exceeding the speed of sound. Research activities peaked when it was anticipated that supersonic aircraft would be routinely flying across the United States (U.S.). Public complaints about damage resulting from these field test programs and other early sonic overflights provided the motivation for continued laboratory and field tests as well as theoretical investigations. Many of these studies were attempts to explain damage claims that occurred under conditions for which no damage had been expected. This chapter presents the current state of knowledge concerning the effects of sonic boom loads on structures and identifies those areas where additional work is needed.

Within this chapter, the presentation is organized into sections that address topics of interest. The first major section addresses damage to conventional structures. Subsections treat damage from a single exposure, damage from repetitive loadings (cumulative damage), and metastructural effects resulting in load modification. The second major section treats unconventional structures. The third section discusses the effects due to propagation of the sonic boom into the ground, which generates seismic waves (particularly Rayleigh waves) and may induce avalanches or landslides. The final section discusses the effects of low frequency noise on structures.

Before presenting the effects of sonic loads on structures, it is important to have some understanding of the sonic boom phenomena. The sonic boom is the result of the coalescence of pressure pulses generated by the aircraft as it passes through the atmosphere. As the aircraft reaches the speed of sound, the pressure pulses converge on one another and an acoustic shock

results. Ground level sonic boom waves most commonly have a waveform that resembles the letter "N" and are called N-waves. Rounded and spiked variations of this waveform may result from atmospheric effects. On rare occasions, atmospheric conditions or aircraft maneuvers produce a localized "focusing" of the boom into a U-shaped wave. The sonic boom wave travels until it strikes an object, where it produces a dynamic loading on that object. The loading produced on the object, or structure, is dependent on the geometry of the structure, the orientation of the incident wave with respect to the ground and the structure, the strength and shape of the wave as it approaches the structure, and the geometry of the surrounding terrain and other structures.

The response of the structure to the imposed loading and the capacity of the structure to withstand the particular type of loading determine what level of damage the structure will sustain. Damage, as used in this context, includes not only typical building damage, such as broken windows and cracked plaster, but also damage to loose objects within the structure, commonly known as bric-a-brac, which may "walk," slide, or topple.

There are three general steps in the analysis of structures: determining the loading, analyzing the response, and assessing the capacity. Of the three general areas, the highest uncertainty currently exists in the area of structural capacity: that is, the ability of the structure to withstand the response resulting from a particular imposed loading.

## 2.1 Conventional Structures

### 2.1.1 Single Exposure

The subject of structural response to sonic boom loading is complex because there are many variables involved. The response of a particular building to a particular sonic boom depends upon the intensity, rise time, and waveform shape; the direction of the incident wave with respect to the building; the age and quality of construction of the building; and the geometry of the building and the surrounding terrain. In spite of all the variables, several facts clearly stand out:

1. Well built structures subjected to nominal sonic boom loadings do not experience severe structural damage (references 112,132,148,167).
2. Secondary damage (e.g., cracked windows and plaster) to the same buildings can and does occur at unexpectedly low load levels (references 132,167,265).
3. Essentially all of the damage at low load levels is to building elements in a weakened condition or subject to stress raisers (references 72,132,137).
4. Ground motion normally induced by sonic booms does not appreciably affect building structural response (references 69,139,156).

Field testing has proved to be the most useful method of determining the effects of sonic booms on structures. Theoretical studies are most valuable in providing a framework for reducing, evaluating, and analyzing the experimental data. The strength of the field testing is the evaluation of all the different variables for a particular set of conditions. The

weakness of the field testing is the cost and complexity associated with evaluating different conditions as well as the difficulty in understanding the interaction of the different variables. The strength of the theoretical approach is the ability to study, with economy, the response of the individual variables associated with the response of structures to sonic booms. The main weakness of the theoretical approach is simplification, involving assumptions, required to reduce the actual structure to a workable model. Furthermore, the theoretical approach gives no information concerning the response levels of either the overall structure or its components at which failure occurs.

The most common method of obtaining field test information is via community overflights. The information is obtained in two basic ways: 1) information inferred or observed as a result of damage claims; and, 2) data obtained from instrumented test structures.

The three most extensive community overflight investigations conducted in the United States to date were those in St. Louis, Oklahoma City, and Chicago. Most complaints, received as a result of these tests, were for broken glass (80%), bric-a-brac or fallen object damage (15%), and plaster and/or stucco damage (5%) (reference 148).

Interpretation of community overflight data should be done with care. Damage reports depend on citizen complaints. These reports may overstate or understate the actual damage depending on the community reactions. A common attitude in the United States has been to react to the nuisance of sonic boom by deliberately attempting to find damage that might have been caused by sonic boom. This attitude has resulted in large numbers of complaints about damage that careful technical evaluation showed to be from sources other than sonic boom. In

contrast, in Great Britain it has been observed that the effort required to file a complaint results in many minor-damage incidents not being reported. Another element which adds to the difficulty in interpreting field test information is the type of follow-up investigation made to damage complaints.

Substantially fewer claims have been judged valid when investigations were performed by engineers than when performed by USAF investigators. Furthermore, the condition of the damaged item prior to the incident, in most cases, cannot be determined accurately. However, damage claims do give an excellent view of damage that can be expected to occur to conventional structures exposed to nominal sonic booms. The field test database provides the evidence that well-built structures do not sustain significant structural damage as a result of sonic booms.

Several overflights conducted at Oklahoma City, White Sands, N. Mex., and Edwards Air Force Base, Calif., included instrumented structures as part of the test. A significant result of these tests is that the measured stresses associated with the range of sonic boom overpressures estimated for routine military and commercial aircraft operations are relatively small compared to design stresses. The stresses induced by the sonic boom overpressures are of the same order of magnitude as those associated with everyday occurrences, such as door slamming or raising attic stairs (references 132,144,176,178). Another observation based on these tests is that the preexisting stress state of the individual component or the existence of stress raisers can significantly influence the amount of damage produced by a particular sonic boom (references 72,132,137).

The theoretical analysis of conventional structures has focused on determining the response of an individual structural element, such as a beam or a plate, to sonic boom pressure loadings. The more difficult aspect of analyzing structural

response is to determine the manner in which a building composed of a combination of such elements reacts to a sonic boom or similar loading. Fortunately, the most important aspect of building response is load modification; with certain well-defined exceptions, this is a second order effect.

Substantial work has been done in the area of individual component response to sonic boom loadings. The most common approach is to model the component as a single degree of freedom spring-mass problem. This model is then used to evaluate the dynamic response of the component compared to the static response for the same load. The ratio of the two responses is called the dynamic amplification factor (DAF). Theoretical analyses were used to study the effects of different modeling assumptions (e.g., type of element -- plate or beam -- and type of support) on the DAF (references 9,65,88,101). Other investigators studied the effect of varying the characteristics of the loading waveform (references 4,42,74,152). Other effects of sonic booms on structures such as Helmholtz resonance (references 10,11,74,165) and nonlinear response (reference 42) were studied analytically. The net result of all this work is a very thorough understanding of how the individual building component reacts to an assumed sonic boom pressure load. To date, no systematic study of overall building response to sonic boom loading has been made.

The variability of loadings, response, and capacity implies that a probabilistic approach might assist in developing the relationship between sonic boom loading and building component failure. The bulk of the work in this area focused on glass windows (references 2,27,70); only a few studies extended probabilistic methods to other materials or components (reference 27). Two approaches were employed. Some investigators developed regression equations based upon claims data or test information relating the probability of damage to

overpressure. The other technique generally employed was to attempt to compute the probability that the stress caused by the sonic boom would exceed the ultimate stress of the material. Typically, the stress caused by the load in question is computed using an appropriate analytical model. This stress is then compared to the distribution of ultimate stress (determined by laboratory testing) for the material. The probability of failure is the ratio of the fraction of the distribution of ultimate stress lower than the calculated stress. The accuracy of this approach depends on the analytical model used to transform the load into stress, the statistics developed for the stress, and the validity of the assumptions concerning the ultimate stress distribution. The probabilistic approach can also be used to correlate the response model and/or ultimate stress distributions from the field test data. Such comparisons substantiate the technique but also reveal the need for further work in both the modeling techniques and material data. Use of the field data also can address the question of overall structural response, but little has been done in this area to date.

Based on the data available today, we know that competent structures do not suffer extensive structural damage due to sonic boom loads. The damage that does occur is generally confined to glass breakage, plaster cracking, and bric-a-brac breakage. Methods have been developed to analyze the damage due to sonic boom loads. Figures 2-1 through 2-3 show typical damage curves for these materials. Table 2-1 provides an overview of what is known.

Considerable refinements in these damage calculation methods are possible. Because of inherent uncertainties in the planning process, only a few will enhance the capabilities of the planner. These capabilities include uncertainties which result in variations in effective load (e.g., flight paths, weather,

**Table 2-1 Failure Patterns in Conventional Buildings**  
 (Adapted from Unpublished Material Developed by  
 Dr. D.R. Webb of RAE)

SONIC BOOM  
 PEAK OVERPRESSURE  
 NOMINAL

SUPPORTING REMARKS	ITEMS AFFECTED	SUPPORTING REMARKS
The bulk of these types of 'damages' is in private houses where fragile objects, friable plaster and glass are widespread.	<p>0.5 - 2 psf</p> <p>Cracks in <u>plaster</u></p> <p>Fine; extension of existings; more in ceilings; over door frames; between some plaster boards.</p> <p>Cracks in <u>glass</u></p> <p>Rarely shattered; either partial or extension of existing.</p> <p>Damage to <u>roof</u></p> <p>Slippage of existing loose tiles/slates; sometimes new cracking of old slates at nail hole.</p> <p>Damage to outside walls</p> <p>Existing cracks in stucco extended.</p>	<p>Areas of lath/plaster. Ceilings at ~ 2 psf.</p> <p>Glass in rusty frames very vulnerable; can fail at 1 psf (prior faults obvious).</p> <p>Older-type roofs can slip partially or wholly. Con-fined to roofs when excessive nail corrosion; especially slurry wash roofs.</p> <p>Old and tall double stone walls can collapse. Always due to prior excessive damage to rubble core.</p>
<u>Modern buildings and industrial complexes are rarely affected.</u>	Stained glass windows not affected unless in very bad condition already.	

Table 2-1 Failure Patterns in Conventional Buildings (Continued)

SONIC BOOM PEAK OVERPRESSURE NOMINAL	ITEMS AFFECTED	SUPPORTING REMARKS
0.5 - 2 psf (Continued)	Bric-a-brac  Other	Those carefully balanced or on edges can fall; fine glass, e.g., large goblets.  Dust fall in chimneys  Blockage of ducts previously unswept - smoke damage.
SONIC BOOM PEAK OVERPRESSURE NOMINAL	ITEMS AFFECTED	SUPPORTING REMARKS
2 - 4 psf	Glass Plaster Roofs Ceilings	<p>Failures show which would have been difficult to forecast in terms of their existing localized condition. Nominally in good condition.</p> <p>Worst of these failures, will be caused by a combination of good dynamic coupling and lower-bound (statistical) strength. No glass flying.</p> <p>Nearly always due to acoustic coupling between the sonic boom and the roof space. Bungalows vulnerable.</p> <p>Breakage of eroded but otherwise effective nails/pegs.</p> <p>Clean breaks in plaster board joints especially in bungalows (coupling effect).</p>

Table 2-1 Failure Patterns in Conventional Buildings (Continued)

SONIC BOOM  
PEAK OVERPRESSURE  
NOMINAL

	ITEMS AFFECTED	SUPPORTING REMARKS
4 - 10 psf	<u>Glass</u> Regular failures within a population of well-installed glass; industrial as well as domestic; green houses; ships; oil rigs.	Some glass will fail due either to dynamic coupling alone or lower-bound strength alone. Glass pieces can drop out; some flying.
	<u>Plaster</u> Partial ceiling collapse of good plaster; complete collapse of very new, incompletely cured or very old plaster.	Roof space dynamic coupling.
	<u>Roofs</u> High probability rate of failure in nominally good slate, slurry-wash; some chance of failures in tiles on modern roofs; light roofs (bungalow) or large area can move bodily.	Slates/tiles damaged by bounce (acceleration more than 1g) large roofs lifted by negative overpressure part of sonic boom waveform.
	<u>Walls</u> (outside) Old, free-standing walls in fairly good condition can collapse.	The usual requirement is for the boom wave front to be normal.
	(inside) 'party' walls known to <u>move</u> at 10 psf.	Usually due to acoustic coupling in the room.
Greater than 10 psf	<u>Glass</u> Some good glass will fail regularly to sonic booms from the same direction. Glass with existing faults could shatter and fly. Large window frames move.	Due to forced response: a) edge failures - frame impact; b) center failures - mass stress mode.

Table 2-1 Failure Patterns in Conventional Buildings (Continued)

SONIC BOOM  
PEAK OVERPRESSURE  
NOMINAL

ITEMS AFFECTED SUPPORTING REMARKS

Greater than 10 psf (continued)	<u>Plaster</u> Most plaster affected.	Large ceiling movements especially in bungalows.
	<u>Ceilings</u> Plaster boards displaced and nail popping.	
	<u>Roofs</u> Most slate/slurry roofs affected, some badly; large roofs having good tile can be affected; some roofs bodily displaced causing gable-end and wall-plate cracks; Domestic chimneys - dislodge- ment if not in good condition.	- Chimneys are not easily affected because they don't couple well with sonic boom characteristics.
	<u>Walls</u> Internal party walls can move even if carrying fittings such as hand basins or taps; secondary damage due to water leakage.	Mainly due to room acoustic coupling.
	<u>Bric-a brac</u> Some nominally secure items can fall, e.g., pictures; especially if fixed to party walls.	

and detailed structural configurations) and uncertainties which affect capacity of response (e.g., exact dimensions of vulnerable elements and exact boundary conditions). Areas in which enhancing the state of knowledge will result in significant improvement of the ability of a planner to anticipate sonic boom damage to conventional structures are:

1. Development of an appropriate characterization of the effective strength reduction associated with glass which has stress raisers or has already been damaged.
2. Development of an appropriate description of the effective strength of very new (unused) plaster and very old/partially damaged plaster.
3. Development of a statistical description of the frequency of occurrence of these weakened elements related to some parameter(s) easily observable by a planner.

#### 2.1.2 Metastructural Effects

During the course of the sonic boom field tests conducted in the United States, a number of damage complaints were made for which the damage was inconsistent with the capacity of materials in good condition subjected to the anticipated loads. Investigations of these anomalies addressed the possibility of three conditions: 1) preboom damage to the structure which might reduce its capacity, 2) mechanisms which would result in enhanced response of structural elements, and 3) conditions which would result in an effective load larger than anticipated. Enhanced loads result from three classes of factors: 1) aircraft maneuvers inducing focusing, 2) atmospheric characteristics resulting in focusing, and 3) metastructural

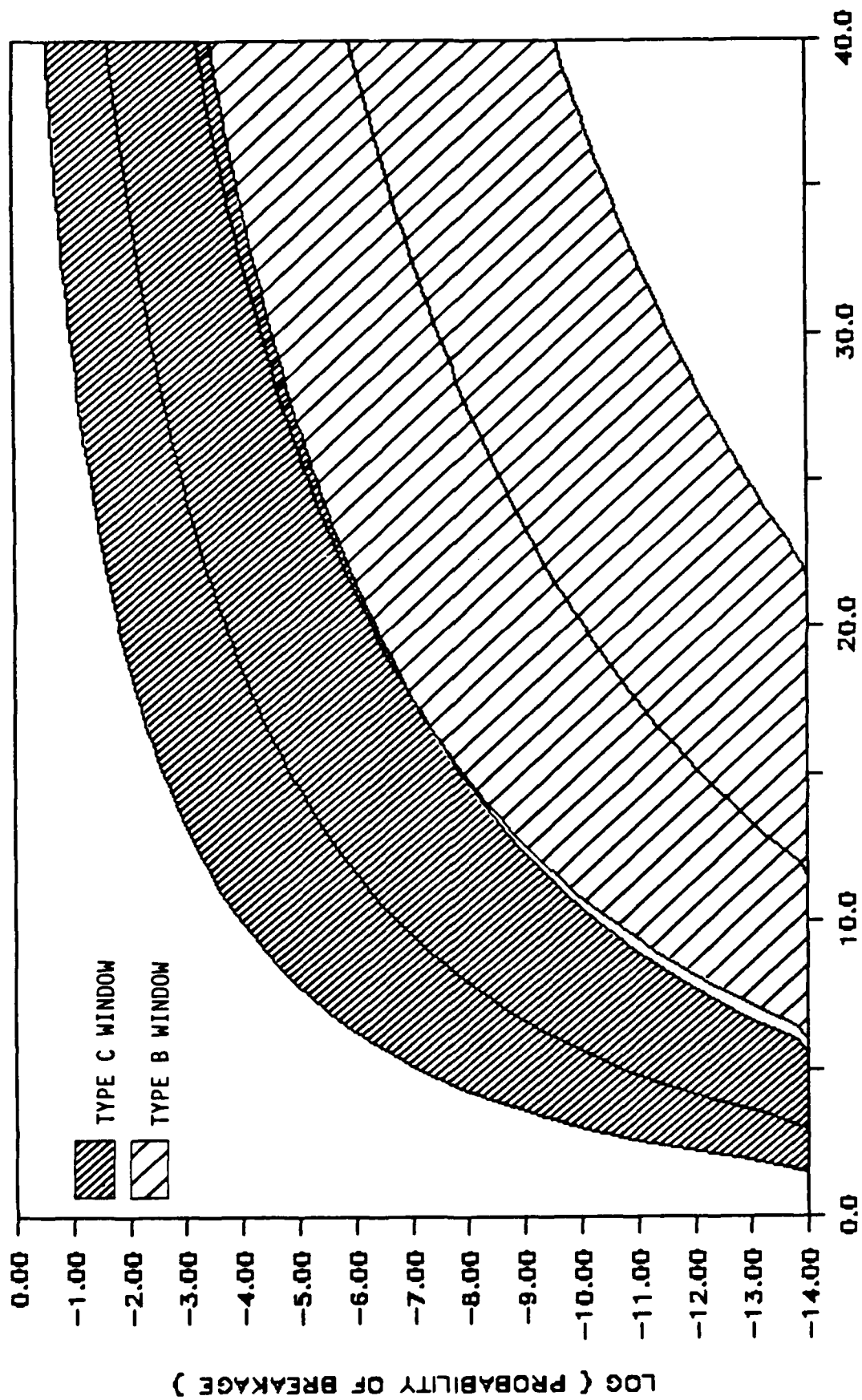


Figure 2-1. Probability of Breakage for Type B and C Windows (Mean  $\pm$  One Standard Deviation Bounds)

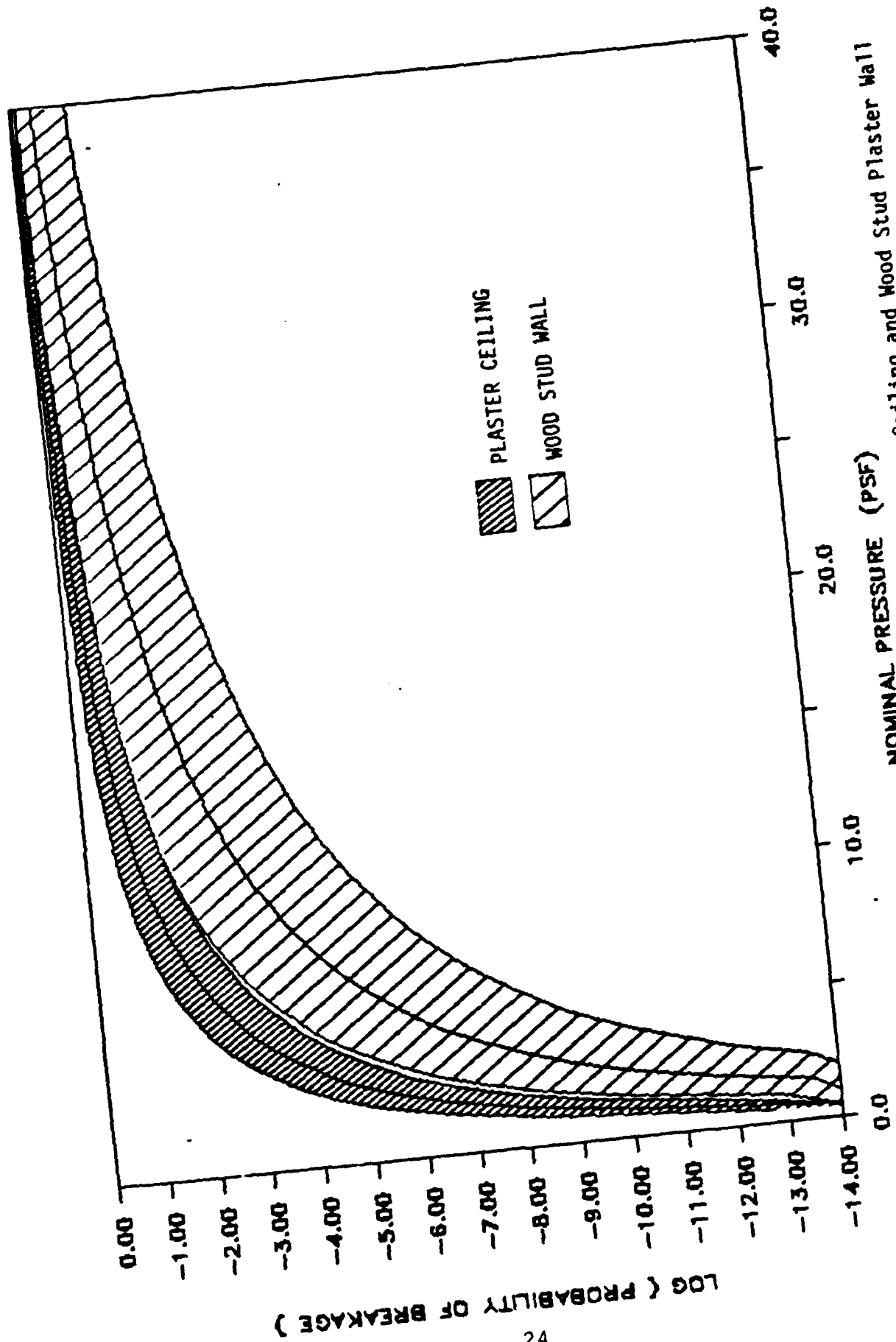


Figure 2-2. Probability of Breakage for Plaster Ceiling and Wood Stud Plaster Wall (Mean  $\pm$  One Standard Deviation Bounds)

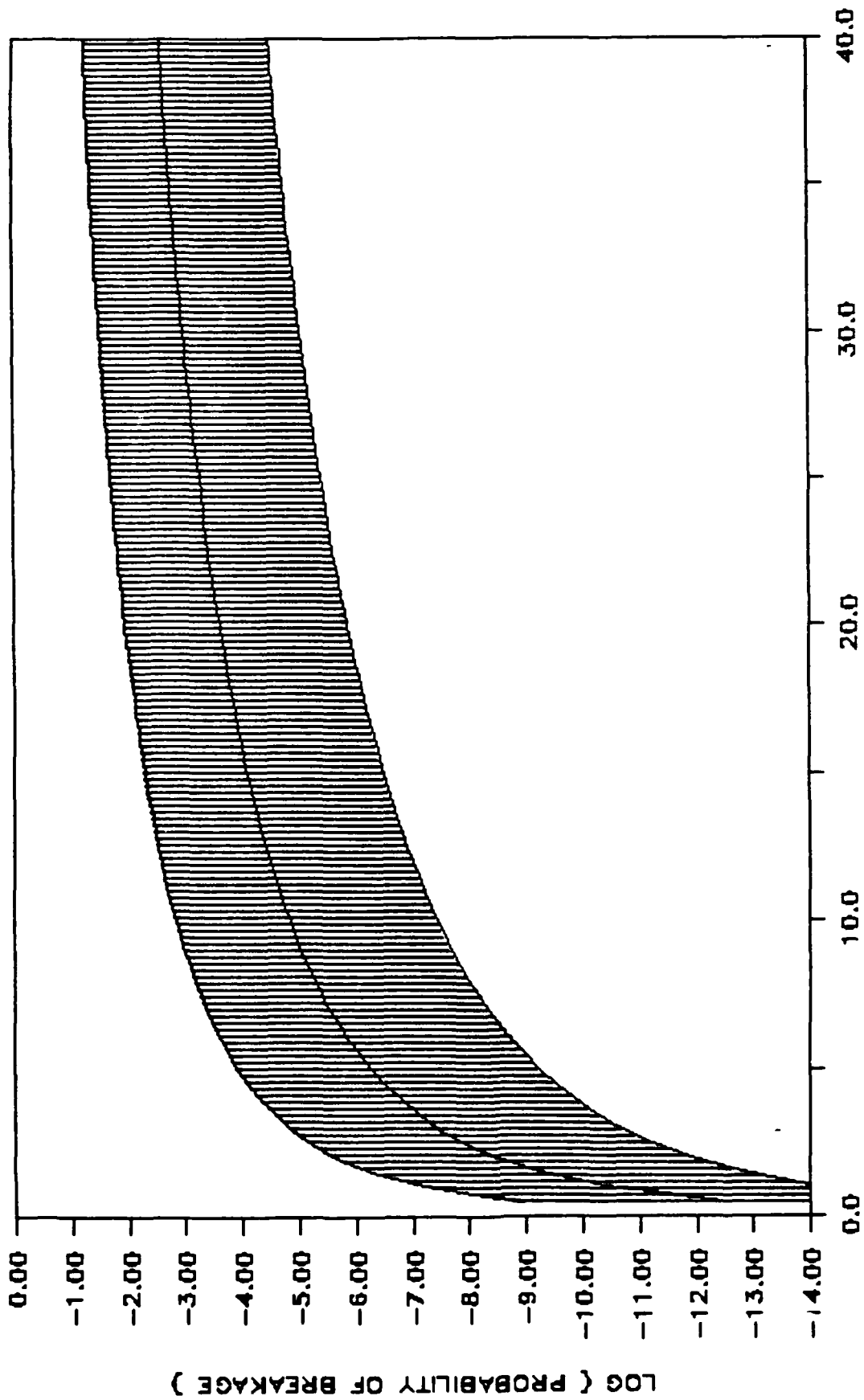


Figure 2-3. Probability of Breakage for Bric-a-Brac (Mean  $\pm$  One Standard Deviation Bounds)

effects of combinations of particular structural and terrain effects that modify overpressures.

Three categories of metastructural effects are addressed in the literature: 1) Helmholtz resonance, 2) diffraction, and 3) reflection.

Certain structural configurations behave as a Helmholtz resonator. A typical configuration is an opening in the structure (in one chamber) to the outside (an open window for example) and a constricted opening or narrow passageway connecting the first chamber to the remainder of the structure. Air in this connecting passageway "... behaves as an incompressible slug of fluid" which transmits pressure changes between the chambers. The Helmholtz resonance effect appears as oscillations in the pressure within the structure.

In the case of windows, a potentially critical condition has been postulated in the event that the fundamental frequency of the window matches the frequency of the Helmholtz resonator. If this frequency matching occurs, it may be possible for the window response to be amplified. However, the occurrence of this resonant condition requires a specific combination of the controlling parameters, which include the window size, the room volume, and the sizes of the openings in the room. Because a very precise combination of the parameters is required for the natural frequencies of the windows in a building to match the frequency of the Helmholtz resonator (reference 72), and even a slight mismatch of these frequencies eliminates any significant increase in window response, it is very unlikely that Helmholtz effects will substantially amplify window responses. This conclusion has been verified in an analytical and experimental study (reference 11), wherein the Helmholtz resonator effects did not increase the window response. In summary, it is not

likely that Helmholtz resonance is a critical factor for glass breakage.

Under the proper conditions, loads can be significantly enhanced by reflection from topographical and structural shapes. In general, the greatest reflection-induced overpressure enhancements are highly localized and require special geometries. The following summarizes some of the more important factors which have been investigated. Intensification is described relative to the pressures which would be measured at ground level (a rigid plane surface). The maximum intensification associated with the right-angled intersection of two planes is a factor of two at a corner. Parallel walls or overhangs reduce the intensification. Right angle corners formed by the intersection of three rigid planes can produce an intensification at the corner of up to a factor of four; larger intensifications can occur with smaller solid angles. The intensification associated with a paraboloid of revolution is highly dependent on the direction of propagation of the shock wave. When an aircraft flies supersonically along the axis of a paraboloid (e.g., a canyon) the maximum intensification is less than two. By contrast, when the direction of shock propagation is along the axis (recall that the ray cone open angle depends on the aircraft Mach number), a maximum intensification of a factor of 7 may be observed at the focus of the paraboloid. In all cases, intensification falls off rapidly with distance (reference 608).

Diffraction phenomena depend critically upon the relative dimensions of the incoming waveform and the intervening obstacle. For the case of a sonic boom N-wave and a large building the linear dimensions are comparable.

For a building of infinite width a "shadow zone" would exist within the area from the building to the ground intersection of

a straight line drawn through the upper rear corner of the building in the direction of wave travel. Within this zone no direct wave propagates. For a real building of finite width the wave diffracts around the upper and side edges. The relative amplitude of the sonic boom on this face depends on the incident angle of the wave and the building height and width measured in wavelengths of the N-wave.

The overpressure near the top of the forward face of a tall building is approximately equal to the direct overpressure multiplied by the building reflection factor; near the base of the building the reflected wave from the building will be superimposed on the reflected wave from the ground. When the shock angle with the ground is small, maximum overpressures on the front ground level are significantly reduced by diffraction losses for building heights less than three-quarters of a wavelength. When the ground shock angle is large this reduction only occurs for buildings less than one-quarter wavelength in height (reference 284).

The physical principles governing metastructural effects which modify sonic boom loads are understood. These effects are, by their nature, highly configuration dependent. Helmholtz resonance is not regarded as an important issue for the environmental planner. Enhanced window response will occur only when the Helmholtz frequency of the affected structure closely matches the fundamental frequencies of exposed windows in that structure. In contrast to this response, the effects of reflection and diffraction on the applied load are real and should be detected in any meaningful statistical sample.

While it is possible to generate significant load enhancements (up to a factor of seven) as a result of reflection, for planning purposes the load variations must be treated statistically. At present, the primary statistical

basis for this effect are the results of the White Sands Missile Range Tests (reference 62). Although these data give a reasonable representation of the statistical variation resulting from the built environment, no known study provides a comparable statistical characterization of topographic effects.

### 2.1.3 Cumulative Damage

Cumulative damage due to sonic booms is defined to be the damage from repeated booms in excess of the net sum of the damage from each individual boom. This type of damage can be interpreted as a fatigue effect. Quantifying the cumulative damage then requires a relationship between the damage and the boom strength, as well as the number of boom exposures.

The current knowledge regarding the cumulative damage effects of repeated sonic booms on conventional structures is based on experimental testing. Both full scale field tests and laboratory tests have been conducted. The test programs have dealt with glass and plaster, the brittle materials most susceptible to sonic boom damage. However, the cumulative damage effect has not been conclusively shown.

Federal Aviation Administration (FAA) sponsored overflight field tests were conducted from 1964 to 1965 at Oklahoma City and the White Sands Missile Range (references 67,72). One of the intents of these studies was to investigate the damage to structures by repeated sonic booms. Residential structures were targeted for study since they comprise the majority of damage claims. Plaster walls and ceilings were carefully monitored and inspected to study the rate at which cracks developed. Crack measurements were made during the overflight tests and during the "quiet" periods without sonic booms. In the White Sands tests, cracking tended to increase more rapidly during the boom periods than during the nonboom periods for nominal

overpressures of about 10 psf. In the Oklahoma City tests, there was no evidence of damage or of a cumulative damage effect for overpressures up to 2 psf. In both test programs, a cumulative damage effect could not be verified. We found that the natural environmental conditions produced substantial variability in the crack measurements, which made it difficult to distinguish the damage from the sonic booms. However, an important outcome of these tests was the concept of a cumulative damage threshold, because the data suggested that there may be a cumulative damage effect for overpressures greater than about 10 to 11 psf.

By considering the cumulative effects of repeated booms over an extended period of time, the damage observed in a structure will be partly due to naturally occurring forces. Such damage can be due to temperature, humidity, wind loads, foundation settlement, or human activity. It has been found that the long term effects of environmental factors may be more severe than the effects of repeated booms. The White Sands site was revisited 7 years after the overflight tests to evaluate the damage that had occurred during that period (reference 223). By comparing the observed damage for the two periods and using information on the sonic boom activity during the interim years, we found that the natural deterioration was far greater than the damage contributed by the sonic booms. This situation, however, was atypical in that there was no routine maintenance of these structures during this period. The cumulative damage effect could not be defined as a function of boom strength and number.

The relative magnitude of the damaging effects of naturally occurring forces has also been recorded in tests on the effects of ground vibrations from underground blasting (reference 20). We found that temperature and humidity variations-or human activity-produced strains in plaster walls which were equivalent to those corresponding to a peak ground velocity of 3.048 cm

(1.2 in.) per second. For comparison, the minimum damage threshold for underground blasting corresponds to a ground velocity of 2.54 cm (1.0 in.) per second. Relating the ground motion to sonic boom overpressures, it has been estimated that a peak ground velocity of 2.54 cm (1.0 in.) per second corresponds to an overpressure of about 3 psf. It can be interpreted that at low overpressures, the effects of environmental factors are more severe than those from the sonic booms.

Since the cumulative damage effect could not be positively identified in the field tests due to the environmental influences, laboratory testing provides another means of evaluating the effects of repeated booms. With laboratory testing, the environmental factors can be controlled and the effects of the repeated booms can be studied separately. To describe the cumulative damage effect, one approach has been to try to establish fatigue relations for glass and plaster, relating the material capacity to the number of sonic boom exposures. This then could provide a means of quantifying the cumulative damage by noting the change in the material capacity for increasing numbers of boom exposures. However, testing has been limited, and the results are inconclusive regarding a cumulative damage effect.

In the test programs for glass panes (references 91,222), the test data show great scatter. For a given applied overpressure, the number of boom exposures required for pane breakage generally shows a wide variation. The variability in the breaking strength of the glass outweighs the cumulative damage effect. Due to the scatter, a fatigue relation developed from one test program (reference 222) has substantial uncertainty. The postulated fatigue relation cannot be considered definitive due to the scatter and uncertainty. A limitation of the glass pane tests is that the specimens were mounted in special fixtures which provided secure clamped

conditions and were free from stress raisers. This alone would tend to increase the observed capacities of the glass panes, because stress raisers and the support conditions usually have a strong influence on window damage. Stress raisers concentrate local stresses, and impact or abrade the glass during the dynamic response.

As with glass, there has been little testing on the effects of repetitive sonic booms on plaster. One test program (reference 332) used 40.64 cm<sup>2</sup> (16 in<sup>2</sup>) pure plaster panels. That is, the specimens had no lath or other supporting members. A fatigue relationship for plaster was estimated through regression analysis. As was observed with glass, the data show substantial scatter and the regression equation has substantial uncertainty. After subjecting each of the specimens to 1000 simulated N-waves with peak overpressures of 10 psf, it was concluded that damage to plaster walls and ceilings would be unlikely in buildings in good repair when subjected to repeated sonic booms.

Another test program was conducted on full-scale, standard wood-frame construction plaster wall panels. These results show that plaster cracks are initiated by stress raisers. The specimens were subjected to 500 simulated sonic booms, each at nominal overpressures of 1.0, 1.8, and 2.6 psf. At such low overpressures, the cracks in the plaster were not generally visible to the naked eye. To detect the cracks, ultraviolet light was used. The plaster cracks began in the vicinity of the nails used to attach the gypsum board lath to the wood studs; in other words, the nails acted as stress raisers.

To summarize, the cumulative damage effect from repeated sonic booms is poorly understood. There are no models for predicting the damage to glass, plaster, or bric-a-brac as a function of boom strength and the number of boom exposures.

From the test programs, there is no strong evidence for a cumulative damage effect. In the field tests, the contributions of environmental factors to observed damage make it very difficult to identify the damage solely due to the repeated booms.

Test data also indicate that, at low overpressures, the effects of the environmental factors may be more severe than those from the sonic booms. However, the test data also suggest that, if there is a cumulative damage effect, it is associated with a minimum nominal overpressure threshold. The fatigue testing of glass and plaster are inconclusive. Only a few test programs address repeated boom effects. The fatigue relations obtained from the testing are subject to substantial uncertainty. In addition, the testing has focused on the fatigue behavior of the glass and plaster alone. Nevertheless, there is evidence that the damage from repeated booms may be more strongly influenced by stress raisers located where the glass or plaster is supported.

## 2.2 Unconventional Structures

The early investigations of the possibility of sonic boom structural damage were largely directed toward residential construction. A limited portion of these investigations included storefronts and office buildings. As indicated in an earlier section, these studies culminated in generalizations regarding damage thresholds for the structural elements used in this type of construction and, for some elements, damage prediction algorithms.

In addition to these structure types, there are a wide range of special or unconventional structures of concern to the public. These structures have, in general, been studied in less detail. A partial list of such concerns might include:

historic natural monuments or archaeological structures,  
indian caves with ancient petroglyph drawings,  
older historic buildings,  
wells or large open water tanks, and  
radio telescopes/antennae

At this time, no comprehensive list or definition of what constitutes unconventional structures exists, let alone lists of vulnerable structural elements of these structures. Nevertheless, for certain types of unconventional structures, extensive investigations have been made.

Windows figure predominantly as a vulnerable element in unconventional structures, just as they do for conventional structures. An English study of greenhouses (reference 591) confirms results of the vulnerability of glass panes in more conventional structures. At overpressures ranging from 1 to 4 psf, the observed damage correlated highly with the pretest condition of the windows. Precracked panes, panes abraded at installation by clips or supporting sprigs, and panes weakened by wind-induced vibration against sprigs accounted for the breakage in these tests.

In Europe, concern was expressed about possible damage to historical churches and cathedrals. Most of the investigations were directed toward evaluating the potential damage which might be caused by supersonic Concorde flights. Consequently, most investigations addressed overpressures on the order of 2 psf.

A monitoring program was performed at St. David's Cathedral during the flight tests of the Concorde. The construction of St. David's Cathedral in its present form was begun in 1180. There have been numerous alterations and additions since then. As a consequence of initially inadequate foundations, there has

been significant structural movement during the life of the structure. An example of this structural movement is the outward leaning of the nave pillars. Enormous buttresses were built in the 15th century to strengthen the nave. Further construction took place through the middle of the 19th century. At the time of testing there were further cracks indicating additional structural movement had occurred. The nave ceiling is flat; it is made of carved oak. Although the main members of the ceiling were reported to be well-constructed, the paneling is fragile. Some of the panels were reported to be loose or broken.

This monitoring program produced some cautious conclusions regarding possible damage to this type of structure at overpressures up to 2.7 psf. No detectable damage was observed from these tests. Moreover, vibration amplitudes measured suggest that the organ and wind loads are more likely to cause damage than low amplitude sonic booms (reference 120).

A rather extensive series of investigations were performed in Europe regarding potential damage to leaded glass windows (references 119,120,221,369). These investigations involved both explosive simulations of sonic boom N-waves as well as limited Concorde overflights. While these investigations did not produce damage algorithms, they did produce some important results.

Leaded glass windows differ from ordinary windows of comparable dimensions in three important ways. In comparison to ordinary windows, the panes composing a leaded window are small. This comparison results in short fundamental periods of vibration in response to low level sonic boom loads. The panes in leaded windows are supported by a lead extrusion. This lead extrusion support results in a high level of damping (empirically 3.5% to 6%) in comparison to a typical level (2%)

for ordinary glass. Finally, leaded windows are frequently stiffened by being wired to regularly spaced metal saddle bars, which are in turn attached to the window frame. The effect of these stiffeners is to reduce the maximum displacement under a specified load (reference 119).

Under a specified load, strains in the center of a leaded pane are comparable to those for an ordinary pane. One series of tests, involving 25 simulations of loads up to 5 psf, produced no damage (reference 119). In another series of tests, incipient damage in the form of putty dust fans was noted at 48 psf, lead buckling occurred at 61.4 psf, and leaded panes cracked at 96 psf. In that same test sequence, comparable "24 ounce glass" broke at 57.6 psf and 67.2 psf (reference 221).

While in general these results suggest that leaded glass is less vulnerable than ordinary glass to sonic booms, two caveats are in order. These results are based upon simulations and empirical results to evaluate potential damage to European leaded glass from the Concorde. Results need to be adjusted for differences between European and American leaded glass construction practices. In addition, because the duration of a fighter signature is approximately one-third that of the Concorde, leaded window responses need to be increased to reflect this closer match of load duration and pane fundamental period.

In the United States, concern about Concorde noise affecting historical structures was addressed using the response probability density function technique employed earlier for sonic boom damage to windows (reference 260). This investigation is important; it illustrates how these techniques may be applied to noise and illustrates the process of identifying critical elements in historical structures.

not sufficient to identify the credibility of the particulars of this application.

A field investigation at the Valentine MOA addresses the vulnerability of Indian pictographs and petroglyphs. This investigation demonstrates that, for sonic boom durations characteristic of fighter aircraft and overpressures up to 5 psf, damage is improbable. Moreover, if a previously defoliated rock slab remains attached to a rock mass by at least 1% of its total surface area, it is likely to withstand these small levels of sonic boom loads (reference 40).

In response to concern about how Concorde flights might affect satellite-communication earth-station aerials, a combined theoretical/empirical study was performed. The study establishes several important results (reference 593). Because sonic boom wavelengths are long in comparison to the diameter of the antenna reflector, the effect of reflection will be a superposition with a time delay of the incoming and reflected signals. Analyses show further that the potentially vulnerable portions of the structure are a quartz waveguide window and a quartz vane polarizer in an aerial feed. Sonic booms were simulated by detonating charges. Under simulated loads of up to 6 psf and durations of approximately 250 ms, no damage was sustained nor was there any interference with the operation of the facility.

Additional arguments are presented based upon wind load design considerations. In the absence of wind, it is concluded that the facility should tolerate at least 7.5 psf (reference 593). These observations must be treated with the caveat that the critical components may have fundamental periods significantly shorter than the duration of the loads for which they were tested. Thus, application of these results to fighter sonic booms requires an adjustment for load duration.

A theoretical study (reference 193) of the risk of sonic booms initiating an explosion produced the following results:

- o The threshold overpressure for initiating an explosion is on the order of 10,000 psf. Thus, it cannot be caused by operational sonic booms.
- o Overpressures on the order of 100 psf could disrupt automatic controls in an explosive manufacturing facility, if the controls are not properly vibration isolated. This disruption should be regarded as a highly improbable sequence because of the required overpressures.
- o An explosive plant not equipped with blast-resistant windows has a moderate probability of suffering window damage at the upper limits of common sonic boom overpressures (10-30 psf). If highly sensitive initiating explosives are in the path of the falling glass, an explosion could be initiated.
- o At common sonic boom overpressures (1-3 psf), reagent bottles may walk across surfaces and personnel may experience startle reactions. Repetitive sonic booms could cause a sensitive reagent container to reach an edge and topple, possibly producing a hazard, if no intervention were to occur. This reaction is unlikely for a well-maintained facility. Similarly, a startle reaction by operational personnel could, under the right circumstances, produce a hazard.

A number of tests have been performed to evaluate the vulnerability of aircraft to sonic boom damage (reference 310). Except for one plexiglass door damaged at approximately 8 psf, no damage was produced.

At present, no adequate comprehensive definition exists for the category of unconventional structures. To provide the planner with a framework to deal with the question of sonic impacts on unconventional structures, a taxonomy of unconventional structures should be developed. Because it is virtually impossible to perform an exhaustive tabulation of every type of unconventional structure, the taxonomy should provide a basis for a planner to extrapolate from the work that has been performed during the NSBIT program to a particular concern.

Within this taxonomy would be structural types for which vulnerable structural elements could be identified and, conceivably, those for which identification of structural elements would not be possible. The initial efforts to develop damage algorithms for structural elements (reference 260) should be extended to include this list. The damage algorithms should be extended where possible, using the previously summarized information regarding selected types of unconventional structures and bounding analyses.

## 2.3 Terrain Effects

### 2.3.1 Seismic Waves

When a sonic boom shock wave strikes the ground, wave energy is transmitted to the ground; this excites seismic waves. The sonic boom then affects structures both directly, by the N-wave, and indirectly, by the ground motion. Rayleigh waves, which travel along the surface of the ground, are the most critical of the induced seismic waves. Analytical and experimental studies have been conducted to investigate the severity of these seismic effects.

An analytical study (reference 139) investigated the response of structures to the Rayleigh-wave motion produced by sonic booms. In this study, the ground was idealized as a semi-infinite elastic medium. The shock wave pressure acting on the ground surface was modeled as a line load traveling at a constant velocity. The greatest ground motion and structure acceleration response occur under the resonant condition when the velocity of the sonic boom pressure wave is equal to the velocity of the Rayleigh waves in the ground. The study found that the resonant peak was very narrow. If the velocity of the sonic boom shock wave deviated more than 10% from the Rayleigh wave speed, the acceleration response of the structure was not substantially amplified. When the shock wave velocity substantially differs from the Rayleigh wave speed, the resulting ground motion is insignificant. Because of this result, the amplifications in the structure response as the resonant condition is approached would not be harmful. The study concluded that significant structure response from the Rayleigh waves is very unlikely due to the very specific conditions required to produce the resonant condition, i.e., the aircraft traveling with a constant velocity equal to the Rayleigh wave velocity in the ground.

A comprehensive study combining analytical and experimental work has also been conducted (references 7,79). Field measurements of the ground particle velocities produced by sonic booms were made during overflight tests at Edwards Air Force Base, Calif., the Tonto Forest Seismological Observatory near Payson, Arizona, and the Uinta Basin Seismological Observatory near Vernal, Utah. The measured ground velocity data were correlated with the local geologic data and the parameters influencing the sonic boom loading (overpressure, flight characteristics, and meteorological data). These data were used to verify analytical methods for predicting peak ground velocities generated by a given N-wave.

The key findings of this study are summarized below:

1. The maximum ground particle velocity generated by a sonic boom is linearly related to the peak overpressure for overpressures up to 5 psf.
2. The peak particle velocities produced by sonic booms are well below the damage thresholds established by the U.S. Bureau of Mines. For example, a sonic boom with an overpressure of 3.5 psf produced a maximum ground velocity of .033 cm (0.013 in.)/second which is less than 1% of the structural damage threshold of 5.08 cm (2.0 in.)/ second.
3. The peak particle velocities recorded at the edge of the sonic boom pressure envelope are attenuated by a factor of 6 relative to the particle velocities measured on the flight track.
4. It is highly unlikely that the required geologic conditions will exist for Rayleigh waves to build up such that structures will be damaged from the ground motion.

To summarize, the ground vibrations normally produced by sonic booms are not sufficient to cause damage in structures. Granted that the experimental results are associated with only a few geologic site conditions, analytical studies indicate that it is highly unlikely for the ground motion to become severe enough to cause damage. Structures are at greater risk from the direct incidence of the sonic boom.

### 2.3.2 Avalanches/Landslides

In general, the effects of sonic booms on open terrain are benign. However, there is the possibility that certain topographical features may be destabilized by sonic booms, creating hazards to people and structures. For example, in mountainous areas subject to heavy snowfall, there is the concern that sonic booms may trigger avalanches. Similarly, for cliffs and steep slopes, there is the possibility that landslides may be initiated.

Only one study has been conducted investigating whether or not avalanches could be triggered by sonic booms (reference 138). A field test program was conducted near Star Mountain in Colorado. Overflights by fighter aircraft produced sonic booms with overpressures ranging from 1.5 to 5.0 psf. No avalanches were triggered by the sonic booms. However, the snow conditions were such that the avalanche hazard was rated as "low" during the test program. No conclusive results were obtained from the tests. It is currently unknown whether sonic booms can trigger avalanches under high or low hazard conditions.

No studies have been conducted on the possibility of triggering landslides by sonic booms. It has been proposed that mud flow-type failures of earth slopes should be considered (reference 176). This type of failure is associated with a sudden increase in the internal pore water pressure within the soil. Another possibility is the triggering of rock slides from cliffs and canyon walls (reference 176). Natural rock slides are the result of long term movement, slippage, and weathering by natural environmental forces. It is plausible that a sonic boom could trigger a rock slide. However, a sonic boom-initiated rock slide would most likely be a premature occurrence of the natural event.

The potential for sonic booms to trigger avalanches and landslides is largely unknown. The possibility of the sonic boom to act as a trigger appears to be very sensitive to the condition of the snow or soil.

## 2.1 Low Frequency Noise

Low frequency noise generated by subsonic aircraft produces an acoustic pressure load on structures which is very different from sonic booms. While a sonic boom is an impulsive load with a wave duration of about 10-30 ms, low frequency noise may produce sound pressure waves lasting several seconds. Although the duration is much longer than for sonic booms, the peak overpressures for low frequency noise are generally very low, about 105 dB or 0.07 psf.

The most vulnerable structures are those located close to take-off and landing areas (reference 627), because these areas are closest to the source of the noise. Because the overpressures are so low, the noise is generally not expected to cause damage. A comparison of the response levels for windows and walls indicates that the responses due to low frequency noise are lower than those for sonic booms (references 26,363,627).

The acoustic loading from the noise can cause walls, ceilings, and floors to vibrate. These vibrations can set loose objects into motion, causing rattling. For example, pictures, mirrors, and other wall-mounted objects can vibrate and rattle when the wall vibrates. Similarly, bric-a-brac items seated on a shelf can vibrate and walk. While some unstable or fragile items may be broken by the low frequency noise, the rattling and vibration generally do not result in serious damage. The rattling is primarily an annoyance to the occupants of the building.

Overflight tests have been conducted to investigate building vibrations induced by noise from the Concorde. The tests were conducted in areas near Dulles International Airport in Washington, D.C., and John F. Kennedy Airport, in New York (references 49,348,349,350,494). The test sites ranged from about 3 to about 17 miles from the runways. The vibration responses of windows, walls and ceilings were measured. It was found that the acceleration response was linearly related to the maximum sound pressure level. The measured response levels were less than those corresponding to the minimum damage threshold established by the Bureau of Mines for ground vibration. However, the response levels were comparable to levels perceptible to people. Another important finding of tests was that some everyday events (e.g., closing windows or doors) which produce impulsive loads result in responses equal to or greater than those associated with the Concorde noise.

A method for predicting damage due to the Concorde noise has been developed by extending a sonic boom damage method (reference 260). The method is based on a probabilistic factor of safety which results in probabilistic damage estimates. Although the basic methodology is well defined, the capacity models are not well defined. For example, the load capacity of a window pane subjected to the low frequency acoustic noise is not known. It is not clear whether the capacity under this load condition can be simply extrapolated from static load data. There were not enough data to determine the validity of the models.

The effects of low frequency noise are less severe than for sonic booms. The maximum pressure loads produced by the noise are smaller than those encountered with typical sonic booms. The acceleration response levels of windows, walls, ceilings, and floors are lower than those for sonic booms. However, damage thresholds for these types of building elements have not

been established for subsonic aircraft noise. Because the typical durations of the noise are much longer than sonic boom durations, the building elements excited by the noise will undergo more cycles of oscillation than for a sonic boom. It is not known whether the additional cycles will produce a substantial cumulative damage effect. However, the elements at greatest risk from the low frequency noise are architectural elements, bric-a-brac, and other loose items. Another important factor with regard to environmental impact is the annoyance to building occupants. The low frequency noise is bothersome because: (1) the noise is audible and can be very loud, (2) the vibrations induced in buildings are perceptible, and (3) the rattling of objects can be an annoyance.



### 3. CONCLUSIONS

This chapter summarizes the key findings of the literature review of the current state of knowledge and technology gaps regarding the sonic effects of aircraft on structures. The major topics treated in the literature include sonic boom effects on conventional structures, sonic boom effects on unconventional structures, sonic boom effects on the terrain, and low frequency noise effects. Under the topic of conventional structures, the literature treats single exposures to sonic booms, and sonic boom load enhancement from metastructural effects.

#### 3.1 Current State of Knowledge

For conventional structures exposed to single event sonic booms, the sources of damage information are overflight field tests, damage claims data, and theoretical analysis. Damage data focus on specific building elements rather than for an entire building. The most vulnerable building elements are windows, plaster walls and ceilings, and bric-a-brac. It has been found that:

1. Well-built structures subjected to nominal sonic loadings do not experience severe structural damage.
2. Secondary damage (e.g., cracked windows and plaster) to the same buildings can and does occur at unexpectedly low load levels.
3. Essentially all of the damage at low load levels is to building elements in a weakened condition or subject to stress raisers.

4. Ground motion normally induced by sonic booms does not appreciably affect building structural response.

The sonic boom loads experienced by a structure can be modified by metastructural effects which include Helmholtz resonance, diffraction, and reflection. These effects are highly dependent on the configuration of the structure as well as the surrounding environment. Helmholtz resonance is not considered a critical factor for window damage. Amplified window response can occur only when the Helmholtz resonator frequency of the structure very closely matches the natural frequency of the window pane. The effects of diffraction are understood and generally do not lead to substantial increases in the sonic boom load. The effects of reflection have been found to produce large load magnifications, but are very sensitive to the terrain. For example, when an aircraft flies in a canyon, the load magnifications may range between 2 and 7.

The cumulative damage effect from repeated sonic booms has not been conclusively shown. From overflight tests, there is evidence that there may exist a cumulative damage threshold overpressure. That is, if there is a cumulative damage effect, it occurs above a threshold overpressure. However, it has also been found that the damage from environmental factors over time may be more severe than the effects of the repeated booms. Laboratory tests investigating the effects of repeated booms on glass and plaster have not provided strong evidence for a cumulative damage effect. The fatigue relations obtained from testing are subject to substantial uncertainty. There are no models in the literature for predicting the damage to glass, plaster, or bric-a-brac as a function of boom strength and number of boom exposures.

For unconventional structures, there is no comprehensive

list or definition of the types of structures that would be categorized as unconventional. A partial list might include:

historic natural monuments or archaeological structures,  
indian caves with ancient petroglyph drawings,  
older historic buildings,  
wells or large open water tanks, and  
radio telescopes/antenna

Considerable testing has been conducted in Europe on several types of unconventional structures. Windows in unconventional structures are vulnerable elements, just as they are in conventional structures. The most vulnerable windows are those that are in a preweakened condition. Leaded windows in Europe have been found to be very resilient to sonic boom loads. However, it cannot be directly inferred that the leaded panes are less vulnerable than ordinary glass. There are differences in the construction of European and American leaded glass. Also, the results come from simulations of sonic boom loads from the Concorde, which has an N-wave duration approximately three times that of a fighter aircraft.

Field testing has been used to investigate the vulnerability of Indian pictographs and petroglyphs. We found that damage is improbable for sonic booms produced by fighter aircraft at overpressures up to 5 psf.

Seismic waves are generated when a sonic boom shock wave strikes the ground. Rayleigh waves, which travel along the surface of the ground, are the most critical of the induced seismic waves. The greatest ground motion is generated under the resonant condition when the velocity of the sonic boom shock wave is equal to the velocity of the Rayleigh waves in the ground. However, a slight mismatch in velocities results in small ground vibrations. In general, the ground vibrations

normally produced by sonic booms are not sufficient to cause damage in structures. Testing at a few different geologic sites resulted in peak ground vibrations from overpressures of 3.5 psf that were less than 1% of the damage threshold established by the Bureau of Mines.

It has been postulated that sonic booms may trigger avalanches and landslides. The triggering of such events would be highly dependent on the condition of the snow or soil. However, it is not known whether a sonic boom could act as a trigger. Field tests attempting to trigger avalanches were unsuccessful. No tests have been conducted on the possibility of triggering landslides by sonic booms. However, if a sonic boom does initiate a landslide, it would most likely be a premature occurrence of the natural event.

The effects of low frequency noise are known qualitatively. The pressure loads from subsonic aircraft are much lower than typical sonic boom overpressures. The responses of windows, walls, and ceilings due to the acoustic noise are generally lower than those for sonic booms. The most vulnerable elements are architectural elements, bric-a-brac, and other loose items.

### 3.2 Technology Gaps

This section summarizes the gaps in technology in the sonic effects of aircraft. This discussion includes the effects on conventional structures, metastructural effects, cumulative damage from repeated sonic booms, effects on unconventional structures, effects on terrain, and low frequency noise effects. In conventional structures, damage to glass and plaster most often occurs in elements in a preweakened condition or those subject to stress raisers. For glass panes, a characterization of the reduction in the effective strength of the pane due to stress raisers is needed. It is qualitatively known that stress

raisers have a strong influence on damage. However, it is not known quantitatively the magnitude of the effect of stress raisers. The variability of this effect is also unknown. Similarly, a description of the reduction in effective strength of very old, partially damaged plaster is also needed. Noting that damage often occurs in glass and plaster elements in a pre-weakened state, a statistical description of the frequency of occurrence of these elements within the total exposed population is needed.

Metastructural effects can result in substantial load magnifications. The physical principles controlling the metastructural effects are understood. However, there is no statistical description of the variation in sonic boom loads resulting from topographic effects.

Cumulative damage effects from repeated sonic booms are not well understood. It is not known whether a cumulative damage effect truly exists. Further testing is required and models are needed to predict damage to glass and plaster as a function of boom strength and the number of boom exposures. In addition, the contribution to damage from environmental factors over time is not quantitatively known.

For unconventional structures, there is no comprehensive definition of the types of structures in this category. Also, there is no method for defining the vulnerable elements and appropriate damage algorithms for those elements. In the literature, structures that may be categorized as unconventional have been dealt with case by case. A taxonomy of unconventional structures should be developed that will contain structure types and vulnerable structural elements.

The ground vibrations normally produced by sonic booms are not sufficient to cause structural damage. However, tests have

been conducted in only a few sites with different geologic conditions. It is not known whether certain geologic sites could develop ground vibrations severe enough to cause damage.

It is unknown whether a sonic boom can trigger an avalanche or a landslide. The natural occurrence of avalanches and landslides is highly dependent on the conditions of the snow and soil. It is unknown what, if any, combination of terrain conditions and sonic boom overpressures would be required to trigger an avalanche or a landslide.

The effects of subsonic aircraft noise on structures are qualitatively known. However, the quantitative details are largely unknown. Windows and plaster elements are less likely to be damaged by low frequency noise than by sonic booms. However, the damage thresholds for these elements for subsonic aircraft noise are unknown. A description of the material capacities for glass and plaster under the low frequency acoustic loading is needed. In addition, it is not known whether there is a cumulative damage effect from repeated exposures to the low frequency noise.

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Note: Numbers in parentheses (000) correspond to the Citation Database accession numbers.

**APPENDIX A**

**PLAN FOR THE PREPARATION OF A COMPREHENSIVE DATABASE  
FOR STRUCTURAL IMPACTS FROM NOISE AND SONIC BOOMS**

**Technical Operating Report Number 2**

Technical Operating Report Number 2

PLAN FOR THE PREPARATION OF A COMPREHENSIVE DATABASE  
FOR STRUCTURAL IMPACTS FROM NOISE AND SONIC BOOMS

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6 Nov 87

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## ABSTRACT

This report provides a plan for the development of a comprehensive database, assessing the current knowledge and identifying technology gaps for structural impacts from subsonic and supersonic aircraft operations. The database will include current scientific and technical knowledge, analytical methods and experimental data, and assessment criteria essential to the Air Force planning community for assessment of the effects of aircraft operations on structures.

This report supplements the definition of a Citation Index Database prepared by BBN under Task 0003 of Contract F33615-86-C-0530 by defining the specific adaptations to this design required to incorporate the structural impacts of these aircraft operations.

## 1. INTRODUCTION

### 1.1 Objective

Public Law 96-588, the National Environmental Policy Act of 1969 (NEPA), requires the Air Force to conduct environmental assessments of its flight activities. NEPA and other regulations apply not only to flight operations near air bases, but also to operations in about 350 Military Operating Areas (MOAs) and Restricted Areas (RAs), and along 400-odd Military Training Routes (MTRs), encompassing roughly a half million square miles of domestic airspace. Compliance with statutory and regulatory environmental requirements is not a simple task for the Air Force; it poses technical and practical challenges to providing a complete assessment of the potential consequences of these operations and in responding to the public concerns about possible consequences.

Task 0010 of Contract F33615-86-C-0530 addresses these needs by the development of a comprehensive database of the literature related to the sonic effects of aircraft operations on structures and the development of a White Paper summarizing the current state of knowledge and technology gaps. The first step in this process is the development of a plan to compile data in the areas of noise and sonic boom effects on structures. The data are to be incorporated into the Noise Environmental Planning Aid database developed as part of an automated environmental planning aid (Assessment System for Aircraft Noise, or ASAN) being developed under Task 0003. This document identifies the planned approach to identify sources of data, evaluate the data for pertinence, completeness and credibility, and incorporate the citations on structural effects in the overall Noise Environmental Planning Aid database.

## 1.2 Background

At present, an Air Force environmental planner charged with assessing the environmental effects of aircraft operations has no well-defined method for performing this assessment. Moreover, as a consequence of Air Force procedures of rotating assignments, the planner may have little opportunity to develop personal knowledge and experience to assist him in this task. In order to address these needs, NSBIT has funded the development of a planning aid, the Assessment System for Aircraft Noise (ASAN). A key component of ASAN will be a database characterizing the current state-of-knowledge as reflected in pertinent studies, reports and data sets. In addition, this database will provide a means of integrating and organizing the results of research addressing sonic boom propagation and effects. This plan defines the steps which will be employed for the purpose of developing the database for the assessment of subsonic and supersonic effects on structures.

While the ASAN system will provide a planner with the means for directly assessing the impacts of aircraft operations on structures, it is important that the planner be able to address unusual situations or points of view that may not be reflected in the basic ASAN modules. By identifying primary sources of information, the database will enable the planner to investigate alternatives. In addition, the database will assist the planner in responding to comments and objections raised during public hearings, scoping meetings, claims hearings and litigation.

In order to meet this need, a broad list of pertinent literature is required. For the most pertinent and the most controversial articles, abstracts must be prepared to define clearly the position taken in the articles, analytical or empirical bases, and the strengths and weaknesses of the positions expressed. On the other hand, efforts will be focused to assure an optimum

benefit return for the finite budgeted resources. Figure 1 outlines a procedure developed by BBN for this purpose. Throughout this plan we will refer to this figure in addressing its application to the effects of noise on structures.

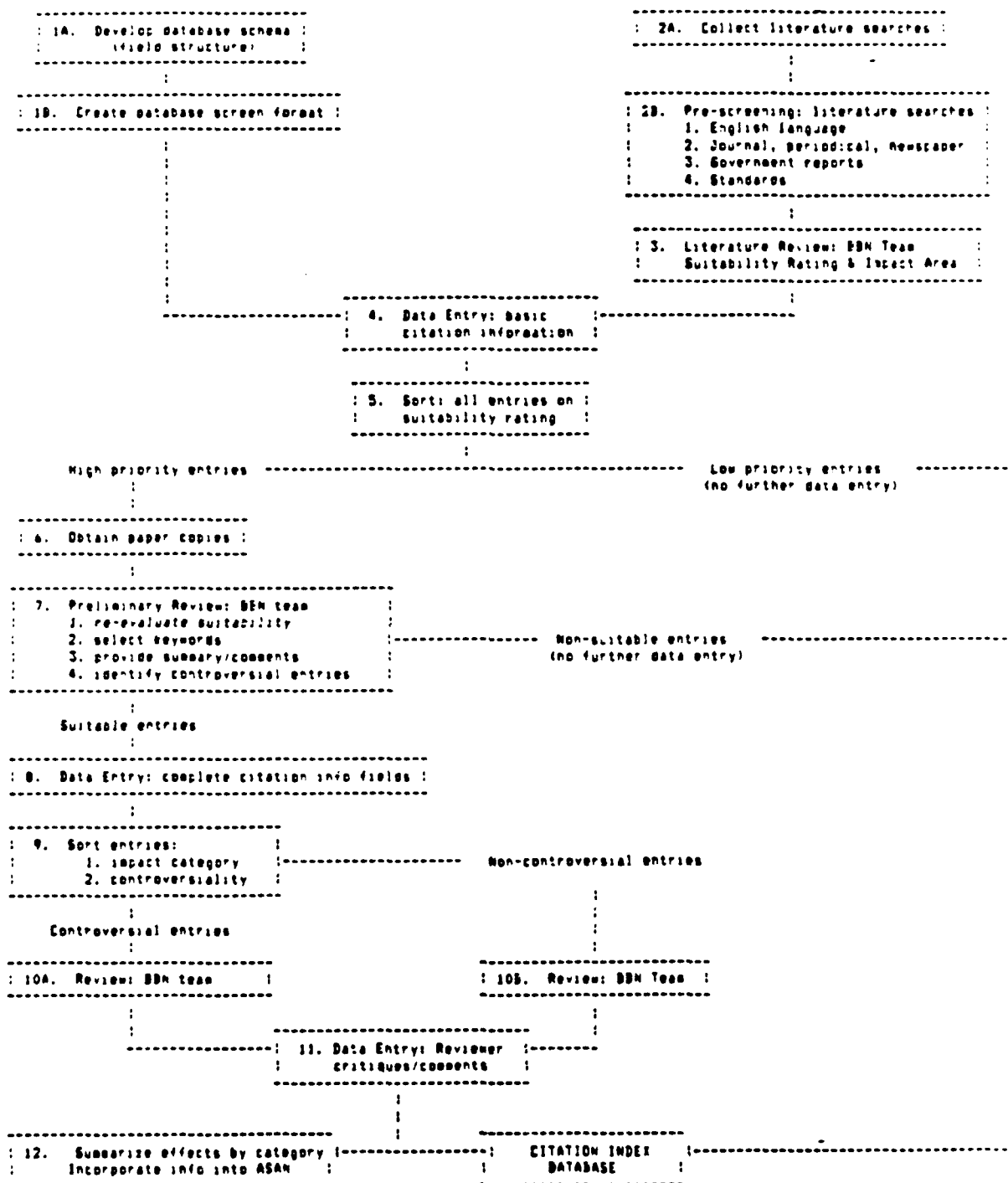


Figure 1. Development Procedure: Citation Index Database

## 2. SCOPE: DEFINITION OF STRUCTURES AND LOADS

An environmental planner must be able to assess the effects of aircraft operations on a wide variety of structures. In this context the meaning of the word structures is extended to include not only modern man-made structures such as residences, offices, and manufacturing facilities, but also historical, archaeological and other unconventional man-made structures such as delicately or critically aligned equipment. In a much broader sense, the word structures is to include terrain which may enhance the hazards of the airborne waves through focusing or ground coupling (primarily in connection with Rayleigh waves) and terrain features which may be excited to trigger a secondary hazard (e.g., avalanche or landslide). Much of the literature treats conventional structures in terms of the response of particular elements such as windows, plaster walls, wall connections, bric-a-brac and so forth. On the other hand, discussions of unconventional structures tend to be confined to a specific structure of interest.

The sonic effects of interest include damage to a structure or its contents as well as structural response that has an adverse effect on other structures or their occupants. Thus, the planner is concerned not only with damage to a structure but also how the structural response may annoy the building's occupants or enhance the loads to which another structure may be subjected.

From the planner's perspective, the loads of interest are the airborne sonic booms generated by supersonic aircraft, low frequency airborne noise generated by subsonic aircraft, and the seismic signals imparted into the earth by the two types of airborne waveforms. When significant sonic booms are generated by an operation, they may be expected to dominate the other effects under most situations.

Ample data are found in the literature for some combinations of structural types and loading conditions, in other instances data are sparse or nonexistent. In order to supplement the aircraft noise and sonic boom effects literature, it is necessary to consider other analogous loads such as blast, wind, and thunder. To make use of these other loading conditions, it is necessary to consider their differences from the loading wave forms of interest and identify procedures for reconciling them.

Sonic booms, blast waves and thunder are all impulsive loading forms. Their amplitudes and waveforms, however, may differ significantly. Moreover, while sonic boom is normally an airborne waveform, a significant amount of blast energy may be transmitted from the source to the receptor through the ground. In addition, it may be argued that the waveform incidence angle, with respect to a structures will be different for sonic booms than blast waves because of the location of the source.

In the case of wind loading, many analyses are based on a constant load as opposed to an impulsive load. However, an analyst can convert a dynamic impulsive problem through the use of the properly defined load factor and mode participation factor. Thus, selected articles on the response to wind loads may be expected to be useful in understanding the response to low-level, low-frequency loads, and in understanding the response of selected building elements (notably windows) to sonic booms.

The above-cited issues have varying degrees of significance in assessing the applicability of articles regarding these loading waveforms to aircraft noise effects. The following outlines the recommended approach to each issue:

**Wave incidence angle:** The angle of incidence of the wave on a structure will affect the load that the structure will see. At

typical sonic boom overpressures the load applied by a normally incident wave is twice that applied by a grazing wave. When analyzing a specific source of energy and a specific structure the distinction between an elevated source (sonic boom) and one at the surface (blast) may be significant. However, the planner must consider many structures, aircraft and flight paths. This will result in a distribution of angles of incidence. Moreover, while one might argue that the distinction between an elevated and surface source will affect this distribution, the magnitude of this effect is more than offset by the uncertainty in the particular air traffic patterns which will occur, approximations which must be made in characterizing the structural environment at risk, and the need to omit or drastically simplify the effects of meteorology on sonic boom propagation.

**Waveform differences:** A comparative analysis of the maximum dynamic load factors (DLF) for sonic boom waves and blast waves shows that a sonic boom wave-forcing function generally produces a larger DLF than a blast wave of equivalent peak pressure and duration. Figure 2 illustrates the variation in the structural responses, DLF, due to different waveforms.

Figure 3 shows an example of a graph of resultant peak stress versus wave peak pressure which can be developed to correlate the responses produced by different waveforms.

**Airborne versus Seismic Waves:** In contrast to sonic boom, in some cases a significant portion of the energy from an explosion will be imparted into the ground. As a consequence of the difference of propagation speeds of air and ground, the airborne blast wave will normally arrive later than the groundborne wave. This leads to the possibility of separating the effects of the two loads when adequate data have been gathered by the investigator.

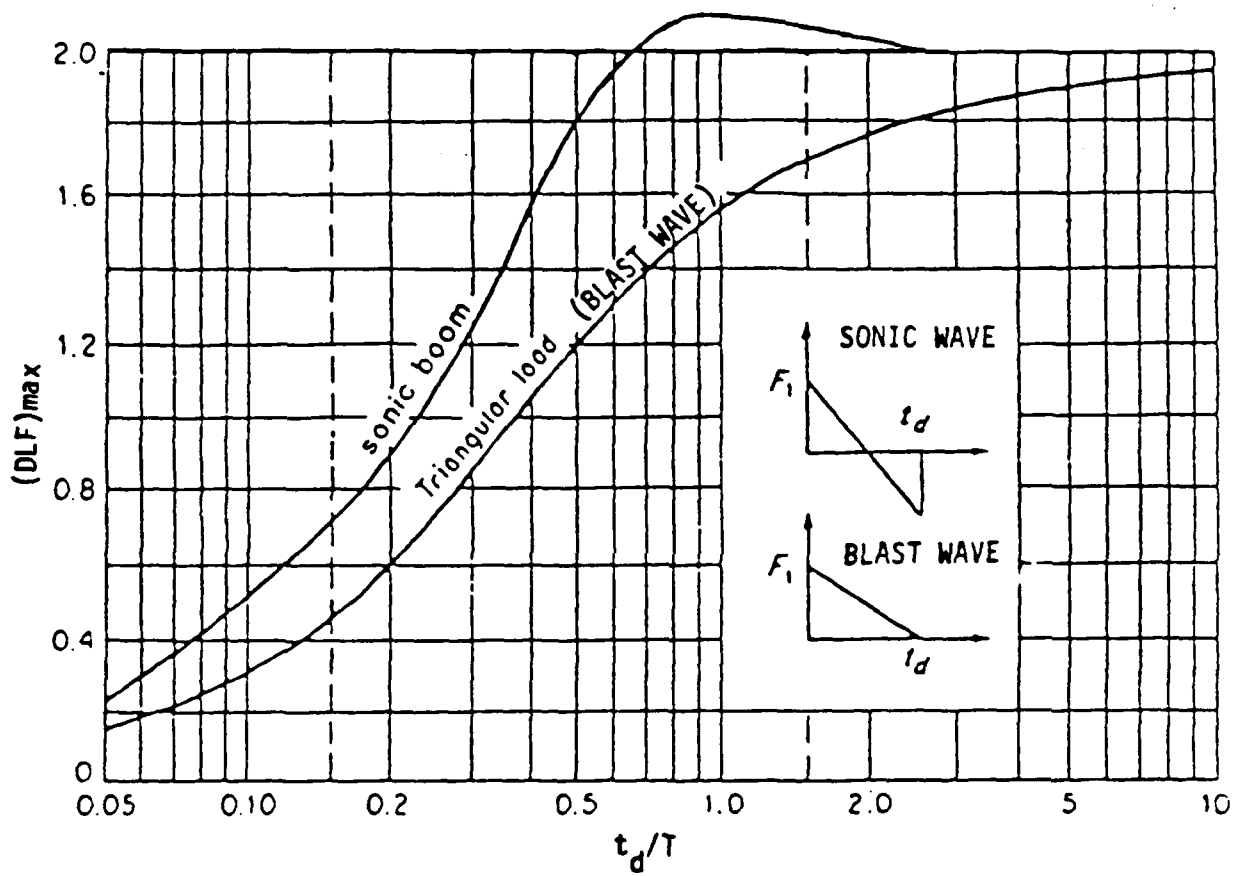


Figure 2. Variation of  $(DLF)_{max}$  with Different Wave Forms

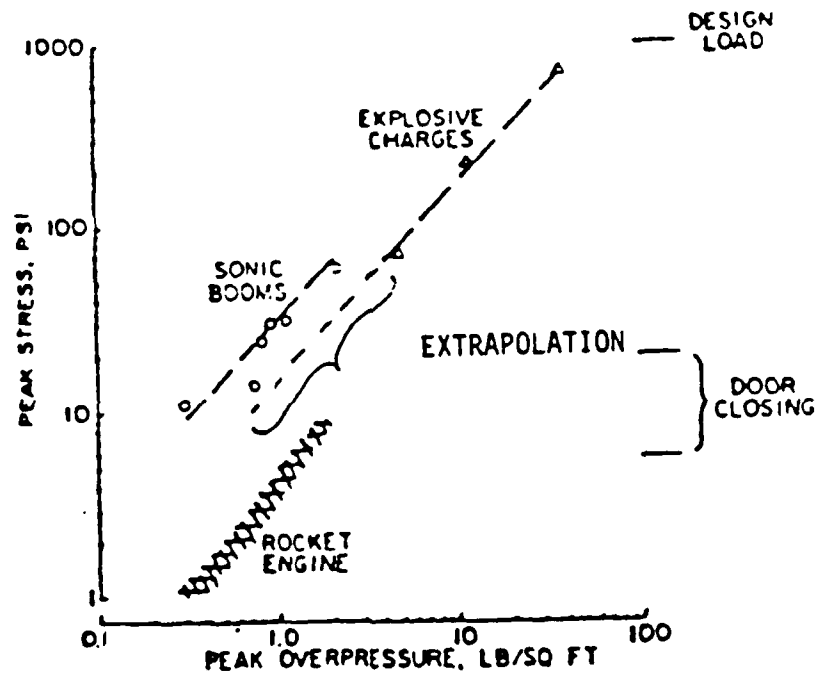


Figure 3. Variation of Peak Stress Due to Different Wave Forms at Various Peak Over-Pressures (W.H. Mayes and P.M. Edge, Jr., "Effects of Sonic Boom and Other Shock Waves on Buildings," Mater. Res Stand. 4, 588-593 (1964))



### 3. DATABASE DEVELOPMENT PROCEDURE

The following discussion will outline the database development procedure. Step numbers referenced in this discussion are those indicated in Figure 1.

#### Step 1A -- Develop Database Schema (Field Structure)

The basic database schema was developed as part of Task 3. (See Appendix A, Section A.4 of NSBIT Technical Operating Report No. 1, "Proposed ASAN Database Development Procedure", September 10, 1987). The following material is confined to modifications to the original database schema.

The original schema specified four noise types: impulse, aircraft traffic and other. Three subtypes -- sonic boom, blast, and seismic -- have been introduced for impulsive acoustical loading; two subtypes -- wind and terrain effects -- were introduced for the noise type "other".

The original schema identified the structural impact area as one of several areas of impact. This has been expanded to include the following structure identifiers:

- Windows
- Interior Walls and Ceilings
- Exterior Walls
- Wall Connections
- Delicate Contents
- Contents other than delicate
- Archaeological
- Historical
- Other Unconventional
- Avalanche
- Landslide

Material Mechanical Properties  
Cumulative Effects

Step 1B -- Create Database Screen Format

Most of the database screens required for data entry will have been developed as part of the Task 0003 effort. Adaptations to incorporate the items outlined in Step 1A above will be coordinated with the Task 0003 team.

Step 2A -- Collect Literature Citations

Citations to be considered for entry into the database will be developed from computer-generated literature searches, consultation with researchers in this effects area, referrals from NSBIT project personnel, selected journals and compilations of indices and abstracts, and recent summary literature.

The following computerized literature searches and index reviews will be performed:

1. University of California
2. California State University
3. California Institute of Technology
4. Defense Technical Information Service
5. NASA Scientific and Technical Aerospace Reports (STAR) Index
6. American Institute of Aeronautics and Aerospace Index
7. International Aerospace Abstracts

Key words employed in the search will include sonic boom, structure, windows, panels, glass, supersonic, subsonic, acoustic, pressure wave, noise, plaster, stiffness, deterioration, impulsive, vibration, acceleration, triggering effect, rattling, shattering, blasting, low-frequency, damage,

pulse, flexure, structural response, material properties and N-waves.

Citations will also be selected from the past 25 years of issues of the Journal of Sound and Vibration and the Journal of the Acoustical Society of America.

Expert input will be solicited from the following sources:

present or former NASA personnel or NASA contractor personnel involved in the structural effects area (candidates include Dominique Maglieri, Harvey Hubbard, and John Nixon);

present or former employees of the Federal Aviation Administration or its contractors involved in the structural effects area (Candidates include Tom Higgins, John Wiggins, and Robert Hershey); and

A representative landslide expert from the United States Geological Survey (possibilities include Robert Shuster, Robert Fleming, or Robert Bucknam).

#### Step 2B -- Pre-screening: Literature Searches

Citations from the literature will be pre-screened using the following criteria:

1. The entry must be directly related to the effects of aircraft noise on structures. (The inclusion of loads such as blast and wind will make the determination of "directly related" a judgment call relying on the experience of the staff of the BBN team members.)
2. The entry must be one of the following types of publication:
  - a. a refereed published journal article,

- b. a government report, standard or publication;
- c. a published book.

3. Citations must be in English.

### Step 3 -- Literature Review

This step will refine the literature to be included in the database by ranking it as to its suitability to the NSBIT goals. This review will be based on the reviewer's previous knowledge of the citation and, if available, abstracts. The categories to be used to rate each publication for inclusion in the database are as follows:

1. The publication is directly applicable to the NSBIT goals and should be included in the database.
2. The publication may be directly applicable to the NSBIT goals and should be included in the database.
3. The publication is indirectly, remotely, or potentially applicable to the NSBIT goals and should be included in the database.
4. The publication should not be included in the database.

In assigning these ratings, high priorities will be assigned to empirical data associated with sonic boom and noise from subsonic aircraft and their impact on the structural environment. Analogous loading waveforms (blast and wind) will be assigned lower priorities. Theoretical papers' ratings will be related to the load and structure being analyzed. Notwithstanding the preceding comments, it should be underscored that the primary emphasis of this step is to determine which articles should not be included in the database.

#### Step 4 -- Data Entry: Basic Citation Information

The first phase of data entry includes the basic citation information for all articles deemed suitable (ratings 1 through 3) for inclusion in the database. The first eleven fields will be used to generate a complete reference:

1. Title of document
2. Title of Journal (if appropriate)
3. Journal volume, issue number, and page numbers
4. Date of publication
5. Document type (book, journal article, technical report, government report, ANSI/ISO standard, or bibliographic listing)
6. NTIS number, ISB number and Library of Congress call number
7. Performing organization and sponsoring organization
8. Performing organization report number and government contract number
9. Publisher's name and address (if appropriate)
10. Impact Area (human, animal, structures, modeling)
11. Suitability rating

#### Step 5 -- Sort Entries Based On Suitability Ratings

A computerized sorting process will be conducted on the basis of suitability ratings assigned in Step 3 and entered in Step 4. Higher priority entries will be processed with additional data entry and expert review. Lower priority entries will be processed as time and funding permit.

### Step 6 -- Obtain Paper Copies of Publications

Paper copies of high priority entries will be obtained from the NTS Engineering library, BBN Laboratories' library, government agencies, or local universities and public libraries. If a paper copy of an entry is not available locally, interlibrary loan agreements and contacts with experts will be used to obtain copies of publications.

Paper copies will be tagged with a unique entry number and filed in numeric order for future reference. If the paper copy is not available (for example, the publication is out of print), then an explanatory note will be placed in the hard-copy files. The computer database will also be updated to indicate a missing paper copy.

### Step 7 -- Preliminary Review

The paper copies will be assembled for review and analysis by the team. These reviews will involve 1) further re-evaluation of the suitability rating, 2) selection of key words, 3) development of summary/comments, and 4) identification of controversial entries with a brief explanation of the reason for identifying the articles as controversial.

#### **Re-evaluation of the Suitability Rating**

The suitability rating from Step 3 will be re-evaluated based upon additional information available from the paper copy of the publication. In addition to the criteria considered in Step 3, the following additional factors will be considered:

- a. Uniqueness: Is the relevant material presented in the article presented elsewhere by the same author or others?

- b. **Clarity and Completeness:** If the relevant material presented in the article is covered elsewhere in the literature, is this the clearest, most thorough presentation of the material?
- c. **Topic Significance:** Does the article cover topics especially useful to the planner, such as flaws or myths in previous writings, or empirical data on effects on structures?
- d. **Frequency of Citation:** Is this an article which is cited frequently in the literature? This will be an indicator of both well-accepted perspectives and controversial writings.

#### **Select Key Words**

The key words will describe the citation type (field study, laboratory experiment, literature review, or research proposal); the impact category (structural); the type of structural configuration being investigated (windows, interior walls or ceilings, exterior walls, wall connections, delicate contents, contents (other than delicate), archaeological, historical, other types of unconventional structures, avalanche, landslide, or terrain effects on signal (such as "metastructural" focusing or Rayleigh waves)); and the type of load under investigation (impulse, aircraft noise, wind, or other).

#### **Provide Summary/Comments**

If the abstract of the original author(s) is incomplete or unavailable, the BBN team will prepare a brief summary of the publication. Very lengthy abstracts will similarly be edited before inclusion in the database. Abstracts modified or written

by team members will be tagged with the reviewer's initials. When possible, abstracts will indicate the loading conditions, provide a further elaboration as to structural configuration; indicate the type of impacts assessed, the method of assessment, and the criteria for impact; and report conclusions.

### Identify Controversial Entries

Controversiality ratings will be assigned based on the following criteria:

1. The publication is highly controversial due to its research approach, methodology, or stated conclusions (i.e., "noise kills"). Most researchers would take an opposing position on the given research topic.
2. Some elements of the publication are controversial due to its research approach, methodology, or results.
3. The publication is noncontroversial. (Most publications will be assigned this rating.)

### Step 8 -- Data Entry: Complete Database Information

Entries that have been judged suitable for inclusion in the database will be updated with complete database information.

Entries that have been judged unsuitable, or of a lower priority than would justify a full review, will remain in the database for bibliographic purposes. Previously entered information will not be deleted; however, no new information will be added.

### Step 9 -- Sort Entries: Impact Categories and Controversiality

All entries will be sorted a second time on the basis of controversiality rating. Entries that have been identified as having some degree of controversy (rated 1 or a 2), will be accorded special treatment to reduce bias. When possible, three independent reviewers on the BBN team will review these articles. If any doubt remains as to whether bias has been eliminated by this procedure, they will be forwarded to non-BBN team experts for review. Noncontroversial entries will be treated as previously described.

When the sorting process is complete, computer print-outs of all the information in the database will be generated so that the information can be checked for accuracy.

### Step 10A -- Review of Controversial Articles

Articles rated as "controversial" in Step 7 will be provided a special review procedure to help reduce bias in entry selection and protect the integrity of the database. When three independent reviewers can be identified on the team capable of reviewing the particular article such a team will be formed for its review. Otherwise, the article will be submitted to an outside expert for review.

### Step 10B -- Review of Noncontroversial Articles

Entries that were rated as noncontroversial will be reviewed by BBN team experts. The results will be summarized with the most significant attributes and conclusions of the study identified. Pertinent data useful to the EIAP will be documented.

### Step 11 -- Data Entry: Reviewer Critiques/Final Comments

The final data entry process will include any additional comments regarding controversiality of entries. Once all entries are complete, a final error check will also be conducted.

### Step 12 -- Summarize Effects

The final step in the database development procedure will be the preparation of a comprehensive summary of the information available in the structural impact category. The summary will be presented as a "white paper" and will include a critical evaluation of all available information and of the technical gaps in this area.

Included in the summary will be an identification of the loading conditions and types of structures treated, types of impacts identified and criteria used to define the impacts, and methodologies used to assess impacts. For identifiable combinations of structures and loading conditions found in the literature, the effects associated with these impacts, the methods used in assessing these impacts, and the uncertainty in assessing the impacts will be presented.

#### 4. PROJECT SCHEDULE

Figure 4 presents a schedule for the performance of Task 0010. The schedule has been characterized in terms of the database development steps outlined in Section 3 and augmented with milestones such as briefings and reports.

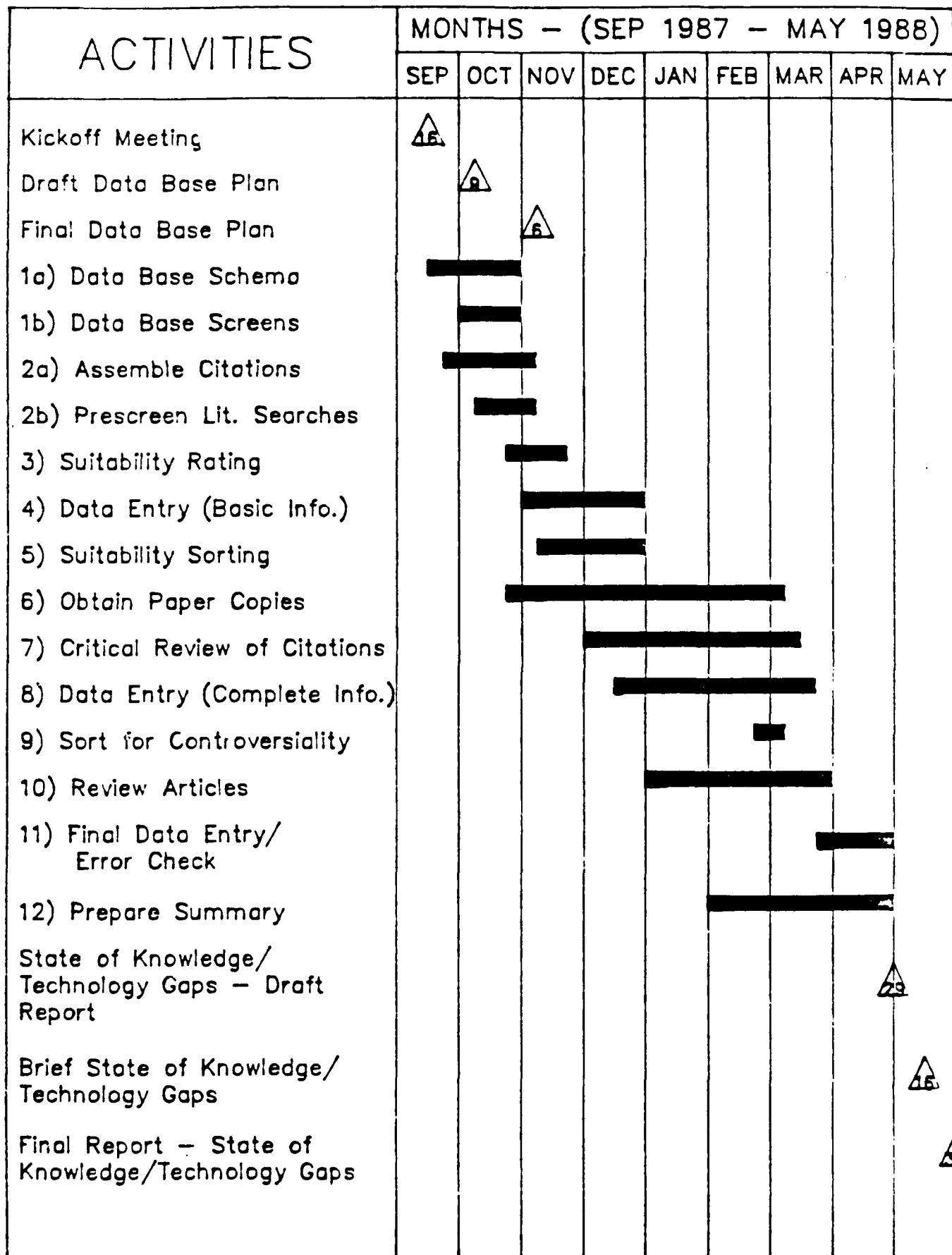


Figure 4 - Data Base Development Schedule

**APPENDIX B**  
**CONTACT DATABASE**

This appendix presents a database listing of persons who can be contacted to identify historical structures in each state and in the District of Columbia. The contacts are listed by state, and addresses and telephone numbers are included for each contact.

NO	STATE	TELEPHONE	ADDRESS
1	ALABAMA	(205) 261-3184	Mrs. Allen Mertins Coordinator for National Register Alabama Historical Commision 725 Monroe Street MONTGOMERY, AL 36130
2	ALASKA	(907) 762-2627	Mrs. Jo Antonson State Historian Office of History & Archaeology P. O. Box 107001 ANCHORAGE, AK 99510
3	ARIZONA	(602) 255-4009	Dr. Shreen Lerner, SHPO State Historic Preservation Office 800 W. Washington Suite 415 PHOENIX, AZ 85007
4	ARKANSAS	(501) 682-2763	Mrs. Tonia Jones National Register Constituent Coordinator 225 E. Markham Suite 200 LITTLE ROCK, AR 72201
5	CALIFORNIA	(916) 445-8006	Mrs. Catharyn Gualtrian, SHPO Office of Historic Preservation Department of Parks & Recreation P. O. Box 94296 SACRAMENTO, CA 94296-0001
6	COLORADO	(303) 866-2136	Mrs. Barbara Sudler, SHPO State Historic Preservation Office 1300 Broadway DENVER, CO 80203
7	CONNECTI- CUT	(203) 566-3005	Mr. John W. Shannahan, Director State Historic Preservation Office 59 S. Prospect Street HARTFORD, CT 006106

NO	STATE	TELEPHONE	ADDRESS
8	DELAWARE	(302) 366-7780	Mrs. Walarie Cesna New Castle County Dept. of Planning 2701 Capitol Trial NEWARK, DE 19711
9	DISTRICT OF COLUMBIA	(202) 727-7360	Mr. Steve Raiche, Chief Historical Preservation Division 614 H Street North West WASHINGTON, DC 20001
10	FLORIDA	(904) 487-2333	Mrs. Susane P. Walker, Chief Bureau of Historic Preservation 500 S. Bronough Street TALLAHASSE, FL 32399-0250
11	GEORGIA	(404) 656-2840	Mrs. Elizabeth Lyon, Chief Historic Preservation Section Department of Natural Resources 205 Butler Street Suite 1462 ATLANTA, GA 30334
12	HAWAII	(808) 548-6408	Mr. Don Hibbart Director, Historic Site Division Hawaiian Dept. of Land Development 1151 Punch Bowl Street Room No. 310 HONOLULU, HI 96813
13	IDAHO	(208) 334-3861	Mr. Tom Green, Deputy SHPO Idaho State Historical Society State Historic Preservation Office 210 Main Street BOISE, ID 83702
14	ILLINOIS	(217) 785-4512	Miss Ann Swallow Assistant National Register Coord. Illinois Historic Preservation Agency Division of Preservation Services Old State Capitol SPRING FIELD, IL 62701

NO	STATE	TELEPHONE	ADDRESS
15	INDIANA	(317) 232-1646	Dr. Richard Gantz, Director Division of Historic Preservation & Archaeology 202 North Alabama Street INDIANAPOLIS, IN 46204
16	IOWA	(515) 281-4385	Mr. Jim Jacobsen, Bureau Chief State Historic Society Capitol Complex DES MOINES, IA 50319
17	KANSAS	(913) 296-7080	Mr. Richard Pankratz, SHPO Historic Preservation Department Kansas State Historical Society 120 W 10th Street TOPEKA, KS 66612
18	KENTUCKY	(502) 564-7005	Mr. David Morgan, Director Kentucky Heritage Council Capitol Plaza Tower, 12th Floor FRANKFORT, KY 40601
19	LOUISIANA	(504) 342-8160	Mr. Jonathan Fricker, Director Division of Historic Preservation P. O. BOX 44247 BATON ROUGE, LA 70804
20	MAINE	(207) 289-2132	Mr. Kirk Mohny Archetectural Historian Maine Historic Preservation Commission 55 Capitol Street, Station 65 AUGUSTA, ME 04333
21	MARYLAND	(301) 974-2212	Mr. J. Rodney Little, Director Maryland Historical Trust Department of Housing and Community Development 21 State Circle ANNAPOLIS, MD 20715

NO	STATE	TELEPHONE	ADDRESS
22	MASSACHU- SETTS	(617) 727-8470	Mrs. Valarie Talmaga Executive Director Massachusetts Historical Commission 80 Boylston Street BOSTON, MA 02116
23	MICHIGAN	(517) 373-0510	Dr. Martha M. Bigelow, Director Bureau of History 208 North Capitol Avenue, 3 <sup>rd</sup> Floor LANSING, MI 48918
24	MINNESOTA	(612) 726-1171	Mrs. Nina Archabal, Director Minnesota Historical Society Fort Snelling History Center ST. PAUL, MN 55111
25	MISSISS- IPPI	(601) 354-7326	Mr. Ken P'Pool, Director Historic Preservation Division Division of Archives and Historic P.O. Box 571 JACKSON, MS 39205
26	MISSOURI	(314) 751-2479	Mrs. Claire Blackwell Program Director Historic Preservation, Division of Park P. O. Box 176 JEFFERSON CITY, MO 65102
27	MONTANA	(406) 444-7715	Mrs. Patricia Bick, Deputy SHPO State Historic Preservation Office Montana Historical Society 225, North Roberts HELENA, MT 59620
28	NEBRASKA	(402) 471-4787	Mr. David Murphy, Deputy SHPO Nebraska State Historical Society Historic Preservation Office P. O. Box 82554, 1500 R Street LINCOLN, NE 68501

NO	STATE	TELEPHONE	ADDRESS
29	NEVADA	(702) 885-5138	Mr. Ron James, Deputy SHPO Historic Preservation & Archaeology 201 South Fall Room 106 CARSON CITY, NV 89710
30	NEW HAMPSHIRE	(603) 271-3483	Mr. R. Stuart Wallace, Director State Historic Preservation Office P. O. Box 2043 CONCORD, NH 03302-2043
31	NEW JERSEY	(609) 292-2023	Mrs. Nancy Zerbe, Administrator Office of New Jersey Heritage CN 404 TRENTON, NJ 08625
32	NEW MEXICO	(505) 827-8320	Mr. Thomas W. Merlan, SHPO The State Histori Preservation Division 228 East Palace Avenue SANTA FE, NM 87503
33	NORTH CAROLINA	(919) 733-6545	Mr. Michael Southern Branch Head North Carolina Department of Cultural Resources Survey and Planning Division 109 E. Jones Street RALEIGH, NC 27611
34	NEW YORK	(518) 474-0479	Mr. David Gillespie, Director New York State Park, Recreation & Historic Preservation Agency Building 1, Empire State Plaza ALBANY, NY 12238
35	NORTH DAKOTA	(701) 224-2666	Mr. Mel Bernett, Director The Historical Society Historic Site Division North Dakota Heritage Center BISMARCK, ND 58505

NO	STATE	TELEPHONE	ADDRESS
36	OHIO	(614) 297-2470	Mrs. Barbara Powers Ohio Historical Society Historic Preservation Department 1985 Velma Street COLUMBUS, OH 43211
37	OKLAHOMA	(405) 521-2491	Mrs. Melvina Heisch, Deputy SHPO Historic Preservation Division Historical Building 2100 N. Lincoln Boulevard OKLAHOMA CITY, OK 73105
38	OREGON	(503) 378-5001	Mr. Dave Powers, Manager Historic Preservation Office 525 Trade Street South-East Suite 501 SALEM, OR 97310
39	PENNSYLVANIA	(717) 783-8946	Mrs. Brenda Barrett, Director Bureau for Historic Preservation Pennsylvania Historical & Museum commission Box 1026 HARRISBURG, PA 17108
40	RHODE ISLAND	(401) 277-2678	Mr. Edward S. Sandorson Executive Director Rhode Island Historic Preservation Commission The Old State House 150 Penefit Street PROVIDENCE, RI 02906
41	SOUTH CAROLINA	(803) 734-8608	Mr. Andrew Chandler Manager of National Registor Office P. O. Box 11669 COLUMBIA, SC 29211
42	SOUTH DAKOTA	(605) 677-5314	Mr. Paul Putz, Director Historical Preservation Center P. O. Box 417 VERMILLION, SD 57069-0417

NO	STATE	TELEPHONE	ADDRESS
43	TENNESSEE	(615) 742-6716	Mr. Herbert L. Harpter Executive Director Tennessee Historical Commission 701 Broadway NASHVILLE, TN 37219-5237
44	TEXAS	(512) 463-6094	Mr. Jim Steely, Director The Texas Historical Commission National Registor Department P. O. Box 12276 AUSTIN, TX 78711
45	UTAH	(801) 533-6017	Mr. Kent Powell Preservation Coordinator Historic Preservation Office 300 Rio Grande  SALT LAKE CITY, UT 84101
46	VERMONT	(802) 828-3226	Mr. Eric Gilbertson, Director The Vermont Division for Historic Preservation 58 E. State Street MONTELIER, VT 05602
47	VIRGINIA	(804) 786-3143	Mrs. Beth Hoge, Archivist Division of Historic Landmarks 221 Governor Street RICHMOND, VA 23219
48	WASHINGTON	(206) 753-5010	Mr. Jacob Thomas, SHPO State Historic Preservation Office Office of Archaeology & Historic Preservation 111 W. 21st Avenue OLYMPIA, WA 93504
49	WEST VIRGINIA	(304) 348-0240	Mr. Bill Farrar, Deputy SHPO The Historic Preservation Office Cultural Center Capitol Complex CHARLESTON, WV 25305

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NO	STATE	TELEPHONE	ADDRESS
50	WISCONSIN	(608) 262-1339	Mr. Jeff Bean, SHPO Division of Historic Preservation State Historical Society 816 State Street MADISON, WI 53706
51	WYOMING	(307) 777-6311	Dr. Dave Kathka, SHPO Wyoming State Historic Preservation Office 2301 Central Avenue Barnett Building CHEYENNE, WY 82002

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