Feasibility study of a supersonic business jet based on the Learjet airframe

B. Chudoba and G. Coleman
The University of Texas at Arlington
Arlington, USA

P. A. Czysz
HyperTech Concepts LLC
St Louis, USA

C. M. Butler
Aircraft Design Services
San Antonio, USA

ABSTRACT

Since the dawn of the jet age, passengers on all jet transports, except Concorde, have traveled at about the same speed — a standard Mach 0·83-0·87 range as a practical compromise. After 27 years of supersonic commercial travel, British Airways and Air France retired their fleet of Concorde aircraft at the end of 2003 because it was considered no longer profitable. Clearly, with the retirement of Concorde, the world has lost the only aircraft offering passenger transportation at supersonic speeds. Over the past several years manufacturers have proposed new aircraft designs that promise an increase in transportation speeds. In particular, the business jet market appears to present a business case for an exclusive supersonic business jet (SSBJ). However, there is a key-hurdle which has, until now, prevented the successful launch of a SSBJ hardware program: the development cost for an all-new aircraft quickly eradicates the sought-after business case. This paper presents the results of a parametric sizing study which aims to answer the following question: is it possible to drastically reduce the development effort of a supersonic business jet design by converting an existing Learjet airframe into a supersonic vehicle while sustaining FAA interest and approval? This paper discusses selected aircraft sizing trades and operations related constraints. The feasibility study indicates some level of technical plausibility for the case of converting an existing airframe into a certifiable lower-cost supersonic aircraft. Acknowledging the range of actual complications related to the task of economically modifying and certifying a legacy airframe towards a SSBJ, it appears that a larger size SSBJ offers significant technical and economical advantages which outweigh the 'off-the-shelf' Learjet case.

NOMENCLATURE

A_{max}	maximum cross-sectional area
AR	aspect ratio
AR_{wet}	wetted aspect ratio
b	wing span
BFL	balanced field length
C_{D_0}	zero-lift drag coefficient
C_{D_f}	skin friction coefficient
C_{D_F}	wave drag coefficient based on frontal area
$C_{D_{wave}}$	wave drag coefficient (either based on frontal area (F) of wing reference area (ref))
C_L	lift coefficient
C_{L_A}	lift coefficient (approach)
$C_{L_{max}}$	maximum lift coefficient
$C_{L_{T0}}$	lift coefficient (take off)
C_{L_α}	aircraft lift-curve slope
D	drag force
D_0	zero-lift drag force
$D_{0/q}$	zero-lift drag area
DOC	direct operating cost
e	Oswald or Weissinger span efficiency
ff	fuel fraction
g	acceleration due to gravity
h	altitude; fuselage cabin height
I_{sp}	specific impulse
K	factor based on critical Mach number
K_0	wave drag factor determining how close the actual shape is to the Sears-Haack body (K_0 =1 ideal)

Paper No. 3073. Manuscript received 20 February 2006, revised version received 16 February 2009, accepted 4 June 2009.

l length
L lift force
$L_{1\cdot5}$ fuselage length required for 1·5 Mach
L' subsonic and supersonic induced drag factor
L/D aerodynamic efficiency
L/D_{SS} aerodynamic efficiency at supersonic speed
L/D_{TS} aerodynamic efficiency at transonic speed
LE leading edge
m L/D parameter (m = 1 for L/D_{max})
M Mach number
M_{cr} critical Mach number
PAX passengers and luggage
OEW operating empty weight
OWE operating weight empty
q dynamic pressure
R range
R_{SS} supersonic range
R_{TS} transonic range
R&D research and development
s lifting surface (wing) half-span
S area
S_F maximum cross section minus 0·95% stream tube; maximum frontal area
S_{max} maximum cross-sectional area
S_{ref} reference area (usually wing area)
S_{wet} wetted area
SL sea level
T thrust
T_c thrust during cruising flight
T_{max} max thrust
T_{sl} thrust at sea level
T_{un} uninstalled thrust at sea level
T/W thrust to weight ratio at take-off gross weight
TOGW take-off gross weight
TSFC thrust specific fuel consumption
$TSFC_{SS}$ thrust specific fuel consumption at supersonic speed
$TSFC_{TS}$ thrust specific fuel consumption at transonic speed
USD United States dollar
V total volume of the body, velocity
w fuselage cabin width
W weight
W_{fuel} fuel weight
W_{pay} payload weight
W/S wing loading (at TOGW)

Greek Symbols

β parameter, $\beta = \sqrt{M^2 - 1}$

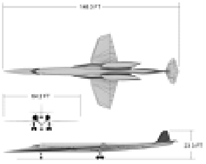
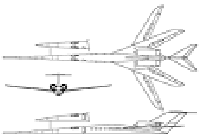
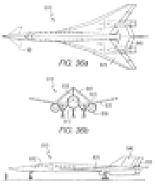
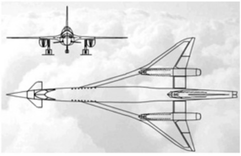
1.0 INTRODUCTION

The concept of the supersonic business jet (SSBJ) has been proposed throughout the last two decades beginning in 1988. These projects do share a common characteristic: being high-performance and high-technology vehicles accompanied with a high price tag. Table 1 introduces representative projects with mission statement and estimated purchase cost. To date, the primary focus of SSBJ projects has been on developing performance optimal aircraft with large luxuries cabins in analogy to their ultra-long range transonic counter parts. Given the uncertainty in sonic boom regulations, overall environmental implications, today's energy crisis, and the associated high development, purchase and operational cost, the majority of projects have been put on hold or serve as a general company-internal technology catalyst.

The Aerospace Vehicle Design (AVD) Laboratory has been tasked to evaluate a low-technology SSBJ alternative based on Learjet 24/25 derived fuselage hardware components. The hypothesis of this study has been to simplify the SSBJ design by basing it on (a) available industry capability (low technology) and to (b) constrain the design to Learjet 24/25 fuselage elements including wing attachment hard points, cabin diameter, and others. The overall study goal for the SpritLear SSBJ has been to explore if such approach is able to reduce the development and purchase cost for this novel class of aircraft. This project consisted of a market assessment and mission definition phase[6,7], followed by a technical feasibility phase[8]. The primary results from these studies can be summarised as follows:

1. While a modification of the Learjet 24/25 airframe into a SSBJ appears technically possible, little may remain of the original Learjet structure and systems translating into no tangible design, cost, time, and certification advantages. However, the notion of the low-technology 'mini-Concorde' type SSBJ, based on available industry capability, is of interest. Such approach may pose a viable alternative to the prevailing high-technology and high-cost SSBJ projects seen to date. Then, the primary discriminator between both trains of thought becomes the flight performance required versus the performance delivered by the respective designs at what cost.
2. It can be expected that the low-technology high-boom SSBJ is able to enter this dedicated marketplace before any high-technology low-boom competitor product. This translates into the advantage of saturating some of the available SSBJ market demand. With the current sonic boom regulations prevailing, the low-technology high-boom aircraft can capitalise on the fact

Table 1
Performance and cost comparison of representative SSBJ projects

	Aerion[1]	Gulfstream QSJ[2]	LM/SAI QSST[3]	Sukhoi S-21[4]	Dassault Trijet[5]
					
V_{cruise}, R	1·50M; 7,400km 0·95M; 7,400km	2·00M; 7,400km	1·8M; 7,400km 0·95M; 7,400km	2·00M; 7,400km	1.80M; 7,400km 0·80M; 7,400km
Pax: design: max:	8 12	8 12-14	8 18	4 10	8 10
DOC	$10·2/nm (supersonic) $11·8/nm (subsonic)	-	-	-	-
Price (per aircraft)	$80m	$70-90m	$80m	$40-50m	$70-80m

https://doi.org/10.1017/S0001924000003171 Published online by Cambridge University Press

that most time savings for supersonic flight occur during the over-water portion of the transatlantic and transpacific missions. At this point in time it is unclear what enabling low-boom technology will eventually transition into readily available industry capability, thereby allowing supersonic flight over land. Acknowledging the already existing market niche for a dedicated SSBJ, the low-technology high-boom aircraft concept represents a first-to-the-market, less costly and overall less risky first-generation SSBJ solution concept which complies with today's requirement to fly subsonic over land.

With the following we are introducing the parametric sizing methodology and its ground rules utilised throughout the feasibility study[8]. This first-order parametric sizing methodology has been custom devised to determine the correct flight mission, airframe size, propulsion system, selected technical requirements and cost projections for this minimum-complexity high-boom SSBJ. Clearly, the parametric sizing study aims to first identify the solution space for this class of aircraft before a more complete conceptual design configuration assessment study is undertaken. The flight vehicle gross solution space is answering the following questions: '*…is the mission feasible with the currently available industrial capability? …*', and '*…what is the approximate vehicle size, propulsion requirement and projected cost for an aircraft meeting such mission?*' The parametric sizing study is addressing the above questions by (a) examining the SSBJ mission requirements from the market assessment[7,8], (b) analysis of similar SSBJ projects for comparison and validation of methods, and (c) parametrically sizing a minimum-complexity SSBJ to the mission specified.

The parametric sizing process employed consists of a design convergence logic based on the classical sizing approach described by Loftin[9]: the sizing approach first defines the general mission while adopting basic geometry assumptions and relationships; it then iterates through a series of technical disciplines (aerodynamics, propulsion, performance, weight, cost) until the output geometry parameters converge to the input parameters. Figure 1 presents an overview of this custom-developed SSBJ sizing methodology in structogram form while providing reference to the primary disciplinary methods selected for this study. Note that parametric sizing methodologies have to rely, in general, on analytical methods and semi-empirical handbook methods due to the high level of abstraction involved (minimum input data available, chronic time shortage, etc.). Objective of the present paper is to identify, visualise, and narrow the gross design solution space such, to provide a correct starting point to a follow-on conceptual design study using more elaborate computer based techniques.

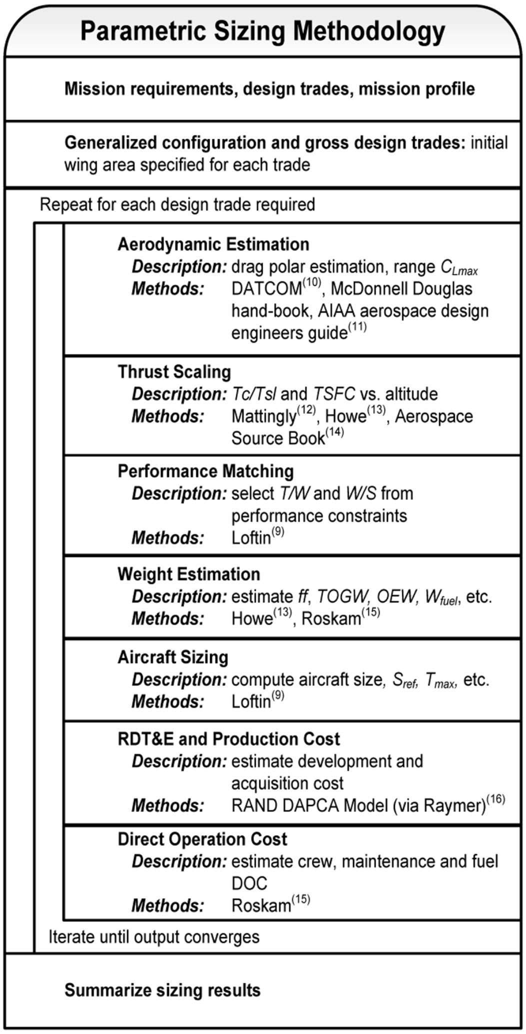


Figure 1. SSBJ parametric sizing methodology.

2.0 MISSION DEFINITION

References 6 and 7 have identified a dedicated market niche for SSBJs. Such situation has been interpreted to present an opportunity for capturing an early market share with a low-technology (performance sub-optimal) SSBJ product based on readily available industry capability. In comparison, a significant time delay to market has to be expected for the development and subsequent transitioning of low-boom technology into available industry capability, followed by a required modification and approval of the existing over-land flight certification rule body. Low-boom technologies under development today are Aerion's supersonic natural laminar flow wing[1], Gulfsteam's quiet spike concept[2], and Lockheed Martin and Supersonic Aerospace International's inverted V-tail configuration[17]. In analogy to the original Learjet 23 account where a small and inexpensive business jet revolutionised the corporate market, a high-boom but low-cost SSBJ with sufficient transonic cruise range for overland flight could present a quicker and cheaper introduction of this class of aircraft to the market.

The market and operational analysis study[6,7] concluded that a high-boom SSBJ would have to comply with the design mission goals as presented with Table 2 while meeting FAR 25 certification requirements. The mission requirements are divided into two specific sets: a practical mission range (7,400km/4,000nm) and a Learjet 24 constrained 'maximum' mission range (5,560km/3,000nm). Note that both sets are a direct result of the operational analysis study. The initial feasibility study did demonstrate that the Learjet 24 hardware constraints do result in a wing span limitation for the SSBJ. The Learjet 24 primary wing box and associated loads dictate the maximum size of the SSBJ within a reasonable fineness ratio, thereby adversely affecting maximum range and balanced field-length (BFL). Clearly, fulfilling the desirable 'practical operational mission' outlined in Table 2 would require a larger airframe.

A range of take-off field lengths has been defined (based on the minimum and maximum take-off field lengths of competing SSBJ designs[7]) to allow for flexibility with existing propulsion systems. Sizing results presented in Chapter 5 will demonstrate the effect of range and BFL on overall aircraft size and feasibility. Note that the payload for the SpritLear SSBJ (design PAX 4) is significantly smaller compared to most SSBJ projects (design PAX 8). The larger

https://doi.org/10.1017/S0001924000003171 Published online by Cambridge University Press

Table 2
Design mission requirements for the SpiritLear SSBJ

Mission requirements	Practical operational mission	Learjet 24 constrained mission
W_{pay}		
crew (2)	184kg (410lb)	184kg (4,10lb)
max passengers (8)	800kg (1,764lb)	800kg (1,764lb)
design passengers (4)	400kg (881lb)	400kg (881lb)
R		
supersonic	7,400km (4,000nm)	5,560km (3,000nm)
transonic	7,400km (4,000nm)	7,400km (4,000nm)
V		
supersonic cruise	1·4-1·8M	1·4-1·8M
transonic cruise	0·8-0·9M	0·8-0·9M
h		
max operating	15,540m (51,000ft)	15,540m (51,000ft)
Take-off field length		
[TOGW]	1,500m-2,440m	
(6,000-8,000ft)	1,500m-2,440m	
(6,000-8,000ft))		
Landing field length		
[max landing weight]	1,520m (6,000ft)	2,438m (6,000ft)
Fuel reserves	45min,1,524km (5,000ft)	45min, 1,524km (5,000ft)

SSBJ projects may provide a large fuel and payload capacity in the interest of range performance and comfort, but not necessarily productivity. By comparison, by reducing the payload and cabin diameter for the SpritLear SSBJ due to Learjet 24 hardware constraints, a smaller vehicle size results, thereby delivering reduced comfort but as well a significantly reduced aircraft price. Still, it needs to be investigated what range performance the small SSBJ is capable to produce at what cost.

3.0 SIZING PROCESS VALIDATION AND CALIBRATION

Before utilising the sizing process for the SpritLear SSBJ, it has been a requirement to validate and calibrate the methodology and disciplinary methods for this type of flight vehicle. Given the fact that no SSBJ hardware program has ever been launched, the design methodology has been validated using a wide range of high-speed flight vehicles[18], followed by a first-order SSBJ calibration using data available for the proposed Lockheed Martin/SAI QSST[3] and Dassault Trijet[5]. These representative SSBJs are designed for a supersonic cruise range of 7,400km (4,000nm) with differing payload and cabin sizes (LM/SAI: design PAX 8, max PAX 18; Dassault: design PAX 8, max PAX 9). The other major distinction between both vehicles is the fact that the LM/SAI QSST is a low-boom design whereby the Dassault Trijet represents a high-boom design. Clearly, the low-boom design will enable supersonic flight over land (assuming a relaxation of current sonic boom regulations) while the high-boom design requires a balanced transonic over-land and supersonic over-water range capability. The reverse-sizing of these industry proposed vehicles has calibrated the dedicated SSBJ methodology while demonstrating robustness of the total-system convergence process. In addition, this activity has been providing valuable physical understanding of the relevant gross design parameters and their sensitivities to decision making. Table 3 shows the results of the parametric sizing process and the error when compared with published data for the QSST and Trijet.

Table 3 demonstrates that the methods chosen for this reverse-sizing activity provide reasonable results when compared with published data. At this point it is worth noting that the additional cabin size of the QSST is resulting in an increased TOGW (additional 24,600kg) and fuel weight (additional 12,700kg) relative to the Trijet. Such increased operational capability and comfort comes at the price of additional $7m per unit purchase price and a DOC increase of 30%. Although the unit cost increase is rather insignificant for a business jet of this size, the 30% lower DOC could give the smaller Trijet a competitive advantage.

The evident reduction in operating and unit cost due to the size reduction begs the question: '*How small can a SSBJ be and still be operationally viable?*' Both the QSST and Trijet are sized for a design payload of eight pax while Refs 7 and 8 identified that typical business jets fly with four pax. If the cabin is reduced from a stand-up cabin (used in the QSST and Trijet) to the sit down cabin of the Learjet 25 (a stretched version of the Learjet 24) and the design pay load is limited to four pax, the resulting business jet could be significantly cheaper to develop and operate.

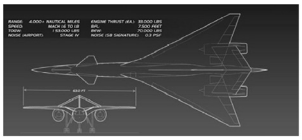
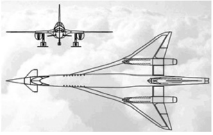
4.0 TECHNICAL SIZING CONSIDERATIONS

Before parametrically sizing the SSBJ, the following key configuration considerations translate into design and operational assumptions and constraints. These assumptions and constraints are derived from the mission specification and are based on past experience with supersonic aircraft which include (1) aircraft fineness *vs* aspect ratio considerations, (2) transonic drag rise considerations, (3) supersonic cross-sectional area distribution considerations, and (4) propulsion system considerations.

4.1 Aircraft fineness vs wing aspect ratio considerations

The challenge of designing a supersonic cruise aircraft is primarily one of aircraft fineness ratio, not wing aspect ratio. Figure 2 presents the difference in wing fineness ratio when overlaying the Learjet 24 with the Sukhoi Su-21 supersonic business jet (SSBJ) project, both scaled to the same cabin width. Then, the span of the Learjet 24 (minus tip tanks) is almost identical compared to the span of the Su-21 while the lengths of both aircraft differ significantly. When examining the wing aspect ratios of both aircraft, it is apparent that the Su-21 employs a wing of significantly lower aspect ratio in comparison. Does this mean the lower aspect ratio wing Su-21 has given up subsonic range for supersonic range performance? Not

Table 3
Parametric sizing results for QSST and Trijet are in good agreement with published projections

		Lockheed Martin/SAI QSST [3] 			Dassault Trijet [5] 	
	Predicted	**Actual**	**Error**	**Predicted**	**Actual**	**Error**
Performance						
R_{SS} (km)	7,400	7,400	0·00%	7,400	7,400	0·00%
R_{TS} (km)	7,400	7,400	0·00%	7,400	7,400	0·00%
BFL (km)	2,286	2,286	0·00%	1,500	1,500	0·00%
Geometry						
S_{ref} (m^2)	183	197	–7·08%	133	130	2·36%
b (m)	19	19·204	–0·01%	17	17	0·00%
l (m)	40·4	40·4	0·00%	34	34	0·00%
Aerodynamics						
L/D_{SS}	6·3	-	-	6·1	-	-
L/D_{TS}	11·0	-	-	10·5	-	-
Propulsion						
$TSFC_{SS}$ (/h)	0·819	-	-	0·828	-	-
$TSFC_{TS}$ (/h)	0·651	-	-	0·656	-	-
T_{un} (kN)	317	294	7·96%	189	-	-
Weight						
OWE (kg)	31,020	31,751	–2·30%	19,114	18,241	4·79%
W_{fuel} (kg)	35,541	36,849	–3·55%	22,881	20,775	10·14%
W_{pay} (kg)	800	800	0·00%	800	800	0·00%
TOGW (kg)	67,545	69,400	–2·67%	42,979	40,000	7·45%
ff (kg)	0·53	0·53	–0·90%	0·53	0·52	2·50%
Cost						
($/unit)*	$79	$80	–1·52%	$72	80	–10·45%
Supersonic**						
DOC $/hr	13,393	-	-	9,238	-	-
DOC $/km	8·89	-	-	6·10	-	-
DOC $/nm	16·47	-	-	11·30	-	-
Transonic**						
DOC $/hr	7,155	-	-	5,235	-	-
DOC $/km	9·18	-	-	6·06	-	-
DOC $/nm	17·01	-	-	11·22	-	-

* *Per unit cost based on a 20% profit margin and fleet size of 300 aircraft*
***DOC based on crew, fuel and maintenance costs for a block range of 1,000nm with a 4·30 $/gallon fuel price*

necessarily. Wing aspect ratio alone does not make a long range aircraft, a fact conveniently illustrated by Nicolai[19] for two subsonic long range aircraft.

Figure 3 compares the high aspect ratio wing Boeing B-47E tail-aft configuration (TAC) with the low-aspect ratio delta wing Avro 698 Vulcan BMk2 flying wing configuration (FWC). When quantifying the lift to drag ratio (L/D) for a parabolic drag polar, it appears that it is the aspect ratio that drives aerodynamic efficiency, see Table 4. This expression is commonly used to identify wing aspect ratio as the key geometry driver for obtaining maximum lift-to-drag ratio (L/D_{max}). However, only a few aircraft have sufficiently installed thrust to actually fly at L/D_{max} since the drag coefficient at L/D_{max} is twice the zero-lift drag coefficient, C_{D0}, and this would result in a very large sea level (SL) installed thrust requirement.

Clearly, it is a common misconception that large aspect ratios definitely yield large flight ranges; that is not necessarily true for high-speed designs. In general, it is the high value of S_{wet}/S_{ref} that causes the tube & wing TAC to lose cruise performance. This and other facts initially motivated R. Liebeck of formerly Douglas Aircraft Company to demonstrate the performance potential of the blended-wing-body (BWB) FWC over the B707 type TAC shapes; this is why the Avro Vulcan FWC has nearly identical aerodynamic efficiency compared with the B-47 TAC. These examples demonstrate that subsonic range primarily focuses on wing span and not wing aspect ratio[20-23].

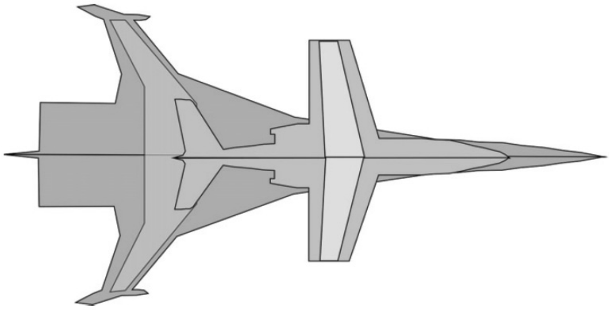
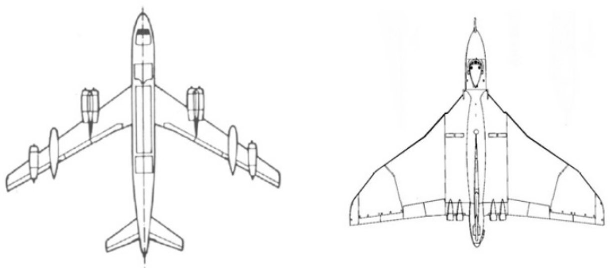


Figure 2. Size comparison of Learjet 24 and Sukhoi Su-21.



	Boeing B-47E	Avro Vulcan
Reference Area	1,428 ft^2	3,964 ft^2
Wetted Area	11,300 ft^2	9,600 ft^2
Wing Span	116 ft	111 ft
S_{wet}/S_{ref}	7.91	2.42
Aspect Ratio	9.42	3.11
Wetted Aspect Ratio	1.19	1.28
$(L/D)_{max}$	17.2	17.8

Figure 3. Wing aspect ratio is not the sole determinant of flight performance.

If we compare a military combat aircraft designed for supersonic cruise like the SCAF-7 project from the 1970s (super cruise with modest maneuverability like the F-4 Phantom) to the McDonnell Douglas F-15 Eagle which is designed for subsonic and supersonic high *g* loading and specific excess power, the differences become clear; see Fig. 4. There is a significant discrepancy in zero-lift drag coefficient, C_{D_0}, compared to a small difference for the induced drag factor, L'. The reason is that C_{D_0} is determined by the magnitude of the maximum cross sectional area, S_{max} and the quality (smoothness and closeness) to the Sears-Haack area distribution with axial body station. In contrast, L' is slightly affected by whether the wing leading edge (LE) is supersonic or subsonic, but is primarily determined by the trailing edge (TE) sweep angle. For wings with the same trailing edge sweep angle, L' should be essentially equal. Aspect ratio determines the subsonic L' parameter but has little

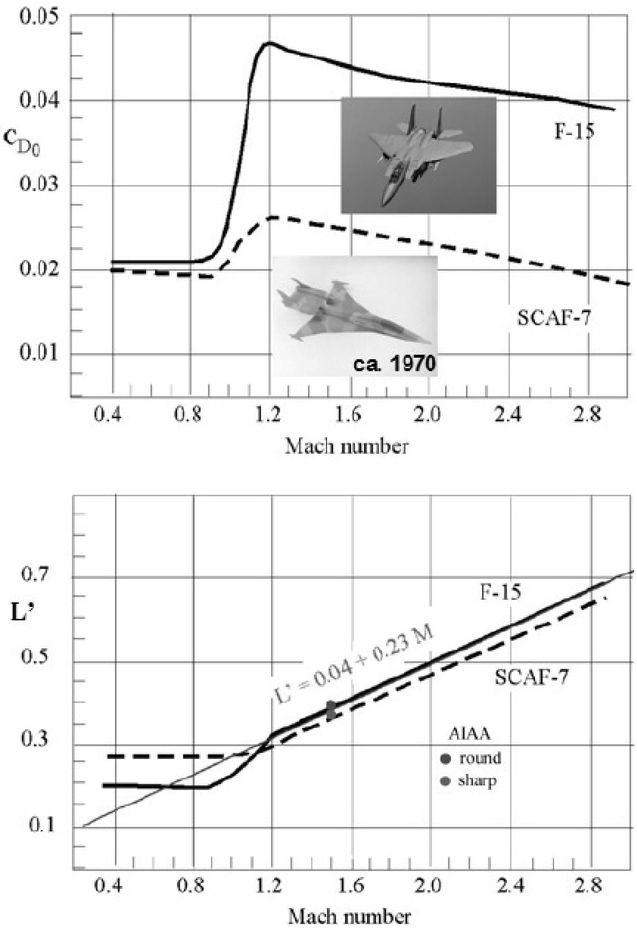


Figure 4. Comparison of zero-lift coefficient and induced drag factor for two fighters (McDonnell Douglas, Advanced Design).

Table 4
Analytical relationships relating geometry to aerodynamic efficiency

L/D relationship	Description
Maximum L/D	
$\left(\frac{L}{D}\right)_{\max} = \frac{1}{2\cdot\sqrt{L'\cdot C_{D_0}}}$	maximum lift to drag ratio for a parabolic drag polar
$L'_{subsonic} = \frac{1}{\pi\cdot AR\cdot e}, L'_{supersonic} = \frac{1}{C_{L_\alpha}} - \Delta L'$	induced drag factor for subsonic and supersonic flow
Cruise L/D	
$\left(\frac{L}{D}\right)_{cruise} = \frac{0.5}{\sqrt{\left(\frac{C_{D_f}}{e^2}\right)\cdot\left(\frac{S_{wet}}{b^2}\right)\cdot\frac{1}{\pi}}} = \frac{0.5}{\sqrt{\left(\frac{C_{D_f}}{AR_{wet}\cdot e^2}\right)\cdot\frac{1}{\pi}}}$	the McDonnell Aircraft Aerodynamic Archives (1966) provide the definition of the cruise lift-to-drag ratio, L/D_{cruise}; in this equation the wetted area aspect ratio based on *wetted area* rather than *wing reference area* is used:
$AR_{wet} = \frac{b^2}{S_{wet}} = \frac{AR}{S_{wet}/S_{ref}}$	wetted aspect ratio definition

https://doi.org/10.1017/S0001924000003171 Published online by Cambridge University Press

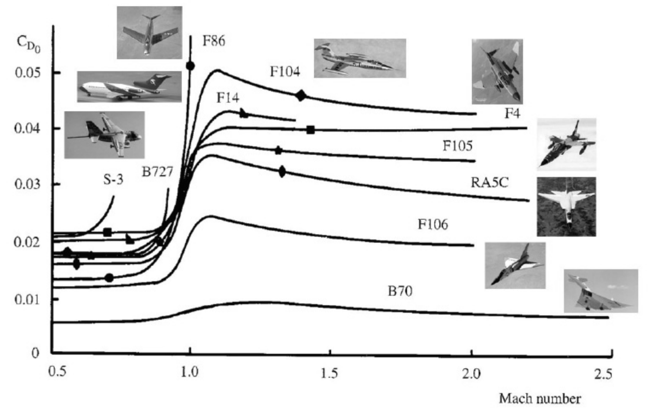
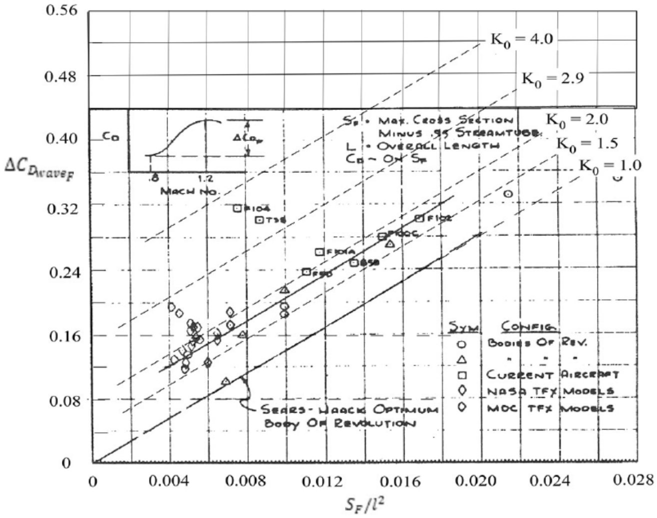


Figure 5. Zero-lift drag coefficient for 1960's aircraft. As slenderness improves, drag rise reduces. Modified from Ref. 16.



$$\Delta C_{D_{wave_{ref}}} = \Delta C_{D_{wave_F}} \cdot \frac{S_F}{S_{ref}}$$

Figure 6. Wave drag increment based on frontal area and length. From McDonnell Douglas, St Louis, Advanced Design, *circa* 1967.

effect on the supersonic L' value. The solid symbols in Fig. 4 show L' determined from Ref. 11 for subsonic leading edges (round) and supersonic leading edges (sharp) compared to the results obtained by the McDonnell advanced design aero group method, see Ref. 24. Concluding, the SpritLear SSBJ will be initially sized with a trailing-edge sweep at a constant zero degrees and a constant finesses ratio (not aspect ratio) which is determined from supersonic and transonic wave drag considerations.

4.2 Transonic wave drag rise considerations

Raymer[16] compares the C_{D_0} polars for historical operational high-performance aircraft. Figure 5 shows the abrupt drag rise for subsonic aircraft like the S-3 Viking, B727, and F-86 Sabre. In contrast, the North American B-70 Valkyrie has been able to cruise supersonically. Note that the B-70 has its drag peak much lower and later compared to the other aircraft, a fact contributed by its highly swept delta wing (66° LE sweep) and canard configuration. The next low-drag aircraft is another delta wing design, the Convair F-106 Delta Dart, employing a 60° LE sweep delta wing. In order to balance both the transonic cruise and low speed performance with

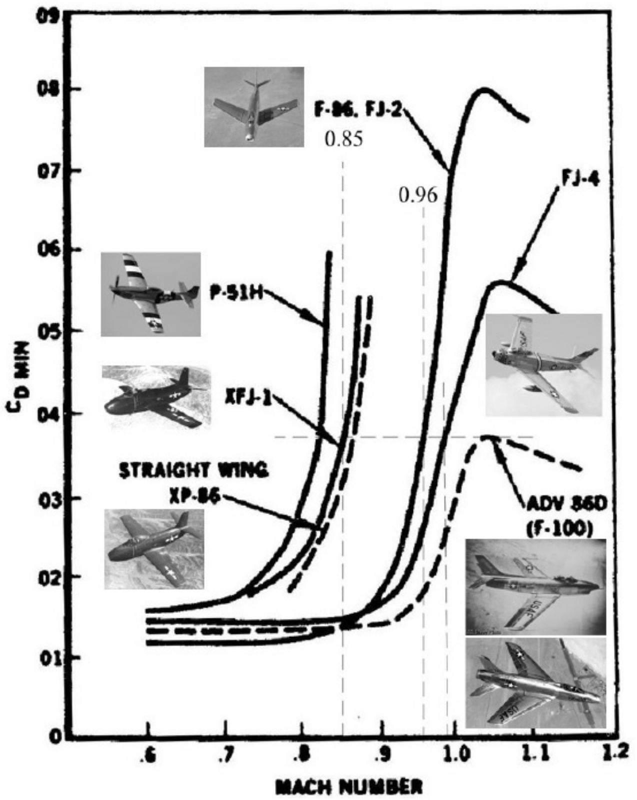


Figure 7. Comparison of transonic drag rise for 1950's military aircraft. Modified from Ref. 26.

the supersonic cruise design point, a delta wing of 60° leading edge sweep has been selected for the SpritLear SSBJ.

In industry it is common practice to use drag correlations for obtaining a first-order estimate of the transonic drag rise. The required aircraft database is usually assembled with supersonic capable aircraft having smooth area distributions (no abrupt and severe changes in cross-sectional area). Therefore, the Douglas Aircraft Company's aerodynamic drag rise correlations shown with Fig. 6 are valid for aircraft like the Sukhoi Su-21 or any other clean supersonic capable design. The nominal combat aircraft values for the wave drag factor, K_0, typically range between $1{\cdot}5 < K_0 < 2{\cdot}0$.

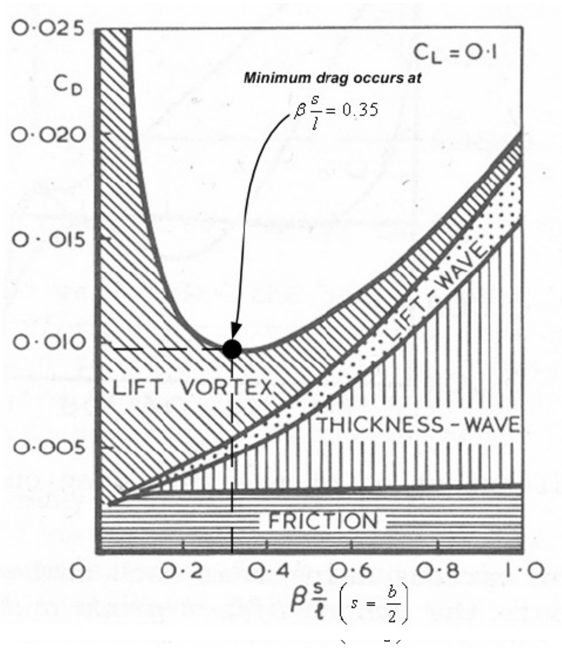
The Sears-Haack zero-lift drag minimum[25] ($K_0 = 1{\cdot}0$) is shown in Fig. 6. Note that the F-104 and T-38 (both utilise an unswept thin wing with supersonic leading and trailing edge) have large drag rises, even though the former is a Mach 2 aircraft and the latter a Mach 1·3 aircraft. For the operational aircraft shown, K_0 ranges from 1·5 to 2·0. It is reported that newer operational high maneuverable aircraft have values of K_0 in the 2·9 range. Commercial and business aircraft can encompass $K_0 > 5$.

For an approximate design-target value of $K_0 = 1{\cdot}5$, this gives a transonic drag coefficient rise of 0·0785 for a total drag coefficient of 0·092 at Mach 1.2. This is in accordance with other transonic aircraft that have been evaluated at supersonic Mach numbers, see Fig. 7. Therefore, a target K_0 value of 2·0 would be required for the SpritLear SSBJ. This implies that the fineness ratio and area distribution be correctly tailored to reduce the drag rise accordingly.

4.3 Supersonic cross-sectional area distribution considerations

The solution to low drag bodies can be attributed to original work done in Germany during the period 1930 to 1950, where the fundamental design drivers determining high speed drag have been

https://doi.org/10.1017/S0001924000003171 Published online by Cambridge University Press



Mach	β	C_D	s/l	$l_{1.5,1.75,2.0}$
1.50	1.12	0.0161	0.233	64.3 ft
1.75	1.44	0.0125	0.200	75.0 ft
2.00	1.73	0.0104	0.175	85.7 ft

Figure 8. Drag components that constitute total supersonic drag at Mach 2·0, C_L = 0·1[20] and fuselage lengths required for three selected design speeds and a wing span of 30ft for the indicated slenderness ratio.

identified. From work in 1947, D. Küchemann[20,21] recognises that for Mach numbers greater than 1·0, the wave drag of a body is driven by essentially two parameters, volume and length. The wave drag associated with the volume and length of a body may be written:

$$C_{D_{wave}} \cdot S = \frac{D}{q} = \frac{128}{\pi} \cdot \frac{V^2}{S \cdot l^4} \cdot K_0 \qquad \ldots (1)$$

In Küchemann's words "*This indicates that the square of the volume and the inverse of the fourth power of the overall length are dominant* ..."[20]. In this context, the R. Seebass sonic boom equations provided with Ref. 27 are also a function of body length raised to the 2·5th power to determine design shock overpressure conditions where the shock ideally does not reach the ground.

Figure 8 shows the relative magnitude of the four primary supersonic drag sources as a function of scaled half-span to length for a Mach 2·0 aircraft at a lift coefficient of 0·1. This understanding was used by D. Küchemann[20,21] to show the required fineness ratio for what was to become Concorde. This graph is of importance because it provides a start value for the minimum total drag coefficient given the half-span to length ratio of the aircraft. The minimum drag occurs for the abscissa value of 0·35 and an ordinate value of 0·010. For a 30ft wing span, the fuselage lengths are given with Fig. 8 for three design speeds (M1·5, 1·75, 2·0). Consequently, a Learjet-based supersonic Mach 1·5 aircraft should be in the 64ft length range.

The Learjet 24 cross-sectional area distribution shown with Fig. 9 is compared with the area distribution for the McDonnell Douglas SCAF-7 supersonic cruise fighter project. Author P. Czysz was manager of the Advanced Concepts Group that developed the configuration using Douglas's advanced supersonic transport wing.

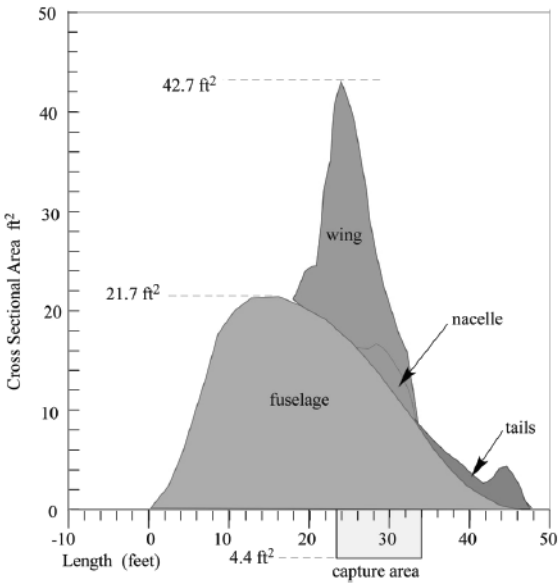


Figure 9. Learjet 24 cross-sectional area distribution without tip tanks shows abrupt area changes.

In the present context the SCAF-7 area distribution is used as a template for the SpritLear SSBJ area distribution that can be approximated to match a supersonic Mach 1·5 area distribution with minimum excess power, thereby translating into the design requirement $K_0 < 2{\cdot}0$, see Fig. 10.

Consequently, the supersonic Learjet 24 area distribution has been stretched to 65ft length and the cross sectional area has been reduced to 29·3ft². The area has been filled in with additional volumes to fit the approximate Sears-Haack distribution. If one complements the horizontal tail with a carefully placed canard, a three-surface configuration (TSC) results. This arrangement promises a minimum induced drag solution since the total lift is distributed over three longitudinal lifting surfaces[28]. The induced drag of a trimmed Mach 1·5 TSC can be reduced to about 45% of the equivalent trimmed conventional tail-aft configuration (TAC). Ventral fins have to be added to maintain supersonic directional stability since most supersonic combat aircraft have significantly reduced inherent directional stability near maximum speed. The challenge remains to inverse-size an actual aircraft geometry which matches this pre-defined area distribution. The SpritLear SSBJ will be sized to a constant s/l = 0·233 for a supersonic cruise Mach number of 1·5 to limit fuselage length. The area distribution will be maintained as close as possible as the span and length are enlarged from the 3,000nm mission to the 4,000nm mission while maintaining an approximate $K0$ value of 2·0.

4.4 Propulsion system considerations

The initial feasibility study[8] has considered 14 candidate engines able to meet the required cruise thrust requirements when arranged into either a twin or triple cluster, see Fig. 11. The initial objective has been to find three equal thrust engines that are of sufficiently small diameter to enable integration into the existing nacelles and their original location at the aft fuselage. This 'minimum-change' configuration objective, however, results in unacceptable thrust performance and fuel economy penalties. For the triple engine cluster scenario, economic subsonic operation requires only the two nacelle engines to operate while the third engine is wind milling. The

https://doi.org/10.1017/S0001924000003171 Published online by Cambridge University Press

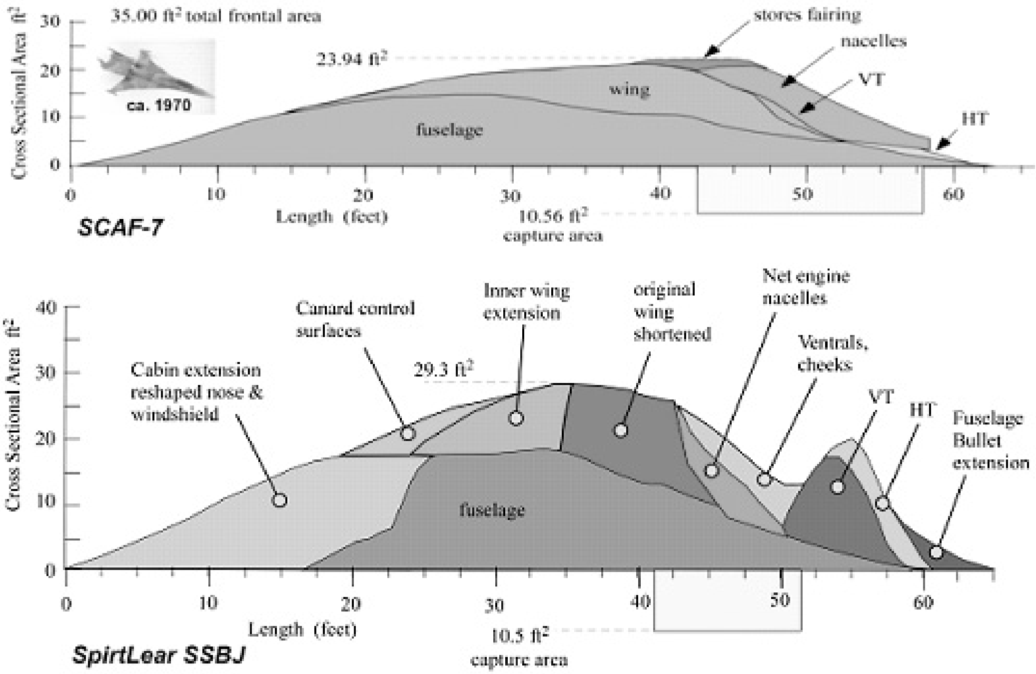
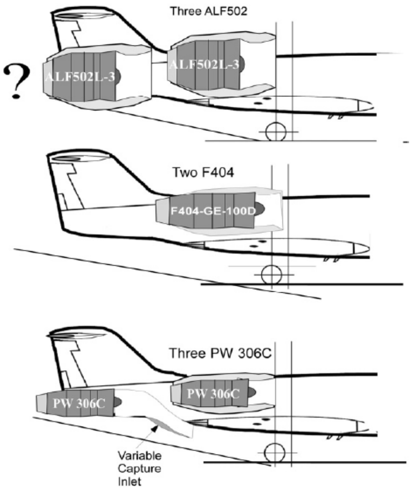


Figure 10. Cross-sectional area distribution for the SCAF-7 supersonic cruise fighter and approximate cross-sectional area distribution goal for the SpritLear SSBJ.

	Engine	Thrust (pounds)	sfc lb/lb-hr	θ	weight (pound)	diameter (Inches)	Isp (seconds)
1	J85-GE-4	2,950	1.010	0.194	440	17.7	3,564
2	FJ 44-2C	3,000	0.460	0.426	450	23.0	7,826
3	TFE731-2	3,500	0.504	0.389	734	39.4	7,143
4	PW305B	5,226	0.391	0.502	993	44.0	9,207
5	ATF-3-6A	5,440	0.503	0.390	1,125	33.9	7,157
6	PW 306C	5,922	0.421	0.466	1,142	26.5	8,551
7	AS 907	6,500	0.420	0.467	1,365	49.9	8,571
8	AE 3007C/C1	6,764	0.630	0.311	1,572	43.5	5,714
9	PW 308C	7,000	0.415	0.473	1,368	39.0	8,675
10	IF 507-1F	7,000	0.397	0.494	1,685	50.0	9,068
11	AS 977	7,092	0.416	0.471	1,354	49.0	8,654
12	ALF502-1F	7,500	0.414	0.474	1,336	50.0	8,696
13	F404-GE-4	11,000	0.640	0.306	1,820	35.0	5,625
14	SPEY Mk 2501	11,995	0.660	0.297	2,740	32.5	5,455

Figure 11. Candidate engines from the initial feasibility study with main characteristics.



	Thrust (lb)	Weight (lb)	T/W installed (1.46M)	Isp (sec)	SFC (lb/lb-h)	V*Isp (nm)
Two F404	22,000	3,640	1.38	6,178	0.583	850
Three PW308C	21,000	3,951	1.12	9,207	0.391	1,267
Three PW 306C	17,766	3,426	1.09	8,551	0.421	1,177
Three ALF502L-3	22,500	3,933	1.20	8,696	0.414	1,196

Figure 12. Possible installation options of recommended engine alternatives.

increased subsonic drag and poor economics of the small diameter engines quickly identifies a show-stopper for the original engine integration constraint. The necessity for larger diameter aft nacelle turbofan engines for both, the twin and triple engine cluster, results in a major redesign of the original nacelles geometry and positions.

Figure 11 identifies engine alternatives providing adequate thrust potential. However, the fuel economy aspect necessitates the consideration of fan engines in the 6,500 to 7,500lb thrust class. Such thrust requirement significantly increases the physical engine dimensions, in particular the engine diameter towards the 4ft range approaching the diameter of the Learjet 24 fuselage. Note that it is not clear at this point if any of these engines have been certified for supersonic operation. In addition, the fan drag of medium bypass engines tends to be high. For example, the Harrier engine, when approaching Mach 1, has as much drag as the entire aircraft. Clearly, the Learjet 24 aft fuselage engine integration task is a particularly challenging task. From Fig. 11, engines 2 to 6, 9, and 12 to 13 have been chosen to provide the necessary 15,000 to 17,000lb sea-level static thrust, uninstalled, in order to cruise at Mach 1·46 at 48,000ft.

Figure 12 visualises possible engine integration scenarios and preliminary engine envelopes with characteristics, showing one

Table 5
Candidate propulsion systems for the 3,000nm and 4,000nm range SpritLear SSBJ

Engine	Thrust*		TSFC*	Dry weight		Bypass ratio	Diameter		Length		Utilisation
	KN	lb	1/hr	kg	lb	–	cm	in	cm	in	
PW308C	26·34	5,922	0·421	518	1,142	4·4	67	26·5	192	75·7	Gulfstream G200
F404-GE-100D	48·93	11,000	0·8	826	1,820	0·34	89	35	226	89	A-4 SU
F404-GE-100Dmod	48·93	11,000	0·64	826	1,820	0·34	89	35	226	89	McDonell cruise fighter
JT8D-17AR	77·40	17,400	0·622	1,633	3,600	1·04	101	39·9	305	120	B727
JT8D-219	96·53	21,700	0·519	2,048	4,515	1·04	125	49·2	392	154	MD-90, Aerion SSBJ
F414-GE-400	97·86	22,000	0·800	1,109	2,444	0·34	89	35	391	154	F/A18E,EA-18G

**Sea-level maximum thrust*

twin-cluster (two identical turbojet engines) and two triple-cluster (three identical turbofan engines), combinations that provide the necessary thrust for Mach 1·46 at 48,000ft. As shown with Fig. 12, only the PW306C and the F-404-GE-100D options offer a diameter below 4·0ft for installation on and in the fuselage while providing reduced fuel flow characteristics. Note that the F404-GE-100D twin engine cluster does not require a third inlet on the aircraft center line. Considering the aft fuselage redesign required for the three-engine design alternative, the twin installation appears to be the favored minimum-change approach.

The parametric sizing trades will demonstrate, however, that the increased 4,000nm range mission does require additional thrust due to the increased fuel load and overall scaled up aircraft. This requires the examination of both, the twin and triple cluster engine alternatives with the larger turbojet and turbofan engines, see Table 5. Note that two versions of the F404-GE-100D are listed in Table 5. The original F404-GE-100D was specifically modified by GE (around 1975, re-scheduling, different fuel controller, core pressure ratio slightly increased) for the McDonnel Douglas SCAF-7 cruise fighter, resulting in improved TSFC at *SL*, M0·91 and M1·5 cruise. The original engine was designed for max combat performance at M0·91. For the present study the engine will be referred to as the F404-GE-100Dmod adjusted for supercruise capability. Note that the selection of the cruise design point at M1·5 due to aircraft length considerations allows for a simple pitot inlet.

4.5 Summary of technical considerations

From these considerations the following technical guidelines have been established for the parametric sizing of the SpritLear SSBJ:

1. Aircraft scaling is based on aircraft fineness ratio not wing aspect ratio. To minimise the transonic drag rise and supersonic induced drag and wave drag, an aircraft slenderness ratio of s/l = 0·233 is maintained for the M1·5 cruise point with a Sear-Haack correlation of K_0 = 2·0 where wing span is traded for fuselage length adjusted to the required slenderness ratio and persevering area distribution shape.
2. A cruise Mach number of 1·5 is selected to avoid excessive fuselage length (due to fineness considerations at higher Mach numbers) and allow for a simple engine pitot inlet.
3. The leading edge sweep angle of the delta wing is selected to an initial 620 start point for obtaining a subsonic leading edge for reduced wave drag during supersonic cruise. The trailing edge sweep angle is set to zero degrees to minimise induced drag during supersonic cruise.
4. Twin engine and triple engine configurations are considered for both, the 5,560km (3,000nm) and 7,400km (4,000nm) range missions.

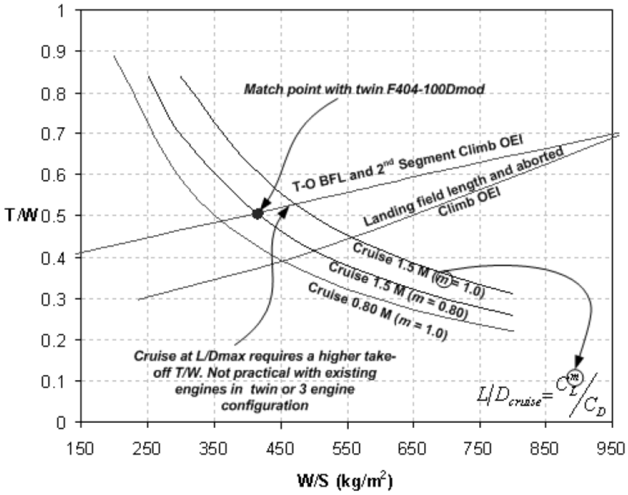


Figure 13. Match point selection balances cruise and take-off thrust requirements.

5.0 PARAMETRIC SIZING RESULTS

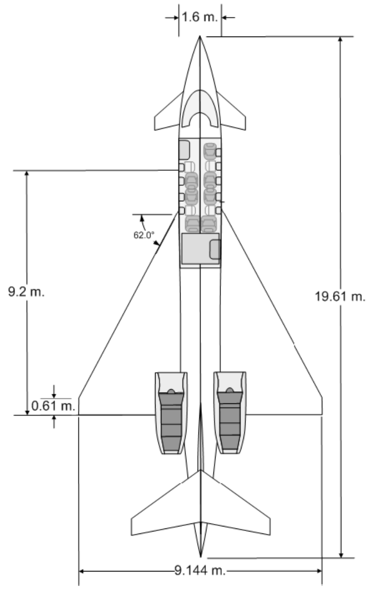
The parametric sizing results for the SpritLear SSBJ are presented in three distinct steps: (1) Sizing to the Learjet 24 constrained mission, 5,560km (3,000nm), (2) sizing to the practical operational mission as derived from the market analysis, 7,400km (4,000nm), and finally (3) comparing the SpritLear SSBJ results to the computed results obtained for the Lockheed Martin/SAI QSST and Dassault Trijet.

5.1 Parametric sizing to the Learjet 24 constrained mission: 5,560km (3,000nm)

Having constraining the fineness ratio $b/(2l)$ = 0·233 and the Learjet 24 wing span to 9·14m (30ft), the challenge becomes balancing the thrust required for the 2nd segment climb gradient with the thrust required to fly at $(L/D)_{max}$ during cruise. Cruising at $(L/D)_{cruise} < (L/D)_{max}$ reduces the cruise thrust required thus the engine size. However, it does increase the fuel weight required for a constant design range and thus increases the TOGW and the maximum sea-level thrust required for OEI climb.

In order to evaluate the effects of flying at different $(L/D)_{cruise}$, the parameter m introduced by Vinh[29] is used. This parameter controls the exponent of the C_L term during cruising flight for a parabolic drag polar as shown in Fig. 13 where m is such that $0 \le m < 2$. For m = 1 we obtain $(L/D)_{max}$. After some iteration an appropriate balance

https://doi.org/10.1017/S0001924000003171 Published online by Cambridge University Press



	SI		English
Performance			
h transonic (km-ft)	10·00		32,800
h supersonic (km-ft)	13·80		45,300
R supersonic (km-nm)	5,556		3,000
R transonic (km-nm)	7,400		3,996
BFL (m-ft)	2,440		8,000
Aerodynamics			
L/D transonic	8·22		-
L/D supersonic	5·93		-
C_{LA}	0.71		-
C_{LTO}	1.01		-
C_{Lmax} clean	1·20		-
Propulsion			
T_{sl} installed (kN-lb)	92·2		20,721
T_{sl} uninstalled (kN-lb)	101·4		22,793
Weight			
OWE (kg-lb)	8,830		19,500
W_{fuel} (kg-lb)	9,238		20,400
W_{pay} (kg-lb)	400		882
TOGW (kg-lb)	18,700		41,000
ff	0·495		-
Cost			
Unit cost $/unit*		$40,700,000	
DOC supersonic**			
$/hr		$4,319	
$/km-$/nm	$3·26		$6·04
DOC transonic**			
$/hr		$3,313	

* *Per unit cost based on a 20% profit margin and fleet size of 300 aircraft.*
***DOC based on crew, fuel, maintenance costs for block range: 1,000nm, 4·30 $/gallon fuel price.*

Figure 14. SpritLear SSBJ sized for 3,000nm range design mission.

is identified for the cruise point at $C_L^{0·80}/C_D = 5·93$, which allows for two F404-GE-100Dmod engines as described earlier.

The performance matching diagram shown with Fig. 13 visualises the cruise and take-off performance trade space. The additional T/W required for cruising at $(L/D)_{max}$ requires a higher thrust level for the OEI second segment climb gradient compared to what is available with the F-404-100Dmod engines. Selecting more powerful engines for the twin-engine cluster or adopting the triple-engine cluster does increases the empty weight of the aircraft such to drive the thrust, fuel, and wing area requirements to unrealistic values where the aircraft does not converge. In analogy with most commercial transports, the cruise point consequently selected for the SpritLear SSBJ follows $(L/D)_{cruise} < (L/D)_{max}$ for this twin engine configuration. Having identified the solution space and selected a match point, the primary vehicle characteristics for the SpritLear SSBJ are summarised with Fig. 14.

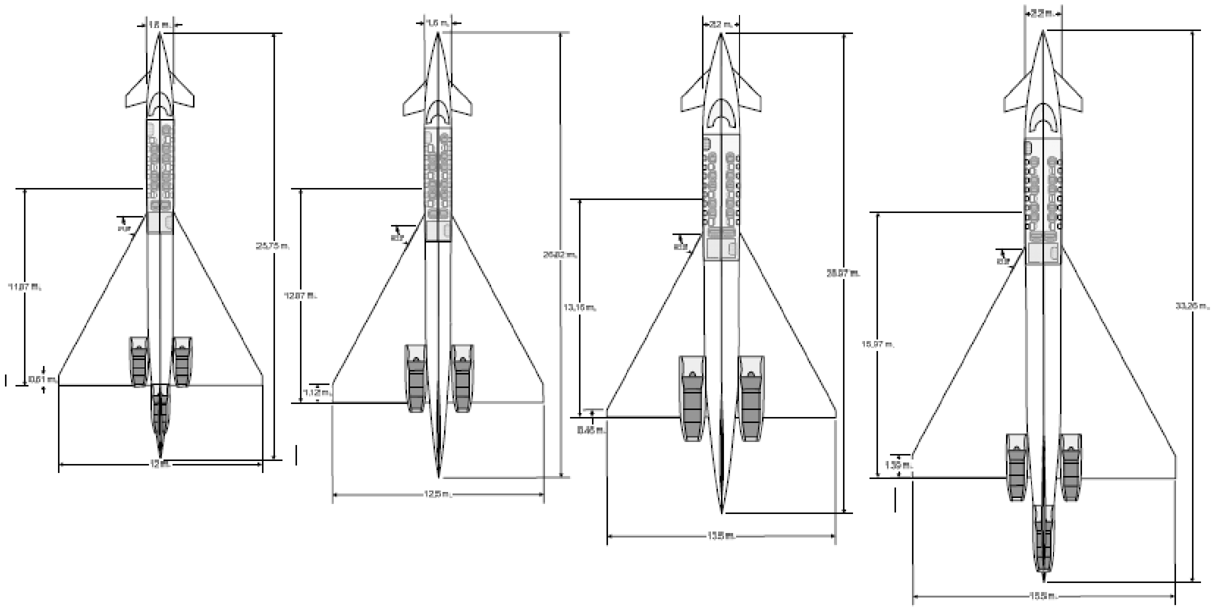
The SpritLear SSBJ sized for 3,000nm range represents a minimum cost solution in terms of both purchase price and DOC. Both, the supersonic and transonic DOCs are lower compared to the Lockheed Martin/SAI QSST and Dassault Trijet. However, this aircraft is not an operationally practical aircraft. With a design range of 5,560km (3,000nm) this aircraft would be restricted to supersonic transatlantic flights only; most destinations would require one stop, thereby eliminating the time savings accumulated with the supersonic over-water leg[8]. In order to keep the required take-off and landing lift coefficients within reasonable values, a BFL of 2,440m (8,000ft) is required to balance the take-off and cruise thrust requirements. Clearly, this vehicle represents an operationally sub-optimal configuration. While the performance could be improved slightly with further refinement of the wing and propulsion system integration, the aircraft is too small for a practical high-boom SSBJ.

5.2 Parametric sizing to the practical operational mission: 7,400km (4,000nm)

The 3,000nm SpritLear SSBJ configuration is operating at the maximum thrust potential of the F404-100Dmod engines. Increasing the design range requires additional take-off thrust, thereby translating into increased fuel weight, increased aircraft weight, and the requirement for additional wing area. Clearly, improving the operational capability of the SpritLear SSBJ requires re-evaluating both, the engine selection and overall aircraft size. This section of the study allows deviating from the Learjet 24 originated hardware design constrains, thus aims at arriving at a practical minimum-complexity SSBJ by determining the correct overall flight vehicle size, by re-evaluating the passenger comfort (stand-up vs. sit-down cabin) provided, and by selecting the enabling propulsion system.

The design iterations for the 4,000nm aircraft are constrained to the same slenderness ratio ground rule as the 3,000nm range aircraft. Aircraft span is the primary design variable to modulate aircraft size; different engine combinations are traded to satisfy the conflicting thrust requirements. The results of this sizing study are summarised with Fig. 15. The original design mission has been increased from four to eight pax without significantly affecting vehicle weight and size. The fuel weight is sizing the SpritLear SSBJ, not payload. As shown with Fig. 15, the 3 F404-100Dmod design (sit down cabin, stretched Learjet 25 cabin) allows for improved BFL due to the third F404-100Dmod engine. The other three configurations shown are sized for a maximum BFL of 2,440 m (8,000ft) to minimise the take-off thrust requirement. Note that the L/D for transonic and supersonic cruise remains relatively constant for each configuration due to their identical slenderness ratio. The required are achievable with the swept delta wings. However, slats and flaps will be required to

https://doi.org/10.1017/S0001924000003171 Published online by Cambridge University Press



	3 F404-100Dmod	2 JT8D-17AR	2 JT8D-216	3 JT8D-17AR
Pax	6	6	8	8
R (km-nm)	7,400 (4,000)	7,400 (4,000)	7,400 (4,000)	7,400 (4,000)
BFL (m-ft)	1,500 (8,000)	2,440 (8,000)	2,440 (8,000)	2,440 (8,000)
Cross-section				
w (m-ft)	1·6 (5·25)	1·6 (5·25)	2·2 (7·22)	2·2 (7·22)
h (m-ft)	1·6 (5·25)	1·6 (5·25)	2·3 (7·55)	2·3 (7·55)
Aerodynamics				
L/D (1.5M)	6·76	6·69	6·44	7·00
L/D (0.9M)	9·40	9·47	9·50	9·84
C_{Lmax} required	1·78	1·26	1·50	1·45

Figure 15. Sizing results for the 2 and 3 engine cluster configurations with sit-down and stand-up cabin. The sit-down cabin retains the Learjet 24 fuselage (stretched); the stand-up cabin resembles the cross section of the Dassault Trijet.

reduce the low-speed angles-of-attack and aircraft attitudes for take-off and landing pilot visibility reasons.

Figure 16 compares the unit price, DOC, weight and uninstalled thrust estimates obtained for the four design concepts shown in Fig. 15. Note that the three-engine sit-down design results in a more expensive yet lighter aircraft compared to both twin-engine sit-down cabin aircraft. This is due to the number of engines integrated and the fact that the F404-100Dmod is having a slightly higher TSFC while being significantly lighter compared to the JT8D-17AR. The net effect is that the three F404-100Dmod SSBJ design is the smallest and lightest alternative despite a unit cost penalty due to the third engine relative to both twin-engine designs.

The most interesting finding from Fig. 16 is the fact that the twin-engine stand-up cabin design (enhanced passenger comfort) is close in unit price and DOC compared to the twin-engine sit-down cabin design (reduced passenger comfort). The enlarged and lengthened fuselage for the twin-engine stand-up cabin design requires more powerful JT8D-216 engines for the take-off and cruise flight segments. However, the larger and more powerful JT8D-216 have a slightly lower TSFC compared to the older JT8-17AR used on the twin-engine sit-down design; thus, some of the additional thrust and TOGW penalties are mitigated. While the fuel weight difference between both twin-engine designs is small, the TOGW difference due to additional structure and propulsion system weight is more pronounced. Although the twin engine stand-up cabin SSBJ requires the highest thrust per engine resulting in the largest engine of the proposed configurations, it still requires less total thrust compared to the triple-engine stand-up cabin. This is due to the increased propulsion system weight and TSFC for the triple-engine (JT8D-17AR) stand-up cabin SSBJ. Note that the triple-engine (F404-100Dmod) sit-down cabin SSBJ requires less overall thrust compared to the twin-engine (JT8D-17AR) sit-down cabin SSBJ. This is due to the excellent thrust to weight ratio of the F404-100Dmod when compared to the JT8D-17AR.

In summary, the most practical configuration for the 4,000nm mission range is the twin-engine (JT8D-216) stand-up cabin SSBJ design proposal. This aircraft offers an acceptable increase in unit purchase price and DOC relative to the twin-engine sit-down cabin SSBJ, while provided additional comfort, payload and cabin layout flexibility.

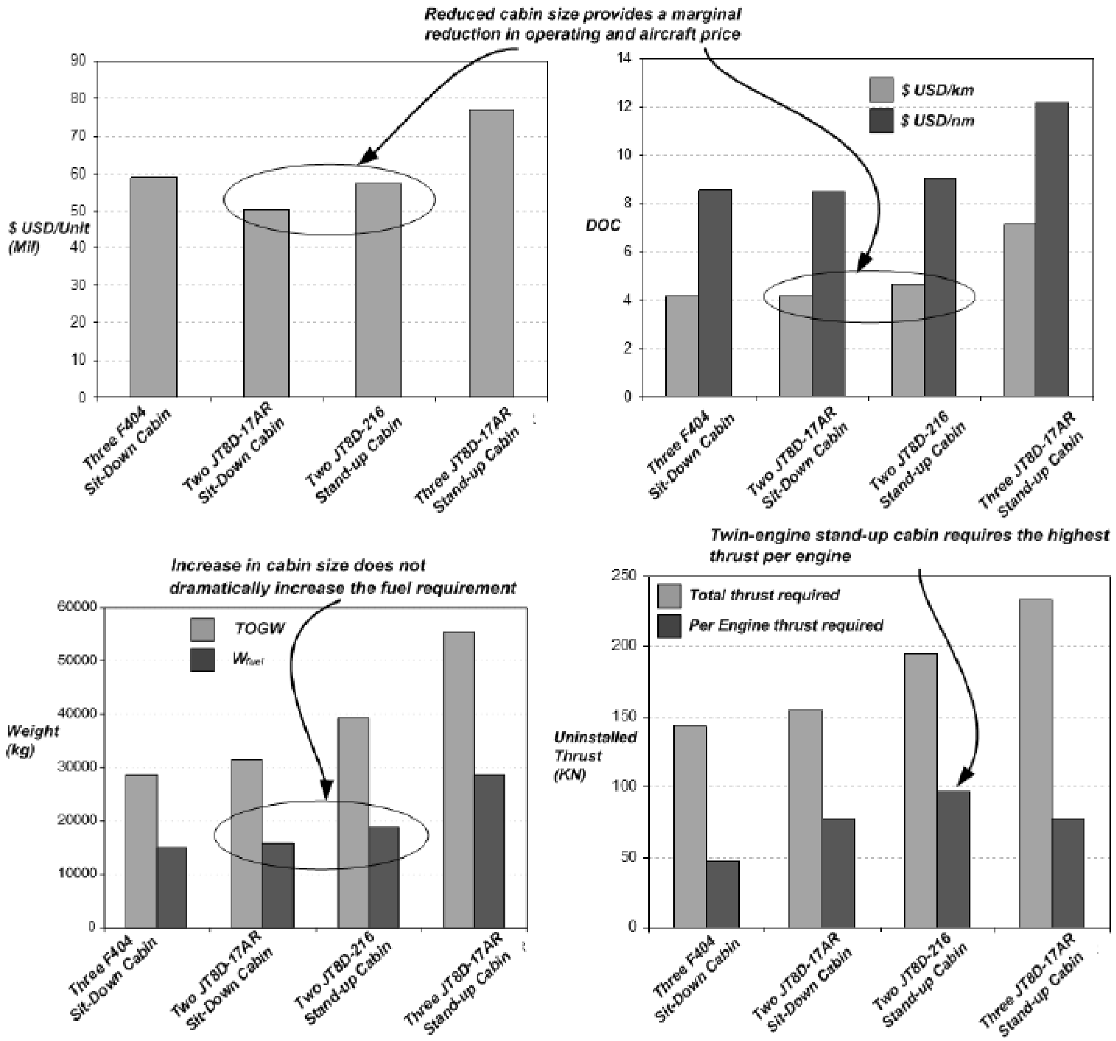


Figure 16. Unit cost, DOC, weight, and uninstalled thrust comparison of the four proposed SpritLear SSBJ alternatives.

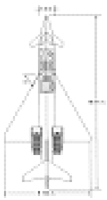
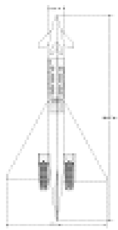
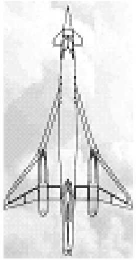
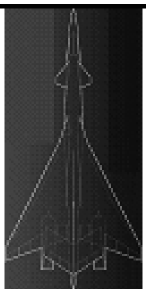
5.3 Comparison of the SpritLear with the LM/SAI QSST and Dassault Trijet

When comparing the Section 3 QSST and Trijet validation and competition analysis results with the Section 5.2 SpritLear baseline design, the different design objectives are offering two distinctly different products. The 4,000nm SpritLear SSBJ design represents, at this point, the best iteration for delivering a low-technology, high-boom performance, low R&D cost and DOC, and low overall project risk compromise. The other extreme is represented by the LM/SAI QSST SSBJ delivering high-technology low-boom performance, high R&D cost, high DOC, and high overall project risks.

Although the 3,000nm SpritLear SSBJ design proposal does promise a quick and cheap entry SSBJ alternative to the mid-weight class business jet market, its inherent operational range limitations, however, will adversely affect its market viability translating into a product show-stopper.

The Lockheed Martin/SAI QSST represents the 'ideal' SSBJ producing sufficiently long range and low-boom characteristics coupled with high-comfort. If the SSBJ market becomes a reality and over-land supersonic flight is permitted, then the QSST will represent the top of the line product from an operational, luxury, and purchase price point of view. At the present time uncertainty prevails related to technical solutions capable of reducing the aircraft supersonic boom footprint intensity for over-land flight to not-yet-known regulatory limits. Consequently, the high R&D cost and high purchase price tends to prevent, until today, the launch of an industry development programme for some time to come.

Table 6
Summary of sizing results: SpritLear concepts *vs* Lockheed Martin/SAI QSST and Dassault Trijet

	3,000nm *SpiritLear*	4,000nm *SpiritLear*	Dassault Trijet[5]	LM/SAI QSST[3]
				
Weights				
Pax	4-6	8-12	8-12	8-18
TOGW	18,600kg (41,100lb)	39,200kg (86,500lb)	43,000kg (94,700lb)	67,500kg (149,000 lbs)
ff	0·495	0·478	0·532	0·526
Performance				
R	5,560km (3,000nm)	7,400km (4,000nm)	7,400km (4,000 nm)	7,400km (4,000nm)
M*	1·5M/0.90M	1·5M/0.90M	1·8M/0.90M	1·8M/0.90M
BFL	2,440 m (8,000ft)	2,440m (8,000ft)	1,500m (4,900ft)	2,440m (8,000ft)
Cost				
USD/unit**	$40·1m	$56·9m	$71·6m	$78·8m
USD/km***	$3·26/$3·81	$4·67/$5·11	$6·10/$6·06	$8·89/$9·18
Risk				
Propulsion	existing	existing	new	new
Aero/structure	conventional delta wing	conventional delta wing	conventional delta wing	conventional delta wing
Sonic boom	high-boom	high-boom	high-boom	low-boom
Supersonic Operation	transatlantic	transatlantic/ transpacific	transatlantic/ transpacific	transatlantic/ transpacific
Comments	moderate risk with existing technology and propulsion system; low operational performance	low risk with existing technology and propulsion system; adequate operational performance	moderate risk requiring new propulsion system; adequate operational performance	high risk due to new propulsion system and change in boom regulations; superior performance.

* *supersonic/transonic cruise*
** *per unit cost based on a 20% profit margin and fleet size of 300 aircraft*
*** *DOC based on crew, fuel and maintenance costs for a block range of 1,000nm with a $4·30/gallon fuel price (supersonic/transonic)*

The 4,000nm SpritLear represents a compromise between the high-end QSST and the low-end 3,000nm SpritLear. When comparing the 4,000nm SpritLear to the Dassault Trijet it is evident that the Trijet is similar in range, payload, and weight. The increased purchase price and DOC for the Trijet are partly due to its higher weight resulting from an enlarged fineness ratio required to cruise at M1·8 compared to M1·5 for the SpritLear. However, the primary factor driving the cost difference between the Trijet and the SpritLear can be attributed to the third engine balancing the increased thrust requirement with the BFL constraint. The different cruise speed and field performance results in an economically viable SpritLear SSBJ able to integrate existing engines. For Dassault, one of the primary reasons to discontinue the Trijet project was the difficulty of finding a suitable propulsion system[30],

With a unit price of $56·9m, a reasonable DOC, a stand-up cabin and supersonic transatlantic and transpacific capability, the 4,000nm SpritLear would be especially attractive to fractional ownership companies. Fractional ownership companies could base the early generation of high-boom SSBJs at coastal cities and operate them over water only for maximum benefit; a scenario where the times savings can be easily justified by executives. The transonic fleet would provide the over-land transportation function.

6.0 CONCLUSIONS AND RECOMMENDATIONS

From this study we can conclude that an inexpensive SSBJ can be developed based on the Learjet 24 airframe. Although this Learjet 24 derived SSBJ could be first on the market, the overall design suffers from operational limitations which are expected to severely reduce its market penetration potential.

Increasing the design mission from 5,560km (3,000nm) to 7,400km (4,000nm) translates into a significantly larger aircraft, on par with other current SSBJ projects. Constraining this longer range SpritLear design to a sit-down cabin with four pax has little effect on reducing overall aircraft size and cost, given that the aircraft size is primarily dictated by the fuel weight required. Then, the aircraft is logically evolving into a larger stand-up cabin design for increased comfort, thus passenger appeal. It appears that the simplest SSBJ design, capable of complying with the 'inexpensive and low-technology' goal, is a high-boom M1·5 cruise speed design with a moderate take off field length of 2,440m (8,000ft).

Having utilising a reduced order parametric sizing process, a correct vehicle size and a first cost estimate has been determined with a focus on overall system convergence. The correctly sized

SpritLear SSBJ serves as the start configuration for the more elaborate conceptual design phase. Note, that issues such as structural layout, control surfaces sizing, internal systems selection/layout, noise considerations, and others, are not quantified at this early sizing stage. It appears that the concept of a low-technology and low-cost SSBJ has the potential to be first to market while stimulating the second generation of SSBJs.

ACKNOWLEDGEMENTS

The presented design trade studies were supported by Spirit Wing Aviation. The AVD Lab is grateful for the constructive work relationship with Calvin Burgess. The views and conclusions contained in this report are those of the authors. The authors like to acknowledge the contributions of the following AVD Lab team members: Xiao Huang, Andy Huizenga, Andy N. Ferguson, Ben Cheatham, and Matthew Simon.

REFERENCES

1. MILLER, J. Program Update — Aerion enters advanced design phase, 5 October 2008, Press Information, Aerion Corporation.
2. HENNE, P.A. Case for small supersonic civil aircraft, *J Aircr*, May-June 2005, **42**, (3).
3. PAULSON, M. SSBJ developments — Putting a 'Q' into supersonic flight, *Professional Pilot*, September 2007, pp 58-62.
4. ANTONOV, V., GORDON, Y., GORDYUKOV, N., YAKOVLEV, V., ZENKIN, V., CARRUTH, L. and MILLER, J. *OKB Sukhoi — A History of the Design Bureau and its Aircraft*, 1996, 1st Edition, pp 259-262, Midland Publishing.
5. DEREMAUX, Y. Intermediate aircraft configuration families, 31 October 2007, Issue 1, HISAC-T-5-27-1, Dassault Aviation.
6. CHUDOBA, B., COLEMAN, G., OZA, A. and CZYSZ, P.A. What price supersonic speed? A design anatomy of supersonic transportation, Part 1, *Aeronaut J*, March 2008, **112**, (1129), pp 141-151.
7. CHUDOBA, B., OZA, A, COLEMAN, G. and CZYSZ, P.A. What price supersonic speed? — An applied market research case study — Part 2, *Aeronaut J*, April 2008, **112**, (1130), pp 219-231.
8. CHUDOBA, B., COLEMAN, G., HUANG, X., HUIZENGA, A., CZYSZ, P.A. and BUTLER, C.M. A feasibility study of a supersonic business jet (SSBJ) based on the Learjet airframe, 2006, AIAA 2006-28, 44th AIAA Aerospace Sciences Meeting and Exhibition, 9–12 January 2006, Reno, Nevada, USA.
9. LOFTIN, L.K. Subsonic aircraft: Evolution and the matching of size to performance, August 1980, NASA RP 1060, NASA Langley Research Center.
10. HOAK, D.E. and FINCK, R. USAF stability and Ccontrol DATCOM, Flight Controls Division, October 1960, revised 1978, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio.
11. ANON. AIAA aerospace design engineers guide, 1998, 4th Edition, pp 7-25, American Institute of Aeronautics and Astronautics.
12. MATTINGLY, J.D., HEISER, W.H. and PRATT, D.T. *Aircraft Engine Design*, 2002, 2nd Edition, AIAA Educational Series.
13. HOWE, D. *Aircraft Conceptual Design Synthesis*, 2000, Professional Engineering Publishing, London and Bury St Edmunds.
14. ANON. Aerospace source book, *Aviation Week and Space Technology*, 2005, **162**, (3).
15. ROSKAM, J. Airplane design — Part I: Preliminary sizing of airplanes, 2003, DARcorporation, Lawrence, Kansas.
16. RAYMER, D.P. *Aircraft Design: A Conceptual Approach*, 1999, 3rd Edition, AIAA Education Series.
17. HAGERMAN, E. All sonic, no boom, *Popular Science*, March 2007, pp 64-67.
18. HUANG, X. and CHUDOBA, B. Overview of a HTHL hands-on SAV design synthesis methodology, 2007, AIAA Paper, AIAA-2007-241, 45th AIAA Aerospace Sciences Meeting and Exhibition, 8-11 January 2007, Reno, Nevada.
19. NICOLAI, L.M. Airfoil and planform selection, 1979, The Annual Aircraft Design Short Course, Bergamo Conference, 8-12 July 1979, Dayton, Ohio.
20. KÜCHEMANN, D. *The Aerodynamic Design of Aircraft*, 1978, 1st Edition, Pergamon International Library, Oxford, England.
21. KÜCHEMANN, D. The aerodynamic design of aircraft — An introduction, Parts 1-6, May 1972, February 1973, August 1973, July 1974, February 1975, September 1975, TM Aero 1421, 1486, 1535, 1580, 1622, 1647, Royal Aircraft Establishment.
22. CZYSZ, P. Hypersonic convergence – Volume 1, December 2004, AFRL-VA-WP-TR-2004-3114, Air Force Research Laboratory.
23. LACHMANN, G.V. (Ed), *Boundary Layer and Flow Control – Its Principles and Application*, Vol 2, 1961, Pergamon Press.
24. SIMON, W.E., ELY, W.L., NIEDLING, L.G. and VODA, J.J. Prediction of aircraft drag due to lift, July 1971, TR AFFDL-TR-71-84, Air Force Flight Dynamics Laboratory.
25. ASHLEY, H. and LANDAHL, M. *Aerodynamics of Wings and Bodies*, 1985, 1st Edition, Dover Publications.
26. ANDERSON, J.D. *A History of Aerodynamics*, 1998, 1st Edition, p 431, Cambridge University Press, Cambridge, UK.
27. SEEBASS, R., Supersonic aerodynamics: lift and drag, Fluid dynamic research on supersonic aircraft, November 1998, AGARD-RTO EN-4, Notes from the Special Course at the von Kármán Institute.
28. CHUDOBA, B. Primary Control Surfaces on Supersonic Transport Aircraft, August 1994, Dipl-Ing. Thesis, Future Projects Department, British Aerospace Airbus, Filton, UK.
29. VINH, N.X. Flight Mechanics of High-Performance Aircraft, 1993, 1st Edition, Cambridge Aerospace Series 4, Cambridge Press, London.
30. ANON. Dassault's supersonic programme advances, *Flight International*, January 1998.