NASA TECHNICAL NOTE

NASA TN D-4677

c.1

NASA TN D-4677

AIRPLANE SIZE AND STAGING EFFECTS ON SST CRUISE SONIC BOOM

by John B. Whitlow, Jr.

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JULY 1968

NASA TN D-4677

AIRPLANE SIZE AND STAGING EFFECTS ON SST CRUISE SONIC BOOM

By John B. Whitlow, Jr.

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ABSTRACT

An analytical study was made to determine the performance requirements and economic penalties involved in reducing the cruise sonic boom of various sizes of a domestic-range SST. No attempt was made to reduce the climb sonic boom since climb might possibly be scheduled over sparsely populated areas. For airplanes in the 200-passenger category, it was found that cruise at nonoptimum altitudes allows reductions up to 10 percent in initial cruise boom at the expense of a 10-percent increase in DOC. By size and weight reductions, cruise boom can be reduced almost 40 percent at the expense of a five-fold increase in DOC. A similar study of a two-stage vehicle with stage separation just prior to cruise revealed that a boom reduction of only about 5 percent is possible with this concept, relative to unstaged airplanes of the same payload capacity.

AIRPLANE SIZE AND STAGING EFFECTS ON SST CRUISE SONIC BOOM

by John B. Whitlow, Jr.

Lewis Research Center

SUMMARY

An analytical study was made to determine the performance requirements and economic penalties involved in reducing the cruise sonic boom of various sizes of a domestic-range supersonic transport. No attempt was made to reduce the climb sonic boom since climb occurs over a relatively short range and can perhaps be scheduled over sparsely populated areas. A similar study was made to determine the improvement in cruise sonic boom that might be obtained by use of a two-stage vehicle having stage separation just before the start of cruise.

For unstaged airplanes in the 200-passenger category, reductions up to 10 percent in initial cruise boom can be obtained at the expense of approximately equal percentage increases in direct operating cost (DOC) by beginning cruise at higher-than-payload-optimum altitudes. Greater reductions in sonic boom (up to a maximum of about 39 percent) can be obtained for this particular configuration with size and weight reductions, but only at the expense of increasingly severe DOC penalties. When a comparison is made between staged and unstaged vehicles of the same payload capacity, the results of this study show that staging will provide a reduction of only about 5 percent in initial cruise boom. Staging thus offers little potential for boom reduction even though the technical problems and additional expense associated with it have been ignored.

Despite the economic penalties involved, even the minimum sonic boom levels considered herein may be unacceptable, especially since booms several times higher than these calculated nominal values may occur under certain conditions. The higher levels of performance that can be expected with evolutionary improvements in the design of airframes and kerosene-fueled engines will probably lower somewhat the economically attainable levels of cruise sonic boom. To completely solve the problem, however, a new approach or significant technological advance is required.

INTRODUCTION

Sonic boom is likely to be the most crucial obstacle to the successful use of the supersonic transport (SST) on overland routes. The current Federal Aviation Administration (FAA) guidelines for SST development call for a maximum initial cruise boom overpressure of 1.7 pounds per square foot (81.4 N/m^2) over the ocean and 1.5 pounds per square foot (71.8 N/m^2) over land. Such high levels of boom may, however, be unacceptable. The present analytical study is an attempt to determine the performance requirements and economic penalties involved in reducing the cruise sonic boom of various sizes of a domestic-range (2400-n.-mi. or 4445-km) SST. Climb sonic boom was held fixed at the 2.00-pound-per-square-foot (95.8-N/m^2) level recommended by the FAA as a maximum limit for overland operation. Cruise sonic boom was considered to be more crucial than climb sonic boom, since a greater area of land would be affected by sonic boom generated in cruise. It is possible that if cruise sonic boom were no longer a problem, the problem in climb could be alleviated by such means as over-ocean climb and acceleration, or at least by selecting a supersonic climb path over sparsely populated areas.

Other studies (ref. 1) have indicated that airplane size and gross weight reductions can reduce the maximum sonic boom overpressure during climb for an SST designed for transcontinental range. No attempt was made to minimize the cruise sonic boom overpressure in the studies of reference 1. Cruise was begun either at the altitude determined by the climb overpressure limit or at the altitude for best cruise performance, whichever was higher. In the present study, however, the climb sonic boom limit is fixed while the effect airplane size and gross weight variations have on cruise sonic boom is investigated.

Cruise sonic boom is lowered by increasing the cruise altitude or by decreasing the cruise weight of an airplane. The airplane figure of merit (e.g., the payload-to-gross-weight ratio, hereinafter called the payload fraction) may suffer severely, however, with the relatively larger engines and/or heavier fuel load required for cruise at altitudes significantly higher than optimum. Reference 2 has shown that staging may allow a reduction in total system takeoff gross weight for a given range and payload. If initial cruise sonic boom (and, hence, altitude) were not a factor, this might be translated into a lower vehicular (second-stage) gross weight at the start of cruise. Another objective of the current study, therefore, is to determine if this potential weight reduction can result in a significantly lower cruise sonic boom. With staging, only the characteristics of the payload-carrying, second-stage vehicle are considered in this study; the characteristics of the associated boost vehicle are ignored.

The sonic boom and aerodynamic characteristics of the NASA-Langley Research Center SCAT 15F (fig. 1) were arbitrarily selected to represent both the staged and unstaged vehicles considered herein. These characteristics (ref. 3) are somewhat optimistic when compared to those of the SST configurations that are presently proposed or under construction. The sonic booms calculated in this study should, therefore, represent levels somewhat below those that could be achieved by similarly resizing or staging those configurations.

In addition to the payload fraction which is considered as a figure of merit for both staged and unstaged vehicles in this study, the DOC is calculated for the unstaged airplanes. The DOC is used to estimate the economic penalty that must be paid for reductions in sonic boom. Such a calculation was not made for a two-stage system, however, since too many uncertainties were involved in cost estimation.

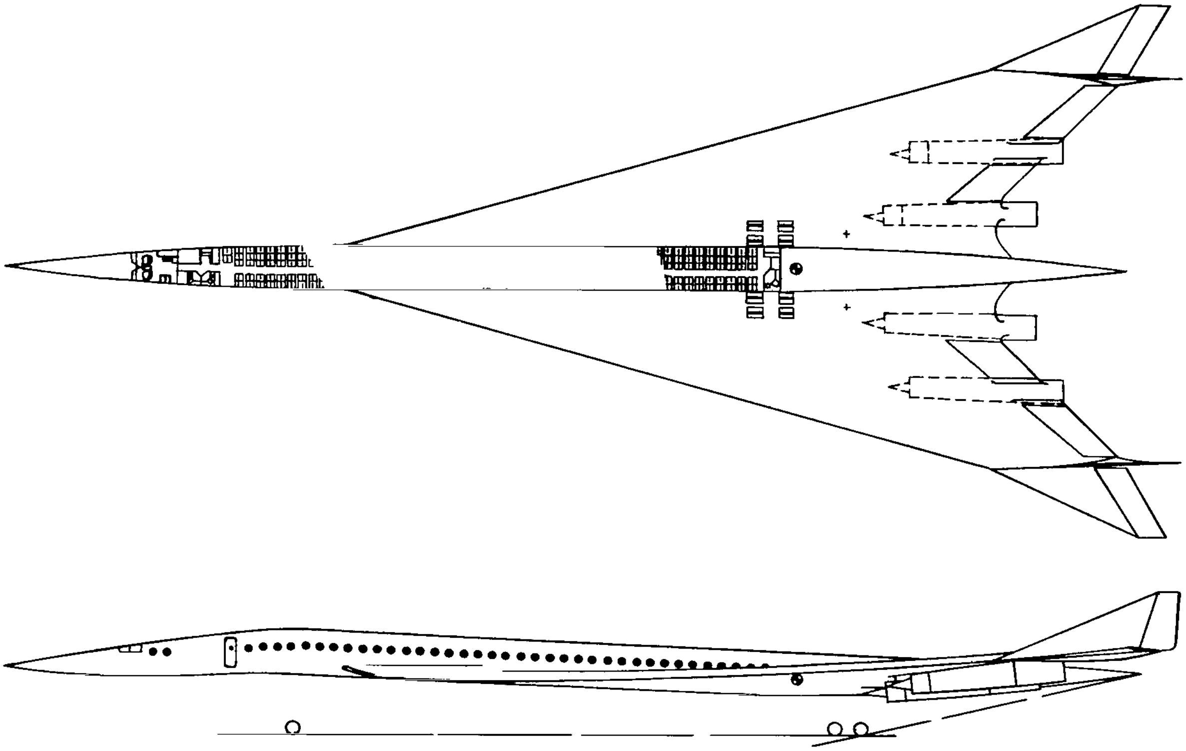


Figure 1. - Typical SCAT 15F design.

Afterburning turbojet engines were the powerplants assumed for all the vehicles considered. Vehicle gross weight, physical size, payload, cruise altitude, and relative engine size (airflow) were varied to determine how payload fraction would be affected by a spectrum of sonic boom limits. During the study, these parameters varied as follows: vehicle maximum gross weight, from 118 000 to 371 000 pounds (mass) (53 524 to 168 283 kg); fuselage length, from 178 to 242 feet (54.25 to 73.76 m); payload, from 4000 to 40 000 pounds (1814 to 18 140 kg) (which corresponds to the weight of from 20 to 200 passengers, respectively, and their baggage); initial cruise altitude, from 70 000 to 84 000 feet (21 336 to 25 603 m); and single-engine airflow, from 124 to 372 pounds per second (58.9 to 168.7 kg/sec). Cruise Mach number was fixed at 3.0 throughout the study. Vehicle designs were refined through a series of iterative calculations to obtain the desired range of 2400 nautical miles (4445 km).

SYMBOLS

B	maximum fuselage width, ft (m)
C_L	lift coefficient
D	maximum diameter of equivalent body, ft (m)
F	net thrust, lb (kg)
H	altitude, ft (m)
K_A	atmospheric correction factor for reference pressure
K_R	ground sonic boom reflection factor
K_S	equivalent body shape factor
L	length, ft (m)
M	Mach number
P	sonic boom reference pressure, lb/ft^2 (N/m^2)
ΔP	maximum sonic boom overpressure on the ground, lb/ft^2 (N/m^2)
P_G	ambient pressure at sea level, lb/ft^2 (N/m^2)
P_H	ambient pressure at altitude of body, lb/ft^2 (N/m^2)
q	dynamic pressure $\left(= \frac{1}{2}\rho V^2\right)$, lb/ft^2 (N/m^2)
S	wing planform area, ft^2 (m^2)
W	instantaneous gross weight, lb (kg)
W_a	sea-level static corrected engine airflow, lb/sec (kg/sec)
W_{eng}	total propulsion system weight (4 engines), lb (kg)

W_{fsys}	weight of fuel system, lb (kg)
W_{fuel}	total fuel load, lb (kg)
W_{fus}	fuselage weight, lb (kg)
W_G	maximum gross weight, lb (kg)
W_{hydr}	weight of hydraulic and electrical system, lb (kg)
W_L	payload, lb (kg)
W_{lg}	weight of landing gear, lb (kg)
W_{sc}	weight of surface controls, lb (kg)
W_{wing}	weight of wing and vertical stabilizer, lb (kg)
β	Mach number parameter, $\sqrt{M^2 - 1}$
ρ	density, slug/ft^3 (kg/m^3)

SONIC BOOM THEORY

The shock-wave patterns developed by airplanes in supersonic flight fan out from the airplane to reach an observer on the ground, where they are interpreted by the ear as a

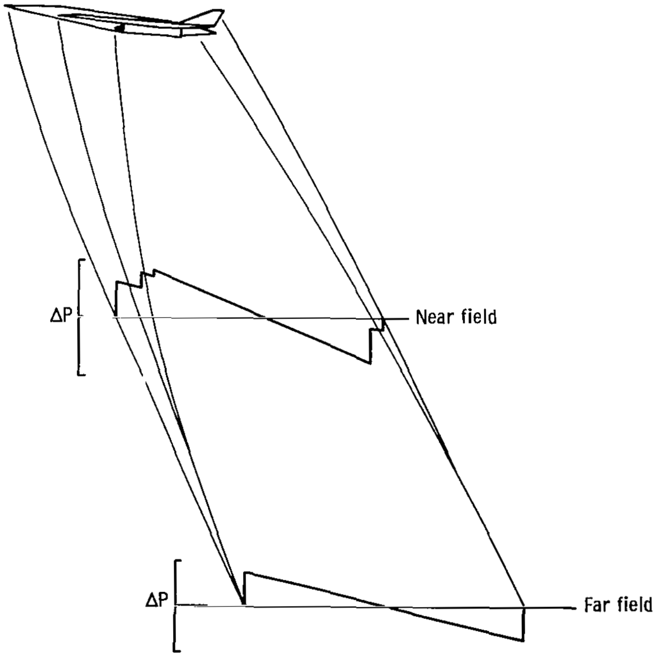


Figure 2. - Airplane pressure field.

sonic boom. Close to the airplane, individual shock waves generated by various components (e.g., wing, fuselage, and nacelles) can be detected in the pressure signature, as shown in the upper pressure signature sketch of figure 2. At greater distances (i.e., in the far field, as opposed to the near field), the individual component shocks coalesce into a single bow shock and a single tail shock which produce an "N" signature, as indicated in the lower signature sketch of figure 2. During cruise, the vehicles considered in this study are at such great altitudes (relative to vehicle length) that far-field conditions exist on the ground. Although it was previously thought that far-field conditions prevailed on the ground throughout the entire supersonic flight regime of the SST, more recent studies (ref. 4) have indicated that near-field conditions may occur during transonic portions of the flight for configurations of the type being considered. When near-field conditions occur, the designer has some latitude in configuring the airplane to minimize the maximum value of overpressure. There is some evidence, however, that the lower level of maximum overpressure thus obtained does not appreciably lower the annoyance to an observer on the ground (ref. 5). In the present study, far-field conditions are assumed to exist on the ground not only during cruise, but also during supersonic acceleration and climb.

Shock-wave strength resulting from supersonic flow of a homogeneous medium about a body of revolution can be predicted by theory developed by Whitham (ref. 6). Theoretical work by Hayes (ref. 7) indicates the method by which an airplane configuration can be converted into an equivalent body of revolution for the purpose of shock-strength estimation. The development of the equivalent body requires a consideration of the longitudinal distribution of airplane cross-sectional area and lift. The cross-sectional area required at any longitudinal station is the frontal projection of the airplane area cut by a plane which passes through the longitudinal axis at that station and is inclined at the Mach angle (ref. 8). Since this angle changes with Mach number, the equivalent body of revolution must vary with Mach number. Because the equivalent body is also developed from a consideration of lift distribution, any change in a flight condition such as altitude or an aircraft characteristic such as weight that will change the lift coefficient will also change the shape of the equivalent body.

Whitham's equation for the far-field bow shock generated by a body of revolution in a uniform atmosphere may be expressed as

$$\Delta P = \frac{PK_R\beta^{1/4}}{\left(\frac{H}{L}\right)^{3/4}}\left(K_S\,\frac{D}{L}\right) \tag{1}$$

where P is the ambient atmospheric pressure. In a standard atmosphere, the ambient pressure will be nonuniform between the body at some altitude and the observer on the ground. Equation (1) will still be valid, however, if the reference pressure P is a mean ambient pressure somewhere between the ambient pressure at the body and the observer on the ground. The value of P that is used in equation (1) may be obtained by applying an atmospheric correction factor K_A to the ambient pressure P_H at the altitude of the body so that

$$P = K_A P_H \tag{2}$$

According to reference 9, the correction factor K_A for a 1962 U.S. standard atmosphere is a function of both Mach number and altitude. Figure 3 (taken from ref. 9) shows how

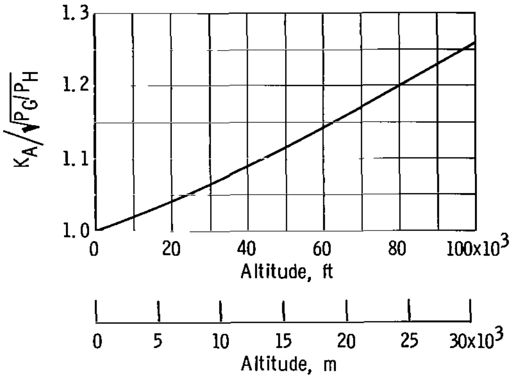


Figure 3. - Variation of atmospheric correction factor with altitude at Mach 3.0 for 1962 U.S. standard atmosphere (ref. 9).

$K_A/\sqrt{P_G/P_H}$ varies with altitude at Mach 3 (the cruise Mach number considered in this study). To obtain the reference pressure P to be used in equation (1), the ordinate of figure 3 must be multiplied by $\sqrt{P_G P_H}$, the geometric mean of the atmospheric pressure at the ground and airplane levels. In equation (1), the reflectivity factor K_R is taken to be 1.9 throughout the study, a value representative of natural terrain. For a smooth, hard surface, that factor would theoretically be 2.0.

Equation (1) may be rewritten in a dimensionless form, as follows:

$$\frac{\frac{\Delta P}{P}\left(\frac{H}{L}\right)^{3/4}}{K_R \beta^{1/4}} = K_S \frac{D}{L} \tag{1'}$$

The quantities on the left side of equation (1'), aside from the sonic boom overpressure

ΔP, are related to flight conditions, atmospheric properties, and the ground-surface condition. The quantities on the right side of the equation are related to the shape of the equivalent body of revolution. According to the appendix of reference 10, the right side of equation (1') can be conveniently expressed as a function of $\frac{\beta}{2} C_L \frac{S}{L^2}$ for a given airplane configuration. For steady-level flight conditions, this parameter may be expressed as $\frac{\beta}{2} \frac{W}{qL^2}$ since

$$C_L = \frac{W}{Sq} \tag{3}$$

In figure 4, the left side of equation (1') is plotted against $\frac{\beta}{2} \frac{W}{qL^2}$ for the SCAT 15F configuration shown in figure 1 (p. 3). Other configurational types could be represented by other curves in the coordinate system of figure 4. The SCAT 15F sonic boom characteristic curve shown in this figure would be applicable for a range of supersonic Mach numbers if changes in area and lift distribution with Mach number could be ignored. Changes in the Mach angle, however, somewhat alter this distribution since the section of the airplane intersected by a Mach plane through a particular axial station will vary. The curve shown in figure 4 is strictly valid only at Mach 3. Significant changes in Mach number would cause slight shifts in the location of this curve.

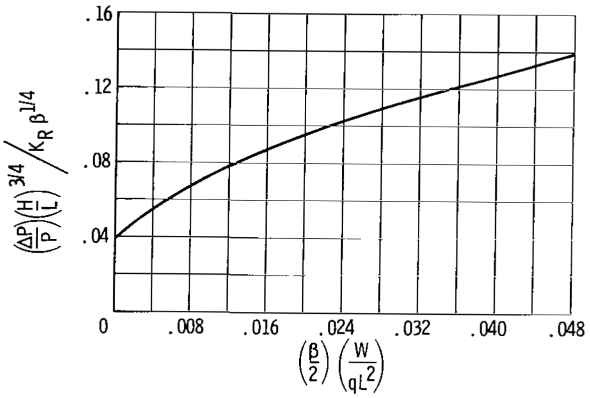
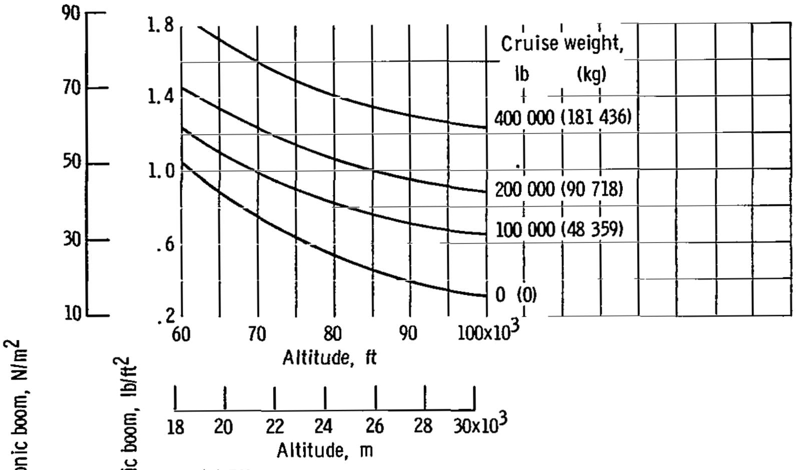
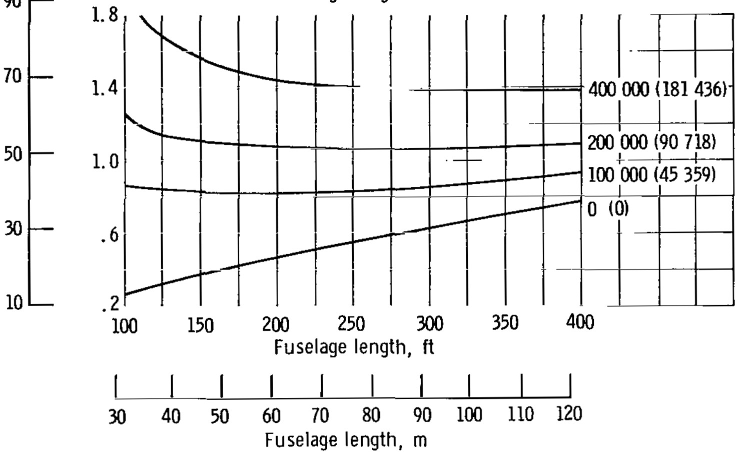


Figure 4. - Far field sonic boom characteristics for SCAT 15F-type configuration during level flight at Mach 3.0.

Using the sonic boom characteristic curve of figure 4, together with the atmospheric correction factor from figure 3, calculations were made to determine the effect on sonic



(a) Effect of vehicle cruise altitude and weight. Vehicle dimensions constant with fuselage length at 250 feet (76.2 m).



(b) Effect of vehicle size. Dimensional similarity maintained among all vehicles. Altitude, 80 000 feet (24 384 m).

Figure 5. - Effect of vehicle size, weight, and altitude on sonic boom during Mach 3 cruise operation.

boom of arbitrary variations in cruise weight and altitude. (The corresponding variations in range or payload and the engine thrust requirements were temporarily ignored.) The calculations were made for a SCAT 15 F configuration of constant volume with a fuselage length of 250 feet (76.20 m). The results are presented in parametric form in figure 5(a). They show that greater altitudes and lower weights tend to reduce the sonic boom and that, as weight is reduced, the point of diminishing return is eventually reached. Even if the airplane could be made weightless, the bottom curve of figure 5(a) shows that there would be some sonic boom due solely to volume considerations.

Figure 5(b) shows the effect of fuselage length and, hence, airplane volume during Mach 3 cruise at an altitude of 80 000 feet (24 384 m) for a range of instantaneous gross weights up to 400 000 pounds (181 436 kg). All airplane dimensions were varied with changes in fuselage length so that dimensional similarity among all the airplanes was maintained. Figure 5(b) shows that as fuselage length is reduced at relatively low values, sonic boom increases significantly when the weight during cruise is 200 000 pounds (90 718 kg) or more. Decreases in fuselage length L cause the value of the abscissa of figure 4 (p. 8) to increase with a consequent increase in the sonic boom parameter (the ordinate of fig. 4). This may be more easily understood when it is recognized that according to equation (3) (p. 8), the lift coefficient C_L increases for a fixed weight W since, because of dimensional similarity, the wing area S decreases as L is decreased. To obtain the greater C_L required when weight remains unchanged and wing area is reduced, the wing angle of attack must be increased so that the airstream can be further deflected. As the angle of airstream deflection increases, the severity of the shock increases, thereby increasing the level of the sonic boom. Of course, the increase in C_L (and, hence, angle of attack) required for a given reduction in wing area is a function of the magnitude of the weight. Hence, as is shown in figure 5(b), the effect on sonic boom is much more pronounced for the heavier vehicles when fuselage length is reduced. In fact, the opposite effect is observed in figure 5(b) for the weightless vehicle. With the weightless vehicle, for example, a fixed value of zero for the abscissa of figure 4 would be obtained regardless of the fuselage length. Since the ordinate of figure 4, although fixed in value for this case, contains the term H/L in the numerator, the value of the sonic boom overpressure on the ground (ΔP) will decrease when the fuselage length L is reduced. This effect is also observed in the other curves of figure 5(b), but becomes increasingly less significant as weight is increased and the effect of the increase in C_L becomes more predominant as fuselage length is reduced.

In the current study, vehicle cruise weights ranged from approximately 90 000 to 320 000 pounds (40 824 to 145 152 kg) with corresponding fuselage lengths ranging from 178 to 242 feet (54.25 to 73.76 m). As may be seen from figure 5(b), such a range of weight and size combinations (i.e., cruise vehicle-densities) will tend to minimize cruise sonic boom as far as possible for the configurational shape under consideration (fig. 1, p. 3).

MISSION

The mission requirements observed in this study are outlined as follows:

Total range, n.mi. (km)	2400 (4445)
Cruise Mach number	3.0
Maximum sonic boom overpressure limit during supersonic climb and acceleration, lb/ft^2 (N/m^2)	2.00 (95.8)

TABLE I. - U.S. TRANSCONTINENTAL RANGES

City pair	Range		
	n. mi.	stat. mi.	km
New York - Los Angeles	2126	2446	3936
New York - San Francisco	2232	2568	4133
Miami - Seattle	2381	2740	4410
Miami - Portland	2360	2716	4371
Boston - San Francisco	2343	2696	4339

All unstaged airplanes considered were designed for Mach 3 cruise with a total range of 2400 nautical miles (2764 stat. mi. or 4445 km). This is greater than any range that will be encountered between major city pairs within the continental United States, as may be seen from table I.

When staging was considered, separation of the boost and cruise stages was assumed to occur immediately prior to the start of cruise, regardless of the initial cruise altitude selected. The range was calculated only for the second (or cruise) stage. The range up to cruise was assumed to be 300 nautical miles (556 km) - a value typical of the climb and acceleration ranges of the unstaged airplanes of this study. Aside from its 300-mile (556-km) contribution to the total system range of 2400 miles (4445 km), the boost vehicle was not otherwise considered in this study.

To optimize the payload fraction or range for both staged and unstaged vehicles, cruise was begun at an altitude where the product of lift-drag ratio, engine specific impulse, and airplane velocity maximized. Cruise was continued along a flight path that maintained this product (herein called the Breguet factor) constant at its maximum value. A constant Breguet factor cruise can be obtained by allowing the vehicle altitude to increase as cruise progresses and weight decreases. As initial cruise altitudes were increased above the range- or payload-optimum values in order to reduce cruise sonic boom, a constant altitude cruise was maintained until the Breguet factor was maximized (if the cruise range was sufficiently great to allow this to occur). After the Breguet factor maximization occurred, cruise was then continued along a constant Breguet flight path. To simplify the calculations, it was assumed that the descent time and range remained constant at 20 minutes and 200 nautical miles (370 km), respectively, with fuel consumption calculated with engines idling.

A typical flight plan for an unstaged 200-passenger airplane of the type studied is shown in figure 6. The flight path in Mach number and altitude coordinates was fixed up to Mach 1. At higher Mach numbers, the altitude was allowed to increase as necessary so that sonic boom overpressures on the ground would not exceed 2.00 pounds per square foot (95.8 N/m^2). The sonic booms at the various flight conditions were calculated by

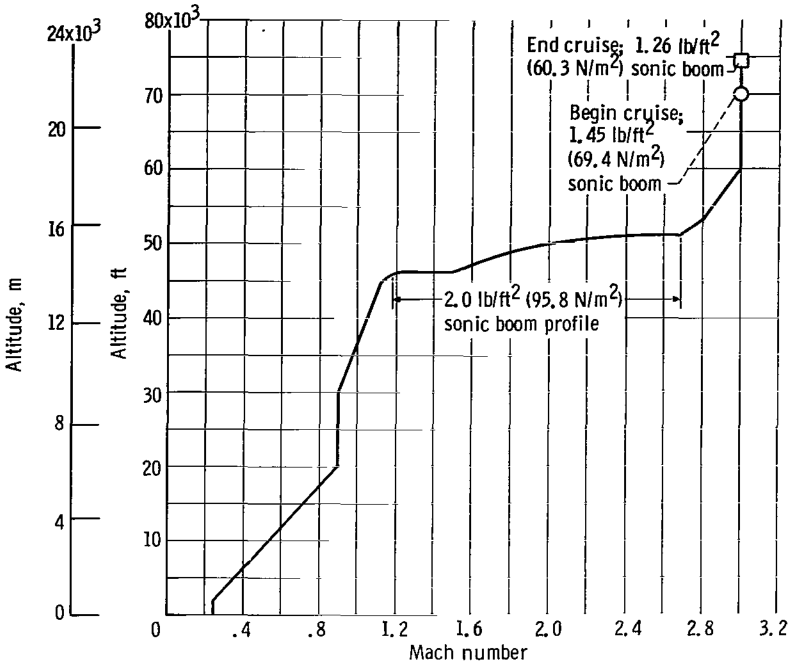


Figure 6. - Typical flight plan for unstaged airplane. Cruise altitude selected for maximum range; total range, 2400 nautical miles (4445 km); 200 passengers; takeoff gross weight, 371 000 pounds (168 283 kg).

use of the nondimensionalized plots of SCAT 15F sonic boom characteristics in reference 3 with correction factors applied for the nonuniformity of a standard atmosphere (ref. 9). The flight paths of all the airplanes considered in this study passed through the Mach 3, 60 000-foot set of coordinates - the condition from which the search for the optimum Breguet factor altitude was begun. Cruise for the case shown in figure 6 was begun at an altitude of 70 000 feet (21 336 m), where maximization of the Breguet factor occurred. A constant Breguet factor flight path was maintained during cruise so that the altitude at the end of cruise was 74 400 feet (22 677 m). For the case shown, the sonic boom decreased from 1.45 to 1.26 pounds per square foot (69.4 to 60.3 N/m^2) from the beginning to the end of cruise.

For the unstaged airplanes of this study, the reserve fuel allowance that was used included (1) an additional amount of fuel equal to 7 percent of the mission fuel, (2) fuel for a 261-nautical-mile (483-km) cruise to an alternate airport at the supersonic cruise altitude and Mach number, and (3) fuel for a 30-minute subsonic hold at Mach 0.6 at an altitude of 15 000 feet (4572 m). In addition to these reserve fuel requirements, an additional allowance was incorporated in the mission fuel for a 25-minute idle prior to takeoff, as well as 1 minute of maximum "dry" (nonafterburning) thrust prior to the start of takeoff roll. For the cruise stage of a two-stage vehicle, the reserve requirements are essentially the same as the preceding except that under item (1), 7 percent of the cruise and letdown fuel is allowed.

METHOD OF ANALYSIS

The effect of cruise sonic boom reduction on an airplane figure of merit (e.g., payload fraction W_L/W_G or range) was determined by "flying" analytically various sizes of the SCAT 15F configuration illustrated in figure 1 (p. 3). Attributes of this fixed arrow-wing design include its relatively high aerodynamic efficiency and low sonic boom. Since altitude and weight are important factors in the determination of sonic boom, initial cruise altitudes above the range-optimum were studied and airplanes smaller than the basic 200-passenger size were considered. Engine sizes were increased when required to minimize sonic boom by cruising at higher altitudes. Theory indicates that, for a given cruise weight, vehicle size (as represented by fuselage length) over a broad spectrum of values is not an important consideration in the determination of cruise sonic boom (as exemplified by the flatness of the top three curves of fig. 5(b), p. 9). Nevertheless, an attempt was made to minimize volume as payload was reduced in order to reduce structural weight and aerodynamic drag. Fuel economies that might thus be realized could result in a further reduction in airplane weight at the start of cruise. When airplane size was reduced, the various airframe components were scaled proportionally in order to maintain dimensional similarity. Hence, the nondimensionalized sonic boom and aerodynamic characteristics (ref. 3) used in the flight calculations were unaffected by airframe size changes.

Vehicle Sizes

Three vehicle sizes representing configurations with three-, four-, and five-abreast seating were considered in the study. Their principal size characteristics are indicated in table II. A seat pitch of 34 inches (86.36 cm) and seat and aisle widths of 19 inches (48.26 cm) were assumed in determining the volume-limited number of seats. The three-abreast-seating configuration with its nominal fuselage width of 7.66 feet (2.335 m) was the smallest size considered since smaller fuselage cross sections were deemed to be unacceptable from the standpoint of passenger comfort.

The basic 200-passenger airplane with five-abreast seating was designed to have a takeoff wing loading of 50 pounds per square foot (2394 N/m^2), the maximum value that could be used if lift-off velocity was not to exceed 165 knots (84.9 m/sec), as shown in reference 11. All the sizes indicated in table II did not necessarily have takeoff wing

TABLE II. - VEHICLE SIZES[a] INVESTIGATED

Number of seats abreast	Fuselage maximum width		Fuselage length		Wing planform area		Volume limited number of seats
	ft	m	ft	m	ft^2	m^2	
Five	10.42	3.176	242	73.76	7420	689.3	200
Four	8.95	2.728	208	63.40	5500	511.0	112
Three	7.66	2.335	178	54.25	4000	371.6	50

[a] Dimensional similarity maintained among all vehicle sizes.

loadings of 50 pounds per square foot (2394 N/m^2), however. In fact, wing loadings below this level are desirable from the standpoint of takeoff performance since lift-off can then be accomplished at lower speeds and in shorter distances. Although takeoff performance improves with lower wing loadings, the overall airplane figure of merit (e.g., payload fraction W_L/W_G) is likely to decrease as the result of a larger wing structural weight fraction (ref. 11).

For some of the airplane sizes considered, it is possible that to keep the takeoff wing loading at or below 50 pounds per square foot (2394 N/m^2) and meet the 2400-nautical-mile (4445-km) design range goal, it may be necessary to off-load passengers. In this study, under such circumstances, passenger furnishings and baggage are also off-loaded, although the fuselage lengths and widths are never changed from the values indicated in table II. Off-loading passengers in this manner, however, results in inefficient utilization of the available fuselage volume. A more efficient way of dealing with this type of situation would be to shorten the fuselage so that the available volume more nearly matches the actual passenger volume. Savings in both structural weight and drag should thus be accomplished. Unfortunately, shortening the fuselage without similarly changing all the other airplane dimensions would change the aerodynamic and sonic boom characteristics assumed for this study. To simplify the calculations, therefore, dimensional similarity was always maintained in spite of the excessive fuselage lengths sometimes encountered. The shortcomings of this procedure are minimized to a large extent in this study by considering three distinct airplane sizes covering a broad spectrum of passenger capacity. Thus, although a large-size vehicle may be forced to fly with less than its volume-limited number of passengers, a smaller (although dimensionally similar) vehicle can often accomplish the mission at the same level of cruise sonic boom with a more efficient utilization of the available fuselage volume.

The payload per passenger, which includes the weight of both the passenger and his baggage, is considered to be 200 pounds (90.72 kg). The weight of passenger furnishings and services that can be off-loaded (per passenger) is assumed to be 116 pounds (52.6 kg).

Engines

A takeoff thrust-to-gross-weight ratio of 0.32 is required to meet takeoff distance and thrust margin requirements, as described in reference 11 for similar types of airplanes. Engine sizes that produce ratios above 0.32 were considered in all cases in order to maximize the airplane figure of merit. The maximum "dry" (nonafterburning) thrust setting of the four single-spool afterburning turbojet engines was always used during takeoff in this study. The "dry" takeoff thrust setting was used because the jet noise problem is more severe at the higher jet velocities associated with afterburning. Even without afterburning, the calculated unsuppressed noise levels on a sideline 1500 feet (457 m) from the airplane centerline range from 2.3 to 3.5 perceived noise decibels (PNdB) above the 116-PNdB level suggested as a maximum acceptable limit (ref. 12). If the thrust setting were increased from maximum "dry" to full afterburning, the unsuppressed noise level would be further increased by about 2.6 PNdB. This would approximately double the amount of suppression required to meet the maximum noise limit. Noise suppressors, which are not considered in this study, usually penalize performance by degrading thrust and increasing engine weight. In order to minimize the amount of suppression required, it was arbitrarily decided in this study to limit the takeoff thrust to the maximum "dry" setting. Other engine characteristics are summarized as follows:

Design compressor pressure ratio	10
Design turbine inlet temperature, $^{\circ}$F ($^{\circ}$C)	2200 (1204)
Compressor bleed air for turbine cooling, percent	10
Maximum afterburner temperature, $^{\circ}$F ($^{\circ}$C)	3000 (1649)
Design compressor efficiency	0.875
Turbine efficiency	0.867
Primary combustor efficiency	0.98
Afterburner combustor efficiency	0.93
Inlet pressure recovery at Mach 3	0.850
Exhaust nozzle thrust coefficient at Mach 3:	
Minimum afterburning	0.977
Maximum afterburning	0.966

For all the unstaged airplane cases considered in this study, afterburning was begun at an altitude of 36 000 feet (10 973 m) where the transonic threshold is encountered and wave drag increases rapidly. Maximum afterburning thrust was then maintained until Mach 3 cruise when the engines were throttled back as necessary for thrust to equal drag. Installed cruise specific fuel consumption ranged from a minimum of 1.63 per hour at maximum "dry" thrust to a maximum of 1.99 per hour at full afterburning thrust. The term "installed" means that performance has been adjusted to include thrust degradation resulting from nacelle wave and friction drag, inlet boundary-layer bleed drag, internal nozzle performance, and external nozzle boat-tail drag.

When engine performance was calculated, the components were matched to satisfy the relations involving continuity of flow, engine rotational speed, and power balance between the compressor and its driving turbine. The procedures used are similar to those described in reference 13. A constant compressor shaft speed was maintained during the entire flight except when thrust was reduced below the maximum nonafterburning setting (e.g., during subsonic hold).

The total propulsion system weight for four engines was estimated from empirical data to be

$$\left.\begin{aligned} W_{eng} &= 47\ 100\left(\frac{W_a}{475}\right)^{1.2} \qquad \text{(lb)} \\ &\left[= 21\ 365\left(\frac{W_a}{215.5}\right)^{1.2} \qquad \text{(kg)}\right] \end{aligned}\right\} \tag{4}$$

This weight includes the weight of the gas generator, nozzle and thrust reverser, accessories, inlet, and nacelle.

The preceding comments apply also to the engines powering the second-stage cruise vehicle except that sizing is no longer related to takeoff or climb performance criteria. Engine size (i.e., sea-level-static-corrected airflow) is determined solely by the trade-off (as measured in terms of range or payload fraction) between the lower cruise specific fuel consumption that may be obtained at lower afterburner settings and the greater engine weight necessary to provide the additional airflow that allows these lower afterburner settings.

Structural Weight

Since variations in the size of both the unstaged airplane and the second-stage cruise vehicle were considered in this study (table II, p. 14) it is necessary to consider the associated changes in weight of some of the principal structural members. Unpublished empirical data from several sources were combined to obtain the following simplified structural weight equations which were used in this study:

$$\left.\begin{aligned} W_{wing} &= 2.36(W_G S)^{0.47} + 0.431\ S \quad (\mathrm{lb}) \\ &\left[= 4.76(W_G S)^{0.47} + 2.105\ S \quad (\mathrm{kg})\right] \end{aligned}\right\} \tag{5}$$

$$\left.\begin{aligned} W_{fus} &= 2.61(BL)^{1.167} \quad (\mathrm{lb}) \\ &\left[= 18.83(BL)^{1.167} \quad (\mathrm{kg})\right] \end{aligned}\right\} \tag{6}$$

$$W_{lg} = 0.0436\ W_G \tag{7}$$

$$W_{fsys} = 0.0209\ W_{fuel} \tag{8}$$

$$W_{hydr} = 0.01485\ W_G \tag{9}$$

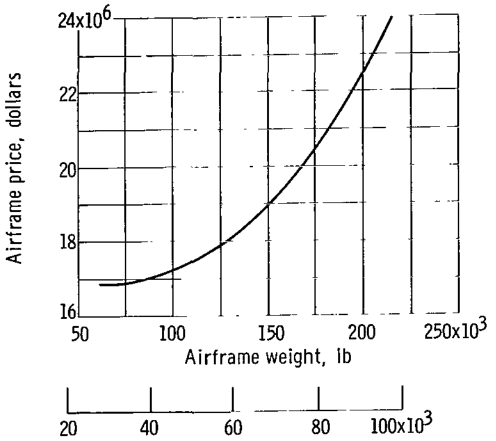
$$\left.\begin{aligned} W_{sc} &= 27.2\sqrt{S} + 5.74\ L \quad (\mathrm{lb}) \\ &\left[= 40.4\sqrt{S} + 8.54\ L \quad (\mathrm{kg})\right] \end{aligned}\right\} \tag{10}$$

The wing area S included in equations (5) and (10) and listed in table II is the wing projected area, including the area surrounded by the fuselage. The wing weight calculated by equation (5) includes the weight of the vertical control surfaces near the wing tips. The same weight equations are used for both the unstaged airplane and the second stage of a two-stage vehicle. For the same size vehicle, even though the same structural weight equations are used, different component weights are obtained for staged and unstaged vehicles. This is because the maximum gross weight W_G is different for the two concepts, since the amount of fuel and the engine size are different. The maximum gross weight W_G affects the wing, landing gear, and hydraulic and electrical system weights (eqs. (5), (7), and (9)) but not the fuselage weight (eq. (6)) or weight of controls for variable geometry aerodynamic surfaces (eq. (10)). The fuel system weight (eq. (8)) is indirectly affected by the gross weight because the weight of fuel required to accomplish a given mission is a function of gross weight. The wing weight is influenced by the gross weight because the wing must provide the lifting support for the entire airplane.

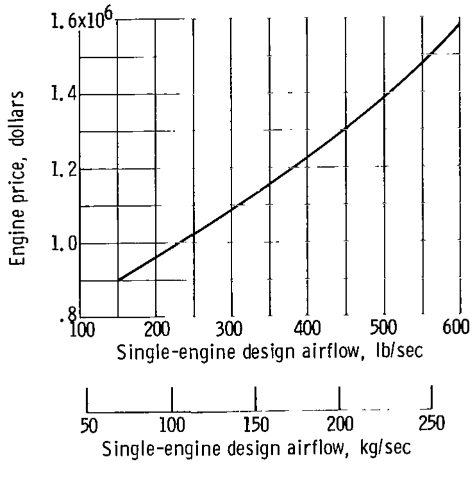
Hence, heavier vehicles require a stronger and thus heavier wing structure. The landing gear weight is also a function of the vehicular weight it must support and is, therefore, a function of the maximum gross weight W_G. In the case of the second-stage cruise vehicle, the same landing gear weight equation is justified on the grounds that the landing gear, as a conservative estimate, should be able to support the fully loaded second stage if an emergency landing is required immediately after separation from the first stage.

Cost Estimation

When accurate pricing information is available, DOC is a better figure of merit than payload fraction or range. In this study, the DOC for unstaged domestic airplanes is



(a) Airframe.



(b) Engine.

Figure 7. - Price estimates used in calculation of direct operating cost. Production of 200 airplanes, 1200 engines assumed, development costs included.

estimated according to a standard method designated by the Air Transport Association of America (ref. 14). Too many uncertainties are involved in the cost estimation of a two-stage system to justify its calculation. For the unstaged airplane, the airframe and engine prices are estimated from a combination of empirical data from several sources to vary with airframe weight and engine design airflow, respectively, as shown in figures 7(a) and (b). In addition, an assumed price of $1 million for electronics is included in the airplane price calculations. These price estimates include development costs and are based on a production of 200 aircraft. Engine pricing is based on a production of 1200 engines, with the viewpoint that each of the 200 four-engine aircraft will eventually require two spare engines. A time between engine overhaul of 2000 hours and a 3000-hour-per-year aircraft utilization are assumed. A fuel price of 11 cents per gallon ($29.06/m^3) is used in the calculations (as per FAA economic ground rules for a domestic SST, ref. 12).

RESULTS AND DISCUSSION

Unstaged Airplanes

Initial design at limiting takeoff wing loading. - As a first attempt in designing an airplane that is acceptable in terms of range and sonic boom, it was assumed that the series of airplanes listed in table II (p. 14) would have the specified maximum takeoff wing loading of 50 pounds per square foot (2394 N/m^2) (ref. 11). For the wing areas indicated in table II, this wing loading stipulation specifies a range of takeoff gross weights from 200 000 pounds (90 718 kg) for the three-abreast-seating case to 371 000 pounds (168 283 kg) for the five-abreast-seating case. Engine size was optimized for each airplane considered (with the constraint that the takeoff thrust-to-gross-weight ratio could not be below 0.32) in order to obtain the maximum range for each set of flight conditions.

Although a range of 2400 nautical miles (4445 km) is desired for each airplane under consideration, there is no guarantee that this goal will be achieved with the volume-limited number of passengers aboard and these takeoff gross weights. The range is largely determined by the weight of fuel on board, which is merely the difference between the gross weight and the weight of structure, fixed equipment, engines, and payload. The results of flight calculations for these dimensionally similar airplanes are shown in terms of range and initial cruise sonic boom in figure 8. Insufficient fuel was available for some of the airplanes with five-abreast seating to meet the 2400-mile (4445-km) range goal, while the airplanes with three- and four-abreast seating had more than enough fuel aboard to meet this goal. The 200-passenger basepoint airplane with five-abreast seating created an initial cruise sonic boom of 1.45 pounds per square foot (69.4 N/m^2) and had the

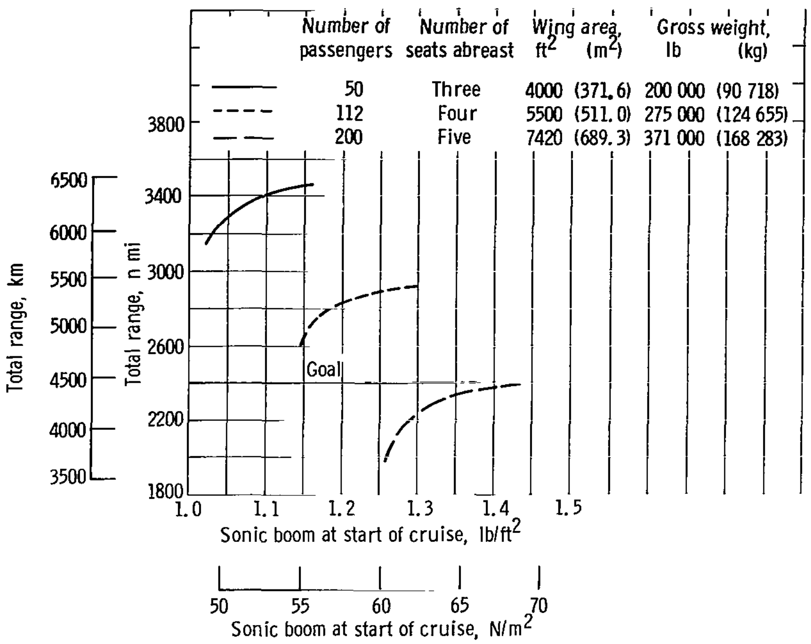
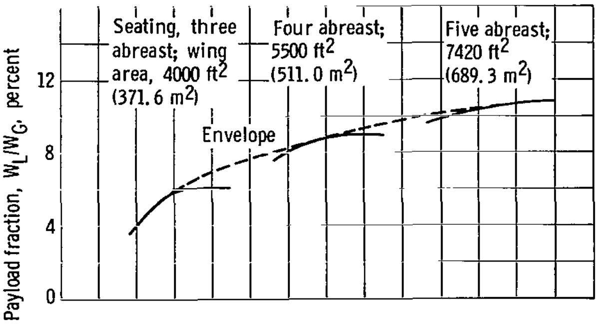


Figure 8. - Effect of initial cruise sonic boom on total range for various sizes of dimensionally similar unstaged airplanes. Takeoff wing loading, 50 pounds per square foot (2394 N/m^2).

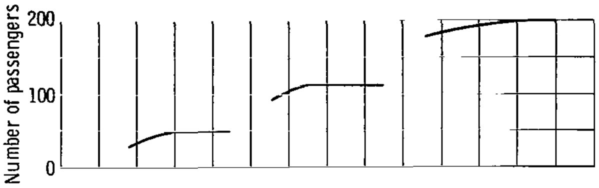
correct amount of fuel on board to meet the range goal. The maximum point at the right terminus of each of these curves represents a flight where cruise is begun at an altitude that maximizes the Breguet factor. The takeoff thrust-to-gross-weight ratio constraint of 0.32 determined the engine size at each of the right terminal points for these three curves. With engines sized in this manner, cruise at the range-optimum altitude is achieved with only a minimal amount of afterburning.

For each of the three airplane sizes considered in figure 8, the sonic boom may be reduced from the levels corresponding to maximum range by increasing the initial cruise altitude. This is accomplished by increasing the afterburner setting at the start of cruise, which results in a higher specific fuel consumption and an accompanying range penalty. If the initial cruise altitude is continually increased, the point is eventually reached where range is maximized by beginning cruise at the maximum afterburner setting, after which further increases in initial cruise altitude require larger engine sizes. As larger engines are installed, additional range penalties are incurred, even though the initial cruise specific fuel consumption remains fixed at its maximum afterburning value, because of the exchange of fuel weight for additional engine weight.

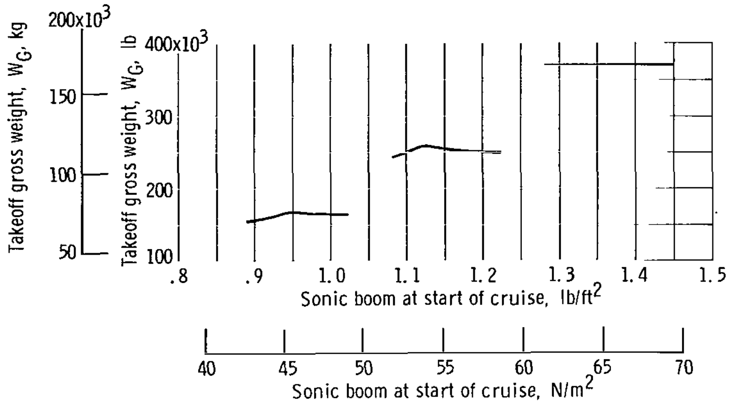
Improved design for a fixed range of 2400 nautical miles (4445 km). - The three curves of figure 8, representing the three airframe sizes, verify also that lighter airplanes produce lower sonic booms. The airplanes with three- and four-abreast seating could be made still lighter than indicated in figure 8 by reductions in fuel load to levels



(a) Payload fraction.



(b) Number of passengers.

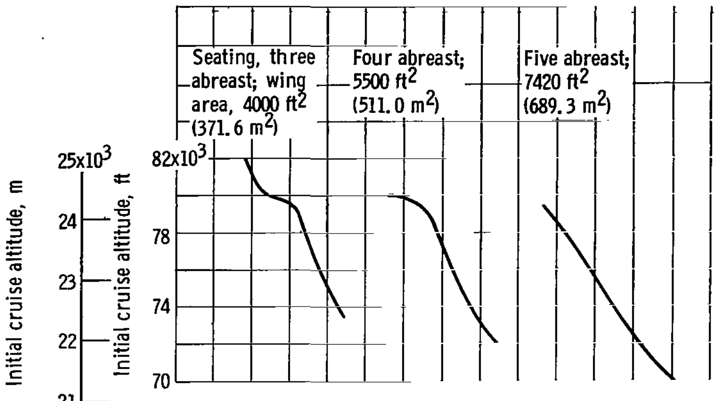


(c) Takeoff gross weight.

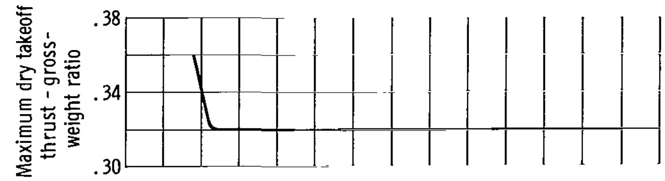
Figure 9. - Effect of initial cruise sonic boom on characteristics of unstaged airplanes. Total range, 2400 nautical miles (4445 km); dimensional similarity maintained among all airplanes.

more in accord with the 2400-nautical-mile (4445-km) range goal. Structural members such as wing and landing gear could be lightened by so doing. Engine weight could be reduced, too, because of the lower airflow which would be required to produce the necessary performance margins. Lower wing loadings would be obtained as a result of the reduced takeoff gross weights achieved with the three- and four-abreast seating configurations because the wing areas would remain unchanged at 4000 and 5500 square feet (371.6 and 511.0 m^2), respectively. Takeoff performance would thus be enhanced.

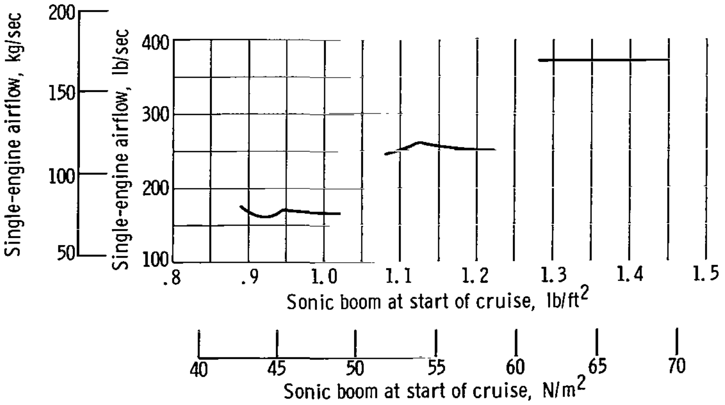
On the other hand, some of the airplanes with five-abreast seating fell short of the



(d) Initial cruise altitude.



(e) Takeoff thrust - gross-weight ratio.

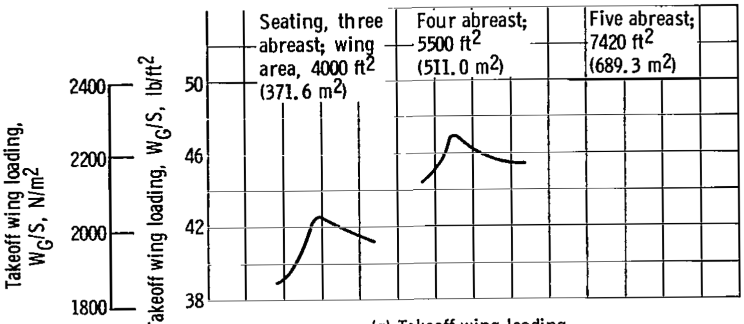


(f) Engine size.

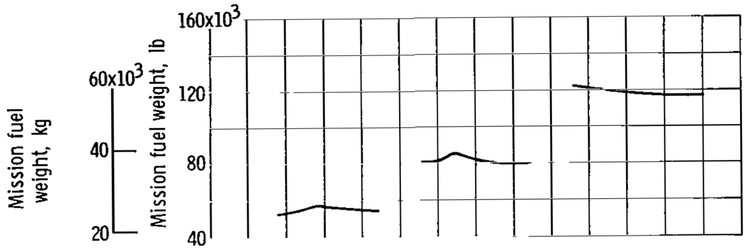
Figure 9. - Continued.

2400-mile (4445-km) range goal when the volume-limited payload corresponding to 200 passengers was carried and the limiting takeoff wing loading of 50 pounds per square foot (2394 N/m^2) was specified (fig. 8). To obtain the range goal, more fuel is required, but the number of passengers (and their baggage, furnishings, etc.) must be reduced to keep the takeoff gross weight from exceeding the 371 000-pound (168 283-kg) maximum imposed by the 50-pound-per-square-foot (2394-N/m^2) wing-loading-limit and the 7420-square-foot (689.3-m^2) wing area of this configuration.

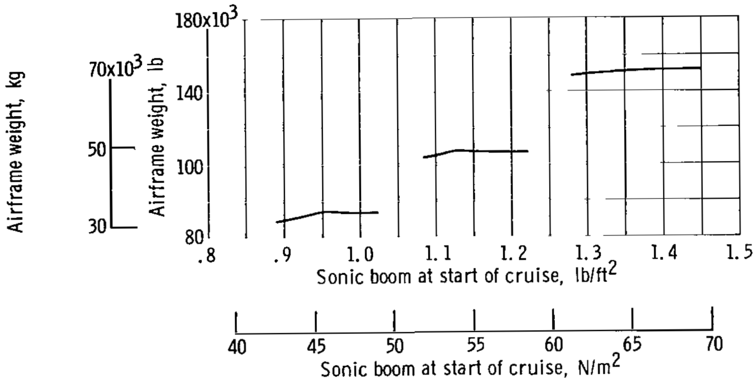
Iterative calculations were made until a 2400-nautical-mile (4445-km) range was ob-



(g) Takeoff wing loading.



(h) Mission fuel weight.



(i) Airframe weight.

Figure 9. - Concluded.

tained for all cases. The results of the study, shown in figure 9(a), indicate the manner in which the payload fraction W_L/W_G varies over a range of initial cruise sonic boom values for the three airframe sizes when the range goal of 2400 miles (4445 km) is met. Although the airframe dimensions are the same for the corresponding curves in figures 8 and 9(a), the weights of some of the structural components (e.g., wing and landing gear) are a function of maximum gross weight and may, therefore, be different. Likewise, since engine sizing is a function of gross weight, differences in engine weight also occur between corresponding curves of figures 8 and 9(a).

For each of the three airplane sizes considered, the payload fraction W_L/W_G decreases as initial cruise sonic boom is reduced. The payloads (as represented by the number of passengers) and takeoff gross weights comprising these payload fractions are shown in figures 9(b) and (c), respectively. Reductions in initial cruise sonic boom for each airplane size are obtained by increasing the altitude at which cruise is begun, as shown in figure 9(d). For the five-abreast-seating configuration, the higher cruise altitudes are obtained by off-loading passengers in exchange for additional fuel. For the two smaller configurations, the additional altitude is obtained, at first, by retaining a constant payload and increasing the weight of fuel and, hence, the takeoff gross weight. A similar situation would have occurred for the five-abreast configuration, too, had it not been for the takeoff wing loading restriction which prevented an increase in gross weight. For the two smaller configurations, a point is eventually reached where further reductions in sonic boom require the simultaneous reduction of both payload and gross weight. This occurs at an initial cruise sonic boom of 1.13 pounds per square foot (54.1 N/m^2) for the four-abreast configuration and 0.95 pound per square foot (45.5 N/m^2) for the three-abreast configuration. A more detailed discussion of these trade-offs will be found in the appendix.

Figure 9(e) shows that for the majority of cases the takeoff performance criterion regarding thrust-to-weight ratio (i.e., $F/W_G = 0.32$) sized the engines. For the three-abreast size of airplane, though, the reduction of initial cruise sonic boom below 0.92 pound per square foot (44.0 N/m^2) required that the engines be sized for the more severe initial cruise conditions. Sizing the engines for cruise allowed the takeoff thrust-to-gross-weight ratio to increase above the 0.32 value needed for adequate takeoff performance since the maximum "dry" thrust setting was always used at takeoff. The engine size (as represented by the corrected airflow at static, sea-level conditions) is seen in figure 9(f) to be influenced by both the takeoff thrust-to-gross-weight ratio and the takeoff gross weight.

Figure 9(g) shows that only the five-abreast configuration was limited by the stipulation that takeoff wing loading could not exceed 50 pounds per square foot (2394 N/m^2). The two smaller configurations have even better takeoff performance than the five-abreast size airplanes since their wing loadings are lower. The wing-loading curves are similar in shape to the gross-weight curves of figure 9(c) since the wing areas for each of the three airplane sizes remain constant.

The curves of mission fuel (excluding reserves) are seen from figure 9(h) to behave, as might be expected, in a manner similar to the curves of gross weight (fig. 9(c)). In regions where gross weight is constant when sonic boom is reduced, however, the mission fuel curves increase somewhat. These increases result partly from a greater expenditure of fuel in climb to a higher-than-Breguet-optimum cruise altitude. Then, too, once cruise begins at the higher altitudes, the time rate of fuel consumption increases as the result of an increase in the degree of afterburning required.

The curves of airframe weight (fig. 9(i)) are also seen to behave in a manner similar to the curves of takeoff gross weight (fig. 9(c)). This, too, might be expected since the weights of some of the airframe components (e.g., the wings and landing gear) are directly related to gross weight. There is another trend evident, also, for the airframe weight to decrease as the payload is reduced, even when there is no change in gross weight. This decrease in airframe weight is the result of the removal of passenger furnishings and services, which are considered to be a part of the airframe.

The various parts of figure 9 (i.e., parts (b) through (i)) which support the basic results of figure 9(a) are discussed in greater detail in the appendix. The important overall result which has been obtained is represented by the payload fraction envelope, the broken curve of figure 9(a), which has been drawn to enclose the family of solid curves representing the three specific airplane sizes considered in this study. If this envelope is considered, a maximum payload fraction W_L/W_G of 10.8 percent is obtained at an initial cruise sonic boom of 1.45 pounds per square foot (69.4 N/m^2). This condition is achieved by the 200-passenger basepoint airplane when cruise is begun at the optimum Breguet altitude. As lighter and/or smaller airplanes are considered to reduce the cruise sonic boom, the payload fraction decreases, as described in the preceding discussion. If airplanes larger than the basic five-abreast configuration considered herein were studied, it would be found that, due to the 50-pound-per-square-foot (2394-N/m^2) wing loading restriction imposed in this study, payload fraction would fall below the 10.8-percent maximum achieved with the basepoint configuration. For instance, if a six-abreast configuration were considered, a fuselage width of 12.08 feet (3.682 m) would be required. Dimensional similarity with the other configurations would permit 318 seats and the wing area would be 10 000 square feet (929.0 m^2). The gross weight of this configuration could not exceed 500 000 pounds (226 796 kg) without exceeding the wing loading restriction imposed in this study. At this takeoff gross weight with all seats occupied, calculations show that the maximum achievable range would be only 1950 nautical miles (3611 km). To achieve the 2400-mile (4445-km) goal, passengers (and their baggage, furnishings, services, etc.) would have to be off-loaded and additional fuel would have to be loaded on board. A payload fraction of only 10.4 percent would result. Hence, for this particular configurational type, the envelope curve of figure 9(a) will reach a true maximum at a payload fraction of about 10.8 percent at an initial cruise sonic boom in the vicinity of 1.45 pounds per squre foot (69.4 N/m^2).

As sonic boom is reduced, the payload fraction envelope curve (fig. 9(a)) is tangent to the curve representing the four-abreast configuration at values of initial cruise sonic boom as low as 1.12 pounds per square foot (53.6 N/m^2), where a payload corresponding to 111 passengers is obtained. At this point, sonic boom and payload fraction have been reduced about 23 and 20 percent, respectively, below the levels corresponding to the maximum point on the envelope curve. Although the real significance of the resulting 8.60-percent payload fraction cannot be determined until the penalty in direct operating cost is computed, it is doubtful that an initial cruise sonic boom of 1.12 pounds per square foot (53.6 N/m^2) is low enough to reduce the level of annoyance appreciably. This becomes increasingly evident when it is recognized that the theoretical calculations quoted herein are for a nominal boom only. Booms several times higher may occur during steady-level flight under certain nonstandard atmospheric conditions or during maneuver or acceleration.

The sonic boom at the end of cruise is somewhat less severe than at the beginning of cruise because of the lower weight and the (sometimes) higher altitude at the end of cruise. For instance, for the case just considered, the sonic boom decreased from 1.12 pounds per square foot (53.6 N/m^2) at the beginning of cruise to 1.03 pounds per square foot (49.3 N/m^2) at the end of cruise. This occurred because the airplane weight decreased from 220 524 to 175 445 pounds (100 028 to 79 581 kg) as the result of the expenditure of the cruise fuel. The altitude, however, remained constant at 79 400 feet (24 201 m) because the optimum Breguet cruise condition was never achieved for this particular case. That is, at the constant altitude condition, the Breguet factor continually increased as cruise progressed. Somewhat better results were obtained in this case by changing the ground rules to allow the airplane to fly a constant overpressure (i.e., slightly descending) cruise flight path until the maximum Breguet factor conditions were obtained. This improved cruise procedure allowed the airplane under discussion to achieve an additional range of about 60 nautical miles (111 km). If the range is fixed at 2400 nautical miles (4445 km), this improvement can be translated into a payload fraction of 8.70 percent instead of the 8.60-percent result shown in figure 9(a).

The sonic boom problem is somewhat mitigated by the fact that the airplane does not go supersonic, in this case, until about 67 nautical miles (124 km) after takeoff, thus giving it ample distance to clear the densely populated area likely to surround the airport. Furthermore, the supersonic climb and acceleration part of the flight occurs over the relatively short range of 266 miles (493 km) while the most severe portion of this (where the sonic boom is 2.00 lb/ft^2 or 95.8 N/m^2) is only about 130 miles (241 km) in range. Hence, if it is decided that the cruise sonic boom of such an airplane is acceptable, it may be possible to route it so that the most annoying part of climb occurs over sparsely populated areas.

As initial cruise sonic boom is reduced still further, the payload fraction envelope curve of figure 9(a) becomes initially tangent to the curve representing the three-abreast configuration at the seat-limited payload corresponding to 50 passengers. The sonic boom at the initial point of tangency is 0.95 pound per square foot (45.5 N/m^2) and the payload fraction W_L/W_G is 5.95 percent. The envelope curve is coincident with the solid curve for three-abreast seating from the initial point of tangency down to the lowest sonic boom considered (0.89 lb/ft^2 or 42.6 N/m^2) because the 7.66-foot (2.335-m) nominal fuselage width of this configuration was considered to be the minimum size acceptable for passenger comfort.

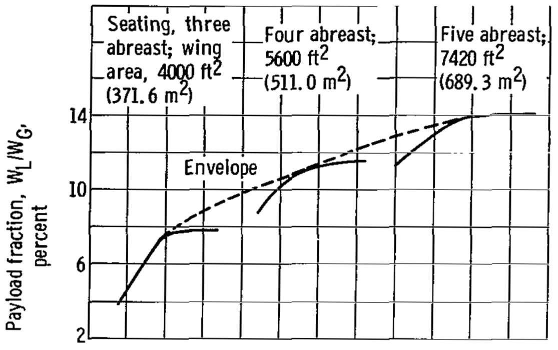
Points on the payload envelope curve located between adjacent solid curves in figure 9(a) represent physically attainable configurations, but the fuselage width dimensions obtained from considerations of dimensional similarity necessitate inconvenient and, perhaps, impractical seating arrangements. The important point to be garnered from the results presented in figure 9(a) is that high payload fraction and low cruise sonic boom, although mutually desirable, are impossible to obtain simultaneously. The best that can be obtained is a moderate sonic boom reduction at the expense of a reduction in payload fraction that may prove to be significant, depending on the outcome of calculations of DOC. Although only afterburning turbojet engines were considered in the present study, previous analytical studies of both duct-burning and afterburning turbofan engines (ref. 15) indicate that their use probably would not significantly change the overall results.

Staged Vehicles

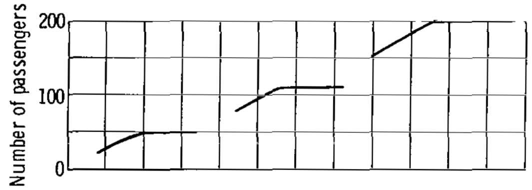
Iterative flight calculations were made for a series of two-stage vehicles until a 2400-nautical-mile (4445-km) range was obtained for each two-stage system. The range up to the beginning of cruise, where staging occurs, was assumed to be 300 nautical miles (556 km). Aside from its 300-mile (556-km) contribution to the total system range of 2400 nautical miles (4445 km), the boost vehicle was not otherwise considered. The payload and initial cruise gross weight of each second-stage vehicle were varied to obtain a 1900-nautical-mile (3519-km) cruise range. As with the unstaged airplanes, a letdown range of 200 nautical miles (371 km) was assumed for all the cruise stages.

The second-stage vehicle sizes (table II, p. 14) were the same as those considered for the unstaged airplanes. In figure 10(a), the three solid curves representing these vehicle sizes show the variation of the cruise stage figure of merit against initial cruise sonic boom after stage separation has been completed. The stage figure of merit considered here is the payload fraction W_L/W_G, where W_G in this case is the maximum (initial cruise) gross weight of the cruise stage only. Hence, these results cannot be directly compared with those of figure 9(a) (p. 21) for unstaged airplanes since, in that case, the figure of merit is the payload fraction based on the gross weight of the entire system at takeoff. Nevertheless, the trends indicated by the curves of figure 10(a) for the cruise stages of two-stage systems are the same as those of figure 9(a) for unstaged airplanes. That is, they show that initial cruise sonic boom for each particular vehicle size can be reduced at some sacrifice in payload fraction and that still greater reductions in boom can be obtained by reducing vehicle size.

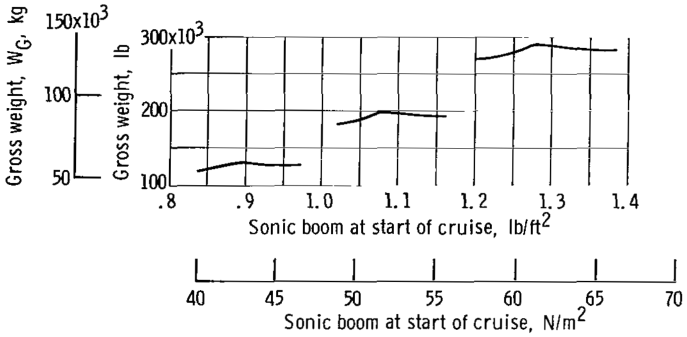
The payloads (as represented by the number of passengers) and the second-stage gross weights comprising the payload fractions of figure 10(a) are shown in figures 10(b) and (c), respectively. The shapes of these curves, with the exception of the five-



(a) Payload fraction, where W_G is second-stage gross weight at start of cruise.



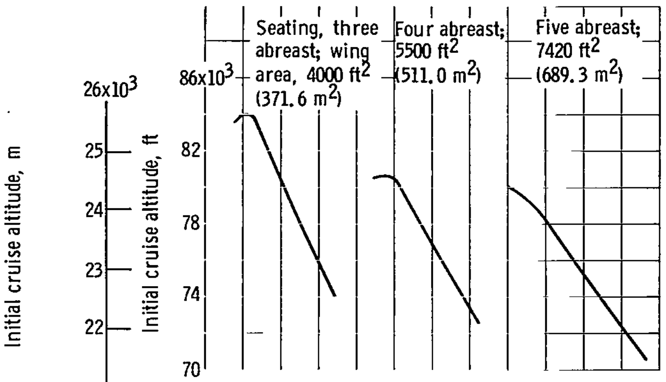
(b) Number of passengers.



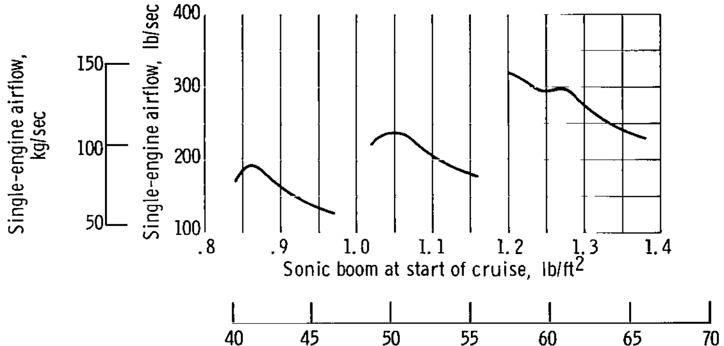
(c) Second-stage gross weight at start of cruise.

Figure 10. - Effect of initial cruise sonic boom on characteristics of second stage of series of dimensionally similar two-stage vehicles. Stage separation immediately prior to start of cruise; second-stage range, 2100 nautical miles (3889 km).

abreast configuration, are similar to their counterparts in figure 9 for unstaged airplanes. The five-abreast, second-stage vehicles are not limited by the wing-loading restriction that affected the corresponding size of unstaged airplane. In general, the reductions in initial cruise sonic boom that are obtained for each configuration are achieved by increasing the altitude, as shown in figure 10(d). Near the lower extremities of sonic boom for the two smaller configurations, however, the gross-weight reductions at the start of cruise are such that increases in altitude are no longer necessary to lower the sonic boom. A more detailed discussion of this and the other trade-offs involved in maximizing the payload fraction at each level of sonic boom will be found in the appendix.



(d) Initial cruise altitude.

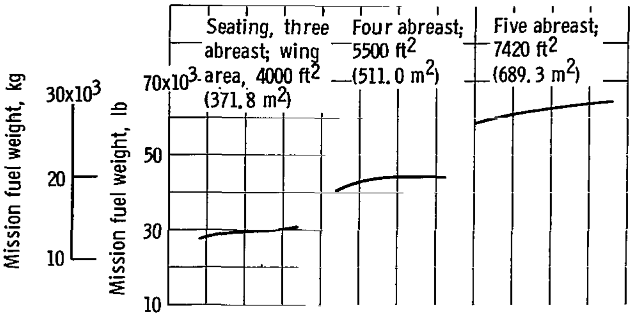


(e) Engine size. Airflow is design corrected airflow at static, sea-level conditions.

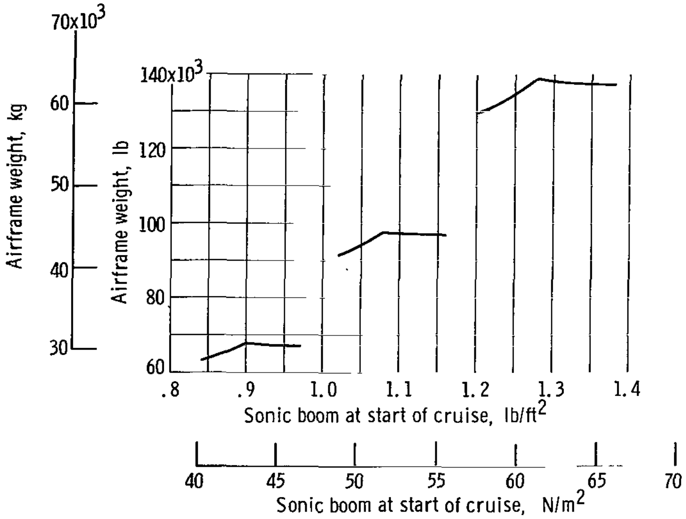
Figure 10. - Continued.

The engine size (fig. 10(e)), in general, rises for each vehicle size as initial cruise sonic boom is reduced. In contrast to the results obtained with unstaged airplanes, takeoff performance levels are not a criterion for determining engine size. The engines, in this case, are always sized for initial cruise conditions. Weight and performance tradeoffs indicate that payload fraction is optimized in all cases with a significant degree of afterburning at the start of cruise. In contrast, with many of the unstaged airplanes having engines sized by takeoff conditions, only a minimal amount of afterburning was required at the start of cruise. This accounts for much of the difference between the shapes of the corresponding curves of figures 9(f) and 10(e). Although the engine size of the second-stage vehicles generally increases as sonic boom is reduced, decreases in initial cruise gross weight or altitude may cause an interruption of the general upward trend. This point is more fully discussed in the appendix.

The curves of mission fuel weight (fig. 10(f)) in many cases display opposite trends than were observed for corresponding sizes of unstaged airplanes (fig. 9(h)). An im-



(f) Mission fuel weight.



(g) Airframe weight.

Figure 10. - Concluded.

portant difference is that with the second-stage vehicles the climb fuel is not included in the calculation of mission fuel. Hence, the mission fuel weight is dependent only on the rate of fuel consumption in cruise and letdown. For all the second-stage vehicles considered, the degree of afterburning at the start of cruise fluctuates only slightly, in contrast to the greater variation obtained with the unstaged airplanes. Hence, a fairly constant initial cruise fuel-air ratio is obtained. The actual airflow, therefore, must decrease to obtain the reduction in mission fuel in spite of the fact that the trend in corrected airflow continues upward as sonic boom is reduced. The decrease in ambient pressure more than compensates for the increase in corrected airflow to produce a decline in actual airflow (see appendix).

The airframe weights of the second-stage vehicles are shown in figure 10(g). The similarity between the shapes of these curves and the three- and four-abreast curves of figure 9(i) is evident. The same reasoning that was previously used to explain the shape of these two curves in figure 9(i) can now be used for all three curves of figure 10(g).

For the interval over which the payload is constant, the airframe weight increases because of increases in the weights of such gross-weight-related components as the wings and landing gear. Over the sonic boom intervals where payload declines, the airframe weight decreases because of a decline in the weights of both the gross-weight-related components and the payload-related items such as passenger furnishings and services.

Figures 10(b) through (g) support the basic results obtained in figure 10(a) concerning payload fraction. The important overall result is represented by the payload fraction envelope, the broken curve of figure 10(a), which encloses the family of solid curves representing the three specific vehicle sizes considered in this study. The envelope curve appears to achieve a maximum payload fraction of 14.1 percent with a five-abreast configuration accommodating 200 passengers. Actually, the envelope probably does not reach a true maximum at this point since there is no wing-loading limitation on larger size vehicles necessitating their operation at less than capacity, as was the case with unstaged airplanes. If the envelope curve is linearly extrapolated to the right from its initial point of tangency with the five-abreast curve, the payload fraction at the 1.38-pound-per-square-foot (66.1-N/m^2) level of sonic boom would be 14.7 instead of 14.1 percent. Exact calculations were not made for larger configurations, however, and since only a slight error could be introduced, for the sake of simplicity it will be assumed in future discussion that the envelope coincides with the solid curve for five-abreast seating from a sonic boom of 1.28 to 1.38 pounds per square foot (61.3 to 66.1 N/m^2). Over this range of sonic booms, the payload remains constant at 40 000 pounds (18 140 kg), corresponding to the maximum capacity of 200 passengers.

As initial cruise sonic boom is reduced below the 1.28-pound-per-square-foot (61.3-N/m^2) level, the envelope of figure 10(a) diverges from the five-abreast curve and becomes tangent to the four-abreast curve at a sonic boom of 1.09 pounds per square foot (52.2 N/m^2) and a payload fraction of 11.2 percent. The volume-limited number of passengers (112) is obtained at the point of tangency with the four-abreast seating curve. The sonic boom and payload fraction at this point have both been reduced about 21 percent below the levels corresponding to the maximum point on the envelope.

Further reductions in sonic boom at the start of cruise cause the envelope curve to diverge almost immediately from the four-abreast seating curve. The payload envelope first becomes tangent to the three-abreast curve at a sonic boom of 0.90 pound per square foot (43.1 N/m^2) where the payload fraction is 7.50 percent. A payload corresponding to 50 passengers, the volume limit for the three-abreast configuration, is obtained at this point. The envelope remains coincident with the three-abreast-seating curve as sonic boom is reduced from 0.90 to 0.84 pound per square foot (43.1 to 40.2 N/m^2). As sonic boom is reduced over this interval, payload fraction correspondingly declines from a level of 7.50 to 3.90 percent and the number of passengers drops from the volume limit of 50 to 23.

Hence, it is necessary to reduce the payload fraction approximately 72 percent below the level obtained at the maximum point on the envelope curve to reduce the sonic boom 39 percent to the minimum level considered in this study (0.84 lb/ft^2 or 40.2 N/m^2). As was shown to be the case with unstaged airplanes, moderate reductions in initial cruise sonic boom can also be obtained with staged vehicles at the expense of significant reductions in a figure of merit such as payload fraction.

Comparison of Staged and Unstaged Vehicles

In figure 11 the payload fraction envelope curves of figures 9(a)(p. 21) and 10(a) (p. 28) have been replotted for comparison. Caution is again drawn to the fact that although the payload fraction W_L/W_G is based on maximum gross weight W_G for the two curves, the maximum gross weight of the staged vehicle is for the cruise stage only since the boost stage was ignored in this study. Hence, the maximum gross weight of the unstaged airplane represents the weight of the entire system (i.e., the takeoff gross weight) whereas the maximum gross weight of the second stage of a two-stage vehicle represents only a part of the total system weight.

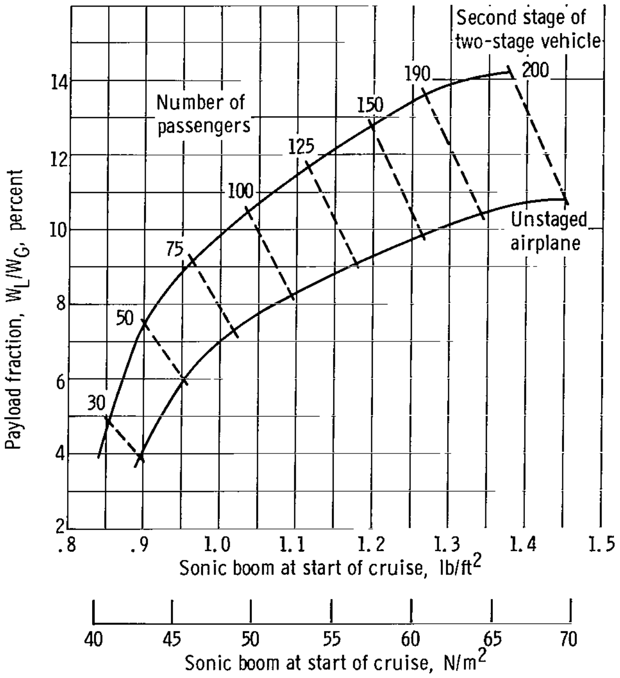


Figure 11. - Comparison of initial cruise sonic booms between staged and unstaged vehicles carrying equal numbers of passengers. Total range, 2400 nautical miles (4445 km); second-stage range, 2100 nautical miles (3889 km) with assumed boost range of 300 nautical miles (556 km); W_G is takeoff gross weight for unstaged airplane and initial cruise gross weight for second stage of two-stage vehicle.

A comparison of the payload fractions between the two curves, therefore, would be meaningless. The only comparison that will be made between them is one of initial cruise sonic boom for equal numbers of passengers. Payload estimates have been made for various points along each of the two curves, and points having equal numbers of passengers have been connected by broken lines, as shown. The comparison shows that staging will allow a reduction of 0.07 pound per square foot (3.3 N/m^2) in initial cruise sonic boom at the high end of the payload spectrum down to a reduction of 0.04 pound per square foot (1.9 N/m^2) at the low end. Over the payload spectrum shown (i.e., from 30 to 200 passengers), staging appears to provide an initial cruise sonic boom reduction of approximately 5 percent. Thus, staging does not offer very significant reductions in cruise sonic boom, even when the technical problems and additional expense associated with it are ignored, as is the case in this study.

Cruise sonic boom is not reduced more by staging because the need for large engines is not entirely eliminated. Although the engines are, in general, somewhat smaller than they are for corresponding sizes of unstaged airplanes, the difference is not as great as might have been expected. The minimization of sonic boom requires flight at very high altitudes where large engines are necessary. The relatively large engines tend to prevent much reduction in the gross weight of the cruise stage. A saving in structural weight is obtained, however, since such components as the wing and landing gear are not required to support the extra weight of the climb fuel. The structural weight savings tend to reduce the gross weight of the vehicle. The net result is that the structural weight savings more than compensate for any increase in engine weight.

The magnitude of the reduction in sonic boom that can be obtained by staging decreases as vehicle size and gross weight (and, hence, the number of passengers) are reduced. The weight of climb fuel for the unstaged airplanes decreases and eventually the engine size requirements of both staged and unstaged vehicles are approximately equal. Hence, the initial cruise gross weight of the staged vehicle begins to approach that of the unstaged airplane and the corresponding sonic booms become more nearly equal.

Direct Operating Cost

In the present study, DOC estimates are made for the series of unstaged airplanes represented by the payload fraction curves of figure 9(a) (p. 21). No DOC estimates are made for a two-stage vehicle since too many unknowns exist to justify their calculation. In addition to information already presented in figure 9 concerning airplane size, weight, and performance, additional information concerning the cost of engine, airframe, and mission fuel is required for the DOC computations. The engine weights can be calculated by means of equation (4) (p. 16) from the airflows presented in figure 9(f). These weights and the airframe weights shown in figure 9(i) can be used in conjunction with the curves of figures 7(a) and (b) (p. 18) to obtain engine and airframe prices. The mission fuel cost can be computed from the mission fuel weights of figure 9(h) and the specific fuel cost (1.64 cents/lb or 3.62 cents/kg).

The results of the DOC calculations for the series of unstaged airplanes are presented in figure 12. A minimum DOC envelope (broken curve) has been drawn around the family of solid curves representing the three airframe sizes under investigation. The minimum DOC was obtained with the basic 200-passenger configuration having a five-abreast seating arrangement. This DOC level of 1.07 cents per seat-statute mile (1.23 cents/seat-n. mi. or 0.665 cent/seat-km) is competitive with the level obtained with subsonic jet transports now in existence.

The minimum DOC envelope very nearly coincides with the solid curve representing the five-abreast configuration as initial cruise sonic boom is reduced from 1.45 to 1.30 pounds per square foot (69.4 to 62.2 N/m^2). A gradual increase in DOC occurs for this configuration as the initial cruise altitude is increased above the payload optimum of 70 000 feet (21 336 m) to a level of 78 400 feet (23 896 m) in order to reduce the initial cruise boom. It appears that reductions up to about 10 percent in initial cruise boom can be accomplished in this area with approximately equal percentage rises in DOC. The gradual rise in DOC for this configuration is the result of the exchange of payload for ad-

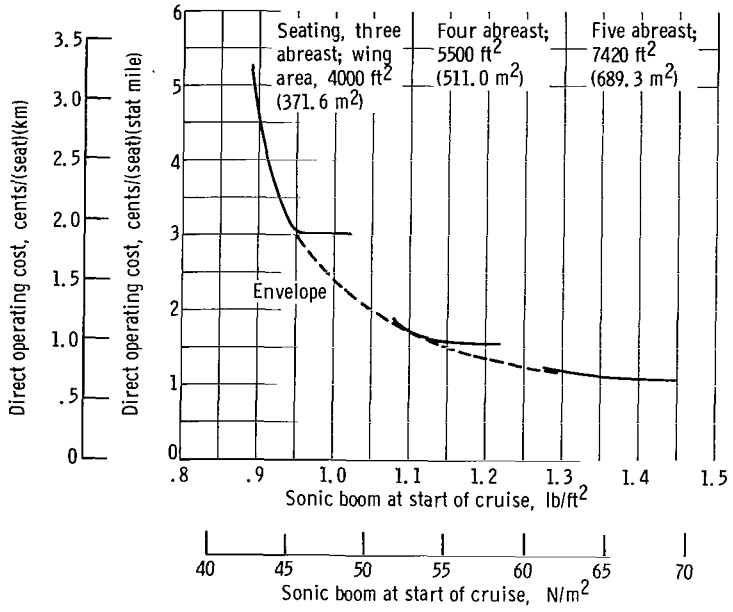


Figure 12. - Effect of initial cruise sonic boom on direct operating cost of unstaged airplanes. Total range, 2400 nautical miles (4445 km); dimensional similarity maintained among all airplanes.

ditional fuel as the initial cruise altitude requirement is increased and takeoff gross weight is held constant at 371 000 pounds (168 283 kg).

For the four- and three-abreast configurations, it is apparent from figure 12 that, as initial cruise altitude is increased above the optimum to reduce sonic boom, the increase in DOC is hardly noticeable at all until the solid curves representing these two configurations become tangent to the envelope curve. This is because the payload remains practically constant at the volume-limited capacity until the point of tangency is reached, since the takeoff gross weight is allowed to increase as additional fuel is added to meet the higher altitude requirements for lower cruise booms. The minimum DOC envelope curve is tangent to the four-abreast seating curve at a DOC of 1.60 cents per seat-statute mile (0.994 cent/seat-km) and an initial cruise sonic boom of 1.12 pounds per square foot (53.6 N/m^2). Although this sonic boom is about 23 percent below the level of the 200-passenger basepoint airplane, the DOC is about 50 percent higher than that of the basepoint. Although, as was previously stated (p. 26), the importance of the 23-percent boom reduction is questionable, one can hardly argue against the premise that a 50-percent increase in DOC is a significant economic penalty.

As sonic boom is reduced still further, the envelope becomes tangent to the three-abreast curve at a DOC of 3.03 cents per seat-mile (1.88 cents/seat-km) and an initial cruise sonic boom of 0.95 pound per square foot (45.5 N/m^2). A DOC almost three times as much as could be obtained with the basepoint airplane is a severe economic penalty to pay for a 35-percent reduction in sonic boom. As passengers and their seats and baggage are removed from the airplane, higher cruise altitudes and lower sonic booms are obtained at the expense of a greater engine-plus-fuel weight fraction. As initial cruise sonic boom was decreased from 0.95 to 0.89 pound per square foot (45.5 to 42.6 N/m^2), payload decreased from 50 to 29 passengers and DOC increased from 3.03 to 5.25 cents per seat-mile (1.88 to 3.26 cents/seat-km). As mentioned in a previous discussion concerning payload fraction (p. 26), the minimum DOC envelope must coincide with the solid curve for three-abreast seating from a sonic boom of 0.95 to 0.89 pound per square foot (45.5 to 42.6 N/m^2) because this configuration was deemed to be the minimum acceptable size from the standpoint of passenger comfort.

CONCLUDING REMARKS

An analytical study was made to determine the amount the cruise sonic boom of a Mach 3 supersonic transport might be reduced by making the airplane smaller and lighter. A similar study was made for a two-stage vehicle with stage separation just before the start of cruise. Staging is admittedly a radical concept, especially after considering the original FAA guidelines on SST development which had characterized an SST as a vehicle flying in a more conventional manner using existing airport facilities. The family of vehicles (both staged and unstaged) chosen for the study was assumed to have sonic boom and aerodynamic characteristics similar to the NASA-Langley SCAT 15F.

The results of the present study show that for a range of 2400 nautical miles (2764 stat. mi. or 4445 km, the approximate range from Miami to Seattle), the initial cruise sonic boom of the basic 200-passenger airplane would be 1.45 pounds per square foot (69.4 N/m^2). A ramp gross weight of 371 000 pounds (mass) (168 283 kg) would be required, resulting in a payload which is 10.8 percent of the gross weight. The corresponding DOC was calculated to be 1.07 cents per seat-statute mile (0.665 cent/seat-km) - a level which is competitive with costs of existing subsonic domestic jets. Initial cruise sonic boom could be decreased to a level of about 1.30 pounds per square foot (62.2 N/m^2) with an attendant DOC rise of 10 percent. This could be accomplished without any sacrifice in total range by increasing the initial cruise altitude from 70 000 to 78 400 feet (21 336 to 23 896 m) while exchanging payload for additional fuel. Further sonic boom reductions could be accomplished only with increasingly severe economic penalties. For example, when the initial cruise sonic boom is reduced to 1.12 pounds per square foot (53.6 N/m^2), the payload must be reduced to a level corresponding to 111 passengers. The DOC then rises to 1.60 cents per seat-statute mile (0.994 cent/seat-km). Hence, to obtain a 23-percent cruise boom reduction, the economic penalty would be a DOC increase of about 50 percent from the level of the 200-passenger basepoint airplane. With the smallest size airplane considered in this study, the initial cruise sonic boom could be reduced to a minimum of 0.89 pound per square foot (42.6 N/m^2) at the expense of a DOC rise to 5.25 cents per seat-mile (3.26 cents/seat-km). In commercial operation, such an increase in DOC would be a severe economic penalty to pay for a sonic boom reduction to this level. Even if such a penalty could be accepted, the significance of the resulting sonic boom reduction is certainly questionable. It must be remembered that the theoretical calculations are for a nominal boom only. The actual boom could be several times higher if atmospheric conditions were nonstandard or if maneuver or acceleration occurred.

The concept of staging appears to offer little potential for an economical low boom vehicle. The comparison made in this study between staged and unstaged vehicles of the same passenger capacity shows that staging will provide a reduction of approximately 5 percent in initial cruise sonic boom for the spectrum of payloads studied. Staging does not provide more significant sonic boom reductions because the need for large engines is not entirely eliminated. The minimization of sonic boom requires flight at very high altitudes where relatively large engines are necessary. The need for large engines, unfortunately, limits the saving in initial cruise gross weight that can be obtained with staging. Staging does permit, however, a reduction in the structural weight of such components as the wing and landing gear since these members are not required to support the extra weight of the climb fuel. The reduced airframe structural weight allows the initial cruise weight of the second-stage vehicle to be somewhat lighter than the corresponding weight for an unstaged airplane of the same payload capacity. Although no attempt is made in this report to analyze the economics of staging, it is almost certain that the additional complexities that would be involved with such a system, when considered together with the very small potential sonic boom reductions in cruise, would discourage its further consideration.

The high level of aerodynamic efficiency and the low sonic boom characteristic of the SCAT 15F designs considered in this study were achieved through extensive use of area ruling and warping of the aerodynamic surfaces. Even if further research yields an airframe with somewhat better aerodynamic or sonic boom characteristics, higher altitudes and lower gross weights at the beginning of cruise are imperative for any further significant reduction in cruise sonic boom. The kerosene-fueled afterburning turbojet engines considered in this study do not provide the high levels of performance that are required for further cruise sonic boom reductions. Previous analytical studies of both duct-burning and afterburning turbofan engines suggest that their use (instead of the afterburning turbojet engines considered herein) would not significantly change the results. The complete solution of the sonic boom problem is not readily apparent.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 3, 1968,
789-50-01-01-22.

APPENDIX - TRADE-OFFS INVOLVED IN MAXIMIZING PAYLOAD FRACTION

Unstaged Airplanes

Airplane size with five-abreast seating arrangement. - As the altitude at the start of cruise is increased in order to reduce the sonic boom, a weight exchange of some of the passengers (including their baggage and passenger furnishings, services, etc.) for extra fuel is necessary to meet the 2400-mile (4445-km) range requirement with the five-abreast airplane size. Thus, as initial cruise boom is reduced from 1.45 to 1.28 pounds per square foot (69.4 to 61.3 N/m^2), the number of passengers (fig. 9(b) p. 21) decreases from 200 to 178 as the takeoff gross weight (fig. 9(c)) remains constant at the 371 000-pound (168 283-kg) maximum limit imposed by the 50-pound-per-square-foot (2394-N/m^2) wing-loading restriction. For this reduction in boom, the payload fraction W_L/W_G (fig. 9(a)) decreases from a level of 10.8 to 9.60 percent.

To achieve this 11.7-percent boom reduction, figure 9(d) shows that it was necessary to increase the initial cruise altitude from 70 000 to 79 500 feet (21 336 to 24 232 m). These higher altitudes were achieved without increasing the maximum nonafterburning takeoff thrust-to-gross-weight ratio F/W_G beyond the 0.32 level dictated by takeoff requirements, as is shown in figure 9(e). Since neither this ratio nor the gross weight change for this size airplane, the engine design corrected airflow at static, sea-level conditions (fig. 9(f)) must remain constant at 372 pounds per second (168.7 kg/sec) as sonic boom is reduced. The actual (i.e., uncorrected) airflow at the start of cruise must decrease, however, because of the decline in ambient atmospheric pressure as altitude increases. The greater performance demands made on these engines at the higher initial cruise altitudes are met by increasing the degree of afterburning, which, in turn, increases the fuel-air ratio.

Despite the greater amount of fuel required to accomplish the mission when cruise is started at a higher-than-Breguet-optimum altitude, the reduction in passengers (and their baggage, furnishings, etc.) permitted the takeoff wing loading (fig. 9(g)) to remain constant at its limiting value of 50 pounds per square foot (2394 N/m^2). Much of the increase in the mission fuel requirement at the lower initial cruise sonic booms is the result of a greater amount of fuel consumed during the climb up to the higher cruise altitudes. In spite of the fact that fuel-air ratio at the start of cruise increases as the altitude is increased, the decline in actual airflow tends to compensate to a degree so that the time-rate of fuel consumption at the start of cruise holds relatively constant over the sonic boom decrement from 1.45 to 1.35 pounds per square foot (69.4 to 64.6 N/m^2). Further reductions in sonic boom, however, tend to cause this fuel consumption rate to increase, as the increases in fuel-air ratio tend to overshadow the declining uncorrected airflow. Figure 9(h) shows that the combination of all these factors causes the mission fuel (excluding reserves) to increase from 116 100 to 121 700 pounds (52 662 to 55 202 kg) as initial cruise boom is reduced from 1.45 to 1.28 pounds per square foot (69.4 to 61.3 N/m^2).

The airframe weight (i.e., the airplane empty weight less the podded engines but including the furnishings, survival equipment, etc.) is shown in figure 9(i). It decreases from 151 000 to 148 600 pounds (68 492 to 67 404 kg) as initial cruise sonic boom is reduced from 1.45 to 1.28 pounds per square foot (69.4 to 61.3 N/m^2). This decrease is attributed to the removal of passenger furnishings and services as the number of passengers is reduced.

Airplane size with four-abreast seating arrangement. - By reducing the airplane size, still lower levels of initial cruise sonic boom are obtained. For the four-abreast-seating size of the airplane, the payload fraction W_L/W_G (fig. 9(a)) decreases from a level of 8.96 to 7.63 percent as initial cruise boom is reduced from 1.22 to 1.08 pounds per square foot (58.4 to 51.7 N/m^2). As may be seen from figure 9(b), the payload fraction at each sonic boom level is maximized over the sonic boom decrement from 1.22 to 1.13 pounds per square foot (58.4 to 54.1 N/m^2) by retaining the volume-limited payload corresponding to 112 passengers. The takeoff gross weight (fig. 9(c)) must increase from 249 800 to 258 000 pounds (113 307 to 117 027 kg) as initial cruise boom is reduced over this interval, since the summation of the engine and fuel weights must increase if payload remains constant and the design range of 2400 nautical miles (4445 km) is retained. As initial cruise sonic boom is reduced from 1.13 to 1.08 pounds per square foot (54.1 to 51.7 N/m^2), the payload fraction is maximized at each sonic boom level by decreasing the number of passengers (fig. 9(b)) from the volume limit of 112 to 93 while at the same time the takeoff gross weight (fig. 9(c)) is reduced from 258 000 to 244 000 pounds (117 027 to 110 677 kg).

As initial cruise sonic boom for the four-abreast airplane size is reduced over the total spectrum from 1.22 to 1.08 pounds per square foot (58.4 to 51.7 N/m^2), the altitude at the start of cruise (fig. 9(d)) increases from the 72 000-foot (21 946-m) level, where the Breguet factor maximizes, to a value of 80 000 feet (24 384 m). There is a reduction in the rate of increase of altitude at the beginning of cruise, with respect to sonic boom decrement, as the region of maximum cruise afterburning is approached. This occurs as the initial cruise boom is reduced below 1.13 pounds per square foot (54.1 N/m^2). Further reductions in cruise sonic boom are obtained by more moderate increases in altitude with some sacrifice in weight.

Over the range of operating conditions considered for this size of airplane, the takeoff engine sizing criterion (i.e., a takeoff F/W_G of 0.32) determined engine size, as may be seen from figure 9(e). Had even lower levels of cruise boom been considered, however, increases in takeoff thrust-to-gross-weight ratio would have occurred. Since this ratio did remain constant for the range of sonic booms considered, though, the engine design airflow (fig. 9(f)) varied only as a function of gross weight. The design airflow of each of the four engines increased from 251 to 259 pounds per second (114 to 117 kg/sec) as initial cruise boom was reduced from 1.22 to 1.13 pounds per square foot (58.4 to 54.1 N/m^2). The engine size then decreased from 259 to 245 pounds per second (117 to 111 kg/sec) as cruise boom was reduced from 1.13 to 1.08 pounds per square foot (54.1 to 51.7 N/m^2).

The takeoff wing-loading limit of 50 pounds per square foot (2394 N/m^2) did not prove to be any restriction to the maximization of the payload fraction at each level of cruise sonic boom for the airplanes of four-abreast-seating size. As may be seen from figure 9(g), the takeoff wing loading increases from 45.4 to 46.9 pounds per square foot (2174 to 2246 N/m^2) as sonic boom is reduced from 1.22 to 1.13 pounds per square foot (58.4 to 54.1 N/m^2). As sonic boom is reduced from 1.13 to 1.08 pounds per square foot (54.1 to 51.7 N/m^2), the takeoff wing loading drops from 46.9 to 44.4 pounds per square foot (2246 to 2126 N/m^2). Since the wing loadings for the airplanes with four-abreast seating fell below the limiting value of 50 pounds per square foot (2394 N/m^2), the lift-off velocities and distances are less than those that occur for airplanes with five-abreast seating. The variation of wing loading with respect to initial cruise sonic boom for the four-abreast configuration is the result solely of the variation in takeoff gross weight since the wing area remains constant at 5500 square feet (511.0 m^2).

The mission fuel weight (fig. 9(h)) increases from 79 700 to 84 600 pounds (36 151 to 38 374 kg) as initial cruise sonic boom is reduced from 1.22 to 1.13 pounds per square foot (58.4 to 54.1 N/m^2) since fuel consumed in climb up to the higher initial cruise altitude must increase and the increasing fuel-air ratio at the start of cruise tends to overshadow the declining uncorrected airflow. As initial cruise boom is reduced below 1.13 pounds per square foot (54.1 N/m^2), initial cruise altitude increases more slowly because of reductions in takeoff gross weight. Although the fuel consumed in climb up to cruise increases somewhat as the result of the slight increase in initial cruise altitude, the more rapid rate of decline in actual airflow overcomes this and the increasing initial cruise fuel-air ratio to produce a decline in mission fuel. Hence, the mission fuel weight drops from 84 600 to 81 200 pounds (38 374 to 36 832 kg) as sonic boom is reduced from 1.13 to 1.08 pounds per square foot (54.1 to 41.7 N/m^2).

The airframe weight (fig. 9(i)) increases slightly from 106 000 to 107 400 pounds (48 081 to 48 716 kg) as initial cruise boom is reduced from 1.22 to 1.13 pounds per square foot (58.4 to 54.1 N/m^2). This slight increase in airframe weight results from increases in the weights of wing, landing gear, hydraulic and electrical system, and fuel system, which are required for the heavier takeoff gross weights and fuel weights (as shown in eq. (5) and eqs. (7) to (9), p. 17). As sonic boom at the start of cruise is reduced from 1.13 to 1.08 pounds per square foot (54.1 to 51.7 N/m^2), the airframe weight decreases from 107 400 to 103 200 pounds (48 716 to 46 811 kg). This weight reduction results from decreases in the weights of the previously mentioned structural components, which decrease as a function of takeoff gross weight. Additional factors affecting this weight reduction are reductions in fuel system weight, which occur as a result of the decrease in fuel weight, and reductions in the weight of passenger furnishings and services, which occur as a result of the drop in number of passengers.

Airplane size with three-abreast seating arrangement. - A similar analysis may be made for the airplanes of three-abreast seating size. The payload fraction W_L/W_G (fig. 9(a)) decreases from a level of 6.06 to 3.72 percent as sonic boom at the start of cruise is reduced from 1.02 to 0.89 pounds per square foot (48.8 to 42.6 N/m^2). Figure 9(b) shows that payload fraction is maximized at each level of cruise sonic boom between 1.02 and 0.95 pounds per square foot (48.8 and 45.5 N/m^2) by retaining the volume-limited payload corresponding to 50 passengers. The takeoff gross weight (fig. 9(c)) increases from 164 800 to 168 000 pounds (74 752 to 76 204 kg) to account for the greater engine-plus-fuel weight requirement at the higher cruise altitudes incurred (fig. 9(d)) as sonic boom is reduced over this same interval. As initial cruise sonic boom is reduced from 0.95 to 0.89 pound per square foot (45.5 to 42.6 N/m^2), the number of passengers (fig. 9(b)) is reduced from 50 to 29 at the same time that takeoff gross weight (fig. 9(c)) is reduced from 168 000 to 156 000 pounds (76 204 to 70 760 kg).

The initial cruise altitude (fig. 9(d)) increases rapidly from the maximum Breguet-factor altitude of 73 500 feet (22 403 m) up to 79 500 feet (24 232 m) as the corresponding cruise sonic boom is reduced from 1.02 to 0.95 pound per square foot (48.8 to 45.5 N/m^2). The altitude increases more slowly as initial cruise boom is reduced still further to 0.92 pound per square foot (44.0 N/m^2), since some of the sonic boom reduction is accomplished by weight reductions (fig. 9(c)).

As shown in figure 9(e), the takeoff thrust-to-gross weight ratio of 0.32 (the minimum allowable from takeoff performance considerations) was adequate as sonic boom at the start of cruise was reduced to 0.92 pound per square foot (44.0 N/m^2), where the altitude and weight were such that the maximum afterburning thrust setting had been reached. As sonic boom was reduced from 0.92 to 0.89 pound per square foot (44.0 to 42.6 N/m^2), the takeoff thrust-to-gross-weight ratio was increased from 0.32 to 0.36 to meet the more demanding thrust requirements at the start of cruise as the corresponding altitudes were increased from 80 000 to 82 000 feet (24 384 to 24 994 m) (fig. 9(d)). The maximum afterburning thrust setting was maintained at the start of cruise as the takeoff thrust-to-gross-weight ratio was increased over this interval.

The engine design airflow (size) is a function of both the takeoff gross weight and the takeoff thrust-to-gross-weight ratio. Over the cruise boom decrement from 1.02 to 0.95 pound per square foot (48.8 to 45.5 N/m^2), the engine airflow per engine (fig. 9(f)) rises as a function of gross weight from a value of 165 pounds per second (74.8 kg/sec) up to 168 pounds per second (76.2 kg/sec). Engine size then drops with gross weight to a minimum value of 162 pounds per second (73.5 kg/sec) as initial cruise boom is decreased to 0.92 pound per square foot (44.0 N/m^2). Further reductions in cruise sonic boom cause the airflow to rise again, as the gross weight reductions are overshadowed by the increase in thrust-to-gross-weight ratio. For the range of sonic booms considered, a maximum design airflow of 176 pounds per second (79.8 kg/sec) is required at the minimum, 0.89-pound-per-square-foot (42.6-N/m^2), sonic boom at the start of cruise.

As shown in figure 9(g), the takeoff wing loading for this size of airplane is always well below the 50-pound-per-square-foot (2394-N/m^2) maximum limit imposed to achieve adequate takeoff performance. The increase in takeoff gross weight that occurs as initial cruise boom is reduced from 1.02 to 0.95 pound per square foot (48.8 to 45.5 N/m^2) causes the wing loading to increase from 41.2 to 42.5 pounds per square foot (1973 to 2035 N/m^2). As the initial cruise boom is reduced from 0.95 to 0.89 pound per square foot (45.5 to 42.6 N/m^2), the wing loading decreases from its maximum value of 42.5 pounds per square foot (2035 N/m^2) to 39.0 pounds per square foot (1867 N/m^2), since gross weight decreases over this interval and wing area, of course, remains constant at 4000 square feet (371.6 m^2).

The mission fuel requirement (fig. 9(h)) increases from 54 800 to 56 700 pounds (24 857 to 25 719 kg) as sonic boom at the start of cruise is reduced from 1.02 to 0.95 pound per square foot (48.8 to 45.5 N/m^2), since both the degree of cruise afterburning and the fuel consumed in climb up to cruise increase. The increase in afterburning at the start of cruise raises the fuel-air ratio, which, in turn, rises so rapidly as to nullify the effect of the declining uncorrected airflow. As the initial cruise boom is reduced still further from 0.95 to 0.92 pound per square foot (45.5 to 44.0 N/m^2), the mission fuel weight decreases from 56 700 to 55 500 pounds (25 719 to 25 174 kg), since the degree of cruise afterburning is increased only slightly to its maximum value and both the corrected and actual airflows decline to produce a lower time rate of fuel consumption in cruise. The fuel consumed in the climb up to cruise actually increases about 600 pounds (272 kg) as initial cruise sonic boom is reduced this amount, but the effect is more than offset by the reduction in cruise fuel. As the initial cruise boom is reduced still further to the minimum level considered in this study (0.89 lb/ft^2 or 42.6 N/m^2), the mission-fuel weight requirement decreases to 53 100 pounds (24 086 kg). This decrease is largely the result of reductions in the amount of fuel consumed in the climb up to cruise. Increases in the takeoff thrust-to-gross weight ratio (fig. 9(e)) provide additional acceleration during climb so that the initial cruise altitude, although higher, is reached more rapidly. Although the rate of climb fuel consumption is thus greater, the time saving more than compensates to reduce the total amount of fuel consumed in climb. The initial cruise fuel-air ratio is fixed over this sonic boom interval because the maximum afterburner setting is required. The actual airflow at the start of cruise decreases for a time and then begins to rise again. The rate of fuel flow at the start of cruise, therefore, behaves similarly since fuel-air ratio is fixed. These fluctuations, however, have little effect on the total mission fuel requirement, which is more greatly affected by the decline in climb fuel over this sonic boom decrement.

Airframe weight is seen from figure 9(i) to remain virtually unchanged, increasing only from 73 300 to 73 800 pounds (33 248 to 33 475 kg) as initial cruise boom is reduced from 1.02 to 0.95 pound per square foot (48.8 to 45.5 N/m^2). This increase in airframe weight is partly the result of increases in the weights of some structural components (e.g., wing and landing gear) which increase with takeoff gross weight. Also, part of the increase is the result of an increase in the weight of the fuel system, which increases with fuel weight. As initial cruise boom is reduced from 0.95 to 0.89 pound per square foot (45.5 to 42.6 N/m^2), the airframe weight decreases from 73 800 to 69 200 pounds (33 475 to 31 389 kg) as the result of decreases in the weights of the structural components related to takeoff gross weight and passenger furnishings and service items related to the number of passengers.

Staged Vehicles

Second-stage vehicle size with five-abreast seating arrangement. - For the five-abreast-seating size of cruise vehicle, the payload fraction W_L/W_G (fig. 10(a), p. 28) decreases from a level of 14.1 to 11.3 percent as initial cruise boom is reduced from 1.38 to 1.20 pounds per square foot (66.1 to 57.5 N/m^2). As may be seen from figure 10(b), the payload fraction at each level of sonic boom is maximized over the sonic boom decrement from 1.38 to 1.28 pounds per square foot (66.1 to 61.3 N/m^2) by retaining the volume-limited payload corresponding to 200 passengers. The maximum (initial cruise) second-stage gross weight (fig. 10(c)) must increase from 283 000 to 291 000 pounds (128 366 to 131 995 kg) as initial cruise boom is reduced over this interval since the engine-plus-fuel weight must increase if payload remains constant and the stage design range of 2100 nautical miles (3889 km) is retained. As initial cruise boom is reduced from 1.28 to 1.20 pounds per square foot (61.3 to 57.5 N/m^2), the payload fraction is maximized at each sonic boom level by decreasing the number of passengers (fig. 10(b)) from the volume limit of 200 to 153 while at the same time the initial cruise gross weight (fig. 10(c)) is reduced from 291 000 to 270 000 pounds (131 995 to 122 470 kg).

As initial cruise sonic boom for the five-abreast vehicle size is reduced over the total spectrum from 1.38 to 1.20 pounds per square foot (66.1 to 57.5 N/m^2), the altitude at the start of cruise (fig. 10(d)) increases from the 70 500-foot (21 488-m) level, where the Breguet factor maximizes, to a value of 80 000 feet (24 384 m). The altitude increase is approximately linear with respect to initial cruise sonic boom until a boom of about

1.25 pounds per square foot (59.8 N/m^2) is reached. Below this level of sonic boom, the altitude increases at a continually lower rate as reductions in gross weight more effectively reduce the boom.

The engine size (fig. 10(e)) increases at a continually faster rate, as initial cruise boom is reduced from 1.38 to 1.28 pounds per square foot (66.1 to 61.3 N/m^2), since initial cruise altitude and gross weight both increase and the afterburner temperature setting remains at an approximately constant value that is slightly below the maximum. The engine size, as represented by the corrected airflow at static, sea-level conditions, increases from 231 to 295 pounds per second (105 to 134 kg/sec) as sonic boom is reduced over this interval. Even if the lower gross weight of the second-stage vehicle is taken into account, it will be found that the engine sizes required for the second stage are smaller than for an unstaged airplane of similar size since the takeoff performance requirements for such an airplane are more demanding than the cruise performance requirements at the altitudes under consideration. As initial cruise sonic boom is further reduced from 1.28 to 1.25 pounds per square foot (61.3 to 59.8 N/m^2), the engine size decreases slightly to 294 pounds per second (133 kg/sec) as initial cruise gross weight begins to decline and the afterburner temperature is increased to its maximum value. Subsequent reductions in initial cruise boom cause the engine size to increase again even though the corresponding stage weight continues to decline. A 318-pound-per-second (144-kg/sec) engine size was obtained at the lowest initial cruise sonic boom considered (1.20 lb/ft^2 or 57.5 N/m^2). Further reductions in sonic boom would probably have required no appreciable increase in engine size since altitude would have increased at a slower rate and gross weight would have continued downward.

The mission fuel weight (fig. 10(f)) decreases from 64 000 to 58 500 pounds (290 299 to 265 352 kg) as initial cruise sonic boom is reduced from 1.38 to 1.20 pounds per square foot (66.1 to 57.5 N/m^2). Over the spectrum of initial cruise conditions considered here, the specific fuel consumption changed very little since the afterburner temperature changed only moderately. The actual airflow through the engines declined as initial cruise sonic boom was reduced even though the corrected airflow increased over most of the interval. The decline of the actual airflow was the result of the ambient atmospheric pressure decreasing at a more rapid rate than the corrected airflow (and, hence, engine size) was increasing. The decline in actual airflow indicates that fuel flow also declined since the relatively constant specific fuel consumption prevented any appreciable variation in initial cruise fuel-air ratio. The decline in the rate of fuel flow as initial cruise boom was reduced caused the mission fuel to decline also since the mission time was constant for all cases.

The airframe weight (fig. 10(g)) increases slightly from 136 900 to 138 400 pounds (62 097 to 62 777 kg) as initial cruise boom is reduced from 1.38 to 1.28 pounds per square foot (66.1 to 61.3 N/m^2). This slight increase in airframe weight results from increases in the weights of wing, landing gear, and hydraulic and electrical systems, which are required for the heavier maximum (initial cruise) gross weights (as shown in eqs. (5), (7), and (9), p. 17). As sonic boom at the start of cruise is reduced from 1.28 to 1.20 pounds per square foot (61.3 to 57.5 N/m^2), the airframe weight decreases from 138 400 to 129 400 pounds (62 777 to 58 695 kg). This weight reduction is the result of decreases in the weights of passenger furnishings and services, which are a function of the number of passengers, as well as the previously mentioned gross-weight-related structural components.

Second-stage vehicle size with four-abreast seating arrangement. - A similar analysis may be made for the second-stage vehicles of four-abreast-seating size. The payload fraction W_L/W_G (fig. 10(a)) decreases from a level of 11.6 to 8.80 percent as sonic boom at the start of cruise is reduced from 1.16 to 1.02 pounds per square foot (55.5 to 48.8 N/m^2). Figure 10(b) shows that payload fraction is maximized at each level of sonic boom between 1.16 and 1.08 pounds per square foot (55.5 and 51.7 N/m^2) by retaining the volume-limited payload corresponding to 112 passengers. The maximum stage gross weight (fig. 10(c)) increases from 193 300 to 198 000 pounds (87 679 to 89 811 kg) to account for the greater engine-plus-fuel weight requirement at the higher cruise altitudes incurred (fig. 10(d)) as sonic boom is reduced over this same interval. As initial cruise sonic boom is reduced from 1.08 to 1.02 pounds per square foot (51.7 to 48.8 N/m^2), the number of passengers (fig. 10(b)) is reduced from 112 to 89 at the same time that the stage gross weight (fig. 10(c)) is reduced from 198 000 to 182 000 pounds (89 811 to 82 554 kg).

The initial cruise altitude (fig. 10(d)) increases linearly from the maximum Breguet-factor altitude of 72 500 feet (22 098 m) to 80 500 feet (24 536 m) as the corresponding cruise sonic boom is reduced from 1.16 to 1.05 pounds per square foot (55.5 to 50.3 N/m^2). Further reductions in sonic boom do not require any increase in altitude, according to figure 10(d). As initial cruise sonic boom is reduced from 1.05 to 1.02 pounds per square foot (50.3 to 48.8 N/m^2), the corresponding altitude remains virtually unchanged at 80 500 feet (24 536 m). Over this decrement in sonic boom, gross weight reductions account for all the sonic boom reduction.

The engine size (fig. 10(e)) increases at a continually faster rate as initial cruise boom is reduced from 1.16 to 1.08 pounds per square foot (55.5 to 51.7 N/m^2) since both gross weight and altitude at the start of cruise increase. The afterburner setting increases over this interval from a level corresponding to 91 percent of maximum thrust up to the maximum thrust setting. The engine size, as represented by the corrected airflow at static, sea-level conditions, increases from 176 to 218 pounds per second (79.8 to 98.9 kg/sec). As sonic boom is reduced from 1.08 to 1.05 pounds per square foot (51.7 to 50.3 N/m^2), engine size increases at a continually slower rate until a maximum of 236 pounds per second (107 kg/sec) is reached. The slower rate of increase in engine size over this sonic boom interval is caused by the drop in stage gross weight. As sonic boom is reduced below 1.05 pounds per square foot (50.3 N/m^2), altitude no longer increases as gross weight declines. Hence, the engine size requirement declines from the maximum of 236 pounds per second (107 kg/sec) to 222 pounds per second (101 kg/sec) as sonic boom is reduced over this interval.

The mission fuel weight (fig. 10(f)) remains constant at approximately 44 000 pounds (19 958 kg) as initial cruise sonic boom is reduced from 1.16 to 1.08 pounds per square foot (55.5 to 51.7 N/m^2). This occurs in spite of the fact that engine size (i.e., corrected airflow) and afterburner temperature setting increase over this interval. The actual engine airflow, however, declines slightly since the ambient atmospheric pressure decreases at a rate slightly faster than corrected airflow increases. The slight increase in afterburner setting over this interval produces a correspondingly slight increase in fuel-air ratio which, when coupled with the decrease in actual airflow, produces a relatively constant fuel flow at the start of cruise. Since the mission time is constant, the mission fuel weight over this sonic boom interval remains constant. As initial cruise sonic boom is decreased further from 1.08 to 1.02 pounds per square foot (51.7 to 48.8 N/m^2), figure 10(f) shows that the mission fuel weight decreases from 44 000 to 40 500 pounds (19 958 to 18 370 kg). Over this interval, the fuel-air ratio remains constant since the afterburner is at its maximum temperature setting, and the engine corrected airflow increases at a slower rate until the boom is reduced to 1.05 pounds per square foot (50.3 N/m^2). Below the 1.05-pound-per-square-foot (50.3-N/m^2) boom level the corrected airflow actually decreases. This combination of corrected airflows together with the ambient pressures corresponding to the altitudes shown in figure 10(d) produces a schedule of actual airflow that declines as sonic boom is reduced from 1.08 to 1.02 pounds per square foot (51.7 to 48.8 N/m^2). Hence, the initial cruise fuel flow and the mission fuel weight decline also.

As sonic boom is reduced over the interval where the volume-limited payload is maintained, the airframe weight (fig. 10(g)) increases slightly from 96 600 to 97 100 pounds (43 817 to 44 044 kg). This weight increase is the result of increases in the weights of structural components which are a function of gross weight (e.g., wing and landing gear). As sonic boom at the start of cruise is reduced from 1.08 to 1.02 pounds per square foot (51.7 to 48.8 N/m^2), the airframe weight decreases from a peak of 97 100 to 91 000 pounds (44 044 to 41 277 kg). This weight reduction is the result not only of decreases in the weights of the previously mentioned gross-weight-related structural components, but also reductions in payload-related items (e.g., passenger furnishings and services) and the fuel system.

Second-stage vehicle size with three-abreast seating arrangement. - For second-stage vehicles of three-abreast-seating size, figure 10(a) shows that the payload fraction W_L/W_G decreases from a level of 7.84 to 3.90 percent as sonic boom at the start of cruise is reduced from 0.97 to 0.84 pound per square foot (46.4 to 40.2 N/m^2). Figure 10(b) shows that to obtain these payload fractions the volume-limited payload corresponding to 50 passengers was retained as initial cruise sonic boom was reduced from 0.97 to 0.91 pound per square foot (46.4 to 43.6 N/m^2). The maximum stage gross weight (fig. 10(c)) increases over this same interval of sonic boom from a level of 127 550 to 130 000 pounds (57 856 to 58 967 kg). This increase in gross weight is the result of the greater engine-plus-fuel weight required to cruise at the higher altitudes (fig. 10(d)) that permit lower sonic booms. As sonic boom at the start of cruise is reduced from 0.91 to 0.84 pound per square foot (43.6 to 40.2 N/m^2), the number of passengers (fig. 10(b)) is reduced from 50 to 23. Over the same decrement of sonic boom, the stage gross weight (fig. 10(c)) remains relatively constant at approximately 130 000 pounds (58 967 kg) and then drops to 118 000 pounds (53 524 kg). The drop in gross weight is, of course, made possible by the reduction in the number of passengers.

The initial cruise altitude (fig. 10(d)) increases linearly from 74 000 feet (22 555 m), the altitude which yields the maximum-Breguet factor, to 83 500 feet (25 451 m) as the corresponding sonic boom is reduced from 0.97 to 0.87 pound per square foot (46.4 to 41.7 N/m^2). Further reductions in sonic boom result in a slower rate of increase in altitude until a maximum of 84 000 feet (25 603 m) is reached at a sonic boom of approximately 0.86 pound per square foot (41.2 N/m^2). As sonic boom is reduced to 0.84 pound per square foot (40.2 N/m^2), the altitude decreases from its maximum value to a level of 83 600 feet (25 481 m). The gross weight reductions account for decreases in initial cruise boom in regions where the corresponding altitude declines.

The engine size (fig. 10(e)) increases at a continually faster rate as initial cruise boom is reduced from 0.97 to 0.89 pound per square foot (46.4 to 42.6 N/m^2) since both gross weight and altitude at the start of cruise increase. As sonic boom is reduced, the afterburner setting is increased slightly to its maximum allowable temperature at a sonic boom of 0.91 pound per square foot (43.6 N/m^2). As sonic boom is further reduced, the maximum afterburner setting is retained. As initial cruise boom is reduced from 0.97 to 0.89 pound per square foot (46.4 to 42.6 N/m^2), the engine size (i.e., corrected airflow at static, sea-level conditions) increases from 124 to 170 pounds per second (56.2 to 77.1 kg/sec). As sonic boom is reduced from 0.89 to 0.86 pound per square foot (42.6 to 41.2 N/m^2), the engine size increases more slowly to its maximum value of 193 pounds per second (87.5 kg/sec). The slower rate of increase in engine size over this sonic boom interval is caused by the drop in gross weight. As sonic boom at the start of cruise is reduced from 0.86 to 0.84 pound per square foot (41.2 to 40.2 N/m^2), the combination of declining altitude and gross weight causes the required engine size to decrease from 193 to 169 pounds per second (87.5 to 76.7 kg/sec). A comparison with the corresponding engine size curve (fig. 9(f), p. 22) for an unstaged airplane will show that for the three-abreast configurations the engine size of the cruise stage is sometimes greater than for the unstaged airplane. The reason for this is that, as the size of the unstaged airplanes is reduced, the fuel consumed up to the start of cruise is significantly reduced so that there is little weight that can be saved by staging at the beginning of cruise. Hence, there is little difference between the initial cruise weights of the unstaged airplanes and the second stages of two-stage vehicles with three-abreast seating. With the four- and five-abreast configurations, however, the weight difference becomes more significant, with the second-stage vehicles having a distinct weight advantage. Since many of the engines for the unstaged airplanes with three-abreast seating were sized by cruise rather than takeoff conditions, it is not too surprising that approximately equal sizes were obtained for unstaged and staged vehicles.

The mission fuel weight (fig. 10(f)) declines slightly from 30 400 to 29 400 pounds (13 789 to 13 336 kg) as initial cruise sonic boom is reduced from 0.97 to 0.91 pound per square foot (46.4 to 43.6 N/m^2) in spite of the fact that both engine size and afterburner temperature (and, hence, fuel-air ratio) are increased. The actual (i.e., uncorrected) airflow, however, declines somewhat over this sonic boom decrement because the ambient atmospheric pressure decreases at a rate slightly faster than the corrected airflow increases. The mission fuel, therefore, declines since the slight increase in fuel-air ratio is overshadowed by the decrease in actual airflow. The engine size (and, hence, corrected airflow) increases at a more rapid rate as sonic boom is reduced from 0.91 to 0.89 pound per square foot (43.6 to 42.6 N/m^2). The increase in corrected airflow and the decrease in ambient pressure over this sonic boom interval compensate to yield a practically constant actual airflow. Since the fuel-air ratio, too, remains constant, the mission fuel is constant. As initial cruise sonic boom is reduced from 0.89 to 0.84 pound per square foot (42.6 to 40.2 N/m^2), the mission fuel weight declines from 29 400 to 27 600 pounds (13 336 to 12 519 kg). Over this interval, the corrected airflow increases at a slower rate and eventually declines. The ambient pressure declines and then increases slightly over this same interval. The two effects combine to produce a declining value of uncorrected airflow which, together with a constant fuel-air ratio, causes the mission fuel to decline.

The airframe weight (fig. 10(g)) increases slightly from 66 700 to 67 200 pounds (30 255 to 30 481 kg) as sonic boom is reduced over the interval where the volume-limited number of passengers is maintained. This weight increase is the result of increases in the weights of gross-weight-related structural components (e.g., wing and landing gear). As initial cruise boom is further reduced from 0.91 to 0.84 pound per square foot (43.6 to 40.2 N/m^2), the airframe weight declines from its peak value of 67 200 pounds (30 481 kg) to 63 000 pounds (28 576 kg). This weight reduction is the result not only of decreases in the weights of the gross-weight-related structural components, but also reductions in payload-related items and the fuel system.

REFERENCES

1. Anon.: Design of a Low Boom Domestic Supersonic Transport, Phases I and II. Rep. No. NA66-1284, Vols. I and II, North American Aviation, Inc., Dec. 1966.
2. Daskin, Walter; Feldman, Lewis; Sanlorenzo, Ernest A.: Staged Supersonic Transports...The Small Airplane Returns. Paper No. 59-SA-31, ASME, June 1959.
3. Anon.: NASA SCAT 15F Feasibility Study. Rep. No. D6-16325, Boeing Co., May 1965. (Available from DDC as AD-478511L.)
4. McLean, F. Edward; and Shrout, Barrett L.: Design Methods for Minimization of Sonic-Boom Pressure-Field Disturbances. J. Acoust. Soc. Am., vol. 39, no. 5, pt. 2, May 1966, pp. S19-S25.
5. Thompson, Jim R.; and Parnell, John E.: Sonic Boom and the SST - An Examination of the Sonic Boom and Its Effects. Aircraft Eng., vol. 39, no. 3, Mar. 1967, pp. 14-18.
6. Whitham, G. B.: The Flow Pattern of a Supersonic Projectile. Comm. Pure Appl. Math., vol. 5, no. 3, 1952, pp. 301-348.
7. Hayes, Wallace D.: Linearized Supersonic Flow. Rep. AL-222, North American Aviation, Inc., June 18, 1947.
8. Carlson, Harry W.; Mack, Robert J.; and Morris, Odell A.: Sonic-Boom Pressure-Field Estimation Techniques. J. Acoust. Soc. Am., vol. 39, no. 5, pt. 2, May 1966, pp. S10-S18.
9. Kane, E. J.: Some Effects of the Nonuniform Atmosphere on the Propagation of Sonic Booms. J. Acoust. Soc. Am., vol. 39, no. 5, pt. 2, May 1966, pp. S26-S30.
10. Hubbard, Harvey H.; Maglieri, Domenic J.; Huckel, Vera; and Hilton, David A. (with appendix by Harry W. Carlson): Ground Measurements of Sonic-Boom Pressures for the Altitude Range of 10,000 to 75,000 Feet. NASA TR R-198, 1964.
11. Whitlow, John B., Jr.; Eisenberg, Joseph D.; and Shovlin, Michael D.: Potential of Liquid-Methane Fuel for Mach 3 Commercial Supersonic Transports. NASA TN D-3471, 1966.
12. Anon.: Supersonic Transport Economic Model Ground Rules. Rep. No. SST 65-7 (Rev.), Federal Aviation Agency, Sept. 1965.
13. Dugan, James F., Jr.: Compressor and Turbine Matching. Aerodynamic Design of Axial-Flow Compressors. Irving A. Johnsen and Robert O. Bullock, eds. NASA SP-36, 1965, pp. 469-508.

14. Anon.: Standard Method of Estimating Direct Operating Costs of Transport Airplanes. Air Transport Assoc. of Am., Aug. 1960.

15. Dugan, J. F., Jr.; Koenig, R. W.; Whitlow, J. B., Jr.; and McAuliffe, T. B.: Power for the Mach 3 SST. Astron. Aeron., vol. 2, no. 9, Sept. 1964, pp. 44-53.

NASA-Langley, 1968 —— 2

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546

OFFICIAL BUSINESS

FIRST CLASS MAIL

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AN
SPACE ADMINISTRATION

030 001 27 51 30S 68168 00903
AIR FORCE WEAPONS LABORATORY/AFWL/
KIRTLAND AIR FORCE BASE, NEW MEXICO 8711

ATT MISS MADELINE F. CANOVA, CHIEF TECH
LIBRARY /WLIL/

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Retur

---

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C. 20546