①

THE SUPERSONIC TRANSPORT - THE SONIC BOOM AND YOU

by

JOHN O. POWERS

KENNETH POWER

Federal Aviation Administration
Department of Transportation
Washington, D. C.

Reproduced by the
CLEARINGHOUSE
for Federal Scientific & Technical
Information Springfield Va. 22151

40

I. Introduction

The rapid advances in the field of transportation have led man to the era of travel at speeds in excess of the speed of sound. It is well known that the British and the French have joined together in the development of the Concorde aircraft which will fly 2.2 times the speed of sound and is expected to be in operation before 1970. The Russians also are developing a supersonic airplane, the TU-144, which will challenge the nations of the free world for pre-eminence in the skies. The United States' program to build a supersonic transport has entered the prototype construction stage. It is the intent of this paper to review the events leading up to the current stage of development, to explore the potential of the SST, and to examine in considerable depth one of the major constraints on supersonic flight, namely, the "sonic boom."

II. Chronology of the U.S. Supersonic Transport Program

Man first entered the age of supersonic flight in 1947 when Air Force test pilot Chuck Yeager flew the Bell X-1 at a speed of 1.5 times faster than the speed of sound. This flight was followed by a series of flights with test vehicles developed and flown by NASA and the military. The X-15 aircraft (the most current of the series) reached flight speeds of 4,000 miles per hour or greater than 6 times the speed of sound. In 1961, President Kennedy requested that a study be conducted to evaluate the feasibility of applying this supersonic flight experience and technology to the development of a civilian supersonic transport. The study was a joint effort of the Federal Aviation Agency, the National Aeronautics and Space Administration and the Department of Defense. Thirty-six separate contractors participated in the study. The findings of this study were reported in 1963 to a 13-member advisory committee under the then Vice President, Lyndon Johnson, who in turn recommended to President Kennedy that the program enter a preliminary design stage. Accordingly, in the summer of 1963, President Kennedy requested an appropriation, $60 million, to proceed with the preliminary design program stipulating two important conditions. These conditions were: (1) that a system of cost-sharing between Government and industry be established, and (2) that a continuing review be established to determine at a later stage whether the work should proceed to a hardware phase. Within this framework, and with the coordination of other Government agencies, the FAA issued a Request for Proposal which established the design objectives of the supersonic transport development program. In 1964, three airframe companies, Boeing, Lockheed and North American and three engine companies, General Electric, Pratt & Whitney and Curtiss-Wright, responded and submitted proposals in the initial design competition. After an intensive 10-week Government/airline evaluation, President Johnson directed that contracts for further design during the period of June 1964 through June 1965, be let to Boeing, Lockheed, General Electric and Pratt & Whitney. He concurrently established the President's Advisory Committee on Supersonic Transport (PACOSST), headed by the Defense Secretary. At this time, President Johnson also directed the Department of Commerce to study supersonic transport economics and requested the National Academy of Sciences to study problems in the sonic boom area. In 1965, acting on the basis of recommendations of the President's Advisory Committee on the Supersonic Transport, President Johnson directed that the four companies proceed with an 18-month effort of detailed design and hardware testing. The goal of this effort was to define prototype configurations of the supersonic transport which could be introduced in time to be competitive, which would be safe and reliable for the passengers and which would have a potential for earning a profit for the airlines and manufacturers. Both of the airframe manufacturers elected to design for a cruise Mach number of 2.7 or 1,786 miles per hour. These flight speeds result in surface metal temperatures of approximately 500 degrees Fahrenheit, requiring the choice of titanium alloys for the desirable strength-to-weight characteristics.

On September 6, 1966, the contractors submitted their proposed designs to the Government for evaluation by a 235-man team composed of members from NASA, DOD and the FAA. On December 31, 1966, General McKee, Administrator of the Federal Aviation

Agency, announced that The Boeing Company had been selected to build the airframe and the General Electric Company had been selected to build the engine of the United States supersonic transport. President Johnson gave the go-ahead for SST prototype construction on April 29, 1967, and the contracts for this work were signed with the Boeing and General Electric companies two days later. The schedule calls for the first prototype to fly before the end of 1970 and the second will follow shortly thereafter. It is planned that 100 hours of flight test work in these aircraft will be completed by the middle of 1971 and that this experience will provide the technical basis for proceeding into the certification and production phases of the SST. If all goes well, the production model could be certificated and ready for airline service before the end of 1974.

Figure 1 depicts the Boeing configuration with its basic variable sweep wing approach. Its cruising speed of 1,786 miles per hour is approximately 3 times the speed of present day jet airlines and its cruise altitude of 64,000 feet is twice that of today's jets. The passenger capacity of 300 is about double the current average capacity of 150 passengers and the gross weight of 670,000 pounds compares with approximately 350,000 pounds for the largest of today's subsonic planes. The length of the Boeing B-2707 is 306 feet which is slightly longer than a football field. The wing span is 106 feet in the swept-back position (180 feet in the swept-forward position) and the wing area is 9,000 square feet.

In the engine design competition, the General Electric Company proposed an afterburning turbojet Figure 2. The engine is in the 60,000 to 65,000 pound thrust class which is more than twice that of current commercial engines. It has been noted that the Spirit of St. Louis, in which Lindbergh flew the Atlantic 40 years ago, is just slightly over two feet longer than the SST engine.

III. SST Potential

The reasons for entering the competition for the supersonic transport market are varied. The most obvious reason is simply the savings in travel time which is so vital in our modern society. Table I shows the comparative flight times over international routes for the B-2707 SST as compared to present day subsonic jets. It is remarkable to think of traveling from Washington, D. C., to London in less than three hours but even more impressive when one considers that over one half of a days travel time will be saved when flying from Washington to India. In addition to these very significant time savings, the SST program represents a firm investment in the economy future of the United States. The payoff to the U.S. economy is significant now and will be even more so in the future. We can expect an economic growth of 20 to 50 billion dollars depending on the number of SSTs built and we can expect that 250,000 new jobs will be created at contractor and subcontractor plants all over the country. The total government investment in the SST program will be in the order of 1.2 billion dollars and this investment will be paid back after the three hundredth aircraft is delivered. After the three hundredth delivery, the government will receive royalties for a period of 15 years which will produce a return on the investment comparable to levels normally received by industry. Current conservative estimates indicate a probable minimum market of 500 aircraft with a potential of up to 1200 aircraft by 1990. The economic validity of the program to the government is shared with the manufacturers and the airlines and will strengthen the United States aviation industry. This very tangible potential of the SST program is supplemented by the intangible benefits that result from this country's ability to demonstrate the technological accomplishments which can be achieved under a democratic free enterprise system.

IV. The Sonic Boom Problem

One of the most controversial and most misunderstood technological problems associated with the development of SST has been that of the sonic boom. For those who have not heard a sonic boom, it is best described by comparing it to a clap of thunder. The first sonic boom one hears is startling.

With continued exposure, however, people tend to accommodate themselves to the sonic boom and accept it as they do the backfire of a car or truck. Actually the comparison of a sonic boom to a clap of thunder is quite good and also quite descriptive. Thunder results from electrical discharges which travel faster than sound, and by suddenly heating the air, displaces it rapidly creating a pressure fluctuation which we hear on the ground as the sound of thunder. In Figure 3, it is shown schematically that the sonic boom is also a pressure fluctuation produced by the displacement of air around the aircraft which is flying faster than the speed of sound. Actually an airplane flying at subsonic speed creates pressure fluctuations but they are distributed, and hence dissipated, over all space, whereas, the supersonic pressure disturbances are contained within the Mach cone and coalesce into the bow and tail shock waves.

A. Popular Misconception

There are two very popular misconceptions about sonic booms which have led to considerable confusion. First, it was believed that sonic booms occurred only at the instant when an aircraft "broke the sound barrier." Actually, the sonic boom occurs when the aircraft slightly exceeds the speed of sound. The boom then occurs once for each ground observer along the flight path under the airplane and also for observers several miles on either side of the flight path. The boom terminates when the aircraft decelerates to subsonic speed.

The second misconception is that all sonic booms are similar. Nothing could be farther from the truth. Sonic booms made by low-level passes of fighter airplanes can create very large "overpressure" levels, and can, in fact, be exceedingly annoying, whereas, a very high altitude supersonic overflight might create a sonic boom which would be barely audible.

B. Generation and Propagation

To better understand the great differences in the sonic booms, it is helpful to review the mechanism of propagation through the atmosphere and to consider the variables which determine the overpressure level. In Figure 4, it is shown that shock waves are generated by various components of the airplane and if the measured pressure near the airplane is displayed as a function of distance, what is known as the "near field" signature is defined. At greater distances from the airplane, the separate shock waves interact with each other and eventually coalesce into just two waves, a bow shock and a tail shock. In this form the pressure signature is called an "N wave" and the pressure signature is referred to as corresponding to the "far field." Figure 4 also shows that as the distance from the airplane is increased, the distance between the bow and tail wave is also increased. An observer on the ground may hear two booms with the time interval between the bow and tail shock between 0.1 and 0.4 seconds.

C. Sonic Boom Intensity

The actual level or the intensity of the sonic boom is controlled by many parameters. The dependence of the sonic boom intensity on several of these parameters is shown in Figure 5. Probably the most important of these parameters is the flight altitude. The reduction of boom intensity is quite rapid with increased altitude and, in fact, decreases with the 3/4 power of the distance from the aircraft. This is one of the advantages of the selection of cruise altitudes in the order of 60,000 to 70,000 feet. The condition of the ground, or the reflectivity, can serve to absorb the incident shock wave or completely reflect it. If the wave is reflected, the intensity is twice the magnitude of the corresponding absorbed shock wave. The airplane speed is a surprisingly insensitive factor in controlling the boom intensity. Once the airplane is fast enough to create a boom, the intensity increases slightly with speed and then further speed increases do not result in an increase in intensity. The reason for this is that as the speed is increased the airplane can support its weight at a reduced angle of attack and, hence, present a better sonic boom configuration.

Increased airplane weight, however, results in increased sonic boom intensity and this is possibly the most difficult parameter to reduce. The reason for this is obvious since increased weight means increased payload, more passengers, and a more profitable airplane. The first generation SST's, which are primarily for the international market, have sacrificed, to a limited extent, the lower boom intensities in favor of improved economic operation by going to large gross weights. It is probable that future domestic SST's will operate at a somewhat reduced gross weight level and, hence, the sonic boom levels will be reduced accordingly.

The final parameter indicated in the figure is the actual airplane configurational design. As might be expected, the bluntness or length to diameter ratio, contributes to the boom intensity with the blunter shapes yielding the greater boom intensities. It is also important from a design standpoint, to distribute the lift properly over the length of the aircraft. Too rapid a buildup in lift leads to increased boom intensities

In addition to the controllable parameters shown in Figure 5, the magnitude of the sonic boom overpressure is effected by changing meteorological conditions. Figure 6 shows the results of an investigation, conducted by the Boeing Company under the sponsorship of the FAA, which indicates the percent changes in sonic boom overpressure due to deviations from standard atmosphere. The upper and lower curves form an envelope of the maximum probable changes in sonic boom intensity for a large variety of nonstandard condition of atmospheric temperatures and winds. In general, the changes are less than five per cent except at Mach numbers below 1.5 down to the "cut off" Mach number of about 1.1. The reason for the greater sensitivity to atmospheric effects at low Mach numbers is illustrated by the two insert sketches and is related to distance the shock travels through the atmosphere.

In Figure 7, we show a comparison of three configurational designs and their effect on the sonic boom overpressure levels. These curves are for an aft wing, an arrow wing and a minimum boom design all weighing 400,000 pounds and 230 feet long. The aft wing design with its rapid lift buildup has the highest boom levels. The minimum boom aircraft, which has the lowest booms, unfortunately has poor drag characteristics. As a result of the poor drag characteristics, it does not provide for efficient cruise characteristics and, hence, is not a good airline configuration. The current United States' SST's are more nearly similar to the arrow wing configuration.

V. SST Operational Problems Related to Sonic Boom

The sonic boom poses a major technical and operational challenge for the supersonic transport. The technologies involved in sonic boom analysis are shown in Figure 8. It is seen that input is needed from the aerodynamicist, the meteorologist, the structural engineer, and the psycho-acoustician before the operational problems related to the sonic boom can be defined. In Figure 9, we show the inter-relationships between the SST, man and the sonic boom. The technology necessary to determine the response of structures to sonic boom excitation is available. Although the principles involved in analyzing structural response are understood, their applications to practical cases is enormously complicated because an almost infinite variety of structures and loading conditions would need to be considered. The subjective response of humans, both singly and in communities, to sonic booms is a considerably less tangible factor. Realistic evaluation of boom effects on humans involves many variables which are constantly changing both with time and place and include all of the factors associated with human behavior.

A. Flight Test Program

In an effort to define the operational problems related to the sonic boom an intensive long-term program of industry, government agencies and research organizations over the last few years has resulted in a reasonable level of understanding of the responses to sonic booms. Many problems, however, remain to be solved. The major part of this effort consisted of aircraft overflight programs conducted at Oklahoma City, White Sands Missile Range and Edwards Air Force Base.

1. Oklahoma City Study

The Oklahoma City Study was conducted for a 6-month period in the early part of 1964. The tests involved 8 booms per day which were generated by fighter aircraft at calculated overpressure levels of 1.5 to 2.0 pounds per square foot. Figure 10 shows a typical U.S. Air Force fighter plane used in this program. A total of 1,253 flights were flown during the test period. The main objective of these tests was to determine human response to sonic booms. In addition, the response of residential structures was observed with 11 typical residences instrumented to measure the effects of the booms.

2. White Sands Study

The White Sands Missile Range in New Mexico was used for a series of tests from November 1964 through February 1965. For these tests a total of 1,499 sonic boom runs were performed by F-104 and B-58 aircraft flying at speeds between 1.0 and 1.5 times the speed of sound at altitudes ranging from 300 to 30,000 feet. The program schedule included as many as 30 sonic boom runs per day generating overpressures ranging from 2 to 24 pounds per square foot. One accidental, unscheduled boom at low altitude generated an overpressure of approximately 38 pounds per foot. The main objective of these tests was to determine the structural response of buildings varying considerably in design. The structural response variables considered in this program are shown in Figure 11. These buildings consisted of old ranch houses, barracks, a warehouse, a radar building, a communication structure and several smaller buildings. They were constructed of wood, concrete, steel, frame and sheet metal construction.

3. Edward Air Force Base Study

The Edwards Air Force Base experiments were conducted between June 1966 and January 1967. In Figures 12, 13 and 14, we show the B-70, B-58 and the F-106 airplanes which were used in these tests in addition to the SR-71, F-104 and C-135B aircraft. During that time, 367 sonic booms were generated over the test site and 220 subsonic missions were flown for subjective noise comparison purposes. Figure 15 shows some of the human response variables considered during this program. The program objectives and requirements were defined by the President's Office of Science and Technology, Sonic Boom Coordinating Committee and the tests were managed by the U.S. Air Force with technical guidance and assistance afforded by NASA and, through contract, with Stanford Research Institute (SRI). The Edwards program objectives included the following:

a. Comparison of structural response and human reaction to sonic booms from aircraft of different size, weight and speed.

b. Comparison of peoples' reactions to sonic booms of varying overpressure with subsonic jet aircraft noise of varying intensities.

c. Obtaining additional data regarding atmospheric variations on sonic boom propagation.

One hundred seventy-three persons were selected for the Psychoacoustical Reaction Studies conducted at Edwards Air Force Base and in Lancaster, California.

test sites. These individuals were asked to make subjective judgments of sonic booms compared to subsonic jet noise and indicate which sound was the more acceptable when heard both inside and outside their homes. One of the primary objectives of the Edwards experiment was to establish the response of structures to aircraft of different sizes, including fighters, bombers, and the world's largest supersonic aircraft -- the XB-70. Instrumentation to measure structural reaction was installed in three test structures at Edwards Air Force Base and these structures were build and furnished as typical homes.

In addition to these studies the United States Department of Agriculture conducted studies on the effects of sonic boom on the behavior and performance of livestock. Ten farms or ranches were selected for observation of animal behavior when exposed to sonic booms and aircraft noise. The observed farms and ranches included one racehorse breeding farm, two beef feeder lots, two turkey ranches, two chicken ranches, one sheep ranch, one commercial dairy and one pheasant farm

B. Results of Sonic Boom Studies

The sonic boom studies conducted to date are considered to yield qualitative indications of the response which may be expected from overland supersonic flight. The results must be qualified because the aircraft involved were not of the supersonic transport class and because the test subjects were alerted before the test flights. The general conclusions and some of the statistics regarding the Oklahoma City and White Sands studies are shown in Figure 16.

1. Structural Response

It was concluded from the White Sands studies that the effects of repeated sonic booms at a scheduled overpressure of 5.0 psf generated by B-58 and F-104 aircraft produced no damage to previously undamaged material. Also no plaster cracks or crack extensions were observed as a result of the 680 successive 5.0 psf booms. Neither nail popping nor motion damage to bric-a-brac or other lightweight furnishings occurred during this period. Tentative damage index levels were established for various structural materials and, in general, it was found that no structural damage occurred below 5.0 psf. The one accidential unscheduled boom of 38 pounds per square foot over pressure, however, did cause damage. Two plate glass windows, 16 small glass panes in a greenhouse and one other small window were broken. This, however, was less than 10 per cent of the glass exposed to the unusually large booms and it was interesting to note that no other significant structural or material damage resulted.

2. **Human Response**

The response of humans to the introduction of a new sound into their daily environment is, at best, a very difficult factor to evaluate. The reasons for this difficulty, in addition to the individuality of people in general, result from differences in surroundings, in atmospheric conditions and in the type of sonic boom signatures. In Figure 17 and 18, we show some of the different signatures actually recorded during those sonic boom programs. For example, sonic booms heard outdorrs appear to be different from those heard indoors. The booms heard outdoors appear to be less annoying than those heard indoors. This is probably related to the secondary vibrations heard by the indoor observer which are not present in the outdoor situation. Such indoor effects are dependent on the structural and geometric characteristics and the orientation of the building housing the observer and vary considerably between different buildings.

Meteorological conditions have a significant effect on sonic boom perception. In general, the condition of the atmosphere is considered to effect the time of the pressure buildup or what is known technically as the "rise time." Sonic booms having very small rise times are usually described as sharp "cracks" whereas booms having much slower rise times are often described as "rumbles."

During the Oklahoma City Study, the National Opinion Research Center conducted interviews to determine public responses and during the Edwards Air Force Base Study, the Stanford Research Institute had paid observers at the test site to determine human reactions. While the results of the Edwards Study have not as yet been evaluated, the results of the Oklahoma City study indicated the following opinions:

A substantial number of residents reported interferences with ordinary living activities and annoyance with such interruptions, but the majority felt they could learn to live with the numbers and kinds of booms experienced during the six-month period. A large percentage, however, believed that the sonic boom caused structural damage. Since direct scientific evidence indicates that the booms did not cause any significant damage to the local test houses, this latter finding accentuates the need to establish sonic boom overpressure damage index levels. It is apparent that there is room for more detailed investigation in the areas of subjective human response to sonic booms.

VI. Summary

In the preceding pages, we have attempted to outline the historical development of the United States supersonic transport development program and to place in proper perspective the national significance of the SST program. We then reviewed in considerable depth the technological aspects and problems of the sonic boom. The actual overflight sonic boom programs to date were reviewed and capsule results were discussed. Conclusions at this point in time would be premature and we look hopefully to the scientific community for assistance and guidance in the resolution of this technological challenge.

TABLE I

INTERNATIONAL COMPARATIVE FLIGHT TIMES
SUBSONIC JETS AND SST TO MACH 2.7

Washington to.	Block Time	
	SST(M=2.7)	Subsonic
Anchorage	2 + 50	6 + 57
Cairo	5 + 30	12 + 09
Buenos Aires	5 + 10	10 + 27
Bonn	4 + 06	8 + 22
Johannasburg	6 + 46	16 + 15
Djakara	9 + 33	21 + 51
Honolulu	4 + 54	9 + 45
London	2 + 58	7 + 18
Manila	7 + 48	18 + 33
Moscow	5 + 08	9 + 45
Tokyo	6 + 13	14 + 21
New Delhi	11 + 12	26 + 06
Sidney	9 + 18	20 + 51
Paris	3 + 04	7 + 40
RIO	4 + 58	9 + 42
Rome	3 + 57	8 + 57

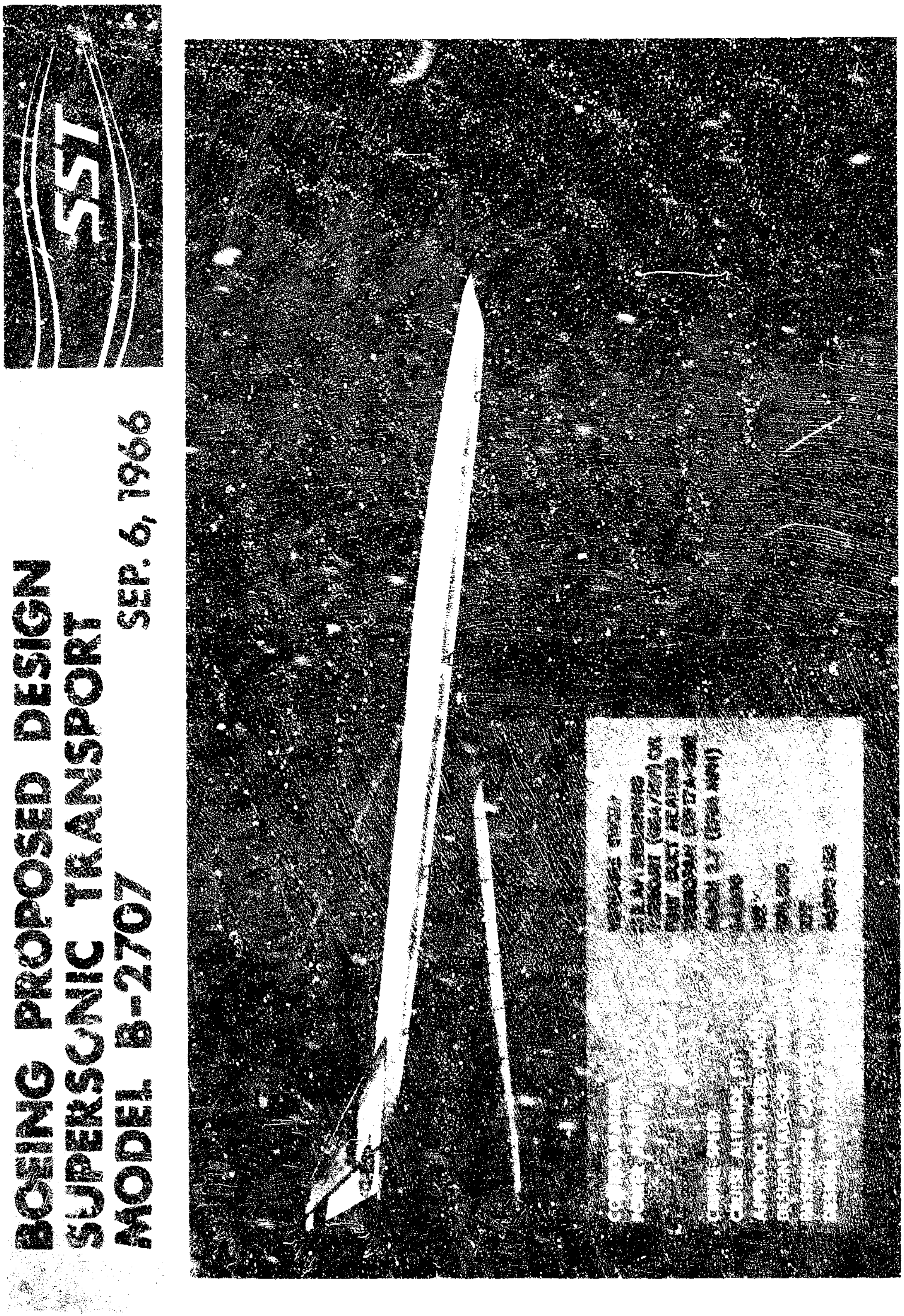
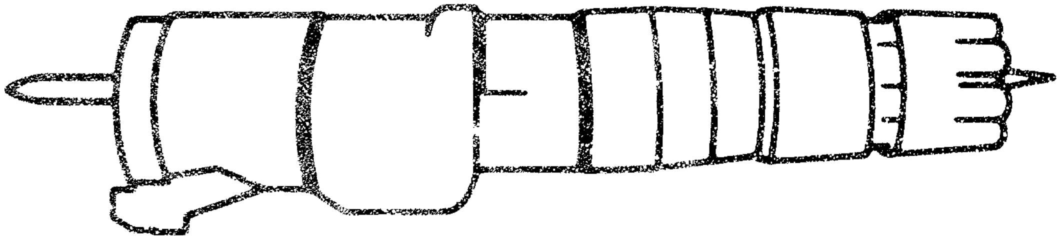

SST
BOEING PROPOSED DESIGN
SUPERSONIC TRANSPORT
MODEL B-2707
SEP. 6, 1966

Fig. 1

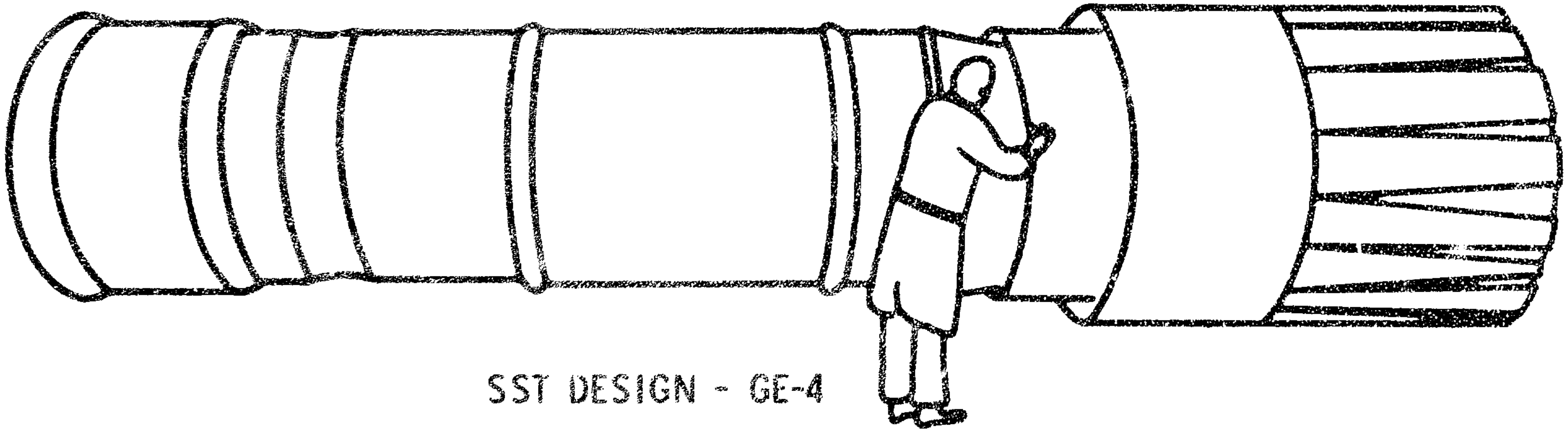
GENERAL ELECTRIC GE-4
ENGINE DESIGN

AFTERBURNING TURBOJET

THRUST	60,000 LB CLASS
LENGTH	25 FEET 8 INCHES
DIAMETER	6 FEET 2 INCHES



CURRENT COMMERCIAL TORBOJET - CJ805



SST DESIGN - GE-4

Fig. 2

Fig. 3

GENERATION OF PRESSURE FIELD

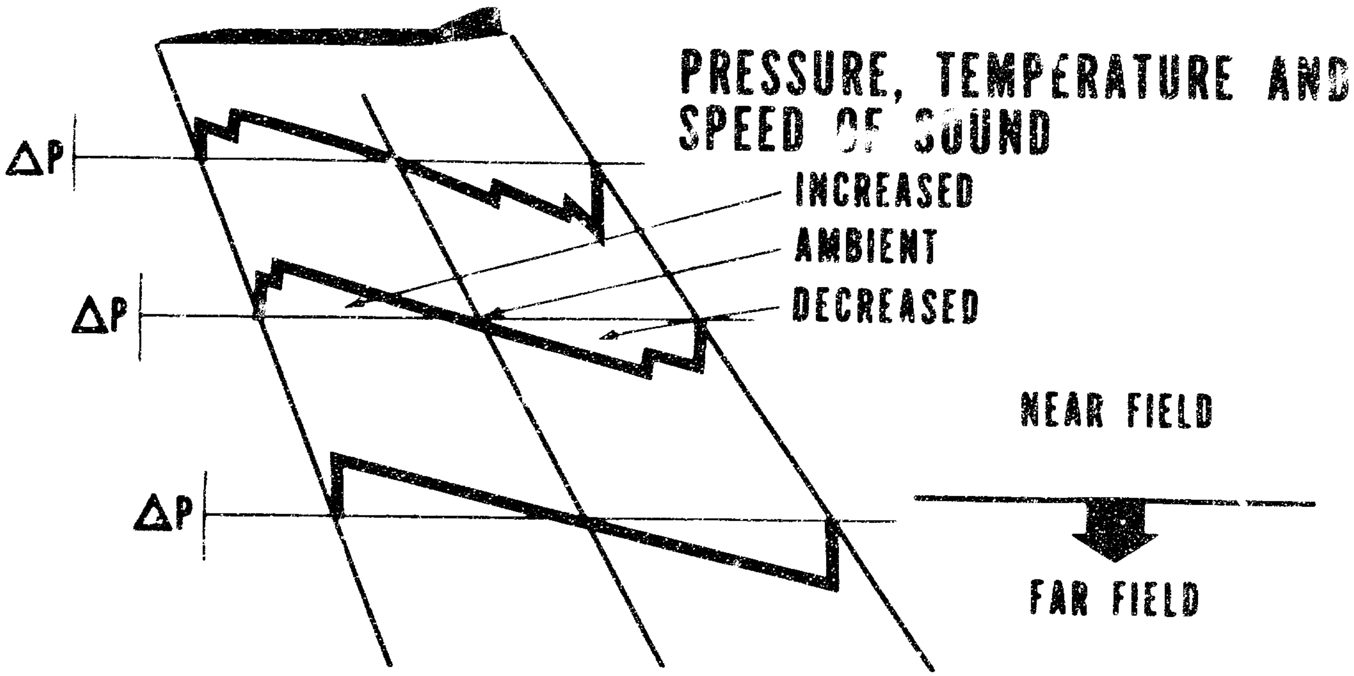


Fig. 4

CONTRIBUTING PARAMETERS

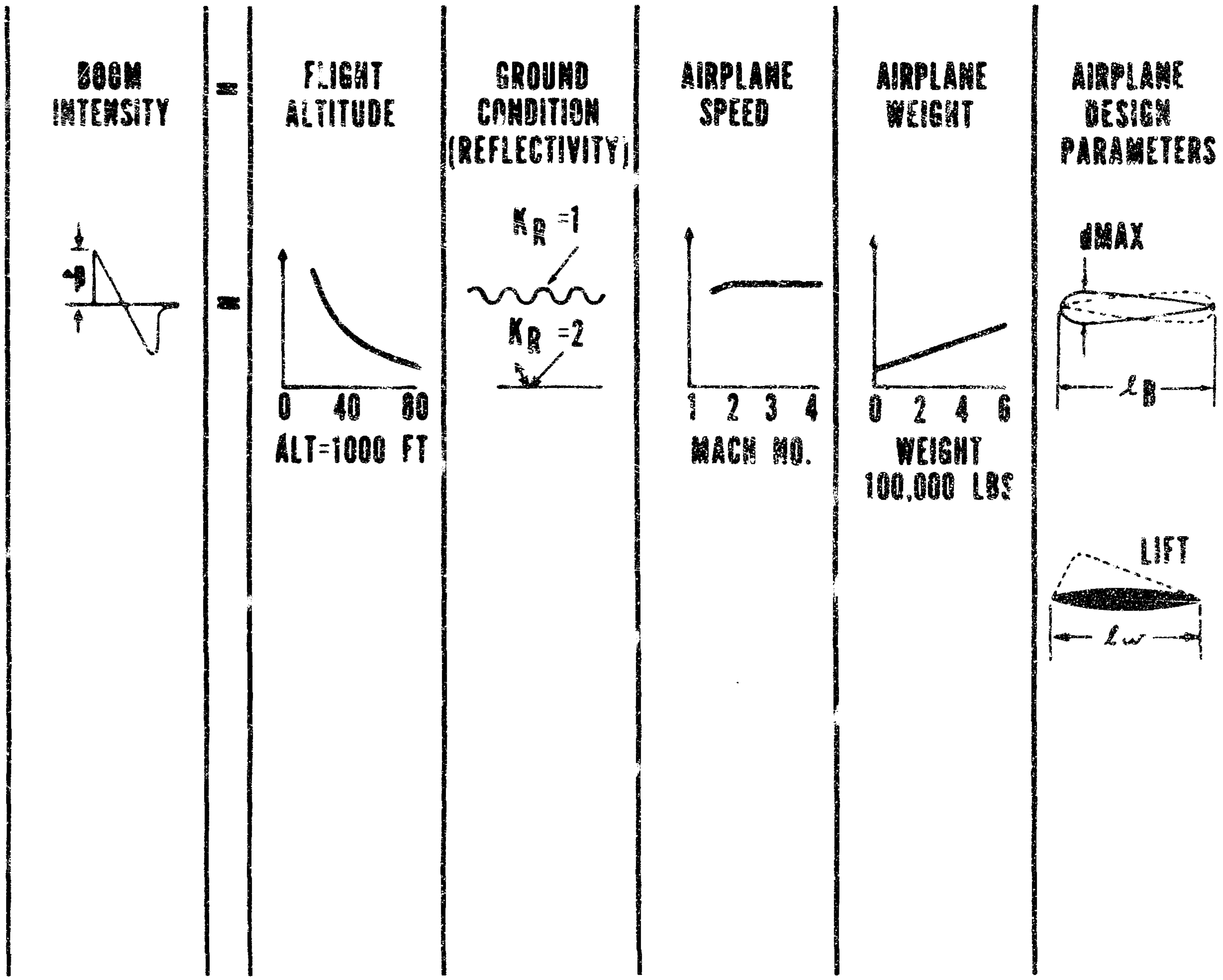


Fig. 5

THE EFFECT OF WEATHER ON SONIC BOOM

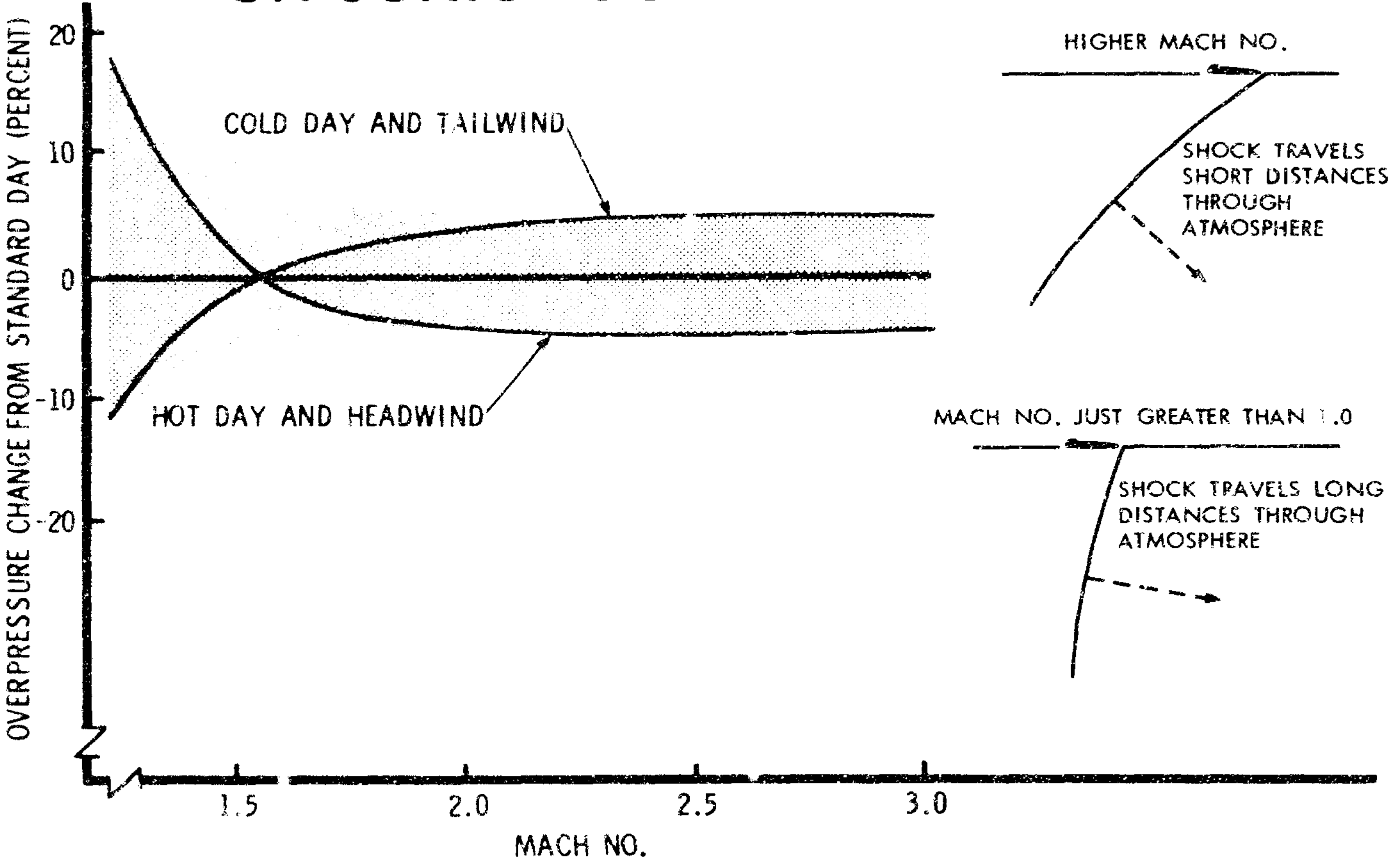


Fig. 6

CONFIGURATIONAL DESIGN EFFECTS ON SONIC BOOM

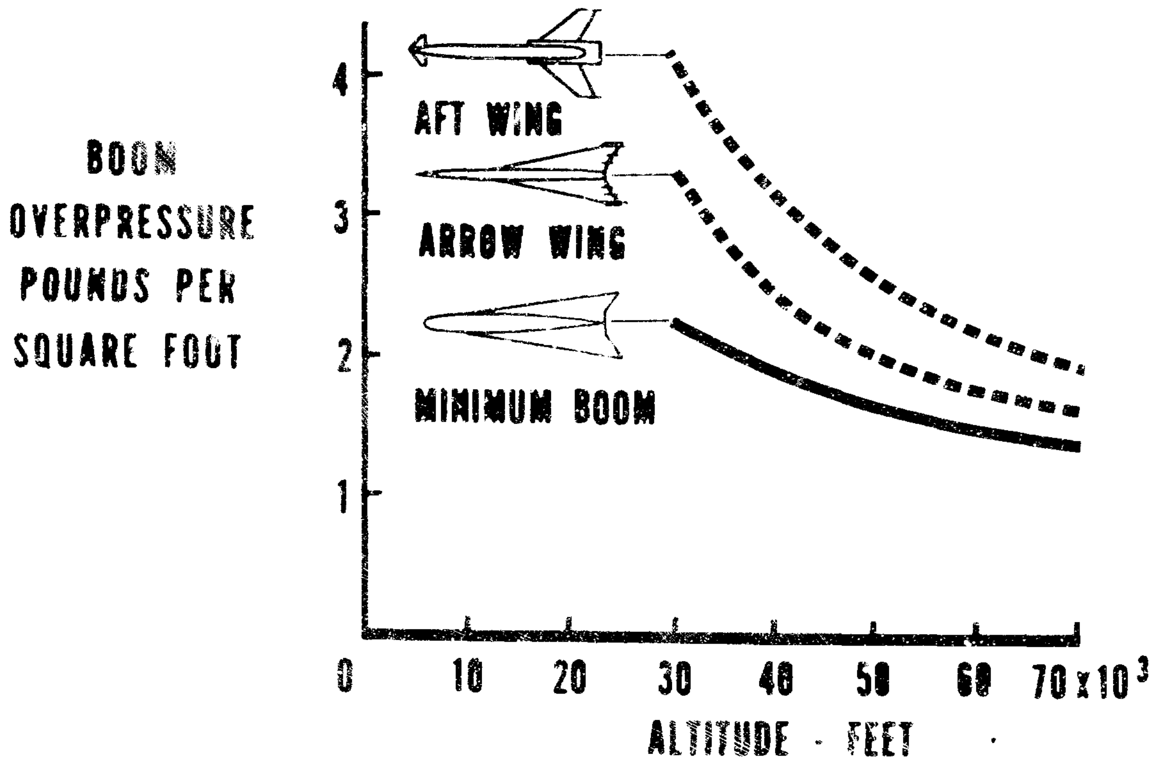


Fig. 7

TECHNOLOGIES INVOLVED IN SONIC BOOM ANALYSIS

PREDICTION OF PRESSURE FIELD

- THEORY REDUCED TO PRACTICE AND CONFIRMED

DISTORTION BY ATMOSPHERE

- ESSENTIALLY STATISTICAL

STRUCTURAL RESPONSE

- ANALYSIS METHODS
- FLIGHT TESTS

HUMAN RESPONSE

- ANALYSIS METHODS
- FLIGHT TESTS

Fig. 8

THE SST, MAN AND THE SONIC BOOM

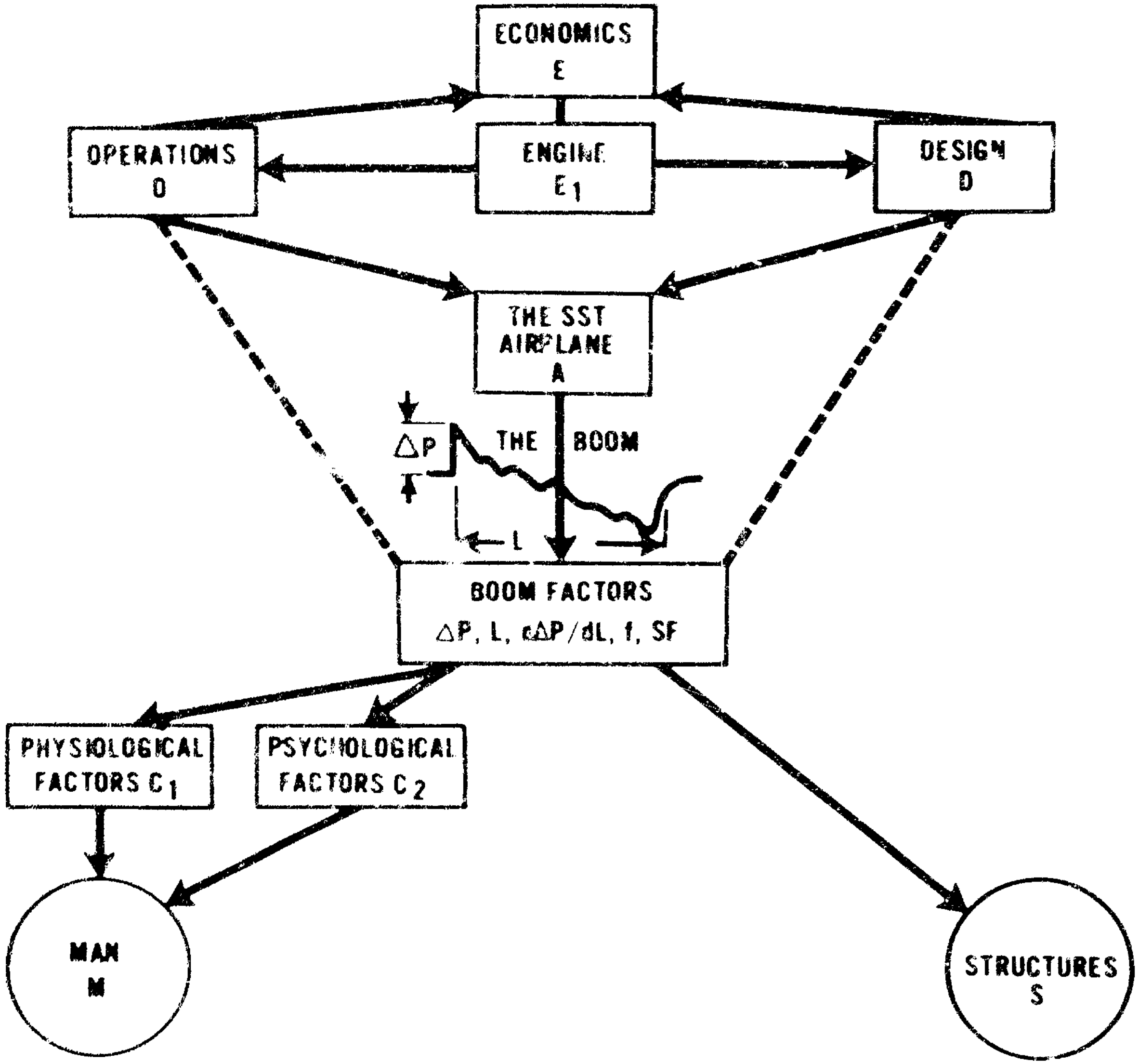


Fig. 9

Fig. 12

STRUCTURAL RESPONSE

WHAT FEATURES OF THE SONIC BOOM ARE SIGNIFICANT FOR VIBRATIONS

WHAT FEATURES OF THE SONIC BOOM ARE SIGNIFICANT FOR STRUCTURAL DAMAGE

WHAT FEATURES OF BUILDING RESPONSE CORRELATE WITH MAN'S RESPONSE INDOORS

- ACCELERATIONS OF COMPONENTS
- VELOCITY OF COMPONENTS
- DEFLECTION OF COMPONENTS
- ACOUSTIC NOISE
- INSIDE PRESSURE VARIATIONS
- PANEL MODES OR RACKING MODES

Fig. 11

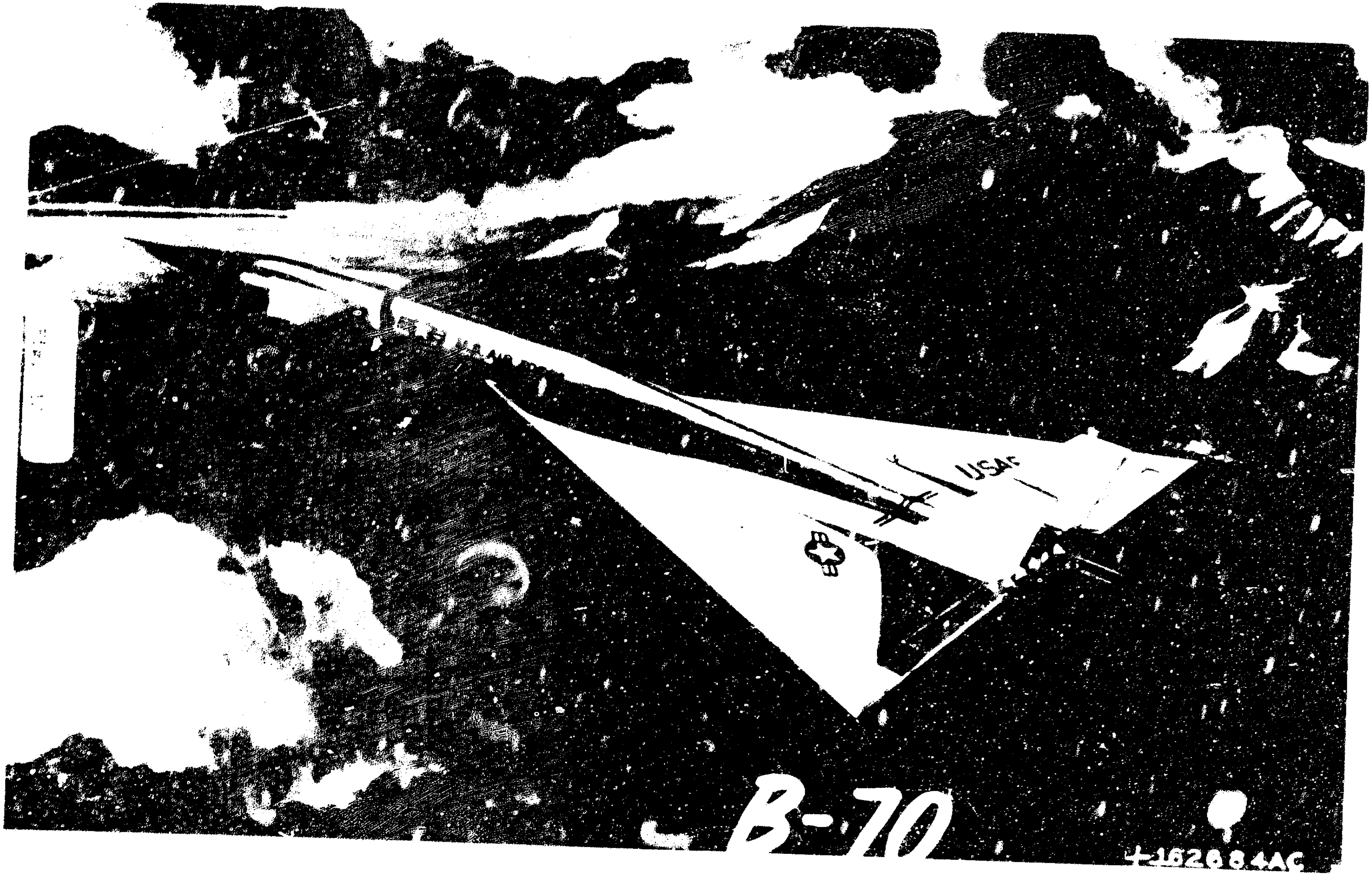

USAF
B-70
4-162684AC

Fig. 13

Fig. 14

HUMAN RESPONSE

WHAT FEATURES OF THE SONIC BOOM ARE SIGNIFICANT

- OVERPRESSURE
- IMPULSE
- TIME DURATION
- RISE TIME
- ENERGY SPECTRUM

WHAT EFFECTS DO STRUCTURAL REACTIONS HAVE ON HUMAN RESPONSE

CAN OUR KNOWLEDGE OF MAN'S RESPONSE TO AIRCRAFT NOISE BE APPLIED TO SONIC BOOM

Fig. 15

FAA SONIC BOOM INVESTIGATIONS

OKLAHOMA CITY-PUBLIC REACTION

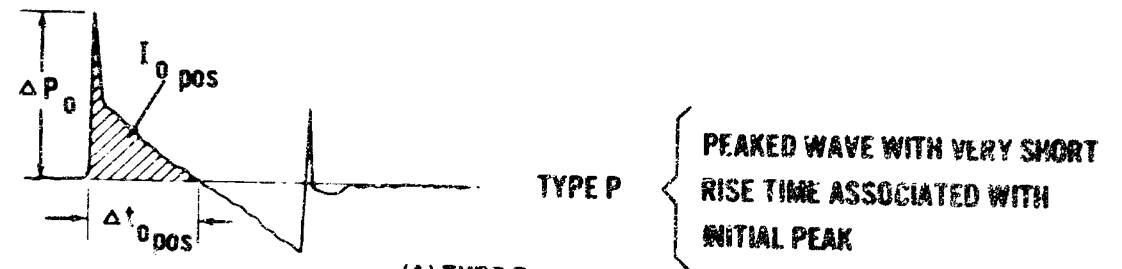
- 6 MONTHS-1253 BOOMS-DAYLIGHT HOURS
- OVERPRESSURE-1.5-2.0 psf
- NO DAMAGE-INSTRUMENTED HOUSES
- 73% POLLED WERE NOT ANNOYED
- 40% POLLED BELIEVED BOOM CAUSED DAMAGE

WHITE SANDS-STRUCTURAL RESPONSE

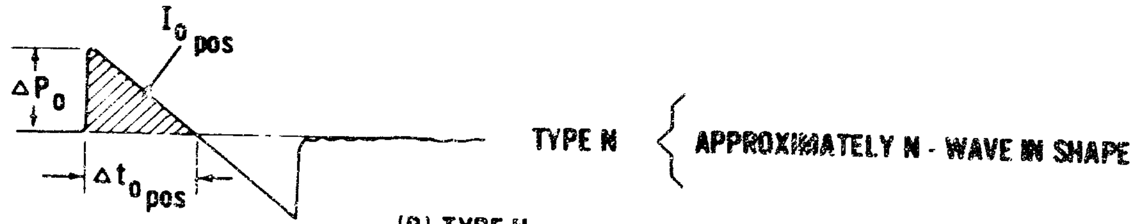
- 738 FLIGHTS-OVERPRESSURE 2-19 psf
- 680 FLIGHTS-OVERPRESSURE 5 psf
- 16 TYPES OF STRUCTURES
- CONCLUSION-SONIC BOOMS TO 5 psf-NO DAMAGE

Fig. 16

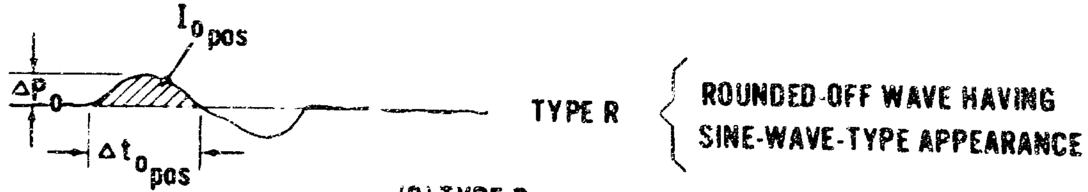
SCHEMATIC DIAGRAMS SHOWING SOME CATEGORIES OF WAVEFORMS MEASURED AT GROUND LEVEL DURING TESTS



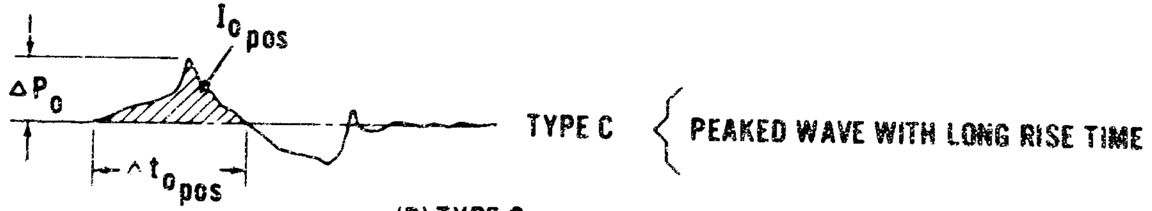
(A) TYPE P.



(B) TYPE N.



(C) TYPE R.



(D) TYPE C.

Fig. 17

SONIC BOOM WAVE FORM CATEGORIES

EAFB - PHASE II

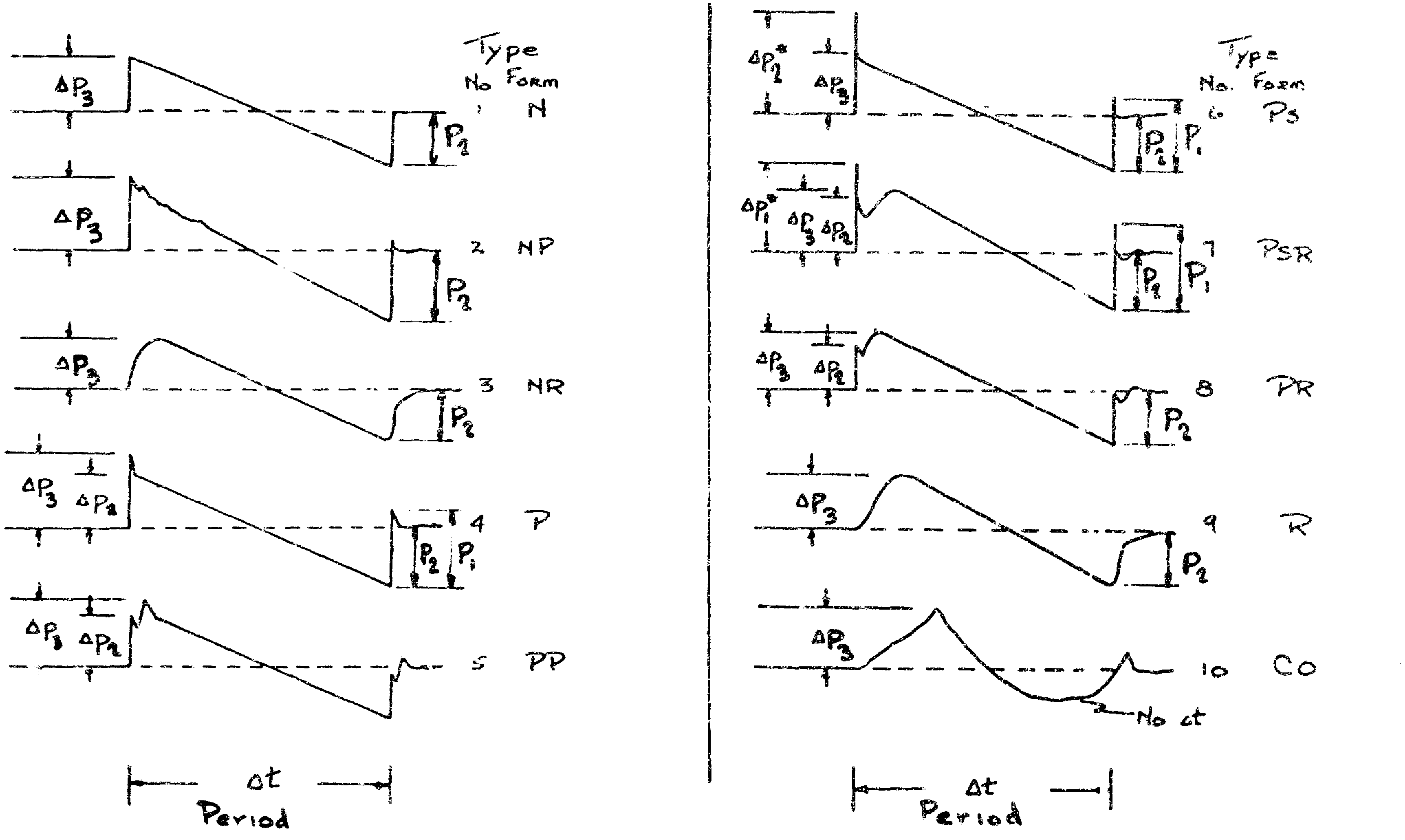


Fig. 18