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SONIC BOOM RESEARCH AND DESIGN CONSIDERATIONS IN THE
DEVELOPMENT OF A COMMERCIAL SUPERSONIC TRANSPORT (SST)

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By

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SONIC BOOM RESEARCH AND DESIGN CONSIDERATIONS IN THE
DEVELOPMENT OF A COMMERCIAL SUPERSONIC TRANSPORT (SST)

Thomas H. Higgins

The sonic boom presents some of the more interesting yet perplexing phenomena associated with supersonic flight. It has been the subject of a series of research programs conducted by U. S. Government agencies beginning as early as 1950.

Supersonic flight research programs in the field of sonic boom conducted over the past several years have examined the basic overpressure phenomenon; the relationship between aircraft types and operational profiles and sonic boom; the effects of sonic boom on materials and light aircraft both on the ground and airborne; public reaction to sonic boom; and factors that could be identified for use in the design and operation of future aircraft to minimize sonic boom problems.

There has also, of course, been extensive military operational experience with sonic boom. Fifteen Air Force and Navy aircraft types are capable of supersonic operation.

Parallel and related to sonic boom flight research programs, NASA engineers at Langley Research Center, Hampton, Virginia, have developed techniques that permit correlation between wind tunnel tests and actual aircraft configurations. It is possible to determine, through wind tunnel tests,

ABSTRACT

This paper presents a short history of sonic boom research and related operational considerations in the development of a commercial supersonic transport (SST). The most intensive public reaction research program to date was conducted at Oklahoma City, Oklahoma. An intensive research program to determine structural reaction to sonic booms was conducted at the White Sands Missile Range. These two programs are discussed and a brief summary of the findings of the programs is presented.

The paper concludes that although much has been learned about the sonic boom phenomena through past flight and research activities, additional research and theoretical studies are warranted.

the probable sonic boom parameters of a particular configuration. This technique complements analytical means and instrumentation that have been developed and successfully applied to sonic boom phenomena.

It was therefore recognized from the start of the SST research program some years ago that the sonic boom was an important consideration in the design and operation of a commercial supersonic transport.

Although much was known about the sonic boom in early 1964, there was a need for more specific answers in certain areas. This was especially true in regard to community reaction to repeated exposure to sonic booms. The Federal Aviation Agency, the National Aeronautics and Space Administration and the United States Air Force, therefore, joined together in initiating the Oklahoma City sonic boom program to study this area further. A brief summary of data generated as a result of this program together with conclusions are presented in this paper.

The Oklahoma City, Oklahoma, research program, completed July 30, 1964, was primarily designed to determine public reaction. A research program to examine effects of sonic booms at varying levels on structures was conducted at White Sands, New Mexico, from November 18, 1964 to February 15, 1965. It provided extensive data on structural response as well as other areas of concern. The results of this program are discussed in a subsequent section of this paper.

Oklahoma City Sonic Boom Study Conditions

A total of 1253 supersonic flights were made over the Oklahoma City metropolitan area at altitudes ranging from 21,000 to 50,000' and speeds with Mach number range of 1.2 to 2.0. This overflown area has an elevation of 1,700 feet above sea level and includes a population of about 600,000 people. Several flights per day were made starting in February 1964 and continuing through July 1964.

The U.S. Air Force provided F-104, F-101, F-106 and B-58 aircraft for use in the program. These aircraft were positioned over the study area and along the prescribed ground track by means of ground-control procedures with the aid of radar tracking. Radar plotting board overlays were obtained for all flights and the data were used to provide information on aircraft plan position and ground velocity. Altitude was also obtained from a Ground Control Intercept station located in Oklahoma City. Each aircraft was directed on the flight track and flown by the USAF pilots in such a manner that the desired Mach number and altitude conditions were maintained. The sonic booms therefore, which were observed at the measuring stations were associated with steady-level flight conditions of the aircraft.

Atmospheric soundings obtained by rawinsonde observations from the U.S. Air Force weather facility located at Will Rogers Field, Oklahoma, were

taken within one hour of the times of all of the supersonic flights. Surface measurements of temperatures, winds, were also obtained along with information relayed by the pilots including indications of turbulence, cloud cover, and precipitation.

Approximately 3,000 adults representing a cross section of local residents were interviewed by personnel of the National Opinion Research Center of the University of Chicago three times during the six months period to determine their reported reactions to the sonic booms. In addition, careful records were kept of all complaints received by the local Federal Aviation Agency representatives.

The responses of eleven residential structures were measured and observed by the Oklahoma City engineering firms of Andrews Associates, Inc. and Hudgens, Thompson, Ball and Associates, Inc. during a 39-week testing program consisting of twenty-six (26) weeks of eight (8) daily controlled sonic booms, followed by thirteen (13) weeks of observations and inspection. The structures consisted of a total of eleven (11) typical residential structures. Eight (8) of these were located within five (5) miles of the regular flight path, one (1) was located ten (10) miles from the flight path, and the remaining two (2) were located about twenty-five (25) miles from the flight path at Norman, Oklahoma, which was beyond the sonic boom area.

The Langley Research Center, NASA, was responsible for the measurement of sonic boom signatures during the study program. Data obtained was tabulated for the use of all agencies participating and various statistical analyses for both overpressure and impulse data were made.

Sonic boom pressure measurements were made both inside and outside three instrumented buildings using specially modified microphones, timing units, d-c amplifiers and oscillograph recorders. Data were obtained at locations on the ground track and at distances from the ground track of 5 and 10 miles. Each outside microphone was shock mounted at ground level in the surface of a plywood reflecting board protected by wind screens. For the inside measurements, each microphone was shock mounted at approximately 5 feet from the floor level near the center of the room.

Sonic boom signature measurements varied widely both in peak amplitude and in wave shape because of atmospheric turbulence effects. The highest overpressure values measured were associated with waves having peaks of short duration while low overpressure values were associated with rounded-off waves resembling sine waves. The ratio of measured to calculated overpressure and impulse data had log normal distributions. However, the overpressures data had a markedly wider range than the impulse data. Measurements made at lateral distances of 5 or more miles indicated wider ranges in the ratio of measured to calculated overpressure and impulse data than similar measurements under the flight track. These measured values were, of course, considerably less than those measured under the flight track.

The Langley Research Center arrived at the following conclusions relative to sonic boom measurements made in the Oklahoma City area over a 6-month period for varying atmospheric conditions and flight conditions. 1/

Wide variations in ground pressure signature were observed with corresponding wide variations in the peak overpressure and to a lesser degree, variations in the positive impulse function.

Variations of overpressure and impulse may be represented by a log normal distribution (normal distribution of their logarithms) over the significant ranges.

One percent of the measured overpressures equaled or exceeded the predicted values by a factor of about 1.5 to 3.0 depending on the distance relative to the ground track; the larger factor was associated with the larger distances and with the lower predicted value.

One percent of the measured impulse values equaled or exceeded the predicted values by a factor of about 1.2 and 2.0 depending on the distance from the ground track, the large factor being associated with the larger distances and with the lower predicted value.

1/ Hilton, David A; Huckel, Vera; Steiner, Roy; and Maglieri, Domenic; Langley Research Center, Hampton, Virginia: SONIC BOOM EXPOSURES DURING FAA COMMUNITY-RESPONSE STUDIES OVER A 6-MONTH PERIOD IN THE OKLAHOMA CITY AREA. (NAS/ TND-2539)

Measurements at several points for a given flight show also a variation in wave shape as a function of distance in the direction of flight. An orderly progression of wave shape is suggested by the data from a highly peaked wave at one point to a rounded-off wave at another and vice versa.

Measured pressure signatures inside of a building were lower in amplitude and longer in duration than the corresponding outside pressure signatures and were dominated by frequency components corresponding to the principal vibration modes of the building.

The levels of the pressures inside of a building in the range of frequencies 100 to 5000 cps are about 30 dB lower than those in the range 0.1 to 5000 cps; thus, an inside observer is subjected to strong pressure variations in the subaudible range, and relatively weak pressure variations in the audible range.

For equal outside overpressures the peak pressures inside a residential-type structure were greater for a longer wave length.

Inside peak pressures were found to correlate well with variation in the positive impulse function of the outside pressure signature. For a given wave length they did not vary appreciably for marked variations in the wave shape.

Personnel of the National Opinion Research Center arrived at the following conclusions relative to community reactions based on three interviews of approximately 3,000 adults during the 6-month sonic boom program. 2/

Substantial numbers of residents reported interferences with ordinary living activities and annoyance with such interruptions, but the overwhelming majority felt they could learn to live with the numbers and kinds of booms experienced during the 6-month study.

Some interferences or interruptions of ordinary living activities, principally house rattles and vibrations, were reported by almost all respondents. Startle and fear of booms were next in importance, being mentioned by 40% of all close residents and 30% of the more distant ones. Sleep, rest and conversation interference were mentioned by 10-15% of the close residents and about 5% of the distant residents during most of the program.

Serious or "more than a little" annoyance with sonic booms was generally reported by a minority of the residents during the first and second interviews, but increased to a slight majority by the end of the 6-month period.

2/ Borsky, Paul N.; National Opinion Research Center, University of Chicago: COMMUNITY REACTIONS TO SONIC BOOMS IN THE OKLAHOMA CITY AREA. (AMRL-TR-65-37) (AD613620)

Direct scientific evidence indicates that the Oklahoma City booms did not cause any significant damage to the local test houses, which were instrumented by the FAA to measure physical effects of booms. Large numbers of residents, however, felt their houses had been damaged. Over 40% overall felt this way, while 50% of the annoyed and 86% of the actual complainers also felt this way. This clearly suggests that belief in all alleged damage increased annoyance and complaint activity.

Respondents were asked to evaluate their own six-month experience with the sonic booms and to report whether or not they felt they could learn to live with eight booms a day for an indefinite period. The overwhelming majority felt they could accept the booms under these conditions. During the first 11 weeks of the study, over 90% felt they could accept the eight daily booms. This number dropped to 81% during the following eight weeks and to 73% during the final weeks of the study.

Most annoyance, reports of damage, desires to complain and actual complaints were reported by the closest residents living 0-8 miles from flight track. Residents in the middle distance group (8-12 miles) were next in order, followed by the most distant residents (12-16 miles away) who reported the least reaction to the sonic booms.

No significant differences in reaction to booms were found between urban and rural residents in the Oklahoma area.

No direct evaluation of night booms can be made since no night booms were generated during the study. Sleep interference reported by daytime sleepers, however, indicates that greater annoyance may be associated with sleep interference. Further study of night booms should determine whether annoyance with such booms also increases hostile reaction to daytime booms.

Measured and observed structural responses of eleven residences to a total of 1,253 sonic booms in the scheduled range of 1.0 to 2.0 pounds per square foot were found by Andrews Associates and Hudgens, Thompson, Ball and Associates ^{3/} to be subject to many variables, and not necessarily directly related to overpressure. However, the magnitudes of stress and deflection obtained were only a small percent of normally recommended design allowables.

Conclusive evidence of significant damage to the structures or furnishings was not produced by this investigation. No increase occurred in the rate at which paint finish on lath and plaster wall interiors cracked during the sonic boom period.

No consistent correlation was established between the rate of alleged damage complaint calls and the rate at which the same type of interior defects occurred in the houses for the same areas and time periods.

^{3/} Andrews Associates, Inc. and Hudgens, Thompson, Ball and Associates, Inc. (A Joint Venture) Oklahoma City, Oklahoma. Final Report. STRUCTURAL RESPONSE TO SONIC BOOMS. (Report No. SST 65-1 Vol. I and Vol. II) (AD610822 - AD610823)

The measured levels of stress (strain) and accelerations produced in primary wood structural framing elements such as studs, joists and rafters were negligible.

Measured strain and deflection produced at the plaster surfaces investigated in the houses were negligible. Some interior wall board surfaces (walls and ceilings) were vibrated so that repeated occurrence may accelerate the rate of paint cracking over nail heads and at corners, particularly during periods of low wood moisture content in structural framing. Measured deflection (and/or strain) of window glass of the houses was not sufficient to damage these types of windows exposed to the types of sonic boom shock waves produced in the testing program.

Dynamic response of window glass is considered by the contractors to be a function of the following factors:

The nature of the shock wave acting on the glass, which includes wave shape, wave length and both positive and negative pressure. The orientation and elevation of a pane are associated with this factor.

Pane size, thickness, edge mounting condition, surface condition, and material (glass type and quality, wire glass, etc.). The natural frequency and strength of a pane is associated with these factors.

The nature of the interior air space which influences damping and possibly resonance effect.

Maximum deflection (and/or stress) often occurs as a function of the negative pressure which is not directly related to design wind load and building code provisions since these normally contemplate positive pressure. Therefore, the contractors conclude that there are many variables of which an indeterminate number could possibly occur simultaneously at random locations, and which could produce glass stresses high enough to crack some substandard or improperly installed glass panes.

Measured ground accelerations of seismic effects produced by sonic booms of this type, and for conditions similar to those at the observed houses were negligible.

Measured response to several types of common occurrences such as poor closing, thunderstorms, wind, walking in attic, stake driving, etc. show that certain structural elements may respond more to some common occurrences than to any of the sonic booms produced in this program. Some of these common occurrences are also considered to contribute to the cause of some types of minor structural deterioration.

Maximum free ground overpressure alone was found by the contractors to be of little value in making structural response correlations since the shape of the wave, and the length of the wave, acting on the structure, plus the natural frequency of the structural element, must be taken into consideration.

For a given aircraft, producing N waves of constant length, the contractor found that the impulse of the wave can be more closely correlated with some structural responses than can overpressure. However, impulses from one aircraft should not be directly compared with impulses produced by a dissimilar aircraft for purposes of structural response.

For purposes of structural response, impulse measurement should include both positive and negative phase portions of the sonic boom signature.

Conclusive evidence of significant damage to the eleven instrumented and observed houses was not produced by the thorough investigation conducted by the two firms.

The wave lengths (Δt) of the four aircraft used in these studies range from .07 to .20 sec. and tend to be matched with many of the natural frequencies of the instrumented and observed houses structural elements. The majority of these natural frequencies were found to range from about 5 to 30 cycles per second.

The SST sonic boom signature will have a wave length(Δt) of about 0.335 seconds or a fundamental frequency of 3 cycles per second. The SST will therefore tend to be matched only with structural elements having natural frequencies of about 3 cycles per second for a wave involving no reflections.

Based upon the foregoing structural response observations, analysis and experience in the Oklahoma City program, the contractors concluded that no conclusive evidence has been found that prohibits operation of a supersonic transport aircraft over populated areas.

White Sands Structural Response Studies

The White Sands structural response study objective was to determine sonic boom overpressure damage index levels of structural material such as plaster, glass, and masonry.

The structural study area at the Oscura Range Camp White Sands Missile Range, N.M., included 21 structures varying in design, construction, and age. Nine of these comprised the range camp prior to the program. Seven were constructed for the study, and five were old ranch houses or range structures within the area subjected to sonic boom over pressures.

The nine previously existing structures included a barracks, a warehouse, a radar building, a radar shop, and a communication structure, along with smaller buildings used for storage and other purposes. They were of wood, concrete, steel frame, and sheet metal construction.

One of the 60-foot sides of the sheet metal constructed warehouse was modified to include three representative glass store fronts having nine panes of glass. Included were two 8-foot by 10-foot glass show windows.

The site also included a number of electronic installations that were observed during the program to assess sonic boom effects on this type of equipment.

An uninhabited farmhouse, located within approximately one mile of the test site, was kept under engineering surveillance during the test period. Associated outbuildings and facilities, including garage, cattle cistern and storage buildings, were also inspected.

Two inhabited ranch houses were located five miles northeast and east of the test site respectively and directly under one of the sonic boom flight tracks. These houses were less than one mile from the missile range boundary. Because of concern over possible damage to the ranches, the owners were contacted as to the feasibility of their temporarily moving from the premises during the tests. The ranchers declined. Instead, they volunteered their ranches for examination, photographing, and engineering analysis as part of the test program.

These properties, an outlying radar facility, and a sheet metal office building were subjected, along with test structures, to sonic booms much higher than those scheduled for supersonic transport operation.

The new structures provided a variety of exterior and interior building materials and windows and two foundation types for study purposes. Six of the new structures were residential-type buildings. One of these was a prefabricated house with attached carport. The seventh new structure was a greenhouse.

Furniture, hung mirrors and pictures, television sets and other home appliances, dishes, crystal, bric-a-brac on "what-not" shelves and standing singly, and various other items, were arranged in the buildings.

Five types of plaster interior finishings were studied - plaster on wood lath, repaired plaster on wood lath, plaster on metal lath, plaster on gyp lath, plaster on concrete block.

The test site was exposed to 1,494 runs during the study program, which was conducted in two flight phases - November 18-December 15, 1964 (Part A); January 15-February 15, 1965 (Part B). Air Force F-104 aircraft stationed at Holloman Air Force Base, New Mexico, and B-58 aircraft stationed at Edwards Air Force Base, California, flew the boom runs. The F-104's generated 1,433 booms; the B-58's 61 booms.

The daily flight schedule provided, in most cases, for 30 runs during a six-hour period. Scheduled sonic boom overpressures ranged from 1.6 to 19.0 pounds per square foot. The maximum overpressure recorded during scheduled study operations was 23.4 psf. An unscheduled boom of approximately 38.0 psf was flown during a demonstration for members of the press.

Sonic booms and structural-material reaction were measured with various instruments. Accelerometers, velocity transducers, seismometers, strain gages, pressure transducers of two types, and scratch gages were used.

During Part A, an average of 63 data collection channels were utilized. The pressure-sensing instrumentation array included two mobile units for far-field measurement. The suspension of two microphones from a tower at heights of 45 and 90 feet was provided to afford correlation of wave pattern information at these heights above the ground with that measured on the ground and adjacent to the structures. During Part B, Boeing and Lockheed aircraft companies provided additional overpressure data collecting and recording equipment through a contract with the Federal Aviation Agency.

Engineer-observer teams monitored the buildings visually throughout the program. This team included representatives from the National Bureau of Standards, Boeing and Lockheed aircraft companies, USAF, England, France, Federal Aviation Agency, and the technical contractor, John A. Blume and Associates Research Division. Observers filled out report forms on structures observed during each day's boom flights. Temperature and humidity content within test structures was monitored and plotted during part of the program. All of the cracks, even those which required a magnifying glass for identification, were observed daily, marked as appropriate, and recorded.

To supplement data gathered by these means and to aid understanding of material behavior, laboratory tests of the materials used in construction and field tests of soils and structure units were made.

John A. Blume and Associates Research Division was responsible for the number and design of test structures, complete instrumentation plan, data collection and report preparation within the terms of the program contract with the Federal Aviation Agency. Wave pattern and structural response data acquisition was planned, implemented, and supervised by this organization.

A preliminary report of data collected in this program was published on March 17, 1965, by the Federal Aviation Agency.^{4/}

The large volume of data collected during the structural response test is now undergoing reduction and analysis. The final report is scheduled for completion in the near future. Preliminary analysis of data and observations made during the program as contained in a report submitted by the technical management contractor, John A. Blume & Associates, sixty days after completion of the program includes the following findings.

Plaster on metal lath, concrete block or on gypsum lath was not observed to crack under any of the booms during the program.

Plaster applied on wood lath was the minimum type wall finishing material observed. This type of plaster, when less than eighteen days old, began to crack more rapidly with booms at an average overpressure

^{4/} PRELIMINARY DATA SONIC BOOM STRUCTURAL RESPONSE TEST PROGRAM
WHITE SANDS MISSILE RANGE, NEW MEXICO. November 1964 - February
1965 - Office of the Deputy Administrator for Supersonic Transport
Development, Federal Aviation Agency, Washington, D.C. - March 17,
1965. (SST 65-4)

of 3.6 psf, at 7.5 psf when between eighteen and thirty-one days old, and at an average overpressure of 13.0 psf when between sixty-two and eighty-eight days old. No identifiable damage was caused to this type of plaster applied to the ceiling of the forty-five year old ranch house which was subjected to sonic booms at designed overpressures of 12.5 psf. The low strength of the new plaster on the wood lath at time of failure was probably a major contributing factor to cracking or failure.

New plasterboard tested was not damaged by any sonic booms generated during the program. Crack extensions occurred in predamaged plasterboard at designed overpressures of 7.9 psf. Incipient damage to plasterboard is characterized more by slight nail popping. This condition, normal in houses using this material, begins to be accelerated by booms at an average overpressure of 8.0 psf. Suspended plasterboard ceilings may experience minor paint chipping along the edges by repeated booms at a design overpressure of 5.0 psf.

Booms at a designed overpressure of 7.9 psf may begin to extend cracks in predamaged bathroom tile. These crack extensions were very difficult to see.

Poorly mounted, undamaged glass in the greenhouse was chipped by impact against nail holding points at a sonic boom overpressure of 12.1 psf. The same type of glass which was already damaged was further damaged at a designed overpressure of 7.9 psf. A large one-ninth-inch thick

window intentionally precracked from corner to corner was further damaged by booms of an average 6.5 psf overpressure.

Of several pieces of bric-a-brac observed during the program, some bric-a-brac fell and broke at a designed overpressure of 10.4 psf.

Cracks that existed in stucco prior to booms extended under a designed overpressure of 7.9 psf. No new cracks were identified as caused by booms.

Observations made during the cumulative-effect portion of the structural response test indicate no significant structural component damage in any of the sixteen structures that were exposed to 680 sonic booms at a 5.0 psf nominal overpressure level.

A flight surgeon was on duty during the test program. No adverse physiological effects were identified for any of the more than 20 personnel involved in the daily program operation.

Continuous audiometric examination of twenty subjects throughout the duration of the test program indicated no hearing impairment caused by sonic booms at very high overpressures.

SST Development Program Status

The present SST contract design work by four companies followed initial design competition in response to an FAA Request for Proposals released to industry in August 1963. Three airframe and three engine companies took part in this initial design phase, which led to government-airline evaluation of proposals during the period January-May 1964, and subsequent entry into design contracts on June 1, 1964.

A second evaluation of proposed designs was conducted in November 1964.

Findings in the two design evaluations were primary elements in program deliberations by the President's Advisory Committee on Supersonic Transport. Other factors considered were findings in sonic boom study programs and economic analyses.

On July 1, 1965, President Johnson announced that the supersonic transport program should move into an eighteen-month phase of accelerated design work by industry designed to bring the program to the prototype-construction stage by the end of 1966.

In accordance with the President's decision to move ahead with the SST program, the FAA awarded increased design contracts for July 1965 to the two airframe and two engine contractors in the program. These contracts were awarded under previously appropriated funds, enabling work to proceed while the Congress considered the program put forward by the President.

The two airframe contractors are the The Boeing Company and Lockheed Aircraft Corporation. The two engine contractors are the General Electric Company and the Pratt & Whitney Division of United Aircraft Corporation.

Principal characteristics of the SST as reflected in current design objectives are as follows:

Payload/range	40,000 pounds at 4,000 statute miles.
Speed	Mach 2.5 - or greater.
Primary Structural Material	Titanium.
Sonic Boom	2.0 psf acceleration and 1.5 psf cruise for domestic operation (2.5 psf acceleration and 1.7 psf cruise allowed for long range international flights over water).
Noise	1,500 feet from centerline of runway, 116 PNdB; 3 statute miles from start of takeoff roll, 105 PNdB; 1 statute mile from runway on approach, 109 PNdB.
Takeoff Speed	160 Knots.
Approach Speed	135 Knots.
Airports	Capable of using existing airports.

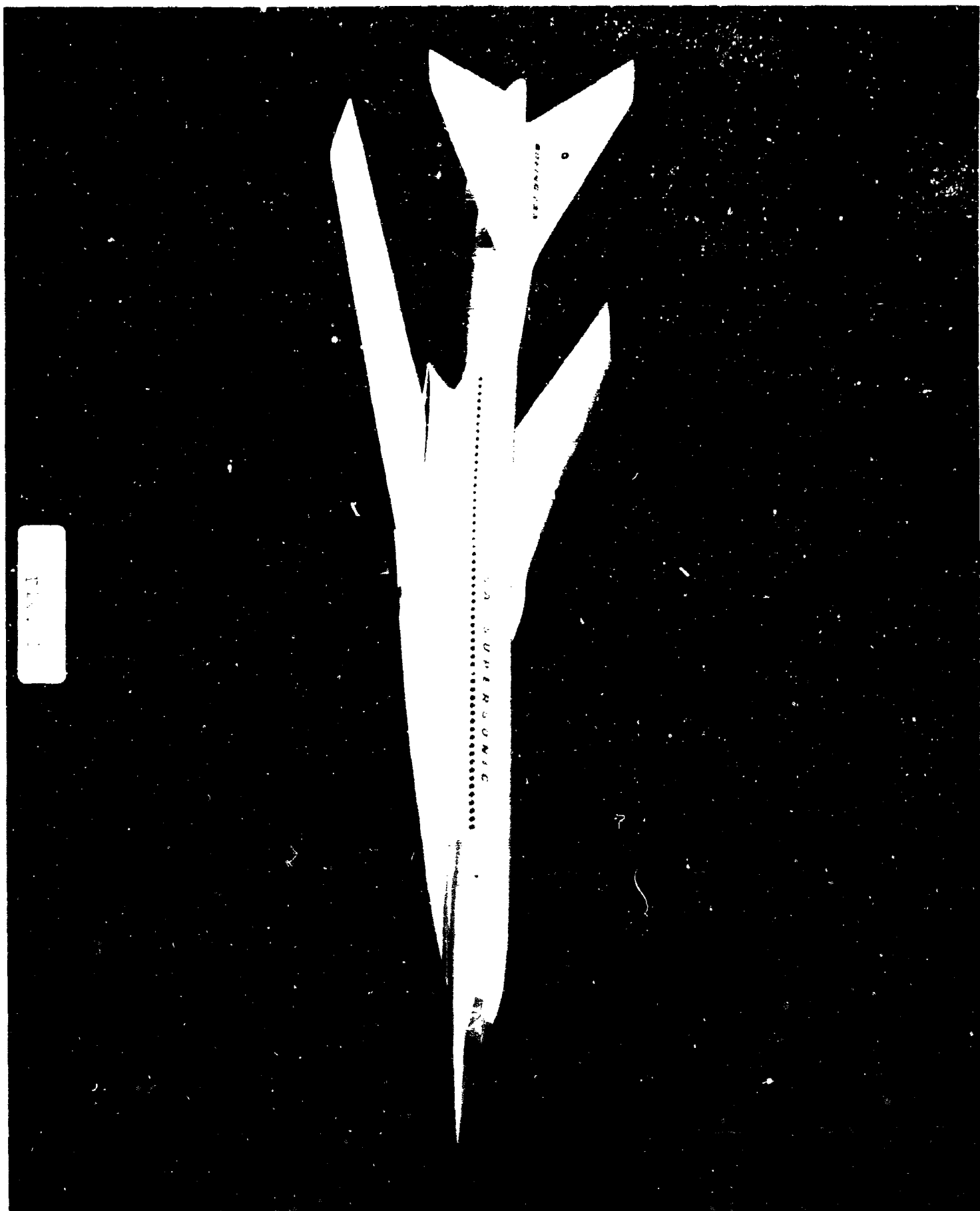
Figures 1 and 2 present pictures of models of the Boeing and Lockheed initially proposed designs, which as you know have now been modified in the course of design effort. Figures 3 and 4 present the general effects of acceleration and cruise design overpressure on direct operating cost and annual earnings. Examination of these four figures makes clear the importance of present sonic boom design considerations on the characteristics of the proposed aircraft and in turn the resulting commercial profitability.

Conclusions

Examination of the results of the foregoing sonic boom overflight programs reveals the validity and reasonableness of current design objectives of limiting sonic boom overpressures to 2.0/1.5 psf for domestic operation over populated areas and 2.5/1.7 psf for long range international flights over water during acceleration and cruise.

Results of previous evaluations reveal that an economically viable SST which will meet these design objectives can be developed.

It may also be concluded that although much has been learned about the sonic boom phenomena through all the past flight and research activities, additional actual flight, simulation, research and theoretical studies are warranted. The use of large supersonic airplanes such as the B-70 in future flight research programs would be especially significant in the study of both human reaction and structural reaction to measured sonic boom signatures.



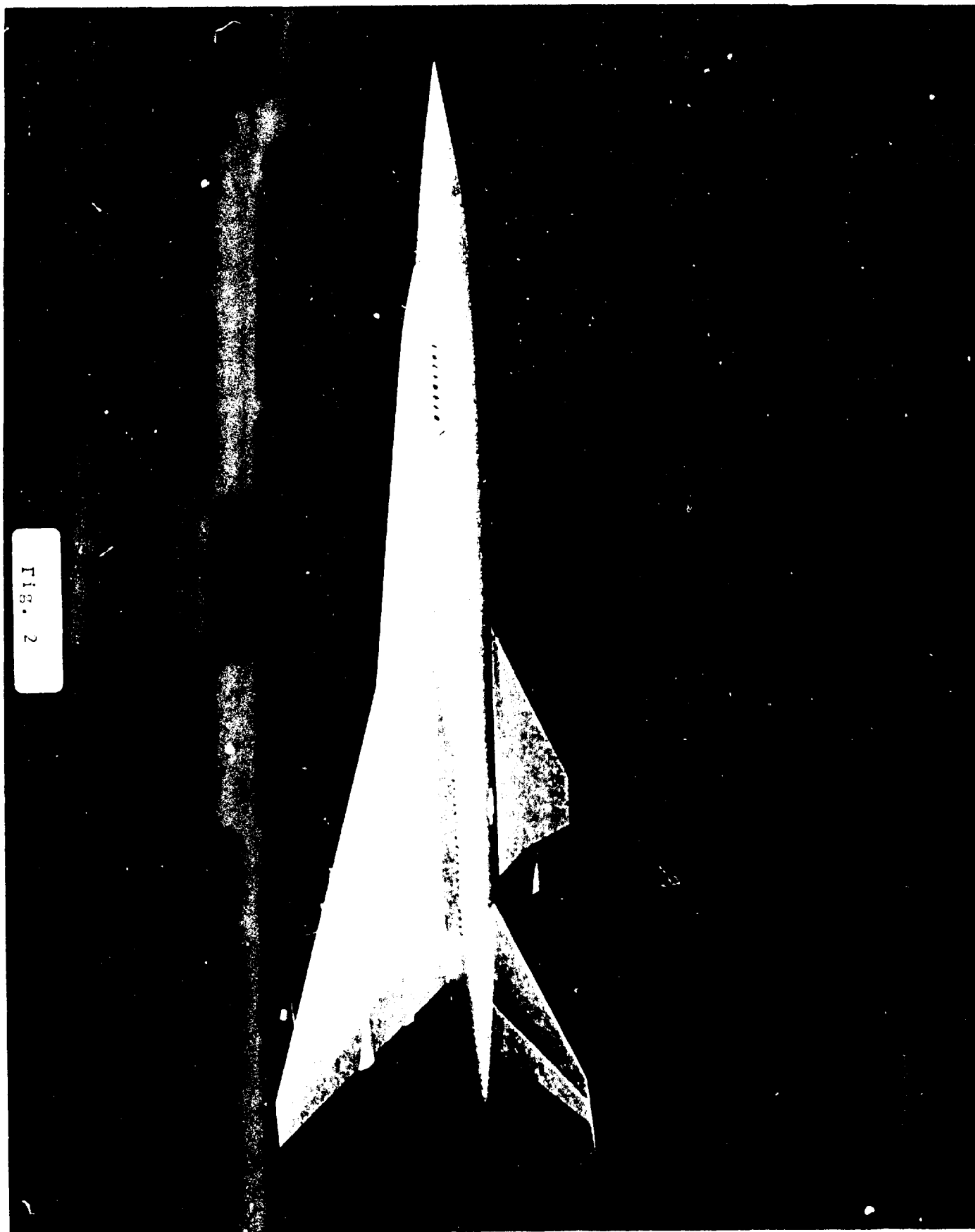


Fig. 2

RELATIVE EFFECT OF ACCELERATION DESIGN OVERPRESSURE ON DIRECT OPERATING COST

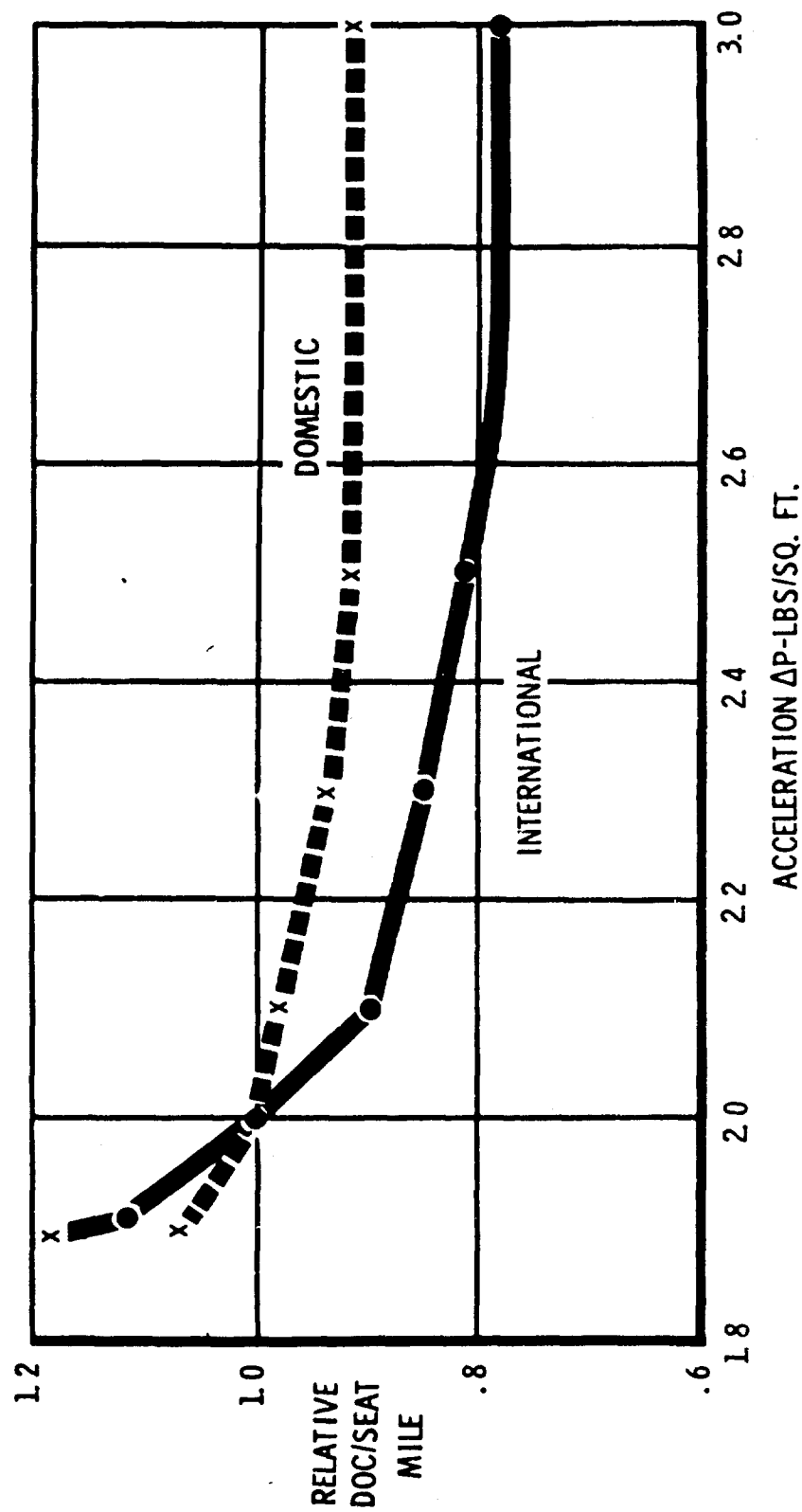
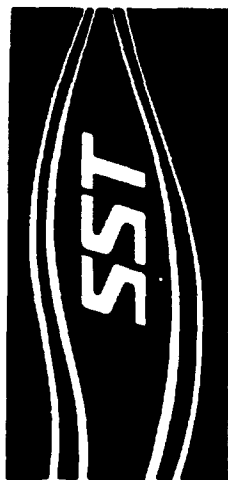


Fig. 3

RELATIVE EFFECT OF CRUISE DESIGN OVERPRESSURE ON ANNUAL EARNINGS

