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The Javelin Concept

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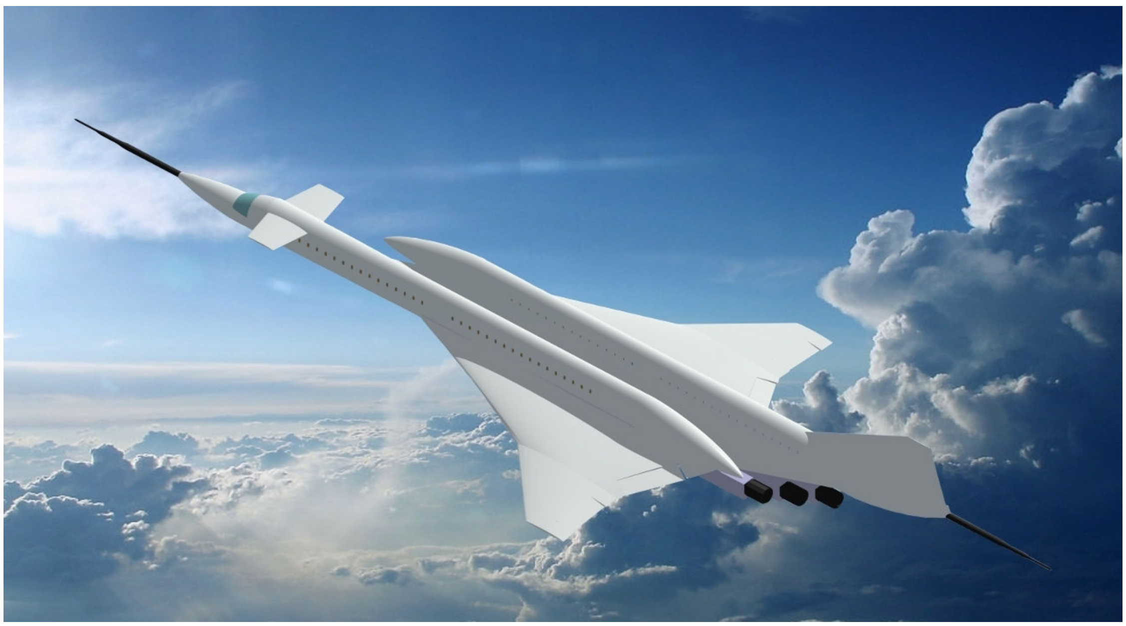

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ABSTRACT

This report proposes a solution to the 2008-2009 NASA Fundamental Aeronautics University Student Competition request for proposal of a low-boom, high-efficiency second generation supersonic transport. Implications of the request and the paradoxical nature behind creating a feasible low-boom supersonic aircraft are described. First generation supersonic transports are briefly discussed as comparison aircraft, then existing modern conceptual designs are identified along with key technologies to enable supersonic flight. The Virginia Tech solution was configured to reflect a novel strategy for achieving a feasible low-boom supersonic aircraft which synergistically incorporates low boom strength and low drag characteristics. Prospective propulsion engines are identified and potential alternative fuels are selected. Pollution considerations relative to supersonic transports are discussed. Analysis of the concept reflects a supersonic mission defined by a 4000 nautical mile range and 1.8 cruise Mach. Further analysis justifies the Virginia Tech solution with respect to combined technologies, features, and research. Airport integration is discussed as an optional challenge for the graduate level competition. Finally, flaws and weaknesses of the solution concept are discussed and conclusions regarding the Virginia Tech solution are drawn to. Closing remarks present suggestions for further research and study in the area of achieving a low-boom second generation supersonic aircraft.

INTRODUCTION: DISPELLING THE MYTHS

In 1903 brothers Orville and Wilbur Wright flew their canard-mounted bi-plane Flyer a distance of 143 ft reaching a top speed of 44 ft/s at Kitty Hawk, North Carolina. The Wright Flyer effectively dispelled the myth that powered fixed wing flight was impossible and propelled mankind into the era of manned heavier-than-air flight [1].

During World War II, Germany successfully built and produced the first production jet aircraft spawning the age of jet flight. The German Messerschmitt 262 fighter featured advanced swept wing technology and turbojet engines. These turbojet engines were first conceived simultaneously and independently by Dr. Hans von Ohain of Germany and Sir Frank Whittle of Great Britain in the early 1930s [2]. The use of gas-driven turbine powered engines for jet flight is the standard propulsion system for modern aircraft.

The creation of jet power and its application to aircraft brought with it the problems of compressibility, first noted to have been observed in the propeller powered Lockheed P-38 Lightning during high speed dives. This brought compressibility effects to the forefront of the technological barriers hindering supersonic flight. Although supersonic flight had been achieved by bullets and rockets, it remained a myth that lifting bodies, such as winged-aircraft, could not fly at supersonic speeds.

In 1947, more than four decades after the first flight of the Wright brothers, Charles Yeager of the United States Air Force piloted the Bell X-1, an orange painted, rocket-propelled trapezoidal wing aircraft. The X-1 achieved a flight speed of 1184 ft/s, successfully breaking the sound barrier in the first manned aircraft to ever fly at supersonic speeds [3]. This flight validated the potential and ability to design and create manned supersonic aircraft, marking the dawn of manned high-speed flight.

With the success of the Bell X-1, a new era of high speed flight was defined that produced many military supersonic aircraft and later civilian supersonic aircraft. The first supersonic commercial transports arrived in the 1960s with the advent of the Soviet Tupolev 144 and the British/French Concorde. These two vehicles proved that commercial supersonic aircraft could carry passengers. However, despite their technological achievements, the aircraft failed to provide a profitable and sustainable market for civil supersonic airliners. This was realized when the Tu-144 was retired from commercial service in 1980 and the final commercial flight of the Concorde took place in 2003 [4].

Eventually military aircraft were created that included stealth constraints early in the design phase. The incorporation of such non-traditional constraints into the design of stealth aircraft is known to have produced an inherently different type of design relative to conventional aircraft, as seen by the F-117 and the B-2. Later, supersonic and stealth requirements would be combined and successfully implemented in the F-22 Raptor and the F-35 Lightning II.

Despite great leaps in aircraft design and an understanding of high speed aerodynamics, humanity has yet to design and produce a sustainable civilian supersonic aircraft. To date, few supersonic unmanned aerial vehicles exist, no commercial supersonic airliners remain in operation, and zero private supersonic business jets exist. In fact, one of the only aircraft in the world flying today with the ability to supercruise, that is, efficiently fly supersonically without the continued use of afterburners, is the F-22 Raptor. Thus, in the dawn of the 21st century, humanity has taken a step backward as there are no civil supersonic aircraft in service today.

The present day absence of civilian supersonic transports is not due to an inability to create and operate supersonic designs. The current lack of a civil supersonic transport is attributed to the inability of current aircraft designers to create an aircraft which would be marketable and profitable in the modern era. This profitability is denied solely on the absence of a single design feature: the ability to supercruise over land while minimizing sonic booms to a socially tolerable level. This inability is known to have hindered the marketability, and therefore profitability of the Concorde, ultimately leading to its retirement.

On August 27, 2003, another historic flight occurred: the flight of the F-5E Shaped Sonic Boom Demonstrator (SSBD) experiment conducted by DARPA/NASA. In this experiment an F-5E with a heavily modified front end was flown supersonically while the sonic boom signatures it produced were recorded at ground-level. The F-5E SSBD established that the shape of the sonic boom could be changed from that of a traditional N-wave signature to a flat-top signature [5]. The traditional N-wave signature was characteristic of all previous supersonic aircraft which had been designed without the incoproration of low-boom constraints. Thus, the historic flight of the F-5E successfully dispelled the myth that the shape of sonic boom N-waves could not be significantly controlled, confirming that the sharp pressure disturbance typical of supersonic aircraft could be shaped to a more acceptable waveform. The incorporation of low-boom constraints early in the design phase, like that of stealth constraints, is expected to produce an inherently different aircraft shape and design process.

The success of the F-5E SSBD experiment has inspired a number of other attempts to alter and minimize the shape of a sonic boom. On August 10, 2006, an experiment was conducted by Gulfstream in conjunction with NASA in which an F-15 was modified with a telescoping rod named the Quiet Spike. The telescoping rod was mounted at the nose of the supersonic aircraft while the resulting pressure disturbances were recorded by a chaser aircraft. This experiment showed that the signature of the resulting shock waves could be modified into a series of parallel shocks. These shocks propagate away from the aircraft independently rather than forming strong aft and bow shocks that define a traditional N-wave. These series of smaller shocks produced a pressure signature of several, smaller stepped ramps theorized as another possible alternative waveform to the sharp N-shaped wave [6]. Currently Boeing and NASA are proposing to modify a NASA F-16XL aircraft to have low boom features and perform further shaped sonic boom studies [7]. With the new art of sonic boom signature shaping established, the myth that supersonic aircraft cannot be made quiet has been displaced but not yet removed. In the following pages the myth that supersonic aircraft cannot be made quiet, efficient, and environmentally responsible is about to be dispelled.

NASA 2008-2009 REQUEST FOR PROPOSAL

The 2008-2009 NASA Fundamental Aeronautics University Aircraft Design Competition Request for Proposal (RFP) directly reflects the desire for civilian supersonic transport aircraft. The key challenges currently hindering high-speed civil transportation are outlined in the RFP, and it also states that with the official retiring of the Concorde from commercial flight in 2003, aviation has taken a symbolic "step backward" [8], leaving the world demand for a high speed intercontinental travel unfulfilled. During the 2008-2009 academic year, NASA requests an aircraft design proposal for a "small supersonic airliner" with an Initial Operational Capability (IOC) projected entry into service by the year 2020. In particular, the NASA graduate competition RFP specifies that the proposed aircraft must meet or exceed all of the following customer requirements:

- Sonic boom intensity: less than 70 perceived loudness decibels (PldB)
- Airport noise levels: less than 20 effective perceived noise decibels (EPNdB)
- Overall payload efficiency: 3 pax-mile/lb_{fuel}
- Range: 4000 nmi
- Cruise Mach: 1.6 – 1.8
- Total passengers: 35-70 (mixed class)
- NO_x emissions: less than 10 g/kg_{fuel}
- Balanced field length: less that 10,000 ft
- High lift for takeoff and landing

An optional graduate challenge is also presented by NASA, requesting a thorough discussion and consideration of how the proposed supersonic aircraft would be successfully integrated with subsonic air traffic at one of the existing major world airport hubs.

The design requirements stated by NASA may be effectively grouped into three general categories:

- Sonic boom and airport noise mitigation
- Aero-propulsive efficiency and payload effectiveness
- Feasibility and integration

These general categories are discussed briefly in the following paragraphs.

Sonic Boom and Airport Noise Mitigation

The required low sonic boom intensity of less than 70 PldB is a main design driver in the NASA RFP. This signature corresponds to a maximum boom peak overpressure of less than 1.0 psf, the maximum allowable magnitude of an aircraft's sonic boom initial overpressure. NASA considers this to be within acceptable human tolerance levels and has identified that achieving this requirement could lead to enabling over-land supersonic flight.

Sonic boom signatures with intensities greater than 70 PldB are considered to be too loud and unpleasant to human observers on the ground and therefore would not likely be permitted to fly over land by the United States Congress or the Federal Aviation Administration. An aircraft that mitigates its sonic boom and produces an intensity of less than 70 PldB is considered tolerable for humans at ground level. This would allow supersonic flight over land, thus expanding possible destinations and profitable routes while effectively increasing the aircraft's marketability in a globalized industry.

An aircraft that successfully fulfills the sonic-boom level requirements will also have to meet other requirements concerning aircraft noise. Noise levels and community exposure to noise from surrounding airports are of major concern and design consideration in the modern aviation industry. The NASA RFP requires that the proposed aircraft operate at takeoff and landing with cumulative noise levels below stage 3 in accordance with current federal aviation requirements (FAR) corresponding to less than 20 EPNdB. As with the sonic boom barrier, the airport noise problem is also a significant reason for limitations on the Concorde's marketability; the Concorde was so loud at takeoff and landing that an exemption from local noise ordinance regulations at JFK and Dulles had to be issued [9].

Efficiency/Payload Effectiveness

Meeting the payload efficiency of 3 pax-mile/lb_{fuel} over the required 4000 nmi range mission is a separate demand that is equally as important as the low boom design driver stated in the NASA RFP. An aircraft that creates an acceptable sonic boom but is inefficient to operate will not be a viable solution to the supersonic challenge presented by NASA. The Concorde, discussed later in this report, is known to have operated with an efficiency of approximately 2 pax-mile/lb_{fuel} and was heavily funded by government subsidies from both Britain and France [10]. The Soviet Tupolev 144D operated with similar efficiency. Modern medium-sized transonic civil aircraft such as the Boeing 737-800 operate with efficiencies of 14.4 pax-mile/lb_{fuel} while large jumbo airliners such as the Boeing 747-400 and the Airbus A380 operate with payload efficiencies of 11.3 and 14.6 pax-mile/lb_{fuel} respectively [11] [12]. Thus supersonic civil flight is naturally less fuel efficient than subsonic flight. Therefore, it is imperative that the proposed solution to the RFP meet the specified efficiency if the concept is to compete with transonic aircraft from an operating cost-effectiveness perspective.

Feasibility and Integration

Finally, a solution aircraft concept that achieves low boom signatures and acceptable payload efficiencies must be realistic and practical to produce and operate. This desired feasibility requires the solution aircraft be integrated with current existing airport infrastructure and subsonic air traffic. This also implies that the technology levels of the proposed solution must almost certainly be available within the next decade in order to meet the IOC of the year 2020. In essence, NASA is requesting a proposed solution that combines current technology and conventional methods in a new and novel arrangement so that a low-boom economically feasible transport may be created within the next decade. Therefore any proposed solutions must be conventional with respect to current technology and configurations, yet advanced in the design process and technology implementation for a solution concept.

DESIGN CHALLENGES

The fundamental problem presented in the NASA RFP is that efficient *and* quiet/low-boom supersonic aircraft *do not* currently exist. Having defined the problem stated by NASA on the previous two pages, the implications of the RFP are discussed here with respect to aircraft design.

Minimizing Sonic Boom

The intensity of sonic booms can be minimized by reducing the overpressure of the sonic boom and/or increasing the rise time of the N-wave, effectively reducing the ground level pressure gradient. Maglierli and Plotkin in conjunction with Hubbard [13] of NASA Langley effectively summarize the four fundamental ways of reducing the intensity of sonic booms as:

Reduced Overpressure Methods:

- *Size:* Simply put, a lighter aircraft will generate less intense sonic booms than a heavier aircraft. This is attributed to the fact that a lighter aircraft will require less lift to stay airborne and impart less momentum on the ambient fluid. Less required lift will decrease the aircraft effective area due to lift.

- *Shape:* The shape of the aircraft, particularly the nose that initially disturbs the ambient air, has proven to be a significant factor in determining the resulting amplitudes of supersonic aircraft shockwaves. As noted in the introduction page of this report, shockwaves propagate and coalesce towards the ground. This is elaborated upon in the next section on this page.

Increased Rise Time Methods:

- *Length:* N-waves are the result of compressible shock waves coalescing into very strong aft and bow shocks. A short aircraft will have less separation between the aft and bow shocks it creates than a longer aircraft. Therefore, a longer aircraft will produce N-waves of lower frequency and increased rise time which decreases the total wave amplitude and impulse intensity of the sonic boom as it is observed on the ground.

- *Airstream Alteration:* Active flow control methods, such as energy addition by flow heating, are proposed to effectively achieve increased rise times by artificially increasing the apparent length of the aircraft "seen" by the fluid.

Combinations of these four fundamental methods of minimizing sonic boom must be effectively incorporated early in the conceptual design of a viable solution aircraft without compromising efficiency.

Implications of the Required Payload Efficiency

High efficiency is desired in almost every airplane design. The fundamental equation describing overall efficiency of an aircraft is the Breguet Range Equation below:

$$R = \frac{V}{sfc}\frac{L}{D}\ln\left(\frac{W_i}{W_f}\right)$$

where R is the specified range of the aircraft, V is the cruise velocity, *sfc* is the specific fuel consumption of the propulsive system, L/D is the cruise lift to drag ratio, W_i is initial weight at takeoff, and W_f is the final weight at landing. This is a powerful equation relating the aerodynamic efficiency, L/D, the propulsion efficiency, *sfc*, and the weight of fuel carried, $W_i - W_f$, to the overall range, R, of the aircraft. A solution to the NASA RFP must be an aircraft that achieves low aerodynamic drag, high L/D, and low *sfc* to minimize fuel burn and maximize overall efficiency for a given range.

Because range and payload efficiency are defined in the NASA RFP as 4000 nmi and 3 pax-mile/lb_{fuel} respectively, the major remaining design parameter that dictates the required fuel burn is the number of passengers. NASA has defined the passenger payload of the aircraft to be between 35 and 70 passengers. Therefore, the number of passengers, or payload weight, of the solution aircraft requires the fuel weight to be less than the amount of fuel required to meet the overall payload efficiency of 3 pax-mile/lb_{fuel}. By defining the payload efficiency and required range for the aircraft, NASA has pre-defined a spectrum of acceptable passenger-fuel combinations. Consequently, special attention to detail concerning the design number of passengers and fuel weight must be considered when determining if a proposed solution will meet the required payload efficiency.

Weight as the Most Important Performance Parameter

The explicit logarithmic dependence on aircraft weight in the range equation has profound implications regarding aircraft performance and design. An aircraft with greater weight requires greater lift, often resulting in a larger wing and higher structural weight. As lift increases, so does the induced drag and the propulsion system will have to produce greater thrust. Producing greater thrust requires more fuel over the specified range, increasing the operating weight of the aircraft and the volume required for fuel storage. This mutual dependence defines the path-dependent cyclical nature of the iterative aircraft weight estimation process.

The gross aircraft weight, consisting of structural, payload, and fuel weight, is the single most important parameter of a aircraft optimization. Every effort must be made to minimize aircraft weight because this will inherently decrease the drag generated by the aircraft and decrease the fuel required by the propulsive system for a set range. In the case of supersonic aircraft, minimizing weight ultimately decreases the strength of the resulting sonic boom. Lighter weight is desired in all aircraft designs, but in supersonic aircraft design the effect of weight on performance is exacerbated due to the extreme performance demands of supersonic flight.

Achieving low boom *and* high efficiency is the main challenge presented by NASA. Often the desired features for low boom are directly opposite those required for efficient supersonic flight, thus establishing the aircraft design paradox. In addition to the implications explained on this page, the main problem in designing a feasible supersonic low boom transport depends on how effectively low boom constraints are successfully implemented into the conceptual design.

THE LOW BOOM/DRAG PARADOX

A summary of sonic boom modeling theory is presented here followed by a discussion of the fundamental paradox of designing for low boom versus low drag in supersonic aircraft. This information is based on the discussion presented by Mack and Needleman of NASA Langley and Lockheed, respectively [14].

Sonic Boom Modeling and Shaping

Sonic boom propagation was first modeled mathematically by Whitham with the creation of his F-function in 1952, relating the second derivative of an area distribution to the pressure disturbances caused by the body in supersonic flowfields [14]. The F-function is then used to model the propagation of these pressure disturbances through a standard stratified atmosphere from the cruise conditions to the ground, creating the far-field sonic boom wave signature. Whitham's method effectively modeled the far field waves as realistic sharp N-waves, typical of supersonic aircraft not incorporating low boom constraints early in the design process. Thus, Whitham is credited to have first created a realistic numerical model for sonic boom propagation of sharp N-waves. However, the sharp N-waves were unacceptable to observers on the ground, and methods to alter the waveform of sonic boom signatures quickly became of interest.

Supersonic Nose Bluntness Paradox

Later, alteration of the waveform shape became a promising idea as a way to lessen the perceived disturbance of the resulting sonic boom wave signature. Jones [15] predicted that the shape of the sharp N-wave could be modified by changing the shape of the nose of the aircraft, therefore greatly affecting shock propagation through the air. In particular, Jones proposed that the nose of the aircraft be altered into that of a blunt leading edge. Essentially, a blunt edge in supersonic flow would produce a normal detached shock rather than an attached oblique shock, the latter of which is typical of sharp leading edges of supersonic aircraft. A strong detached normal shock caused by a blunt leading edge was hypothesized by Jones to propagate towards the ground without coalescing into the sharp N-wave signature, providing an alternative to the waveform produced from unconstrained supersonic aircraft designs. Later in 1972, Seebass and George [16] created a numerical method to calculate reduced sonic boom signatures based on Whitham's method which was modified to incorporate a small amount of nose bluntness.

Although this proposed solution shows promise as an effective method for minimizing observed ground boom signatures, it is well recognized that a blunt edge in supersonic flow produces a severe amount of drag compared to the drag from a sharp, highly swept leading edge. Therefore, using a blunt leading edge to minimize boom was initially thought to be incompatible with the low drag and efficiency demands required for sustained supersonic flight.

Recognizing the negative impact of nose bluntness on the aerodynamics of an aircraft, Darden [17] further modified the theory presented by George and Seebass to allow the nose bluntness to be a variable parameter. This effectively established the present day sonic boom minimization theory. By allowing nose bluntness to vary, an increase in wave drag could essentially be traded for a decrease in sonic boom intensity, and vice versa. Therefore, a fundamental paradox occurs when simultaneously trying to achieve low boom characteristics and low drag aerodynamic performance by incorporating nose bluntness into a supersonic aircraft design. Simply put, a blunt leading edge is desired for low boom signatures while a sharp leading edge is desired for low drag aerodynamic performance.

Required Area Distribution Paradox

Darden specifies a resulting volumetric and lift area distribution that must be matched to achieve low boom overpressure signatures. Although target equivalent volumetric and lift area distributions are specified, the George-Seebass-Darden method provides no information about the necessary vehicle configuration to achieve the target equivalent area distribution. Therefore the method determines a target equivalent area distribution for proposed low boom designs, but does not indicate how to match that definition. The target equivalent area distributions for low boom take on a half-bell shaped curve, distinctly different from the target volume and lift equivalent area distribution required for low drag vehicles. The area distribution for minimum wave drag in supersonic flow is a Sears-Haack body with a full bell-shaped area curve [18], shown in Figure 1 with the equivalent area for low boom. Rallabhandi [19] expands on this method and reports that both the F-function and area curve are highly sensitive to the aircraft shaping, thus a paradox exists between matching the required area distribution and achieving a realistic aircraft configuration.

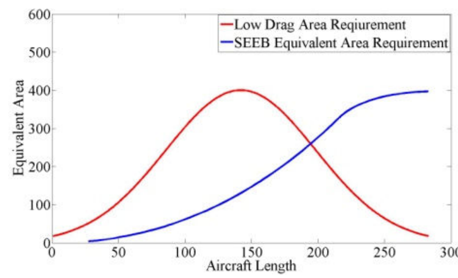


Figure 1. Equivalent area distributions for low drag (red) and low boom (blue)

Increasing the Effective Length Paradox

The method described above is an attempt to minimize boom by shaping the aircraft body. This represents only one of the four fundamental methods to minimize boom, as described on the previous page. Also recognizing that severe drag would result from relaxing the leading edge of a supersonic body, McLean [20] hypothesized that other fundamental methods could be employed to decrease the sonic boom strength. In particular, McLean proposed that the sonic boom signature may be minimized by increasing the rise time of the sonic boom disturbance. This is achieved by shaping the aircraft to be long and slender, effectively increasing the fineness ratio of the vehicle. However, McLean noted that this would only minimize the boom if the aircraft could achieve higher fineness ratios without incurring a substantial increase in vehicle weight. Increasing aircraft length will increase the structural weight and decrease aircraft rigidity, therefore introducing aero-elastic problems. An increase in vehicle weight would most likely negate and overcome the benefits of increasing the rise time of the signature. This length/weight relationship and drag/boom paradox must be addressed early in supersonic aircraft configuration design to achieve minimal boom.

COMPARATIVE AIRCRAFT

Before a solution to the NASA RFP can be presented, it is useful to establish a baseline comparison of existing designs fulfilling a similar mission. For this project the comparison aircraft are the only two civil supersonic transports that exist: the British/French Concorde and the Soviet Tupolev-144D. An overview of these two aircraft is presented in this section. The major defining parameters of the Tu-144D and the Concorde are presented in Table 1.

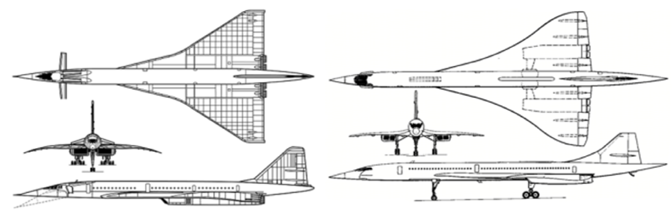
Tupolev 144D

The Tupolev 144, shown in Figure 2a was the first civil supersonic aircraft to take flight. The maiden flight of the first Tu-144 prototype, the Tu-044, took place on December 31, 1968, beating its competitor, the Concorde, by two months. The initial propulsion system of the Tu-144 was the afterburning Kuznetov NK-144 turbofan engine, which had an sfc of 2.23 lb/lb/hr. This *sfc* proved to be unacceptable because the range of the early Tu-144s was limited to 1,577 nmi, far less than the required initial design range of 2,430 nmi [10]. The first versions of the Tu-144 could not supercruise at Mach 2.0 but years later, the Tu-144S was developed and outfitted with NK-144A engines which were able to supercruise without using afterburners and achieved an *sfc* of 1.81 lb/lb/hr. This enabled the Tu-144S to increase the range to 1,944 nmi with a payload of 14,000 lbs. By November 1, 1977, the Tu-144S entered passenger service, carrying no more than 80 passengers over a distance of 1,760 nmi between Moscow and Alma Ata once a week. These service flights were cancelled in May of 1978. Earlier in 1973, the Tu-144 was redesigned with Kolesov RD-36-51 afterburning turbojet engines creating the Tu-144D variant; the most efficient and final version of the Tu-144 to be designed and built. The Kolesov RD-36-51 engines were able to achieve an *sfc* of 1.26 lb/lb/hr. The Tu-144D entered freight service carrying mail between Moscow and Alma Ata on December 26, 1975, but was retired from commercial service in 1980 [10]. The Tu-144 would fly again in the 1990s as an experimental atmospheric research aircraft.

Concorde

The Concorde shown in Figure 2b was a joint effort by the French Aerospatiale company and the British Aircraft Corporation. The Concorde first flew on March 2, 1969, [21] and remained in passenger service for 27 years, serving main routes between London Heathrow and Paris Charles de Gaulle to New York JFK or Washington Dulles destinations while carrying 90 passengers. The last flight of the Concorde occurred on November 26, 2003, leaving the world without an operational civil supersonic transport.

Like the Tu-144, the design of the Concorde was a technical marvel yet had fundamental shortcomings. The Concorde was powered by four afterburning Rolls Royce/SNECMA Olympus turbojets capable of producing over 39,000 lbs of thrust at takeoff and had a cruise *sfc* of 1.23 lb/lb/hr [22]. The engine nacelles had a variable ramp intake used to slow the speed of the incoming supersonic air to subsonic speeds necessary for intake. The Concorde used afterburners at takeoff to achieve the required takeoff thrust. The Concorde also took advantage of low pressure vortices created over the upper surface of its wing and wing-in-ground effect to achieve a lift coefficient of 0.77 at takeoff. Another novel feature of the Concorde was that it used its onboard fuel as a heat sink during high speed supersonic flight. The fuel was also used to trim and balance the aircraft during supersonic flight when the aerodynamic center is shifted considerably aft. A drooped nose was also used to provide pilot visibility during takeoff and landing. High angles of attack were essential during landing for Concorde's ogival swept delta wing to achieve high lift at low speeds. Although not previously mentioned, these technological achievements were also implemented similarly on the Tu-144[21].



a) Tu-144 b) Concorde

Figure 2: Tu-144[a] and Concorde[b] three-view drawings (not drawn to scale)

Although the Concorde is considered an achievement of aircraft technology and design, it is also considered as an economic and environmental failure. During the service life of the Concorde, the aircraft operated with subsidies provided by the French and British governments [10]. The Concorde is also known to have burned 4,000 lbs of fuel during runway taxiing [23], unacceptable by today's economic, pollution, and noise operating standards, as well as NASA RFP specifications. Since the Concorde (and Tu-144) required the use of afterburners, the aircraft was very loud at takeoff, unacceptable for today's aircraft and airport industry.

Table 1. Characteristics of supersonic civil transport

Characteristic	Tu-144D[c]	Concorde[d]
MGTOW (lbs)	456,359	401,328
T_{max} (lbs)	46,297 (x4)	39,073 (x4)
Sref (ft^2)	5,450	3,855
T/W	0.41	0.42
W/S (lbs/ft^2)	83.7	100
W_{empty} (lbs)	218,699	173,503
W_{fuel} (lbs)	207,656	202,825
$W_{payload}$ (lbs)	30,000	25,000
Range (nmi)	4,050	3,550
M_{cruise}	2.20	2.02
$\#pax_{max}$	144	100
($pax\text{-}mile/lb_{fuel}$)	1.95	2.04
SFC (1/hr)	1.26	1.23
Span (ft)	95.5	84.0
Length (ft)	211.5	204.0

[a]Tu-144 3-view acquired from NASA Dryden [75]
[b]Concorde 3-view acquired from www.aerospaceweb.org [76]
[c] data acquired from reference [10]
[d] data acquired from reference [74]

MODERN CONCEPTUAL DESIGNS

Now that comparison aircraft have been identified and overviewed, it is useful to review modern conceptual designs currently in development. There is much research being conducted throughout academia and industry towards developing a second generation supersonic civil transport. Unlike previous attempts such as the High Speed Civil Transport (HSCT) and military derived supersonic aircraft, modern research is primarily concerned with smaller and slower concepts compared to the Concorde and Tu-144. These concepts mainly consist of business jets carrying between 6 and 12 passengers and smaller supersonic airliners carrying between 35 and 50 passengers. Most attempts incorporate a cruise Mach range between 1.6 and 2.0. This cruise Mach range reflects the fact that an aircraft able to cruise at Mach 1.6 will still be almost twice as fast as the modern day transonic airliners cruising between Mach 0.80 and 0.85. An aircraft cruising at Mach 1.80 will avoid the adverse heating effects known to occur around Mach 2.0 [24]. This section presents an overview of selected modern supersonic concepts being researched today.

NASA Low-Boom Supersonic Business Jet

The NASA conceptual 10 passenger supersonic business jet (SBJ) shown in Figure 3 mimics the conventional low-boom supersonic configuration. Aims of this design included cruise of Mach 2.0, gross takeoff less than 100,000 lbs, and sonic boom ground maximum overpressures below 1.0 psf.

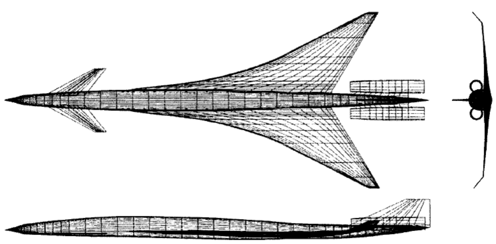


Figure 3. Three view of the Langley SBJ modified with a re-sized, re-located canard, and a re-sized fin/rudder [25]

Basic features of this design are tail-mounted turbofan engines, a highly swept fixed wing, forward canard for low-speed maneuverability and control, and single fuselage with the appearance of high fineness ratio [25].

JAXA Silent Supersonic Aircraft

The Japan Aerospace Exploration Agency (JAXA) 30-50 passenger civil transport concept for low sonic-boom is shown in Figure 4. Features of the JAXA configuration include an area-ruled single fuselage, NACA 64A series airfoil, fixed wing with three sections of different sweep, V-tail, and two turbofan engines. The JAXA concept cruises between Mach 1.6-2.0 at altitudes between 40 and 50 thousand feet.

The estimated takeoff weight with 50 passengers is 136,000 lbs with a fuel weight 63,600 lbs, covering a range of 3,500 nmi. Passenger fuel efficiency for this concept is approximately 2.75 pax-mile/lb_{fuel}, relatively better than both the Concorde and Tupolev-144 but considerably less than the NASA RFP required efficiency. *L/D* range for this concept is 6-9.

The optimized low-boom design in the JAXA study cruises at a lower altitude (~44.4 kft), has a large fixed wing area (~2,519 ft^2) and predicts a maximum N-Wave overpressure of 1.92 psf with an *L/D* of 7.84. This configuration can reduce the sonic boom for initial and final pressure peaks, while flying at higher altitudes to increase the lift to drag ratio [26]. In addition to low passenger-efficiency, the overpressure does not meet the NASA RFP target.

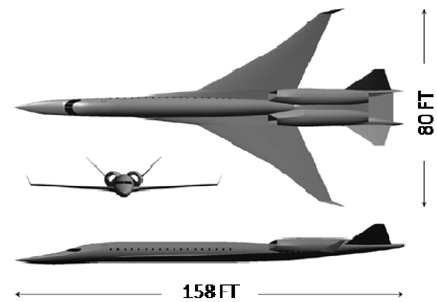


Figure 4. Initial conceptual three-view of silent supersonic aircraft[26]

Aerion Natural Laminar Flow Supersonic Business Jet

The Aerion Corporation envisions a small conceptual 8-12 passenger supersonic business jet with an innovative trapezoidal wing to achieve natural laminar-flow (NLF) at a maximum Mach of 1.6 [27]. The design, shown in Figure 5, draws from laminar flow technology to target low-drag characteristics and create boom-less flight up to Mach 1.1 with improved subsonic aerodynamic performance and fuel efficiency.

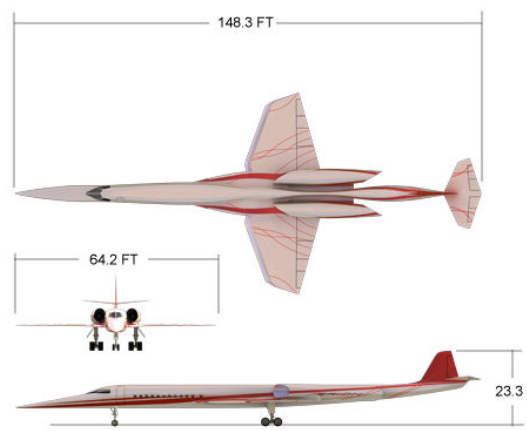


Figure 5. Three view of the Aerion Natural Laminar Flow SBJ [28]

The Aerion NLF concept is considerably smaller than the N+2 target specified in the NASA RFP. The concept, with a fuel weight of 45,400 lbs and range above 4,000 nmi has a passenger efficiency less than the first generation SSTs. It also operates on runways greater than 6,000 ft [28].

Structurally, the Aerion NLF SBJ relies on modern materials and manufacturing technologies, patented installation and design, fly-by-wire system control, and proprietary computer software for airframe and aerodynamic optimization [29]. This concept, like the other supersonic designs, uses highly integrated and advanced design processes in the potential solution. Ideologies from modern concepts like the ones mentioned, if properly combined, will undoubtedly push the industry closer to a desirable and feasible solution.

EXISTING ENABLING TECHNOLOGIES

Modern conceptual approaches vary from the fundamental design philosophies to the selection of technologies that enable aircraft to fulfill its design mission. Since the achievement of manned supersonic flight by the Bell X-1, many technologies have been created allowing for the feasible operation of supersonic aircraft. Aircraft configuration and engine performance are only two of the many critical features that must be carefully considered and optimized while addressing the conflicting paradoxical nature of feasible supersonic transport design. This section discusses features common to supersonic aircraft and emerging technologies available by 2020.

Aerodynamic Wing Technologies

Wing sweep was first widely implemented by Germany in World War II on the Me-262. Today, wing sweep is a common feature on all transonic and supersonic aircraft. Sweep increases the effective chord length the air encounters during flight, delaying the formation of shocks on the upper surface and reducing drag and shearing forces at high speeds. Currently the arrow wing design is among the most popular in the aeronautics industry. Derived from NASA Langley research efforts in the late 1950s, the highly swept arrow wing reflects the optimum shape for supersonic aircraft [4]. Although wing sweep is desired at high speeds for reducing drag, at low speeds sweep is undesirable because considerable lift is lost relative to conventional wings. Drawbacks associated with poor low-speed aerodynamic performance of the fixed arrow wing inspired the creation of variable sweep models intended to achieve better lift in subsonic regimes.

One approach to solving this sweep paradox is to implement wings and surfaces that physically vary wing sweep at different speeds. This helps to optimize the aerodynamics in all flight regimes. The classic example of a variable sweep aircraft is the F-14 Tomcat that can vary its wings between 20 degrees for subsonic flight and up to 68 degrees for supersonic flight. Still, structural components of the variable sweep design almost always adversely affect design weights, often resulting in the need for reinforced structural components generally too heavy to justify the variable sweep benefits. A real world example of this was the Boeing HSCT 2707 concept. The 2707-100 and 2707-200 were initially planned to incorporate variable sweep, and were later cancelled due to uncontrollable weight growth largely attributed to the variable geometry wings [30] and the 2707-300 became a fixed wing concept.

Another promising variable-wing design is the oblique-wing, a concept that has been studied for over fifty years and features a top-mounted pivoting wing. An advantage of the oblique wing is the ability to distribute lift over twice the longitudinal length compared to fixed swept wings. The result is a decrease in induced drag and volume dependent wave drag by factors of 4 and 16, respectively. The oblique wing also achieves higher lift-to-drag ratios with significant improvements in aerodynamic efficiencies and handling qualities throughout the subsonic and transonic regimes. Also, oblique wing tests indicate the configuration can achieve completely boom-free flight up to Mach 1.2, but benefits of the oblique wing are known to rapidly diminish at Mach numbers higher than 1.4 [31].

Alternatively, the delta wing could be called the basic wing for supersonic aircraft. Delta wings benefit in the areas of low structural weight, low transonic and supersonic drag, and increased internal volume for fuel storage, as compared to high aspect ratio swept wings [32]. Advantages of the delta wing can be attributed to the sweep of the wing and simple spar arrangement. Internal spars project perpendicularly from the fuselage and lower bending moments across the entire wing, creating weight savings up to 30% compared to high aspect ratio swept-wing designs. Delta wings also provide a large wing area with more high-lift potential for a supersonic aircraft, especially for take-off and landing.

Propulsion Technologies

The turbojet and low bypass ratio turbofan are the basic engines for transonic and supersonic flight. Today modern gas turbine engines incorporate a number of technologies to increase efficiency and power while decreasing weight and noise. For supersonic flight, advanced engine designs vary their thermodynamic cycles between that of a turbofan and turbojet. Examples of advanced technologies use variable stream control duct burning, tandem variable geometry fans and nozzle deflectors to decrease takeoff noise. These propulsion systems were considered to power the solution concept proposed and are discussed in the subsequent pages.

CG Location Control Technologies

All supersonic aircraft utilize complex systems of fuel pumps and storage tanks to control the location of the center of gravity (CG) as fuel burns. The aerodynamic center (AC) shifts when the aircraft transitions from the subsonic to supersonic flight regimes thus requiring CG location control. Recently, AIRBUS has applied for a United Sates patent utilizing the concept of fuel transfer for CG manipulation in the event of an emergency when the pilot loses power over the control surfaces of a subsonic aircraft [33]. The proposed system would rapidly transfer fuel between tanks in the left and right wings for roll control. For pitch control, fuel would rapidly be transferred between aft and bow tanks. In the future, fuel pumping for CG control will be the standard practice of all supersonic designs.

Boom Minimization Technologies

The Gulfstream Quiet Spike is a progressive technology used for sonic boom shaping at the nose of an aircraft. The telescoping spike pictured on the Gulfstream concept in Figure 6 breaks up the strong bow shocks into weaker shocks, the stronger of which propagate upward, lowering the maximum overpressure and increasing the rise time compared to classic N-wave signatures [34].

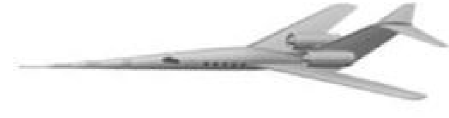


Figure 6. Conceptual Supersonic Aircraft with Extended Quiet Spike [34]

Figure 7 shows the effects of the Quiet Spike on the initial pressure rise time. A normal shock of 0.4 psf is broken into smaller shocks of 0.15 psf and distributed over 25 milliseconds instead of a single strong shock. Overall, initial tests of the Quiet Spike on an F-15 concluded that extensive modifications would have to be made to significantly impact ground signatures. As a new technology, the Quiet Spike proved to be effective in shaping the bow shock at the nose of the fuselage.

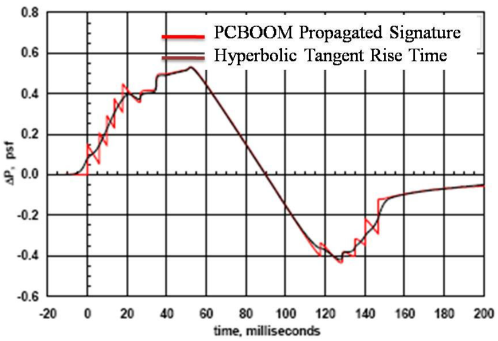


Figure 7. Four-Segment Quiet Spike Waves Signature [34]

Another technology enabling supersonic efficiency and low boom sustainability is airfoil shape. Basic compressible aerodynamic and shock expansion theory indicate that supersonic airfoils deviate from conventional shapes in order to lower drag and minimize detached normal shocks around the body. The double wedge and biconvex airfoils shown in Figure 8 are extremely thin with a maximum thickness less than 6%. They also feature sharp leading edges to keep shocks attached to the wing and decrease the incidence of high pressure regions along the chord [35].

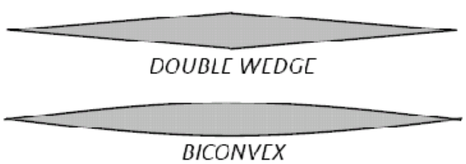


Figure 8. Supersonic airfoil shapes [35]

Tailoring of these shapes to optimize aerodynamic and boom performance is reflected in similar NACA 6A series airfoils, a 65-series being used by the Concorde [36].

Combining the Technologies

A successful quiet supersonic transport will need to incorporate a multi-disciplinary approach to optimize features for a viable and working configuration. Keeping the drag/boom paradox in mind, preliminary conceptual solutions need to address the major restrictions—weight, efficiency, and boom minimization—and add features to offer synergistic solutions to address the other NASA specifications.

Having studied and analyzed the nature of the problem and NASA constraints, and also researched comparative aircraft, modern conceptual designs, and existing enabling technologies, fourteen concepts were generated and assessed in a criteria matrix. The in-house selection matrix was derived from a matrix developed by the Committee on High Speed Research of the National Research Council and others for evaluation of the generated concepts [9].

CONCEPT SELECTION

Fourteen concepts, both conventional and advanced, were initially proposed to fulfill the NASA RFP. These concepts included conventional slender fixed-wing designs, multiple variable geometry configurations, as well as multi-body/fuselage configurations. Of all the configurations considered, the top three designs evaluated from the in-house selection matrix were: a conventional slender delta wing design, an oblique wing configuration, and a symmetrical double fuselage fixed wing design discussed below.

Slender Fixed Wing aircraft

A slender fixed wing configuration was generated as a low-boom concept, similar to the JAXA and NASA SBJ. The slender wing design offers the benefit of a well-understood conventional design, similar to that of the Concorde, and incorporates the length and shaping techniques from the four fundamental methods of sonic boom minimization stated in the Design Challenges section.

Oblique Wing Concept

An oblique wing concept was generated to offer the benefits of a design that could operate with greater efficiency throughout all flight regimes relative to a fixed wing aircraft. The oblique wing was identified as a potential candidate for supersonic flight because of its ability to vary the wing sweep and have an unswept wing during takeoff and climb, desirable for subsonic flight. As the vehicle travels into the transonic regime, its wing is gradually swept back as it rotates about a central pivot point. At supersonic speeds, the aircraft sweeps its wing back even further, effectively lowering the span and decreasing the aspect ratio. For these reasons the oblique wing was a very strong candidate for concept selection. It should be noted however that benefits of the oblique wing generally diminish as the Mach number is increased past 1.4 which is considerably lower than the NASA specified cruise mach of between 1.6 and 1.8 [31] . Despite the oblique wing benefits decreasing in the desired Mach range, the positive attributes of the concept almost justified it as the solution to the NASA RFP.

Double Fuselage/Cranked Delta Wing Concept

A double fuselage concept was identified as a planform for reduced structural, fuel, and operating weight while reducing drag. The double fuselage platform offers the advantage of a semi-conventional design but also imitates the characteristics of an advanced design. The concept also retains all the benefits and characteristics of a conventional slender body-fixed-wing design while incurring few negative attributes. The addition of a low aspect ratio cranked delta wing also saves weight by eliminating the need to sweep the inner wing sections which are typical of a high aspect ratio swept wing [32]. This attempt to save structural weight is the reason the variable sweep oblique wing and other pre-down-selected designs that incorporated large amounts of variable geometry were not chosen. **Due to the critical dependence of minimizing vehicle weight, features that would inherently save weight had to be incorporated into the design. This ultimately led to the selection of the double fuselage concept as the Virginia Tech solution.**

THE VIRGINIA TECH SOLUTION

The following pages describe the Virginia Tech Javelin Supersonic Transport (VTSST) concept depicted in CAD Figures A through E on the following pages**.** The Javelin SST is a low-boom, high-efficiency, non-afterburning, dual alternative fueled concept that establishes an ideology for a practical second generation supersonic transport for the IOC 2020 timeframe. The Javelin SST is the product of an extensive research and design effort and reflects established innovations in the area of supersonic aircraft design. The VTSST addresses all of the concerns stated in the NASA RFP and the projected deliverables of the Javelin SST are:

- Sonic boom maximum overpressure < 1psf
- Design range = 4,000 nmi
- 3pax-mile/lb_{fuel} efficiency
- Takeoff balanced field length of 7,421 ft
- 68 Passenger payload (mixed class)
- Reduced NO_x emissions by current standards
- Compatibility with current subsonic air traffic

Other considerations not explicitly stated in the NASA RFP but were self imposed by the authors are:

- Fuel considerations for aircraft rerouting
- Alternative fueling schemes
- N+3 considerations

The customer requirements listed above were achieved by the novel combination of the following innovative enabling technologies:

- Double fuselage configuration for:
  - increased structural rigidity to reduce aircraft weight
  - harnessing of favorable interference to reduce wave drag by asymmetric staggering
  - decreased cross-sectional area with 1-abreast seating
  - increased effective length for higher fineness ratio and increased sonic boom rise time
  - potential alternative fuel storage
  - simple mixed class seating implementation
- Low aspect ratio cranked delta wing for reduced aircraft weight and structural simplicity compared to variable-geometry or high aspect ratio wings
- Advanced duct-burning turbofan engines with liquid methane fueled duct burner and synthetic kerosene fueled core as a unique system for high propulsive efficiency, reduced noise, and low emissions
- Aft and bow mounted Quiet-Spike-like telescoping rods for shaping of N-wave and increased effective length
- Low sweep laminar flow canard for reduced wing size and increased nose bluntness

The Javelin SST concept embodies a responsibly imaginable[e] novel combination of technologies which synergistically enable high efficiency, low boom, and feasible integration with current airports and air traffic conventions for an IOC of 2020. The ideology of the Javelin SST revolves around optimizing the major performance parameters in the range equation that correlate with decreasing total aircraft weight, increasing *L/D*, and decreasing *sfc*, all while incorporating low boom features into the design. A summary of ideas and beliefs defining the Javelin SST are presented here.

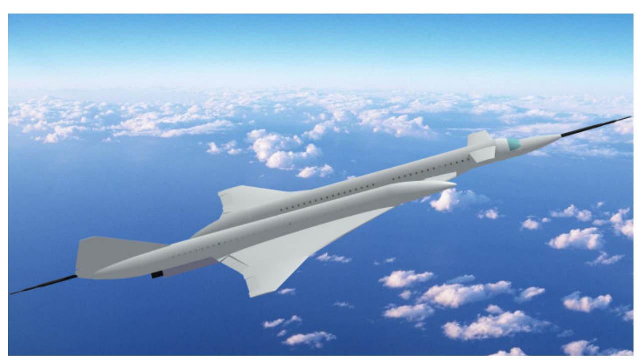
Strategy for Solving the Low Boom/Drag Paradox

As noted earlier in this report, the fundamental problem when designing a low boom supersonic aircraft is establishing a feasible compromise that incorporates low boom features without drastically increasing drag. The heart of the Javelin ideology is centered on exploiting and tailoring the potential of the double fuselage design to solve the low boom/drag paradox. The first step in the design of the Javelin SST was synergistically compromising between low boom and low drag to reduce the weight. Weight reduction is inherent in double fuselage configurations as described on the page 12. Reduced weight automatically decreases the boom strength while also decreasing induced drag from lift.

The second compromise between low boom and drag is attributed to increased aircraft length from staggering the slender fuselages. The length is increased by 47% relative to the symmetric side-by-side configuration initially conceived. By increasing the length, the sonic boom signature rise time is increased while also effectively increasing the fineness ratio of the design to 15.2, thereby accounting for low boom and low drag.

The third minimization technique, the shaping of the shock strength, is achieved by creating favorable interference between the two fuselages, cancelling a significant amount of aircraft wave drag. Designing for favorable interference alters the shockwave patterns for low boom while also decreasing wave drag. Thus the fundamental ideology of the Javelin SST is exploiting the low-drag characteristics of a double fuselage design while simultaneously incorporating low-boom features that accent an efficient supersonic configuration.

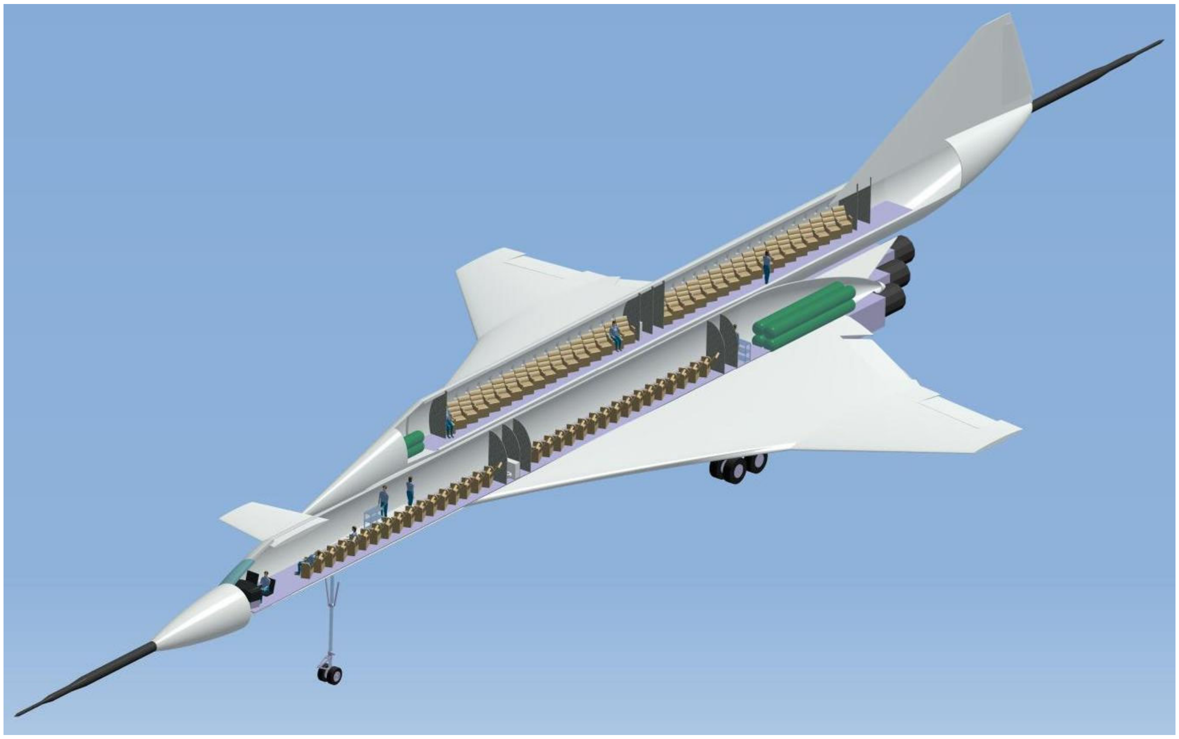
Having established the main strategy for creating a realistically feasible design satisfying the NASA RFP requirements, the following pages detail the research, development, and design of the Javelin SST. The Javelin is illustrated in the following CAD Figures A through E



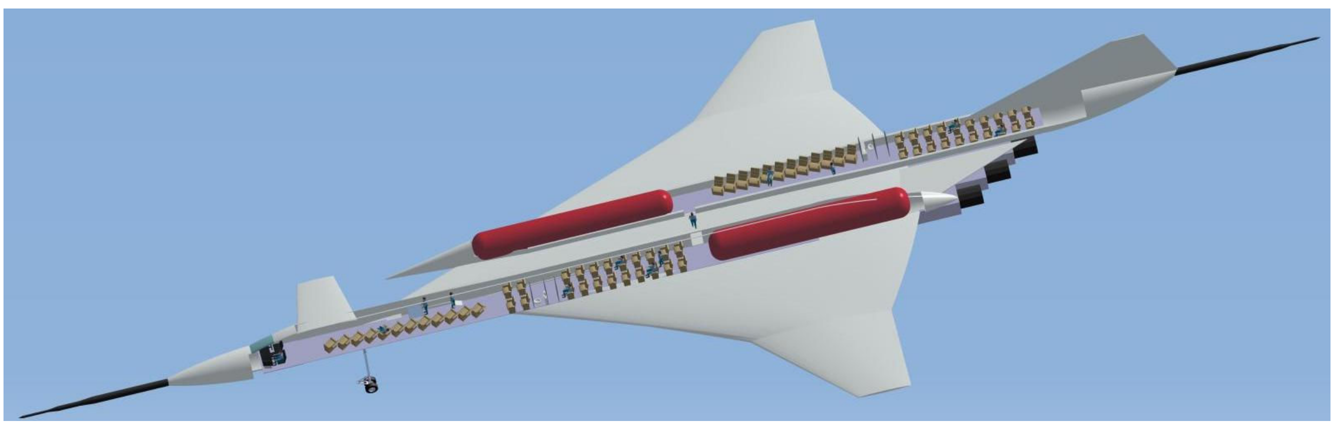
CAD Figure A. Virginia Tech Javelin SST concept

[e]diction borrowed from 1998 AIAA Dryden Lecture [37]

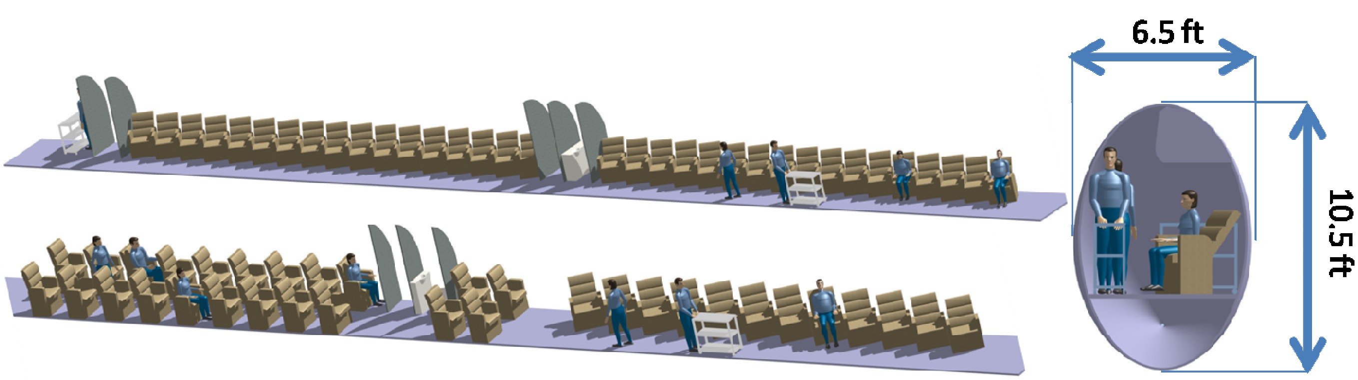
CAD



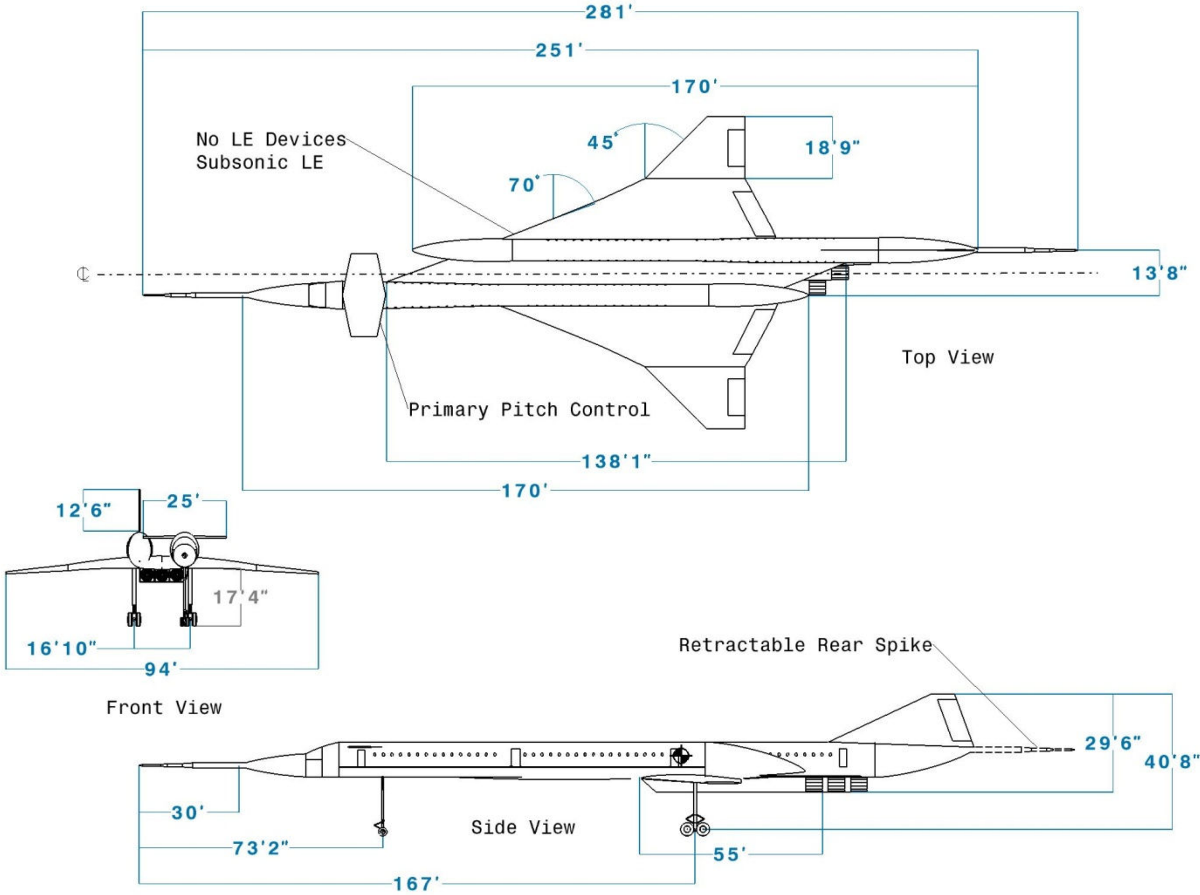
CAD Figure B. N+2 isometric with cabin cut-away of the VT Javelin SST



CAD Figure C. N+3 hydrogen powered variant of the VT Javelin SST



CAD Figure D. N+2 (top) and N+3 (bottom) cabin arrangement with cabin cross-section (right).



CAD Figure E. Three-view of the VT Javelin SST concept

Table 2. VT Javelin SST characteristics and weight breakdown

Characteristic	Javelin
MGTOW (lbs)	242886.00
T_{max} (lbs)	37,000 (x3)
Sref (ft^2)	4135.00
T/W	0.46
W/S (lbs/ft^2)	60.89
W_{empty} (lbs)	102827
W_{fuel} (lbs)	123739.00
$W_{payload}$ (lbs)	16320.00
Range (nmi)	4000.00
M_{cruise}	1.80
#pax	68.00
pax-mile/lb_{fuel}	3.00
SFC_{cruise} (lb/lb/hr)	1.021
Span (ft)	94.00
Length (ft)	281.00
L/D_{cruise} (average)	7.65

Aircraft Component	Fraction
Structures	0.34
Fuel	0.51
Equipment	0.03
Propulsion	0.05
Payload	0.07
Total	1.00

Javelin SST Weight Breakdown

Structures Group	Weight (lbs)
Wing	22386.00
Canard	916.95
Vertical Tail	2541.20
Fuselage	17,566 (x2)
Front Spike	2250.00
Rear Spike	4350.00
Main Landing Gear	9700.90
Nose Landing Gear	2749.20
Nacelles	3112.50
Total Struct. Weight	**83139.00**

Useful Load Group	Weight (lbs)
Fuel	123739.00
Payload (luggage)	3740.00
PAX	12580.00
Total	**140059.00**

Equipment Group	Weight (lbs)
Flight Controls	1380.60
Instruments	526.10
Hydraulics	488.00
Electrical	881.10
Avionics	1506.10
Furnishings	1216.30
Air Conditioning	605.90
Anti Ice	412.70
Handling Gear	123.80
APU installed	1038.80
Total	**8179.40**

Propulsion Group	Weight (lbs)
Engines	10500.00
Engine Controls	461.00
Starter	526.60
Total	**11487.60**

TOTAL	**242886.00**

BENEFITS OF THE DOUBLE FUSELAGE

Bushnell [37] states that the concept of a double fuselage aircraft offers a "comfortable" and well understood "conventional technology". For the same reasons, Torenbeek [38] claims that the twin fuselage concept does not require major advances in design technology that currently hinder other unconventional advanced aircraft concepts. The benefits of the double fuselage were the primary reasons for adopting the configuration over other considered concepts. Required use of current technology to meet the NASA specified IOC in a decade also justifies the double fuselage concept.

Although double fuselage aircraft are currently unconventional, they have been successfully implemented in the past and modern day. Raymer [32] cites the classical example of a dual fuselage aircraft as the North American F-82 Twin-Mustang, shown in Figure 9. The F-82 was created to provide long range escort for allied bombers during World War II and consisted of two baseline P-51 Mustangs which were modified and joined together. The F-82 set a record for the longest nonstop flight of a propeller-powered fighter airplane, Hawaii to New York.

A more modern example of a successful twin fuselage concept is the Virgin Galactic/Scaled Composites White Knight II [39] shown in Figure 10. The White Knight II is a carrier aircraft that ferries Spaceship II to an altitude of 50,000 feet before releasing the spacecraft to rocket to the verge of space. Exhibiting slender fuselages and a trapezoidal wing, the double fuselage concept was chosen for the White Knight II because the structures of the vehicle must withstand a sudden body force and sharp acceleration when the very heavy point mass of Spaceship II is released. With enhanced structural strength, the double fuselage concept again illustrates the potential benefits of this configuration.

Figure 9. F-82 twin Mustang long-range escort [40]

Figure 10. White Knight II carrier vehicle [39]

The double fuselage platform was adopted as the configuration for the VTSST for the structural, weight, and aerodynamic benefits discussed in the next sections.

Weight Reduction Characteristics

The heart of the VTSST is the double fuselage configuration, which inherently decreases total aircraft weight. After thorough design studies of multi-fuselage aircraft concepts, Houbolt [41] concludes that up to 30% structural weight reduction may be realized for a twin fuselage aircraft compared to a conventional single fuselage configuration carrying the same number of passengers. This weight reduction is attributed to the dual fuselages offset from the center of the wing, greatly reducing wing bending moment, translating into higher structural stiffness and rigidity. Torenbeek [38] states that for a baseline conventional transonic configuration, a 13.5% reduction in maximum gross takeoff gross weight can be achieved by utilizing a twin fuselage configuration. These weight savings provide a 15.9% reduction in mission block fuel weight and a 20% reduction in installed thrust required relative to a conventional configuration.

Wood [42] of NASA Langley states that significant weight reductions and aerodynamic benefits can be achieved for a supersonic aircraft with two fuselages rather than one. Wood also states that the benefits of a dual fuselage concept *appear to be independent of operating conditions i.e. cruise speed or Mach*. In a separate source, Wood [43] claims that a doubling of fuselage volume could be obtained with little or no aerodynamic penalty, while a multi body concept can effectively create a longer and thinner configuration, thus increasing the effective fineness ratio of the aircraft, which is desired for efficient supersonic flight. Maglieri and Dollyhigh [44] conclude that a twin fuselage supersonic aircraft will likely have aerodynamic performance that exceeds, or at the very minimum, equals that of a single fuselage configuration having one half the passenger capacity.

Increasing L/D

The double fuselage concept also presents the unique opportunity to decrease wave drag through favorable interference. A theoretical study of the effect of mutual interference has been presented by Nielsen [45] indicating that the drag of a pair of bodies in supersonic flow may be doubled or effectively halved depending on the relative location of the bodies. The drag reduction comes from highly beneficial mutual interference between the two bodies in which a favorable pressure gradient is imparted upon a rearward body from that of a forward body. This produces a thrust in the forward direction which essentially has the same effect as canceling a great portion of the total wave drag and shock waves created by the bodies. In the data presented by Nielsen, it is shown that the wave drag of two bodies can theoretically be reduced by up to 80% relative to the wave drag that would be produced by the same two bodies not affecting each other. Essentially the double fuselage configuration offers the benefit of decreased wave drag of each individual fuselage at the price of higher skin friction drag.

The following pages further describe the supersonic double fuselage concept submitted by Virginia Tech to meet the specifications of the NASA RFP.

MINIMIZING SONIC BOOM

As mentioned in the previous section, solving the low-drag/boom paradox is achievable when the low-drag and low-weight characteristics of the double fuselage configuration are synergistically combined with low-boom technologies and features. This section overviews the boom-minimizing features incorporated into the design of the Javelin SST.

Dual Quiet Spike Technology

The Quiet Spike is an existing enabling technology capable of increasing overpressure rise times and weakening shock intensities at the nose leading edge [46]. The double fuselage incorporates a Quiet Spike-like feature on the nose of the forward fuselage and a rear telescoping rod on the aft fuselage, as shown in CAD Figure E. The spike takes advantage of two sonic boom minimization techniques: shock shaping and increasing aircraft length, described in the Design Challenges section in this report. On the Javelin SST the spikes increase the effective length for higher fineness ratio and favorable wave drag interference. Incorporating weak shocks and a delayed overpressure rise time, the fore and aft Quiet Spike-like rods also add length to the aircraft while enhancing low-boom features. This lessens the overall aircraft sonic boom signature, making the Javelin SST configuration more compatible with the 70 PldB restriction imposed in the NASA RFP.

Towards Optimizing Fuselage Shape

The Seebass [16] and Darden [17] methods for minimizing sonic boom were outlined in the section addressing the low boom/low drag paradox. The method specifies a resulting equivalent area curve based on aircraft volume and lift distribution. Concepts like the silent supersonic JAXA and NASA SBJ reflect the area distribution needed to match the Seebass-Darden method. This half-bell shaped equivalent area curve represents a minimum sonic boom pressure signature. Rallabhandi's [19] research of this method states that the computations can be separated into two processes, the first method attempting to shape the fuselages to match the target equivalent area distribution before any lift enters the calculation. With the fuselage shape frozen, and corresponding area curve relatively fixed, the second step involves matching the remaining volume and lift of the aircraft configuration to this curve. The second step generally causes the F-function and pressure signatures to disagree with target plots.

The Javelin SST concept attempts to create a low drag area distribution, but there is still potential to match the fuselage nose to the initial slope of the curve and better shape the wing-fuselage interface, however presently this has not been optimized. The Javelin SST fuselage nose cones are shaped after parabolic Sears-Haack bodies for low drag. The low-sweep laminar flow canard located in front of the wing acts to add bluntness to the front of the aircraft while serving as a pitch control surface[47]. Further fuselage shaping is required.

Low-Boom Wing Profile

The low-drag/low-boom conflict applies to every aspect of the weight-saving double fuselage configuration. As a compliment to the double fuselage design, the Javelin SST concept features a low aspect ratio cranked delta wing with the potential for structural simplicity and additional weight savings. One feature with the potential to compliment the drag and weight savings of the double fuselage and cranked delta wing combination, as well as incorporate low-boom features, is a well-shaped supersonic biconvex airfoil, as cited in the Enabling Technologies section of this report.

Khandil of Old Dominion University investigated the effects of camber, thickness, and nose angle on supersonic symmetric biconvex delta wing profiles, with technological and software support from NASA Langley [48]. Khandil's research aimed at tailoring the shape of a 5% maximum thickness biconvex delta wing to minimize the ground boom signature relative to a Mach 2 cruise condition.

Khandil's team initially varied the nose angle from 2^o-5^o, thickness from 2-6%, and maximum camber from 0.5-2.0%, individually. Trends of the initial tests reported that decreasing nose angle flattened the overpressure signature, increased lift and decreased drag; decreasing thickness decreased overpressure, and improved lift and drag characteristics; increasing camber weakened shocks and increased both the lift and drag coefficients. Eight configurations varying the three parameters were constructed for optimization using NASA Design Expert Software with CFD analysis. The study concluded that for low overpressure and high *L/D* characteristics from the biconvex delta wing profile at 0^o angle of attack, a nose angle of 2.01^o, thickness ratio of 4% (2.5% upper, 1.5% lower surface), and camber ratio of 1.49% was optimal [48]. The optimal solution produces a ground overpressure of 0.0217 psf compared to the 0.0458 psf ground overpressure of the base symmetrical 5% thickness biconvex delta wing profile, a decrease of 52.62% relative to conventional delta wings.

The sonic boom requirement stated in the NASA Design Challenge section of this report is 70PldB, corresponding to a peak overpressure signature < 1.0 psf. For this requirement, the optimized biconvex delta wing can substantially reduce the overall aircraft sonic boom signature, assuming the remaining components incorporate low-boom features as well. The 50% improvement in the wing's overpressure is further complimented by the achievement of a flat trailing edge overpressure signature. Essentially, the optimal biconvex wing completely eliminates the trailing edge ground overpressure compared to the original delta wing.

Application to the Javelin SST Concept

The aerodynamic considerations of the VTSST ideology have a critical impact on the success of the Javelin. The results of this design effort were factored into the aerodynamic configuration and analysis of the Javelin SST. The low-boom characteristics and features necessary to compliment the double fuselage cranked delta wing contributed to the low-weight and low-drag design goals.

The design must still meet requirements of efficient subsonic, transonic, and supersonic flight and agree with the low-weight assumptions formulated in the preliminary design and concept selection phases. Also, resulting definitions of the Javelin concept must continually remain congruent with the low-boom projections while meeting the NASA defined performance specifications of Mach 1.8 cruise, 4000 nmi range, and 3 pax-mile/lb_{fuel}. The following section briefly overviews aerodynamic considerations of the Javelin SST concept.

AERODYNAMIC CONSIDERATIONS/ANALYSIS

Supersonic Fineness Ratio vs. Drag

The Javelin SST concept is a low-drag design incorporating low-boom features. Originally, a low boom design was envisioned, shown below in Figure 11.

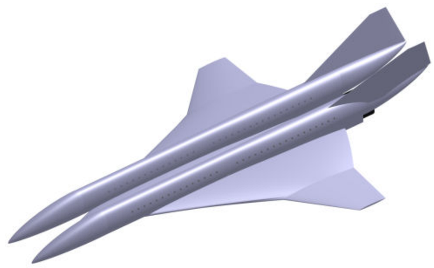


Figure 11: Initial concept, fineness ratio = 10

However, this configuration suffered from a very low fineness ratio around 10, similar to the Concorde. This resulted in very high wave drag, and therefore low *L/D* ratios at supersonic speeds. The effect of fineness ratio on the drag of a body at supersonic speeds is shown in Figure 12, reproduced from Mason [49] who cites Oswald[50]. As shown in the figure, the minimum drag for a body at supersonic speeds occurs when the fineness ratio is equal to 15.2. Consequently, the initial double fuselage design shown above was asymmetrically staggered by placing the starboard fuselage a longitudinal distance of 87 feet behind the port fuselage as shown in CAD Figure E. In addition to increasing the fineness ratio of the aircraft, the asymmetric staggering of the fuselages also creates favorable interference, which further acts to decrease the wave drag at supersonic speed, discussed in the next paragraph.

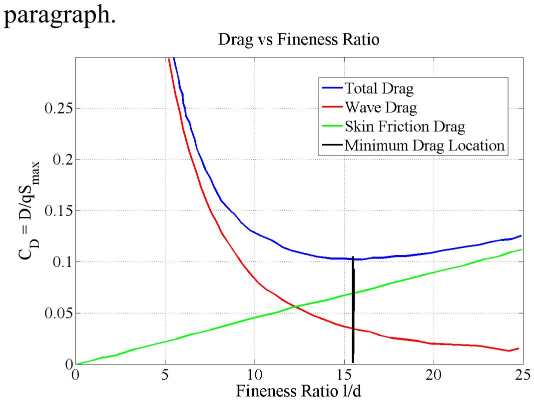


Figure 12. Total drag vs. fineness ratio for a body of specified maximum area reproduced from Oswald [49]

Nielsen of NASA Ames has determined that the wave drag of multiple bodies at supersonic and transonic speeds may be doubled or nearly halved relative to the drag of a single body, depending upon their lateral and longitudinal displacement with respect to each other[45]. Nielsen determined this by mathematically analyzing the effect of multiple arrays of Sears-Haack bodies and notes that this favorable interference may be harnessed to reduce the wave drag as a direct application to a twin-body aircraft. Figure 13, reproduced from Nielsen, shows the displacement of the two bodies relative to one another, creating the resulting change in wave drag. In the figure, the variable *a* is half the lateral distance between the centers of the two fuselages, *b* is the longitudinal distance between the noses of the two fuselages, *L* is the length of one of the fuselages, and beta is parameter equal to the square root of the quantity Mach number squared minus one. These values are illustrated in Figure 13.

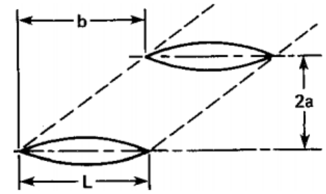


Figure 13: Definitions of variables a and b in Nielsen's favorable interference calculation [45]

Although Sears-Haack bodies are ideal and do not resemble any realistic fuselage shape, Nielsen notes that the difference is small between the wave drag characteristics of a pair of parabolic-arc bodies and the wave drag characteristics of a pair of Sears-Haack bodies. He also notes that parabolic arc bodies could represent a pair of fuselages. This theoretical analysis was supported by Friedmann of NASA Ames, who concluded that the drag of three bodies could be reduced by up to 35% relative to the sum of individual wave drags of each body [51]. In Figure 14 below, it is theoretically estimated that the VTSST reduces wave drag of the two fuselages by about 50% relative to the wave drag of two infinitely separated bodies not affecting one another. Essentially, the Javelin SST benefits from having two fuselages while incurring the wave drag penalties of only 1.3 fuselages.

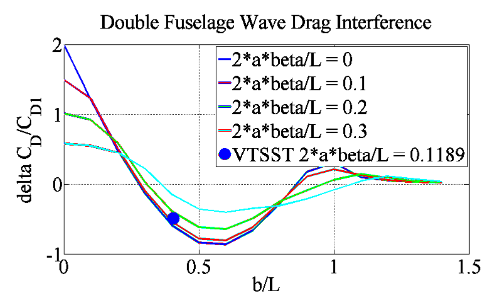


Figure 14: Favorable Interference Drag Reduction Data reproduced from Nielsen [45]

Supersonic Wing Planform

The favorable interference fuselage configuration, coupled with the low-boom biconvex airfoil cranked delta wing and dual Quiet Spike-like rods presented in the previous section, represent the foundation of the Javelin SST aerodynamic ideology. To complete the preliminary configuration and further aerodynamic analysis, the wing planform geometry was modeled after research conducted by Herrmann in the report *CISAP: Cruise Speed Impact on Supersonic Aircraft Planform; a Project Overview* [52]. Herrmann studied various wing planforms designed by partner groups for a 5,000 nmi mission, 1,000 nmi longer than the required NASA range. Partner groups formulated a variety of planforms with various functions including supersonic cranked-deltas, a transonic swept wing with notched trailing edge, and a M-wing, as shown in Figure 15 on the next page.

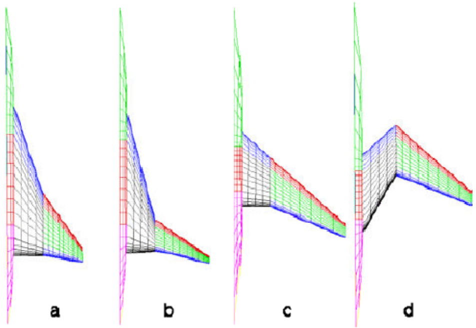
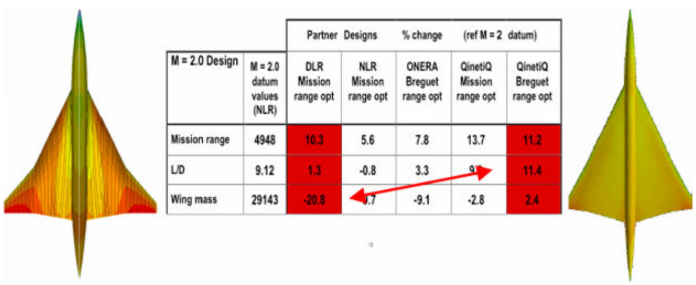


Figure 15. Potential CISAP planforms from a supersonic (a,b), to transonic (c), to M-wing (d) [48].

Hermann states that designs were tested for cruise at Mach 1.3, 1.6, and 2.0, optimizing the planform geometry effects on range, *L/D*, and wing mass. Figure 16 shows the initial performance at Mach 2 for the four partner designs and the percent change of performance parameters relative to initial performance estimates. Notable is the 20.8% decrease in wing weight of the cranked delta identified by the partner groups as "DLR", using a crank and tip twist of 4.18^o and 3.89^o, respectively. The "QinetiQ", optimized for maximum range, improves aerodynamics performance to achieve significantly higher *L/D* and range [52].



		Partner Designs % change (ref M = 2 datum)				
M = 2.0 Design	M = 2.0 datum values (NLR)	DLR Mission range opt	NLR Mission range opt	ONERA Breguet range opt	QinetiQ Mission range opt	QinetiQ Breguet range opt
Mission range	4948	10.3	5.6	7.8	13.7	11.2
L/D	9.12	1.3	-0.8	3.3	[illegible]	11.4
Wing mass	29143	-20.8	[illegible]	-9.1	-2.8	2.4

Figure 16. Comparison of all CISAP designs at Mach 2.0. The DLR (left) displayed the most favorable improvements [52].

Of the four models, two were tested at Mach 1.3 and two at Mach 1.6. Overall, performance was consistent at the various speeds with the wing weight savings of the DLR model, identified as the optimal design. The DLR design reflected a well optimized cranked delta wing generated at Mach 1.6 cruise, congruent with the competition requirements. The clean delta DLR design improved wing weight and supersonic L/D, and was capable of C_L = 0.2 in the transonic regime, but did not meet the specified low-speed or takeoff C_L of 0.63 due to a decreased aspect ratio [52]. As a result of the poor low-speed performance, the Virginia Tech design uses the cranked delta supersonic planform because it offers excellent supersonic and transonic aerodynamic characteristics as well as low-speed performance. The wing was modeled in Raymer's RDS program for mission analysis and Tornado: Vortex Lattice Method (VLM) code to determine if the cranked delta planform could achieve the required lift coefficients relative to initial takeoff performance estimates.

RDS mission analysis of the supersonic configuration returned drag characteristics for the various Mach regimes. Figure 17 shows that the maximum combined parasite and wave drag coefficient for this configuration is less than 0.015.

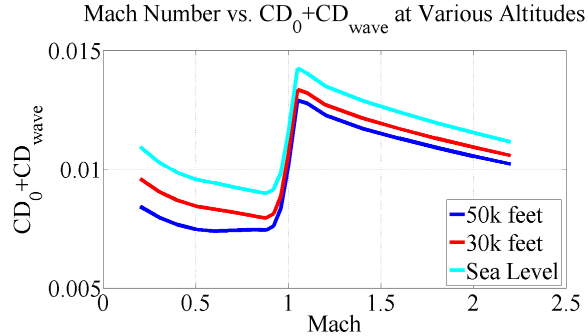


Figure 17. Effects of alt. & Mach on mission C_{D0}+C_{Dwave}

Low-speed/Takeoff Analysis

Justification of the staggered double-fuselage concept with optimized low-boom biconvex cranked-delta (LBCD) wing depends on the low-speed analysis at take-off for a NASA-defined 10,000 ft balanced field length. The biconvex wing data was modeled in Tornado based on a plot generated in the Khandil [48] report, previously referenced in the Minimizing Sonic Boom section of this report.

For the LBCD wing planform with dimensions and takeoff flight conditions displayed in Figure 18, Tornado VLM returned a lift coefficient of 0.77. Lift results for the takeoff condition verified that sufficient lift could be attained at 14^o angle of attack during takeoff with flaps.

LBCD Dimensions	
Wing Area	4135 ft²
Wing span	94 ft
Mean Aero. Chord	69.5 ft
Delta sweep$_{c/4}$	58°
Crank sweep$_{c/4}$	45°
Crank twist	3.89°
Tip twist	4.18°

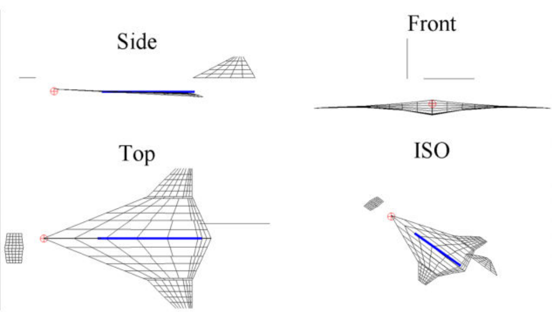


Figure 18. Low-speed LBCD planform modeled in Tornado VLM; flight conditions: Mach 0.3 at sea level, AoA = 14^o

With analysis to support the now frozen LBCD wing, the Javelin SST design efforts shifted integrating propulsive systems into the configuration and calculating mission performance. The Javelin mission, shown in Figure 19 below, was modeled in RDS for performance analysis.

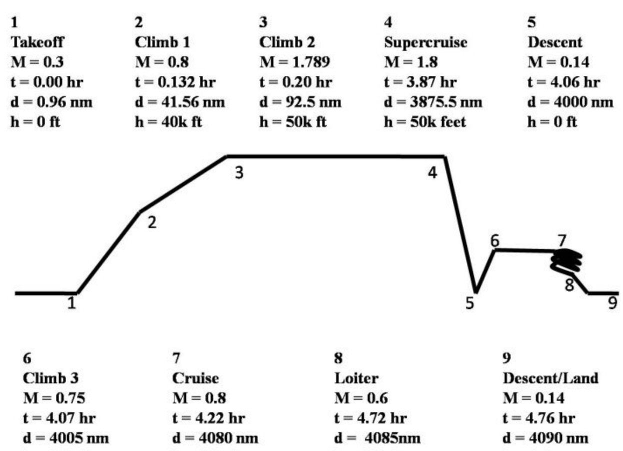


Figure 19. Javelin mission diagram

PROPULSION

Often for innovative and advanced aircraft concepts, the propulsion system and its ability to perform efficiently throughout all parts of the specified mission, or lack thereof, is known to make or break the design. For supersonic aircraft, this dependency on the propulsion system is heightened because of increased performance demands during supersonic flight. This section discusses the engines considered for the Javelin SST.

The wing loading versus thrust to weight plot, presented on page 21 indicates that the Javelin SST would need a *T/W* of 0.45 when operating at a wing loading of 60 psf. For a MGTOW of 242,886 lbs, the total thrust required at takeoff would have to be approximately 109,300 lbs. Initially, three engines were desired for the benefit of wetted area reductions relative to four engines. This resulted in a required max thrust at takeoff per engine of 36,500 lbs. Therefore prospective propulsive systems were investigated to determine if they were capable of producing the required amount of thrust at takeoff.

Analogous to the low-boom/low-drag paradox, a paradox also exists for high-performance/efficiency demands of the propulsive system. For supersonic aircraft at takeoff, landing, and subsonic cruise, a high bypass ratio turbofan engine is desired. This engine is inherently more efficient and less noisy than a low bypass ratio turbofan or pure turbojet. For acceleration to supersonic speeds and thrust during supersonic cruise, a pure turbojet is desired for its high thrust and supersonic efficiency. However, the turbojet has a fundamentally less efficient thermodynamic cycle than a turbofan, thus establishing the engine efficiency/performance paradox. The basic turbojet and turbofan engines are discussed below followed by research on advanced cycle engines and performance modeling.

Turbojet/Turbofan Engines

As noted in the introduction of this report, the turbojet is the fundamental engine for high-speed flight. This consists of a compressor, burner, turbine, and nozzle. The turbofan is a turbojet with an added turbine attached to a fan, in front of the compressor. These two engines were modeled in the gas turbine engine cycle analysis, GasTurb to get an initial estimate of performance at sea level static conditions and supersonic cruise. This analysis was performed to determine if these engines could produce the required cruise thrust of 8,000 lbs.

Advanced Engine Concepts

After researching and investigating the basic engines applicable to supersonic flight, described above, advanced propulsion systems were considered. These consisted of engines from General Electric (GE) and Pratt & Whitney (P&W) both previously proposing very different concepts to achieve the same goal of creating a supercruise engine. The engines proposed by these two companies are described by Timnat [53] as the following:

GE: Double Bypass Engine – This engine features a variable geometry turbofan in which the fan is split into two blocks. Each fan block has its own bypass duct where flow through each fan is controlled throughout the various flight regimes, effectively varying the bypass ratio, thrust, and efficiency. The front fan block features a large bypass ratio for reduced jet velocity and noise during takeoff. The rear fan block is sized for a bypass ratio of 1 during transonic and supersonic cruise for increased efficiency.

P&W: Variable Stream Control Engine – Pratt and Whitney has proposed the use of a variable stream control engine (VSCE). This engine is similar to a conventional two-spool turbofan but incorporates a low emissions duct burner located in the bypass duct and a co-annular exit nozzle. By burning fuel in the outer bypass duct that surrounds the core, a form of distributed propulsion may be achieved because the burners may be operated at independent throttle settings. The operation of this engine is described by Hines [54]. At takeoff, the primary core burner is operated at an intermediate setting while the duct burner operates at maximum temperature. This effectively achieves an inverted velocity profile in which the bypass jet velocity is 60% higher than that of the primary jet core. This reduces jet noise by 8 decibels relative to a first generation SST engine. This velocity profile achieves a significant reduction in takeoff jet noise relative to a constant velocity profile. During subsonic cruise, both burners are operated at partial power, achieving a uniform velocity profile, therefore providing a 20% lower fuel consumption at subsonic cruise relative to first generation turbojets. At supersonic cruise the primary burner is increased to takeoff conditions and the duct burner is operated at partial power. At supersonic cruise the VSCE is estimated to approach the efficiency of a turbojet. A VSCE engine is shown in Figure 20 below.

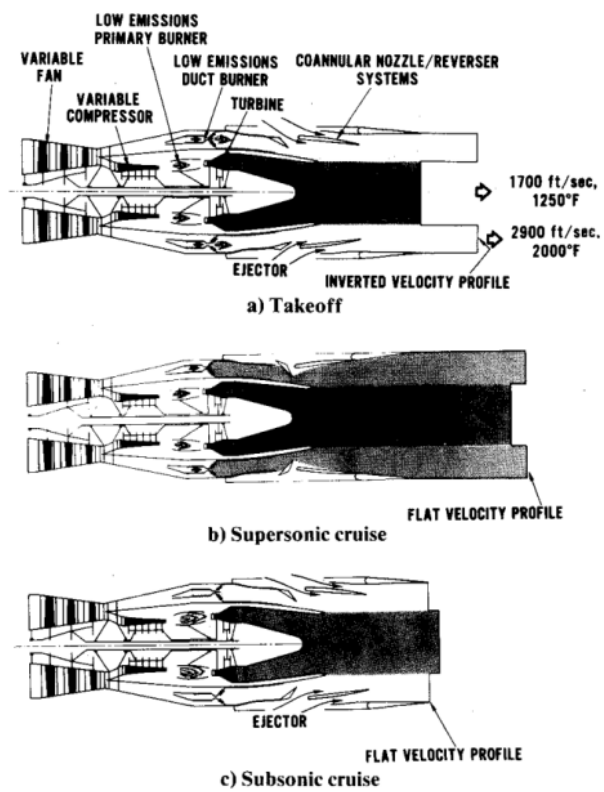


Figure 20. Diagram of VSCE engine at critical operating conditions [54]

Comparison Engines

After advanced concepts were considered, existing comparison engines were identified and investigated. Potential engines for the Javelin SST that currently exist and produce 35,000-37,000 lbs at sea level takeoff were identified from Jane's Aero Engines [22] as:

GE F-120 – a variable cycle engine operating as a turbofan at subsonic conditions and then collapses the bypass to operate as a turbojet at supersonic speeds. It was originally designed as a prospective engine for the advanced tactical fighter (ATF) program, now the F-22 Raptor, but was not selected due to its large amount of varying parts, and required maintenance.

P&W F-119 – a two spool afterburning turbofan was selected as the propulsion system for the ATF over the engine described above. Jane's cites that the F-119 is capable of producing a maximum takeoff thrust of 37,790 lbs, though *with* the use of afterburner. The maximum dry thrust of the F-119 at sea level static condition is 25,418 lbs. The *sfc* of the F-119 during supercruise remains classified. A diagram of the F-119 is shown below in Figure 21

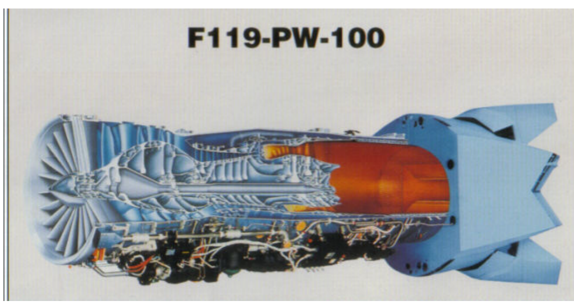


Figure 21: P&W F-119-100 Engine [55]

P&W F-135 – the exclusive engine of the first five production batches of the F-35 Joint Strike Fighter (JSF). The F-135 was based on the F-119 engine, though maximum thrust had to be increased due to the JSF requiring only one engine. One engine was necessary to meet the low weight required for the vertical takeoff and landing constraints of the Marine variant of the JSF. Jane's cites the F-135 is capable of producing 38,200 lbs of thrust at takeoff *without* the use of afterburner. The Marine version of the engine is capable of producing a total thrust from the core, lift-fan, and outboard thrust vectoring roll posts of 39,220 lbs at sea level without augmentation. Jane's lists the *sfc* of the F-135 during transonic cruise as 0.886 lb/lb/hr.

It is of particular interest that the F-135 can produce the necessary thrust required by the Javelin SST without afterburning, but cannot supercruise like the F-119 engine from which it was derived. Therefore some of the features of these two engines are proposed to be combined and modified as the solution engine.

Proposed Javelin Engine System

The solution engine was chosen after reviewing the advanced supercruise platforms of the 1980s described by Timnat [53] and the modern existing engines capable of producing the required thrust necessary to power the VTSST. It is proposed that the P&W F-119 engine be selected as the base system of the Javelin SST propulsion engine with certain modifications. It is also proposed that a similar, de-militarized F-119 engine be created so it can be exported outside of the United States and used for global civil transport. To achieve the required takeoff thrust, the afterburner section would be removed and a duct burner would be installed in the bypass duct with a co-annular nozzle with flow deflectors installed in the exit. By converting the F-119 into a civil VSCE the F-119 based engine could achieve high takeoff thrust necessary through duct-burning. Duct-burning is an augmentation process similar to but distinctly different from afterburning. A low-emissions duct burner and co-annular nozzle both work to achieve the NASA RFP required low emissions and takeoff noise, respectively. The relatively simple duct burner is proposed to be powered by liquid methane while the core of the engine is run on synthetic kerosene.

Propulsion Modeling and Performance

To create a model for a supercruise engine, propulsion data tables provided by Mattingly [57] for a low bypass ratio turbofan were imported into Raymer's RDS mission analysis program. The thrust of the engines were scaled to match the required takeoff thrust of 37,000 lbs, determined by research presented in the previous section to be achievable by a modern advanced turbofan such as the JSF or ATF engines. A turbofan with a bypass ratio of 0.3 was modeled in GasTurb to determine the *sfc* values corresponding to the takeoff, subsonic cruise, and supercruise conditions. By using the standard two-spool turbofan model in GasTurb, the *sfc* at sea-level takeoff, transonic cruise, and supercruise were 0.64, 0.925, and 1.021 lb/lb/hr respectively. The *sfc* table that corresponded to the original thrust table provided by Mattingly was then scaled to match these reported *sfc* values. The data in the modified engine tables served as the necessary propulsion data to perform mission analysis and is presented in Figures 22 and 23.

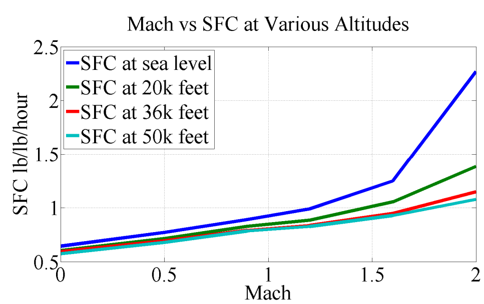


Figure 22: *SFC* table used to perform mission analysis of the VTSST

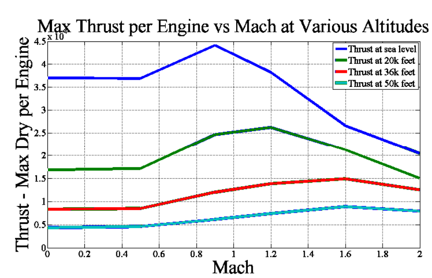


Figure 23: Thrust Table used to perform mission analysis on the VTSST

FUELS

Alternative fuels are essential if the United States is to end dependence on foreign oil. As world oil reserves diminish, jet fuel costs will inevitably increase and alternative fuel research and implementation will become cost effective. Although the NASA RFP did not explicitly require alternative fuel use, the Javelin SST offers several alternative fuel schemes to accommodate for the inevitable demand of alternative forms of energy. Many different alternative fuels were researched and the potential candidates for use in the duct burner and core of the Javelin engines were identified as Fischer-Tropsch synthetic kerosene, liquid methane, and liquid hydrogen.

Fischer-Tropsch Synthetic Fuels

Synfuel is synthetic kerosene that closely resembles current aviation grade fuel. Synfuel is produced from the Fischer-Tropsch gasification process and is currently used in South Africa as a 50/50 blend of Synfuel and JP-8 [58]. Such fuel is already certified for aviation use in South Africa and therefore represents a present-day alternative to oil-derived kerosene. The Fischer-Tropsch gasification process can be used to convert coal or methane natural gas into liquid fuel. Since coal and methane natural gas are among the most abundant fossil fuels within United States borders, the Javelin utilizes these sources as alternative fuels. The benefits associated with Fischer-Tropsch synthetic fuel are discussed below.

The primary strength of Fischer-Tropsch Synfuel is that it may be easily implemented into existing aircraft engine systems and airport infrastructure as the physical properties of the Synfuel are almost identical to standard JP fuel. Because Synfuel is very close to conventional fuel it produces nearly the same levels of pollution as standard jet fuel. However one pollution benefit of Synfuel is that a 50/50 blend of Synfuel and JP-8 results in a 50% reduction in produced smoke because it does not cause engine system O-rings to expand during operation. This is usually due to reduced amounts of aromatics as compared to standard kerosene fuel [58]. Fischer-Tropsch synthetic kerosene has already been successfully tested by the United States Air force in a B-52 bomber and Airbus in an A-380 and it is projected to be widely implemented in the next decade.

Liquid Methane Natural Gas Fuel Alternative

One way of improving the payload fraction and the efficiency of the Javelin SST is to use fuels that are superior to JP type fuels in heating value, heat sink capacity, cost and availability, while being safer and more dense [59]. Since the heating value of cryogenic liquid methane is 13% higher than that of JP and the heat sink capacity is about four times as great, liquid methane is a viable alternative fuel. The downside of liquid methane is that it is half as dense as current jet fuel, thus requiring more storage volume which must be maintained at cryogenic temperatures below -258^{o}F while preventing the liquid in the tanks from boiling off into a gaseous state. If these negative attributes are overcome, the passenger capacity of a methane fueled aircraft could be increased by 31% and the direct operating cost reduced by 25% compared to a JP fueled aircraft [59]. Although use of cryogenic liquid methane is currently unconventional and represents an N+2 technology level, successful implementation of liquid methane has been achieved in the past.

Liquid methane was first successfully used to a power the Russian Tu-155 transonic aircraft in 1988. The Tu-155 was based on a modified Tu-154 with the addition of cryogenic fuel tanks in the rear fuselage, below the passenger cabin, and attached to the wings. The purpose of the Tu-155 experimental test bed was to first prove that an aircraft could successfully be powered by cryogenic fuels [10]. The second purpose of the Tu-155 was to successfully transition Russia towards a completely cryogenically-powered liquid methane and liquid hydrogen fueled air transportation system. After the Tu-155 proved that it was possible to power an aircraft on liquid methane, the Tu-156 civil airliner was conceived, as shown in Figure 24.

The success of the Tu-155 effectively proves that the technology and methods exist to create a liquid methane powered aircraft. This research is the foundation for choosing the Javelin to be partly powered by cryogenic liquid methane in the duct burner of the VSCE engine while synthetic kerosene fuels the engine core. This will serve as the necessary step to creating hydrogen powered aircraft.

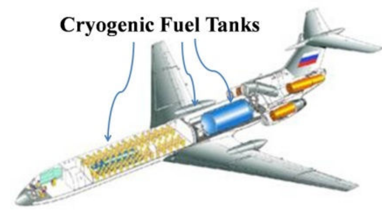


Figure 24: Tu-156 Proposed Cryogenic Airliner [58]

Hydrogen Fuel Alternative

Liquid hydrogen has long been recognized as a clean and efficient alternative fuel to substitute conventional hydrocarbons, though not expected to be cheaply available in the near future, thus establishing an N+3 technology goal. Because liquid hydrogen does not contain carbon, burning of hydrogen results in near zero CO_2 emissions, the primary pollutant of modern aircraft engines. NO_x is also greatly reduced by using hydrogen. The heating value of hydrogen is 2.7 times that of Jet-A and hydrogen is an excellent heat sink, making it highly efficient for use in gas-turbine engines [60]. However, the primary problem with liquid hydrogen is that the density is one-twelfth that of standard kerosene, therefore presenting similar problems introduced by liquid methane. In order to provide the same amount of energy as Jet-A, more than four times the volume will be required at 37% of the kerosene fuel weight [61]. Hence the aircraft volumetric efficiency must be carefully analyzed to attain the full benefits of a hydrogen fueled aircraft.

The N+3 variant of the Javelin SST is proposed to be powered by hydrogen. The dual fuselages of the Javelin offer the necessary large storage volume required for hydrogen without any modifications to the exterior of the aircraft. An entire fuselage may be dedicated to hydrogen storage while the other fuselage is dedicated to carry passengers. This however presents balancing problems. This issue could possibly be solved by dedicating the rear half of the bow fuselage and the forward half of the other fuselage for hydrogen storage, while the remaining halves of the fuselages are used for to carry passengers. This is illustrated in CAD Figure C on page 10.

POLLUTION/ENVIRONMENTAL EFFECTS

NASA goals require NO_x emissions to be 10 g NO_x/kg_{fuel}. In addition to fuel challenges, fuel injection, Synfuel development, and engine component technology must mature in the 21st Century if any supersonic transports are to operate. This was an important lesson learned during the development of the US SST in 1971 and became a deciding factor to cancel the program [9].

The major emissions of aircraft engines are CO_2, NO_x, SO_x, soot, water vapor, and smoke. Nitrogen oxide emissions affect ozone levels in the atmosphere and are directly related to fuel consumption. Any improvement in fuel efficiency directly such as those mentioned on the previous page, reduces pollution. The next section summarizes effects of various emissions and discusses the Javelin SST approach to lessen the environmental impact.

Nitrogen Oxides and Carbon Dioxide Emissions

Even though aircraft nitrogen oxide (NO_x) emissions account for only about 3% of the total tonnage of worldwide NO_x and are therefore relatively small, they are forecast to become significant without regulations [62]. Aircraft emissions of NO_x are more effective at producing ozone (O_3) in the upper troposphere than an equivalent amount of emission at the surface, but increases in ozone in the upper troposphere tend to increase radiative forcing, the global warming from pollution [63]. Because of these increases, the calculated total ozone column in northern mid-latitudes is projected to grow by approximately 1.2% by 2050. However, the sulfur and water vapor emissions in the stratosphere tend to deplete ozone, partially offsetting the NO_x induced increases [63].

According to the Intergovernmental Panel on Climate Change, surface concentrations of CO_2 will be 405 parts per million by volume (ppmv) by 2015, and 509 ppmv by 2050 [63]. In 1992, the carbon dioxide concentration from aviation was 1 ppmv, about 2% of global CO_2 emissions [58] , and this is expected to increase to between 5 and 13 ppmv by 2050, a 1.6 to 10 times increase [63].

Advantages of Fischer-Tropsch Synfuels enriched with methane are low NO_x emissions during combustion and the possibility to use gaseous waste products of refineries in the production of the gas to liquid Synfuels [58]. Liquid methane's lower heat of combustion also reduces combustion temperature, decreasing both NO_x and CO_2 emissions due to lower operating temperature.

Sulfate and Soot Aerosols

The Javelin's engines are based on the F-119 engine that is known to produce no visible smoke or soot [55]. Soot destroys ozone, but the soot is consumed in the process [63]. However, soot particles may act as condensation nuclei for sulfate or other species, modifying cirrus clouds that cover about 30% of the Earth. On average, an increase in cirrus cloud cover tends to warm the surface of the Earth and an estimate for aircraft induced cirrus cloud cover for the late 1990s ranges from 0 to 0.2% of the surface of the Earth [63]. It is estimated that this may possibly increase by a factor of 4 by 2050. The direct radiative forcing of sulfate and soot aerosols from aircraft is small compared to other aircraft emissions but the formation of clouds may play an important role in radiative properties of clouds.

Radiative Forcing and Erythema in Supersonic Aviation

The radiative forcing of civil supersonic aircraft is estimated to be a factor of 5 larger than that of a subsonic aircraft. The Panel on Climate Change concluded that by the year 2050, a supersonic fleet, assumed to cruise at Mach 2 to 2.4, would add an additional 0.08 W/m^2 to the 0.19 W/m^2 assumed for subsonic aircraft. This additional forcing is mainly due to accumulation of stratospheric water vapor. The effect of a civil supersonic fleet is also to reduce stratospheric ozone and increase erythemal dose rate. Erythemal dose rate is defined as UV radiation weighted according to how effectively it causes sunburn. The maximum calculated effect is at 45°N latitude where, in July, the ozone column change in 2050 from the supersonic fleet is -1.3% while the subsonic fleet component is +0.9% for total change in ozone column of -0.4% [63]. The VTSST engine will not affect these levels due to low emissions with dual alternative fuels.

The Javelin SST Approach

One promising emission reduction occurs when hydrogen is implemented into the Javelin design. An ultra-lean premixed combustion is an effective method to reduce NO_x emissions. A hydrogen-blended Synfuel would provide a solution to the immediate need for NO_x reduction and also serves to enable the long term goal of a carbon-free energy system. It was found that up to 20% hydrogen addition, relative to fuel flow, provided NO_x levels of about 3 ppm, a competitive alternative to traditional nitrogen oxide control technologies [64].

The Javelin N+3 technology-driven energy system should rely solely on hydrogen fuel. For non-cruise mission phases of a hydrogen fueled aircraft it was found that using kerosene fuel located in the wings results in a structural relief of the aerodynamic wing load by about 60% of the wing fuel weight [65]. Also, JP fuel in the wings reduces hydrogen volume requirements, improves volume utilization, and thus increases the vehicle density, requiring less propulsive power and resulting in lower emissions from a smaller engine. For a fixed empty weight, range is increased by storing JP fuel in the wings of a hydrogen powered Javelin [65].

Pure hydrogen combustion produces none of the organic specie pollutants and the only product is water vapor. Compared to modern kerosene combustion, a lean premixed injection provides a twenty fold reduction in NO_x pollutants [61]. However NO_x levels depend strongly on mixing in the shear layer of the combustor and proper injection is required to resist flashback and blowouts. To further reduce emissions, the hydrogen must be produced from water using renewable or nuclear energy.

The Javelin SST can handle a wide variety of configurations utilizing cryogenic fuels. Since one of the fuselages can be entirely or partially dedicated to liquid methane or hydrogen storage, one promising scheme uses several smaller tanks that stretch along one of the fuselages to more effectively store the hydrogen longitudinally. This reduces the *L/D* penalty commonly associated with hydrogen fuels [61]. The N+2 Javelin SST proposal is to be powered by a combination of liquid methane stored in cryogenic tanks and Fischer-Tropsch synthetic kerosene stored within the wings. This implementation of cryogenic methane serves as a precursor to an N+3 Javelin which could be powered by liquid hydrogen as mentioned on the previous page. In the future, cryogenic fuel usage will depend on successful integration of the fuel tanks with the aircraft structure.

STRUCTURES / MATERIALS

With most modern aircraft, structural weight is often the price paid to create better aerodynamic efficiency relative to high aspect ratio wings. High lift requires larger lifting surfaces, and high sweep angles in designs further complicate the load and stress analysis. The desire for alternative fuels, increased payload capacity, and passenger efficiency increases overall structural weight as well. As stated by Loftin, future advanced configurations will depend on a blend of conventionality and new technologies, like that of the proposed Javelin concept [66].

Materials

Similar to the ideals of modern conceptual designs like the Aerion and JAXA SST, aluminum-lithium alloys and glass/graphite epoxy carbon fiber composites are proven and widely used to construct fuselages, and other empennages [29]. The same materials are applied to the Javelin SST, thus benefitting from a high stiffness to weight ratio [66] because the wing spars are cantilevered across the fuselages. These materials are combined in the Javelin with superplastic formed/diffusion bonded titanium to reduce structural weight an average of 20% for the wings, fuselage, and engines [47]. Carbon epoxy is common in military and most civil transport wing structures [29] and can also be used to carry the longitudinal loads on the Javelin's cranked delta wing. The cryogenic fuel tanks can be made of common graphite epoxy materials to help the outer surface withstand temperatures up to 250°F. These materials are assumed to be well understood and easily incorporated into modern aircraft such as the Javelin.

Structures

The Javelin SST has a uniquely functional configuration in the double-fuselage design. The two fuselages act as support to reinforce the main wing box, distributing the total lift over three surfaces of the wing instead of the conventional two. This creates a structurally solid wing box with relatively constant lift distribution and low-weight characteristics. With two fuselages, the maximum bending moment is reduced more the 50% as seen in Figure 25 from Torenbeek [38].

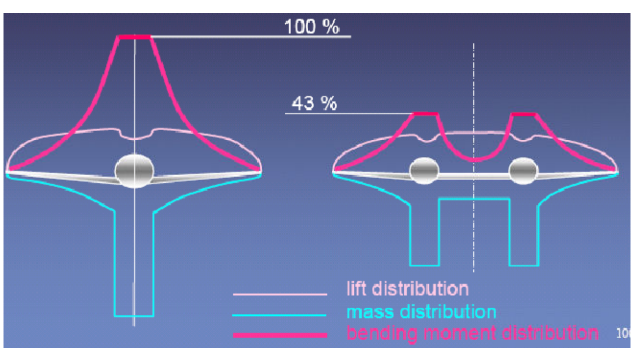


Figure 25. Single and Twin Fuselage wing bending [38]

The Javelin SST fuselages are sized for 1-abreast seating, with maximum cabin diameter of 6.5 ft. The mass distributions in Figure 25 represent an equal number of passengers between the single and double-fuselage designs. Based on the mass distribution of the fuselages compared to a single fuselage design with 2-abreast seating, the double-fuselage design decreases the total fuselage mass by 20%. Structurally, this configuration creates weight savings that support aggressive aerodynamic efficiency and sonic boom requirements.

The outer wing configuration is loosely modeled from the CISAP planform optimization shown in Figure 26. Optimized for Mach 1.6, the spatial arrangement resembles that of a multi-spar delta wing on the inner portion and swept spars on the cranked section. The black strip in the center of the aircraft represents the wheel bay for the landing gear which retracts sideways and inboard [52].

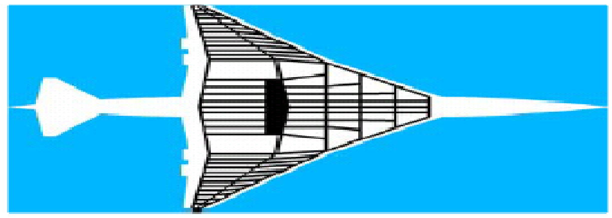


Figure 26. Optimized CISAP structural arrangement at Mach 1.6 [52]

Modifications of the CISAP arrangement for the Javelin SST incorporate the basic outer wing structure while extending the rectangular wing box between the two fuselages, shown in Figure 27. As mentioned before, the fuselages act as two sides of the rectangular portion of the delta wing and long stingers. This configuration also adds forward and aft wing gloves to keep the flow attached and reduce the potential losses of lift.

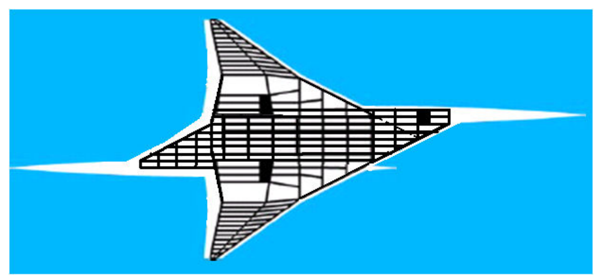


Figure 27. Javelin SST structure from optimized CISAP planform

Gulfstream Quiet Spike

Cowart with NASA Dryden and Gulfstream [46], reported on flight tests that examined the structural feasibility and dynamic response of the Quiet Spike throughout various flight regimes. The ultimate goal of the flight tests was to extend the flight envelope to Mach 1.8 at 45,000 ft, the upper Mach limit in the NASA RFP. In February 2007, Quiet Spike test flights concluded that the Quiet Spike could survive the structural loads imposed in the target flight regimes with minimal flutter, as the Quiet Spike was extended over 50 times at the various altitudes and Mach numbers without incident [46]. These structural tests justify the Javelin's use of the spikes at mission altitudes and required Mach number.

The structural weight benefits and savings discussed in this section were critical in matching the Javelin performance to initial sizing analysis that resulted in high weight requiring increased engine thrust. The next page describes the overall mission performance and how the required efficiencies were approached.

MISSION PERFORMANCE

Preliminary design weight estimations such as those described by Roskam [67] were performed for a 4000 nmi range aircraft with a cruise Mach of 1.8. Weight estimates predicted an aircraft MGTOW of 283,000 lbs with a fuel weight of 146,000 lbs. This is in good agreement with Coen [47] who states that if the Concorde was reproduced at current technology levels, the aircraft would weigh approximately 281,000 lbs. The fuel weight indicated by Roskam's method was deemed unacceptable because 96 passengers would have to be carried to meet the 3 pax-mile/lb_{fuel} efficiency specified by the NASA RFP. This passenger number is outside of the specified 35-70 passenger range required by NASA. Therefore it was determined that to perform the mission and meet the required efficiency, total gross takeoff weight must be reduced significantly to yield a fuel weight of no more than 107,333 lbs, reflecting the maximum number of passengers specified by the RFP. This justifies the necessity of utilizing the double fuselage to reduce weight.

As mentioned before, the Javelin SST was modeled in RDS, a conceptual aircraft design and sizing program coded by Raymer [32]. Also, Aircraft Engine Design (AED) software was used to generate the wing loading versus thrust to weight diagram in Figure 28. Figure 28 shows a plot of wing loading versus thrust to weight and indicates that the most constraining mission segments of the VTSST mission are takeoff, landing, and second climb segments. This originally resulted in a wing loading and thrust to weight of 75 psf and .39 respectively, corresponding to the classical design point. As the design developed, the wing loading and thrust to weight evolved to 60.9 psf and 0.457 respectively.

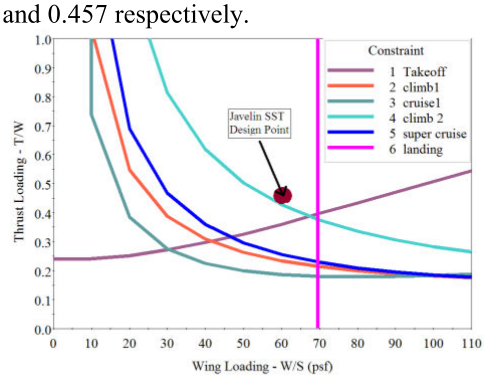


Figure 28. Thrust-to-weight vs. wing loading

Meeting the NASA constraint of a 10,000 ft balanced field length was one of the most constraining requirements. Results from RDS, in accordance with FAR 25 for takeoff are illustrated in Figure 29 below. The balanced field length was calculated to be 7,421 ft with a takeoff parameter (TOP) of 206. A total landing distance of 6,742 ft is required, as shown in Figure 30, and this exemplifies the Javelin's airport integrated design features because it can land in a variety of airports, discussed on the next page.

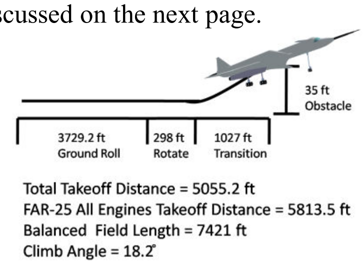


Figure 29. Javelin Takeoff Diagram

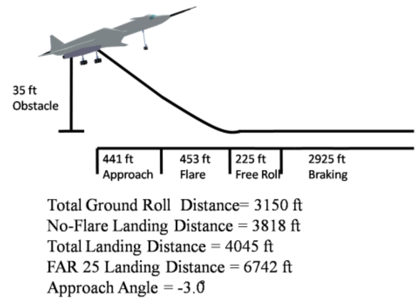


Figure 30. Javelin Landing Diagram

Table 3 illustrates the total mission performance based on RDS calculations. The first descent represents the typical termination of the Javelin mission, outlined in red, and the remaining segments show how the aircraft will perform during rerouting situations. The extra segments contribute to the subsonic traffic and airport integration acceptability of the Javelin because an extra cruise and a loitering segment are included. These extra segments should be performed sparingly and with discretion because overall passenger efficiency with these segments becomes 2.6 pax-mile/lb_{fuel}.

Table 3. RDS mission segment breakdown with emergency segment maneuvers

Mission Segment	Wi/Wo	Total Fuel Burn	CL average	CD average	L/D average	SFC average
Warm up	.9985	372.0	n/a	n/a	n/a	0.966
Takeoff	.9928	1752.6	0.620	0.0125	8.90	0.640
Climb 1	.9725	6667.9	0.249	0.0221	11.2	0.771
Climb 2	.9510	11886.8	0.128	0.0124	10.3	0.925
Supercruise	.5764	102810.3	0.091	0.0120	7.65	1.02
Descent	.5706	104209.3	0.089	0.0150	8.27	0.851
Climb	.5638	105867.7	0.082	0.0096	8.59	0.797
Cruise	.5519	108761.1	0.097	0.0104	9.29	1.18
Loiter	.5127	118266.4	0.075	0.0092	8.14	1.19
Descent	.5076	119510.8	0.089	0.0150	8.27	0.85
Landing	.5051	120126.8	0.582	0.0768	4.52	0.75

Loitering was not part of the original mission because it would not meet the required passenger efficiency demanded in the NASA RFP. However, with 68 passengers and a 4000 nautical mile total range, an aircraft-passenger efficiency of 3.00 is attained with a fuel burn of 104,209 lbs after the first descent, thus meeting the required efficiency.

Specific fuel consumption is also illustrated in the mission analysis and demonstrates the fuel requirements needed for each segment. With emergency and loitering segments, the average *sfc* during flight is 0.9046 lb/lb/hr and without extra mission requirements, average *sfc* is reduced to a promising 0.8461 lb/lb/hr. The Javelin operates at an average supersonic *sfc* of 1.021 lb/lb/hr and an average subsonic *sfc* of 0.893 lb/lb/hr including the extra mission segments, and 0.817 lb/lb/hr without extra segments. The liquid methane fueled duct burner testifies to the lower *sfc* of the modified P&W F-119-based engines used on the Javelin.

During supercruise, the Javelin manages an average C_L of 0.0914 and C_D of 0.012 yielding an average *L/D* of 7.65. A subsonic *L/D* of 11.2 is attainable as indicated in the table. These values correspond well to feasible designs and represent realistic *L/D* ratios. The reroute segment considerations also help to integrate the Javelin with subsonic air traffic at airports.

AIRPORT INTEGRATION

Functions of an airport are associated with: 1) aircraft landing, servicing, and take-off, 2) arrival, unloading or loading, and dispatch of surface vehicles, and 3) the receipt, processing, transfer-in-transit, and dispatch of passenger and cargo traffic [68]. These functions are critical to the success of the Javelin SST airport integration and a receiving airport must provide air access, aircraft servicing via surface vehicle accessibility, passenger processing and handling, accessibility to airport users, and social tolerance.

In an interview with Jon Mathiasen [69], CEO of the Richmond International Airport (RIC), it was concluded that a supersonic transport would have little difficulty integrating into airport infrastructure as long as the aircraft would not require advanced fueling stations or special services. The major impact of new aircraft on airports is passenger accommodation and the baseline Javelin SST carries 68 passengers, thus not presenting heavy requirements on airport passenger accommodation due to the low number of passengers carried relative to modern transonic airliners.

The Javelin SST is further integrated in airport operations by incorporating the ability to loiter during extra mission segments. Loitering permits the Javelin to blend itself into subsonic traffic if necessary, but this will reduce aircraft passenger efficiency below the RFP requirement and should only be used when needed and avoided at all other times. Assuming the Javelin SST is regularly scheduled to land in Dulles International Airport in Washington, D.C., the added 90 nmi cruise segment permits the aircraft to land in Richmond if necessary. The Javelin can land in Richmond because it has a balanced field length of 6,742 ft, less than the 9,000 ft runways at RIC.

One of the most significant issues in planning for arrivals of supersonic transport is the establishment of the "priority of location" for ground functions [70]. This is essentially a ground crew issue involving minimizing ground time, establishing an economic parking situation, and developing flexible facilities. The RIC airport was selected as a reroute because they recently upgraded their infrastructure to reflect these principles, noted in the RIC Master Plan for future development [69]. Dulles International is already suitable for the Javelin SST because the Concorde can land there.

Figure 31 attained from the RIC Master Plan indicates that society's need for large regional jets will continue to increase by 1-3% annually over the next 20 years. It should be noted that small regional jets with less than 50 seats currently dominate the RIC airport market, but will steadily decline over the next two decades. The Javelin SST with 68 seats is a necessary stepping stone towards larger aircraft such as small/medium bodied jets that will have a larger market percentage than large regional jets. Thus the Javelin would be marketable to large and small airports in the future.

Passenger Aircraft Category	2007	2011	2016	2021	2026
Turboprops	2%	0%	0%	0%	0%
Small Regional Jets (<= 50 Seats)	60%	57%	48%	41%	34%
Large Regional Jets (> 50 Seats, <=100 Seats)	17%	20%	22%	24%	25%
Small/Medium Narrowbodies (> 100 Seats, <=150 Seats)	20%	22%	28%	32%	37%
Large Narrowbodies (> 150 Seats, <=200 Seats)	1%	1%	2%	2%	3%
Small/Medium Widebodies (>= 200 Seats)	0.0%	0.0%	0.5%	0.5%	1.0%
Total	100%	100%	100%	100%	100%

Figure 31. RIC Airport Master Plan Results for Future Percentages of Aircraft Types [69]

The market demand is also a deciding social factor in airport integration. Figure 32 displays the cost effective take-off gross weight for a given planform area for cargo and passenger cabin densities, also known as a Czysz-Vandenkerckhove parametric approach [71]. The Javelin fits well with the passenger cabin density trend which indicates it should be profitable.

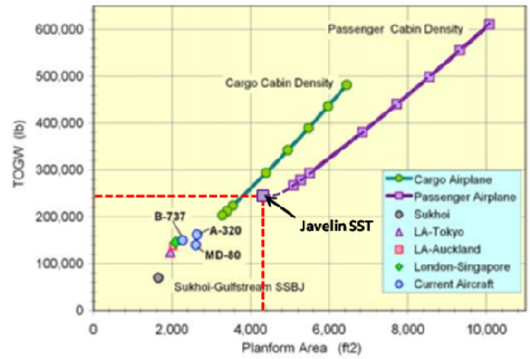


Figure 32. Planform Area vs. TOGW Based on Czysz-Vandenkerckhove Parametric Approach [71]

Another social problem is airport noise and Figure 33 illustrates the problem in areas surrounding the Richmond International Airport [69]. As the aircraft climbs and departs from the airport, noise levels diminish but any location within the 65 decibel DNL contour is significant sound to the surrounding citizens.

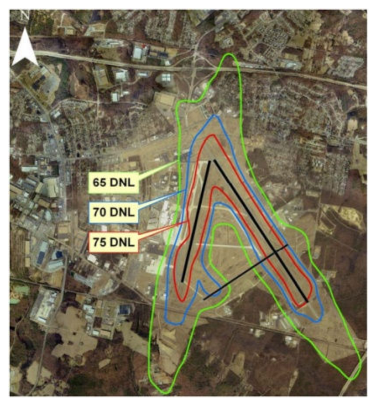


Figure 33: Airport Noise Levels at RIC Airport [69]

The Javelin SST attempts to curtail airport takeoff noise with the use of an inverted velocity profile achieved by the duct burner and co-annular nozzle. Engine noise suppressors, such as the variable vanes in the exhaust bypass stream, reduce the convective Mach number of instability waves that produce intense downward sound radiation [72]. The Javelin incorporates this technology to effectively reduce takeoff and landing noise levels.

With the novel combination of conventional considerations and advanced technology described in this report, the Javelin SST is a versatile solution that can be globally marketed to both large airport hubs and smaller, medium sized airports. The Javelin SST is summarized on the next page.

SUMMARY / OVERVIEW

The VT Javelin SST concept has been presented as a solution to the 2008-2009 NASA RFP. The conceptual ideology was based on research concerning sonic boom and low drag minimization techniques with respect to aircraft design. The Javelin concept is a high efficiency, low-boom, dual alternatively fueled, non-afterburning supersonic transport carrying 68 passengers 4,000 nmi. A summary of the key ideas and features of the Javelin are presented here.

The Low Drag/Boom Compromise

The Javelin represents a low drag design with low boom features incorporated early in the design phase. Low drag characteristics of the Javelin are aimed at achieving a payload efficiency of 3 pax-mile/lb_{fuel} imposed by the NASA RFP. The staggered double fuselages, low-sweep laminar flow lifting canard, and duct-burning engines increase the overall efficiency of this design. The low boom features that were incorporated in the Javelin SST concept minimize the sonic boom by increasing effective length, lowering maximum weight, and shaping the shocks for minimum overpressure and decreased N-wave gradients. The Javelin SST includes Quiet-Spike-like aft and bow spikes to tailor the pressure rise time and shapes the front and rear shockwaves. A low sweep laminar flow canard acts to provide nose bluntness to reduce the maximum overpressure [73] while decreasing main wing area and acting as an all moving pitch control surface. The reduced weight from the implementation of dual fuselages is complimented by the cranked delta wing that acts as both a drag saving and boom reducing technology.

Double Fuselage Ideology

The double fuselage configuration is the heart of the Javelin ideology. As noted above, the double fuselage configuration increases structural rigidity and efficiency while reducing weight. The total length of the aircraft is increased by asymmetrically staggering the fuselages for decreased wave drag, simultaneously increasing the sonic boom rise time and fineness ratio. The double fuselage also provides additional storage volume for cryogenic fuels such as liquid methane and hydrogen which are considerably less dense than standard JP fuel. Finally, the double fuselage configuration functions as the key enabling technology combining low weight, decreased drag, and increased effective length into a single synergistic solution for solving the boom/drag paradox.

Low Aspect Ratio LBCD Wing

The Javelin establishes a low boom cranked delta wing with low aspect ratio as the optimal shape to compliment the asymmetric double fuselage technology. The wing airfoil is derived from optimized data of a low-boom study about biconvex delta wing airfoils. The Javelin SST wing also takes advantage of the simple structural arrangement of the cranked delta wing planform, reducing aircraft structural weight while providing higher wing volume for fuel storage. The aspect ratio of the cranked delta wing causes better low-speed performance than a clean delta wing and creates ground effects, enabling high-lift during takeoff and landing. The low-boom biconvex airfoil shape also adds an effective low-boom feature to the wing design.

Duct-Burning VSCE Turbofan

The P&W F-119 advanced two-spool turbofan, the current engine of the F-22 was selected as the base propulsion engine for the Javelin concept. It is proposed that this engine be modified by removing the afterburner section and adding a burner located in the bypass duct of the engine. The duct burner is to be complimented by a co-annular exit nozzle to combine reduced emissions at cruise with lower noise during takeoff. The conversion to a duct burning turbofan offers the benefits of distributed propulsion because the throttle settings of the duct burner and core burner are varied independently, allowing for better operation in all flight regimes. The addition of the burner, complimented by the co-annular nozzle, allows for an inverted velocity profile known to reduce takeoff noise. Ignition of fuel in the bypass duct acts as an augmentation process to provide the necessary high thrust for takeoff without afterburning. Burning two different fuels in two separate burners and adding cryogenic methane as a heat sink effectively lowers the operating temperature of the engine. This lessens the amount of nitrogen disassociating and forming NO_x during combustion.

Fischer-Tropsch and Liquid Methane Alternative Fuels

Alternative fuels were investigated and Fischer-Tropsch synthetic kerosene and liquid methane are the candidates for an alternatively fueled second generation supersonic transport. Studies suggest Fischer Tropsch kerosene fuel will be more widely produced in the IOC 2020 N+2 time frame. The synthetic kerosene is proposed to power the core of the VSCE engine described in the previous paragraph while the cryogenic liquid methane is proposed to serve as a heat sink for the core. The cryogenic methane decreases the engine operating temperature before it is ignited in the duct burner. The implementation of cryogenic methane is proposed as the necessary precursor to the successful use of liquid hydrogen.

Airport Integration

The Javelin SST passenger requirement fits well with current airport traffic since it carries considerably less passengers than modern transonic aircraft and does not impose difficult changes in passenger accommodation. Also, the Javelin SST concept accounts for loiter and reroute cruise segments in the design, making it more flexible to coordinate with air traffic control. Lastly, the VTSST concept can operate at major and medium-traffic airport hubs that have the infrastructure required to manage supersonic ground functions. Dulles International and Richmond International are two examples of airports capable of handling and accommodating an aircraft of this size.

CRITIQUE/WEAKNESSES

The Javelin SST is not an optimized solution, but consists of a novel combination of ideas to fulfill the NASA RFP. The required initial operational capability by 2020 was a heavy constraint imposed on the design solution. To be initially capable of operation within a decade, several factors were incorporated into the Javelin SST to provide a realistically achievable design. The most significant of these design features was the decision to implement a double-fuselage configuration. The twin fuselage solution represents a well understood semi-conventional platform for an advanced design. A duct burning turbofan was selected for its low level of variable geometry components relative to other advanced engine systems. In the Javelin SST, variable geometry was limited to the rear telescoping spike, conventional variable ramp intakes located at the inlet of the nacelles, and the co-annular flow exit nozzle. A variable sweep wing was not adopted because of the required extra weight and complexity. Although these considerations were incorporated into the Javelin, several important issues remain. Concerns of the feasibility and effectiveness of the Javelin SST are bulleted in this section.

- By no measure is the Javelin a "small" supersonic airliner as requested by the NASA RFP. The wing of the Javelin is bigger than the Concorde's wing by 335 square feet, and the length is 79 ft longer. The Javelin, with 68 passengers, is on the upper level of the predefined acceptable payload-fuel spectrum. A smaller solution to the NASA RFP that carries fewer passengers but meets the required efficiency could exist.

- The maximum wing loading of the Javelin is just above 60 psf, which is considerably lower than the Concorde and Tu-144. Low wing loading aircraft are known to be very expensive, difficult to manufacture, and susceptible to gust response issues.

- Drag savings created by favorable interference are based on idealized calculations presented by Nielsen regarding two Sears-Haack bodies. In reality, the presence of the wing will alter the flow between the two fuselages and could decrease the amount of drag saved.

- The use of a cranked delta wing, while saving considerable weight, requires the wing planform to have a low-aspect ratio. An increase in aspect ratio or span of an aircraft is well known to increase aerodynamic efficiency. However, aspect ratio is not the only determinant of aerodynamic efficiency and it is believed that sufficient aerodynamic performance can be achieved by a low-aspect ratio cranked delta wing.

- Detailed structural analysis was not explicitly performed for this configuration. However, double-fuselage configurations are proven to increase structural rigidity and strength while lowering component weights.

- Stability and control considerations of the asymmetric design have not been addressed. Asymmetric staggering of dual fuselages presents lateral-directional stability and control challenges. This could possibly be resolved by the addition of vertical control surfaces such as XB-70-like folding wing tips, but would introduce more variable geometry, complexity, and weight.

- Currently the area distribution of the Javelin SST requires further tailoring to produce a smoother continuous curve so that the combined area due to vehicle volume and lift may be further analyzed and better matched to the equivalent area distribution required by the Seebass-Darden method.

- Because the equivalent area distribution of the Javelin probably differs from the equivalent area distribution predicted by the Seebass-Darden method, the sonic boom was not modeled. Therefore, uncertainty regarding the Javelin's sonic boom signature exists, though the concept has incorporated several low boom features.

- The engines in this report were modeled after a two-spool turbofan burning standard fuel and do not reflect the proposed use of methane in the duct burner. Further analysis with commercial software is required to determine correct engine properties. The performance of a variable stream control engine has not been explicitly modeled and therefore the exact performance of the engine is unknown though it is expected to be a legitimate option for an efficient supercruise engine based on previous research conducted at Pratt and Whitney.

- Infrastructure required for liquid methane is not currently available at the major airports of the world. This presents a fundamental obstacle in achieving the successful implementation of liquid methane and hydrogen as an alternative fuel.

- Necessary fuel reserves have been incorporated into the Javelin so the aircraft can divert to an alternate destination within 90 nmi and/or loiter for thirty minutes. If the aircraft is diverting because of adverse weather conditions, the weather will most likely be unacceptable at the alternate airport. Loiter fuel must be used to cruise at subsonic speeds to a farther airport.

- The required fuel systems for liquid methane have been assumed to be achievable. More research should be conducted to ensure the necessary fuel systems and storage tanks can be added to the aircraft without exceeding the design weight.

- The Javelin SST does not feature a drooped nose like the first generation supersonic transports and could create problems concerning pilot visibility. This could be resolved through the use of synthetic vision systems as proposed by the 1990s HSCT program [9].

- The VTSST utilizes three of the four fundamental methods to minimize sonic boom: increasing length, decreasing weight, and shockwave shaping. The fourth method, active flow control, could be achieved by using engine exhaust to add heat to the flow therefore artificially increasing aircraft length.

CONCLUSIONS / SUGGESTIONS

Based on the research and design behind the VTSST Javelin concept presented in this report, the following conclusions are drawn:

- With current technology, an efficiency of 3 pax-mile/lb_{fuel} for the VTSST may only be achieved by significantly reducing the max gross takeoff weight to 242,886 lbs with a required fuel weight of 123,739 lbs, relative to the original design point of 283,000 lbs with a fuel weight of 146,000 lbs.

- The required reduction in weight necessary for efficient supersonic flight may be achieved by utilizing key weight saving features in the double fuselage configuration with a cranked delta. The combined configuration offers a reduction in max gross takeoff weight of about 20% relative to conventional designs.

- The double fuselage configuration is a feasible option that offers the benefit of reduced weight, reduced drag, and decreased volume. These benefits are considered critical characteristics of a successful supersonic transport.

- Asymmetric staggering of the dual fuselages reduces wave drag by harnessing favorable interference while simultaneously increasing length and decreasing sonic boom intensity.

- Low takeoff noise and cruise emissions are achieved by the use of a dual fueled duct burning turbofan with co-annular nozzle.

- Staggered, 1-abreast seating inside slender fuselages illustrated in the CAD figures offers reductions in cabin cross-sectional area while distributing the cabin volume longitudinally, thus increasing the fineness ratio and providing ample legroom and comfort for passengers.

- Fischer-Tropsch synthetic fuel and liquid methane are the fuels for powering a second generation N+2 SST.

- Duct burning turbofan offers a unique engine to produce high takeoff thrusts by igniting fuel in the bypass duct. This process is similar to, but distinctly quieter than afterburning.

- A duct burning turbofan also offers a unique system for dual alternative fuel use. Standard or synthetic kerosene fuel powers the engine core while cryogenic fuels are augmented in the bypass duct burner and serve as a heat sink.

Based on conclusions presented above and the critique of the Javelin concept on the previous page, the following recommendations for further research and study are suggested to NASA:

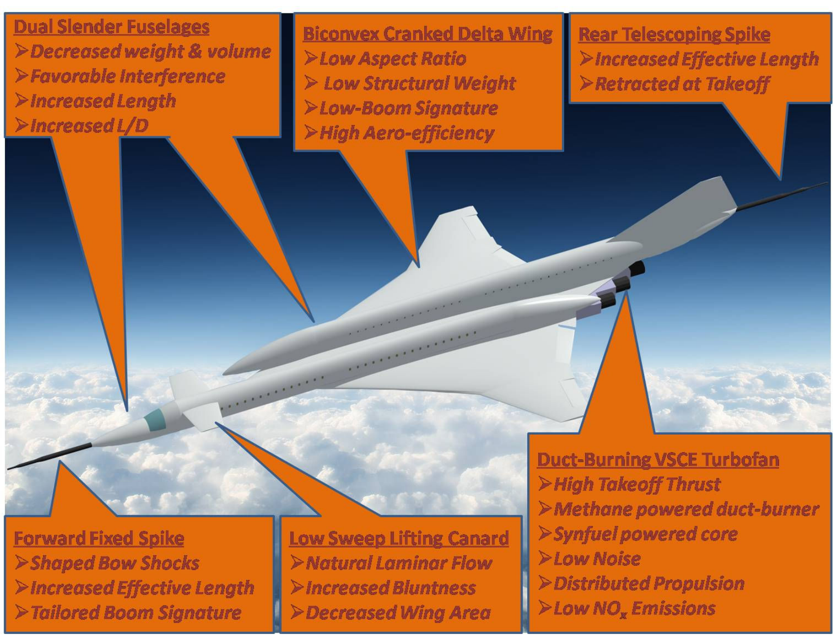
- Research should be conducted to further assess the potential of a double fuselage configuration with cranked delta wing to reduce weight as a key enabling technology for supersonic flight.

- The theoretical and experimental studies presented by Nielsen [45] and Friedmann [51] should be revisited with renewed interest in reducing wave drag for a multi bodied second generation supersonic transport.

- A method should be established to analytically model the performance of a duct burning turbofan.

- Research should be conducted to determine what is required to successfully establish the infrastructure for implementing liquid methane as an alternative fuel at major airports.

- NASA optimization tools and methods should be applied to further investigate the potential of a Javelin-like conceptual aircraft.



CAD Figure F. Summary of Javelin Technology Innovation

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