

## PRELIMINARY DESIGN OF NINE HIGH SPEED CIVIL TRANSPORTS

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### Abstract

Sixty senior design students at Cal Poly, SLO have completed a year-long project to design the next generation of High Speed Civil Transports (HSCT).

The design process was divided up into three distinct phases. The first third of the project was devoted entirely to research into the special problems associated with an HSCT. These included economic viability, airport compatibility, high speed aerodynamics, sonic boom minimization, environmental impact, and structures and materials. The result of this research was the development of nine separate Requests for Proposal (RFP) that outlined reasonable yet challenging design criteria for the aircraft. All were designed to be technically feasible in the year 2015.

The next phase of the project divided the sixty students into nine design groups. Each group, with its own RFP, completed a Class I preliminary design of an HSCT. The nine configurations varied from conventional double deltas to variable geometry wings to a pivoting oblique wing design.

The final phase of the project included a more detailed Class II sizing as well as performance and stability and control analysis.

Cal Poly, San Luis Obispo presents nine unique solutions to the same problem: that of designing an economically viable, environmentally acceptable, safe and comfortable supersonic transport.

### Introduction

Progress in aviation feeds on itself, with each new triumph a stepping stone for the next. For example, it is

the dawn of the commercial airline industry that has truly connected vast continents, and indeed, the world. From this, international tourism and business have flourished, and the demand on the air transport industry is growing.<sup>1</sup>

Global air traffic is estimated to continue to grow at an annual rate of 3.6% well into the next century. This would mean an increase from approximately 986 million passengers today, to about 2,086 million in 2010, generating approximately 2.5 billion revenue-passenger-mile per year. Even more encouraging is that all market areas are charted for healthy growth, especially the Pacific market. It is regions such as this where the need for a supersonic transport (SST) will be felt most acutely.<sup>2</sup>

This demand is driven largely by international business, an area where the time wasted on seemingly endless transcontinental flights is far more costly than airfare itself. Several contemporary studies have shown that whether on vacation or non-business trips, most people would certainly pay a premium to cut this time in half.<sup>2,3</sup> A supersonic commercial transport is ideally suited to this task.

The first and only currently operational supersonic commercial transport was a British and French collaborated aircraft named the Concorde. This Mach 2.2 aircraft entered service in 1974 to a storm of environmental protests. Sonic boom prevented overland supersonic flight, and the noise from the Rolls-Royce Olympus engines gained the Concorde the reputation of being a noisy airplane. For this reason, the Concorde was banned from most airports around the world.<sup>4</sup>

Although it was a revolutionary airplane for its time, only fourteen Concorde airplanes were built. For this reason, the cost per airplane skyrocketed, causing the airframer to lose money. Concorde was limited to first-class only, driving the cost up to \$0.76 per passenger mile

(1974 U.S.D), a 38% increase over current subsonic first class fare. In addition, unexpectedly high fuel costs coupled with the fact that the Concorde was not fuel-efficient drove the cost up further.<sup>5</sup>

Over the past twenty years, many designs for supersonic transports have been evaluated and discarded. Only in the past few years, with NASA sponsoring different programs,<sup>5</sup> has interest in the HSCT been rekindled. With many lessons learned from the Concorde's mistakes, it is believed that a next generation HSCT is imminent. Cal Poly, San Luis Obispo would like to present nine unique solutions to this challenge. Table 1 presents the range of Mach numbers, passenger capability, and ranges for the nine designs.

Table 1 Nine design solutions

	Mach	# Passengers	Range (nm)
OPUS 0-001	2.2	60	4,800
Stingray	2.4	250	4,800
Swift	2.5	250	5,700
TBD <sup>3</sup>	3.0	270	4,800
Phoenix	2.5	152	5,150
MM-122	2.2	250	5,200
The Trojan	2.0	250	5,200
RTJ-303	1.6	300	4,700
The Edge	2.4	294	5,250

**Special Problems in HSCT Design**

There are several areas that pose unique challenges for the designer of an HSCT. The first set of these challenges can be categorized as environmental challenges. These include noise from takeoff and landing, sonic boom considerations, and NOx emissions. Figure 1 shows the areas of concern for takeoff and landing noise. Currently, aircraft must meet stringent FAR 36 Stage 3 noise requirements, and there is indication that a more restrictive Stage 4 requirement is on the horizon. A successful HSCT must make every effort to minimize sideline and takeoff noise. While all nine Cal Poly designs selected engines that do meet Stage 3, it was

concluded by all teams that a supersonic transport could not meet Stage 4 requirements in the near future.

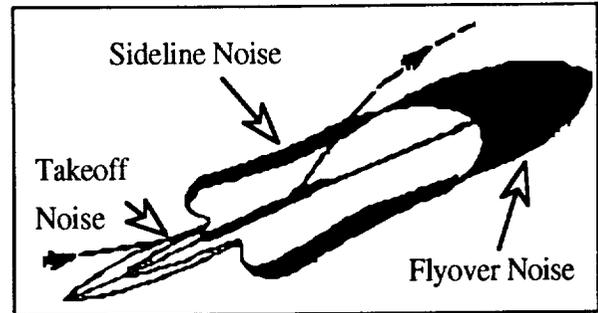


Fig. 1 Typical areas of sideline and takeoff noise

Sonic boom is an obvious concern when dealing with an aircraft that travels faster than the speed of sound. The sonic boom can be characterized by the N-wave shape shown in Figure 2. The effects of a sonic boom can be minimized in two ways: reduce the actual magnitude of the overpressure of the wave or delay the rise time of the shock. This is achieved by extensive aerodynamic tailoring of the aircraft. A long, slender aircraft minimizes sonic boom. Unfortunately, this introduces conflicts in internal volume, manufacturability, aerodynamic efficiency, and airport compatibility. In light of these compromises, it was concluded by all nine design teams that overland supersonic flight was not a feasible goal at this time.

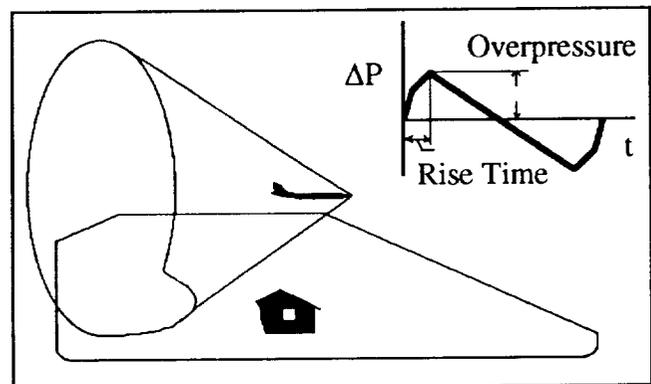


Fig. 2 Sonic boom and N-wave characterization

Aircraft exhaust contains emissions of nitrous oxide that destroy the earth's fragile ozone layer. This ozone layer is found at altitudes of 60,000 to 90,000 feet. Unfortunately, the ideal traveling altitude for a supersonic transport is 55,000 to 85,000 feet. Therefore, every effort was made to reduce engine emissions of nitrous oxide.

The next set of challenges are the technical issues. These include aerodynamics, engine analysis, and physical restraints necessary for airport compatibility. The first of the aerodynamic concerns is the dual flight regimes characteristic of supersonic transports. The aircraft must be optimized for both subsonic and supersonic flight. Often this requires contradictory solutions for optimum performance in each of the two regimes. For example, for subsonic flight, a high aspect ratio wing is ideal. For supersonic flight, however, a low aspect ratio wing provides the most efficient performance. The aircraft designer must make careful tradeoffs to end up with an aircraft that performs well in both regimes.

At supersonic speeds, wave drag becomes a primary concern. This drag, caused by pushing an object through the air at speeds greater than Mach 1, can be minimized by careful area ruling of the fuselage. This introduces restrictions on internal volume. The design challenge lies in optimizing passenger comfort in the form of internal volume, while obtaining maximum aerodynamic efficiency through area ruling.

As an aircraft transitions between subsonic and supersonic flight, the aerodynamic center shifts aft. This can cause severe weight and balance, as well as stability problems, and must also be a design concern.

Finally, aerodynamic heating is of considerable concern. Energy from air molecules slowed down to zero velocity at stagnation points along the aircraft are transferred to the surface of the aircraft in the form of heat. Figure 3 shows the typical temperature distribution along a Mach 2.5 aircraft. These extensive temperatures introduce challenges in terms of material selection. Figure 4 shows the relative decrease in the strength of various materials as their temperature increases. Tradeoffs must be conducted in materials between strength, temperature, manufacturability, and cost.

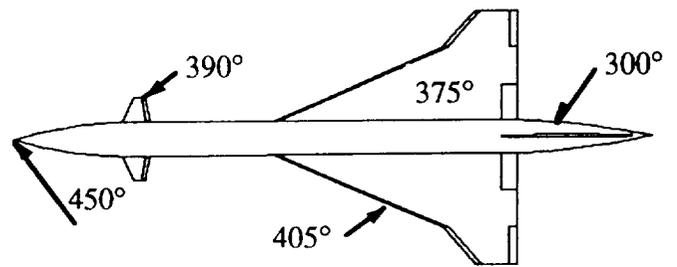


Fig. 3 Typical temperature (°F) distribution for a Mach 2.5 aircraft

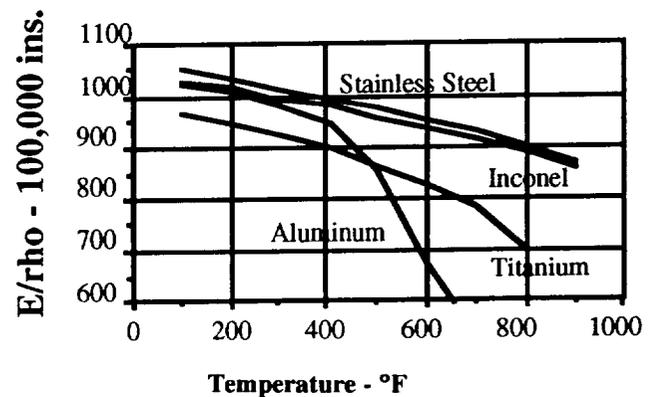


Figure 4- Effect of Temperature on Selected Materials

Propulsive improvements must be made in order for a next generation supersonic transport to be viable. Improvements must be made first and foremost in thrust specific fuel consumption (TSFC). In addition, the engines must be quieter, and produce less emissions, as discussed previously.

Finally, airport compatibility must be addressed. A supersonic transport that cannot operate out of existing airports and gates, or one that requires extensive special equipment, would not be a marketable product. Sheer size is the first concern. Figure 5 shows how an HSCT must fit into the box created by the largest aircraft operated today- the Boeing 747-400.

The Designs

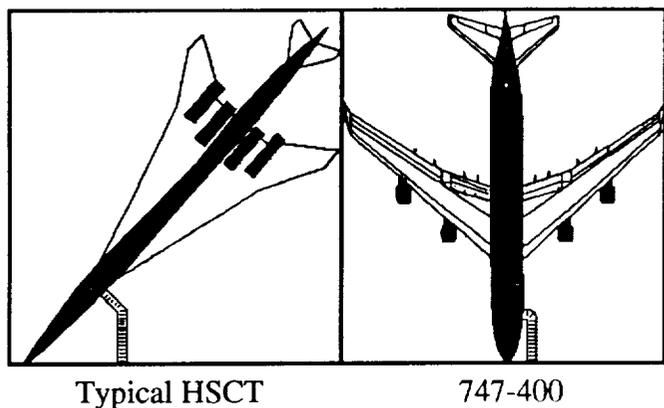


Figure 5- Comparison of size of HSCT to B-747 box

In addition to size, there are other airport compatibility requirements that must be met. It was assumed by all nine groups that extensive airport remodeling to permit an HSCT would not be acceptable. The airport compatibility requirements are found in Table 2. A landing speed of less than 200 knots is required so as to allow smaller aircraft to take off and land relatively quickly after an HSCT. The maximum field length of most major aircraft is 12,000 feet, so viable HSCT must reduce their takeoff and landing distances to this. Current gates can accommodate a sill height of only 17.6 feet, and finally, the pavement loading of the new aircraft must not be greater than that of a 747-400. Damaging the runway is not conducive to promoting an HSCT.

Table 2 Airport compatibility requirements

Landing speed	< 200 kts
Field length	< 12,000 ft
Gate height	< 17.6 ft
Pavement loading	<= 747-400
Fuels	Existing
Service equipments	Existing

With the above considerations in mind, brief summaries of the nine Cal Poly solutions are presented. While extensive Class I and II preliminary designs were performed, space limitations in this document prevent all but the briefest overview. For those interested in the more complete analysis, please feel free to contact the university for copies of individual reports.

Opus 0-001

Based on research into the technology and issues surrounding the design, development, and operation of a second generation High Speed Civil Transport, the Opus 0-001 ( Figure 6) team completed the preliminary design of a sixty passenger, three engine aircraft. The design of this aircraft was performed using a computer program which the team wrote. This program automatically computed the geometric, aerodynamic, and performance characteristics of an aircraft whose preliminary geometry was specified.

The Opus 0-001 aircraft was designed for a cruise Mach number of 2.2, a range of 4,700 nm and its design was based on current or very near term technology. Its small size was a consequence of an emphasis on a profitable, low cost program, capable of delivering tomorrow's passengers in style and comfort at prices that make it an attractive competitor to both current and future subsonic transport aircraft. Several hundred thousand cases of cruise Mach number, aircraft size and cost breakdown were investigated to obtain costs and revenues for which profit was calculated. The projected unit flyaway cost was \$92 million per aircraft.

Stingray

The Stingray (Figure 7) is the second-generation High Speed Civil designed for the 21st century. This aircraft is designed to be economically viable and environmentally sound transportation competitive in markets currently dominated by subsonic aircraft such as the Boeing 747 and upcoming McDonnell Douglas MD-12. With the Stingray coming into service in 2005, a ticket price of 21% over current subsonic airlines will cover operational costs with a 10% return on investment. The cost per aircraft

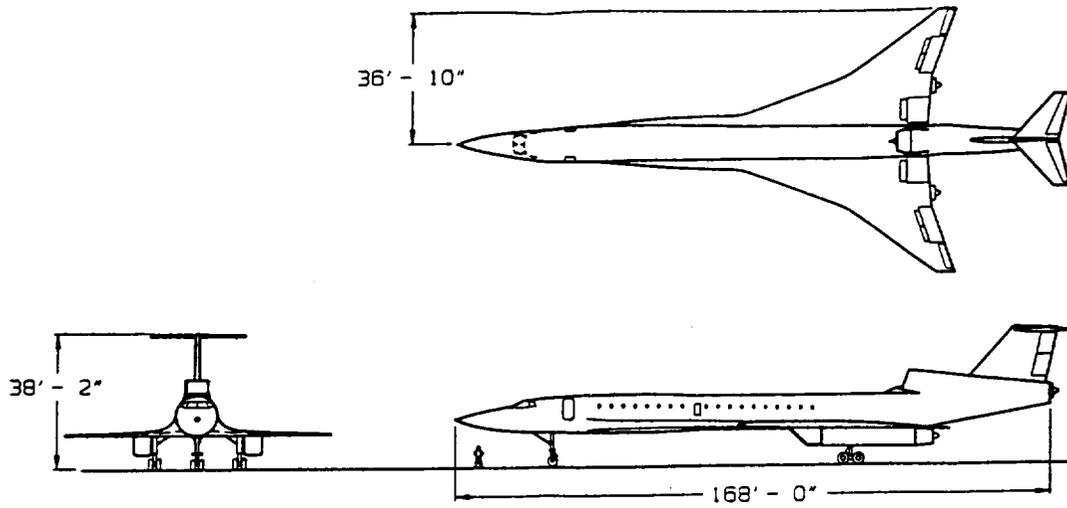


Fig. 6 Three-view of Opus 0-001

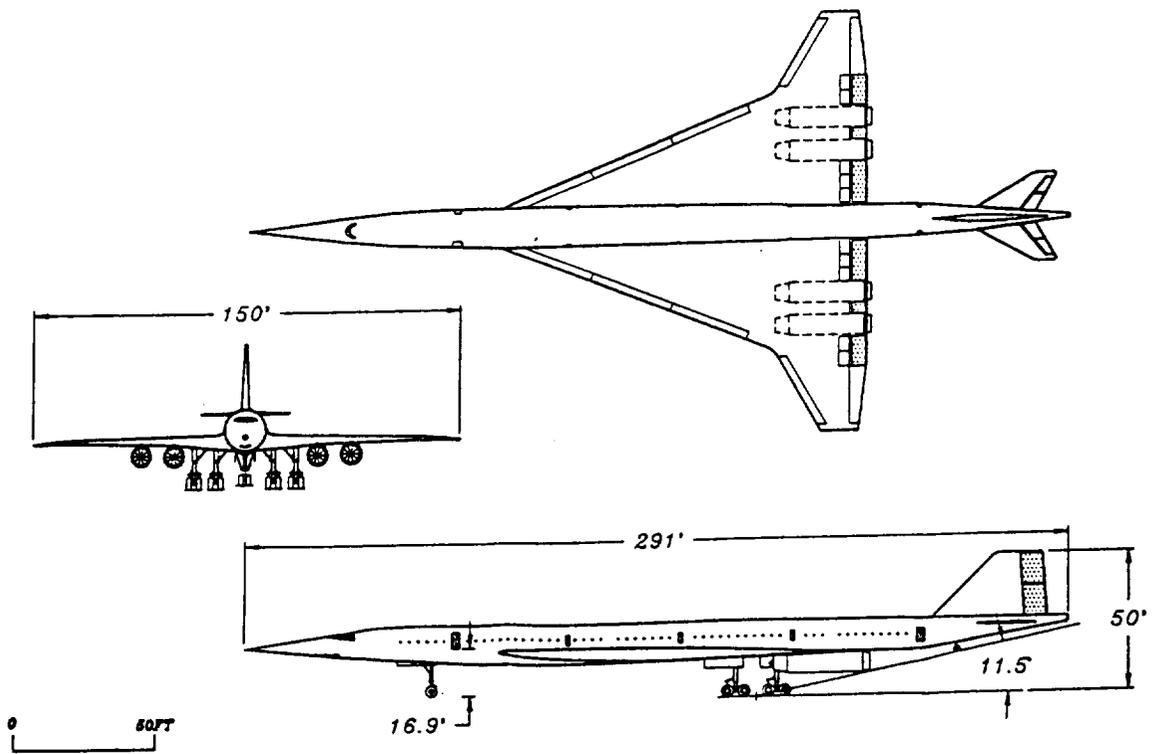


Fig. 7 Three-view of Stingray

will be \$202 million with the Direct Operating Cost equal to \$0.072 per mile per seat.

This aircraft has been designed to be a realistic aircraft that can be built within the next ten to fifteen years. There was only one main technological improvement factor used in this design, that being for the engine specific fuel consumption. The Stingray, therefore, does not rely on nonexistent technology.

The Stingray will be powered by four mixed flow turbofans that meet both nitrous oxide emissions and FAR 36 Stage III noise regulations. It will carry 250 passengers a distance of 5,200 nm at a speed of Mach 2.4. The shape of the Stingray, while optimized for supersonic flight, is compatible with all current airline facilities in airports around the world. As the demand for economical, high-speed flight increases, the Stingray will be ready and able to meet those demands

### Swift

Another solution to the HSCT problem is the Swift (Figure 8) aircraft design. This conventional double delta design is capable of a payload of 246 passengers in three classes. This size of aircraft requires a fleet size of 350 units with a 20% economy class fare increase based on a 50 % time savings, 80 % load factor and a 12 % Return on Investment (ROI). The class distribution is 5 % first, 34 % business, and 61 % coach. The aircraft is powered by four mixed flow turbofans that propel it at Mach 2.5.

The primary design goal of the Swift is simplicity. The aircraft was designed to be feasible using today's technology.

### TBD<sup>3</sup>

The TBD<sup>3</sup> (Figure 9), a 269-passenger, long-range civil transport, was designed to cruise at Mach 3.0 utilizing technology predicted to be available in 2005. Unlike other contemporary commercial airplane designs, the TBD<sup>3</sup> incorporates a variable geometry wing for optimum performance. This design characteristic enabled the TBD<sup>3</sup> to be efficient in both subsonic and supersonic flight. The TBD<sup>3</sup> was designed to be economically viable

for commercial airline purchase, be comfortable for passengers, and meet FAR Part 25 and the current FAR 36 Stage III noise requirements. The TBD<sup>3</sup> was designed to exhibit a long service life, maximize safety, be easy to maintain, as well as be fully compatible with all current high-traffic density airport facilities.

Several interior concerns were addressed in the design. The TBD<sup>3</sup> was equipped to accommodate the many needs of our passenger: first class, business, economy (coach). Specific market studies were analyzed so as to best fit our class breakdown to the projected market needs. In addition to interior concerns, external challenges were also addressed. The materials chosen for the TBD<sup>3</sup> allowed minimum weight penalties while maintaining the safety of high-speed flight. The most sensitive weight component was the swing wing mechanism and wing box which spans the fuselage. The structural design and materials were carefully analyzed to minimize the penalty for the swing wing option. With an aircraft this large, (considering specifically thrust power and weight) control surfaces would contribute heavily into the actual feasibility of the TBD<sup>3</sup>.

### Phoenix

The Phoenix is an aircraft that can succeed where the Concorde failed. It is a true second generation HSCT (Figure 10). The Phoenix can transport 152 people up to 5,150 miles at speeds of up to Mach 2.5 in luxurious comfort. Supersonic flight over land is still prohibited by the majority of countries around the world. The Phoenix will overcome this loss of flight paths by concentrating on the transoceanic routes. This will take full advantage of its supersonic speed. The Phoenix also has acceptable subsonic performance. This will enable it to successfully compete with subsonic aircraft on routes that are partially over land. Using its mixed flow turbofan engines, the Phoenix will meet the stringent FAR 36 Stage III noise requirements. This will allow it to land at airports the world over, further increasing its market share.

Two unique features of the Phoenix are its canard and its leading edge gates. The fully moveable canard helps to provide rotation at takeoff and trim in supersonic flight. The leading edge gates are deflected vertical to the leading edge, adding turbulence and thus strengthening the vortices over the wing, increasing lift. The Phoenix

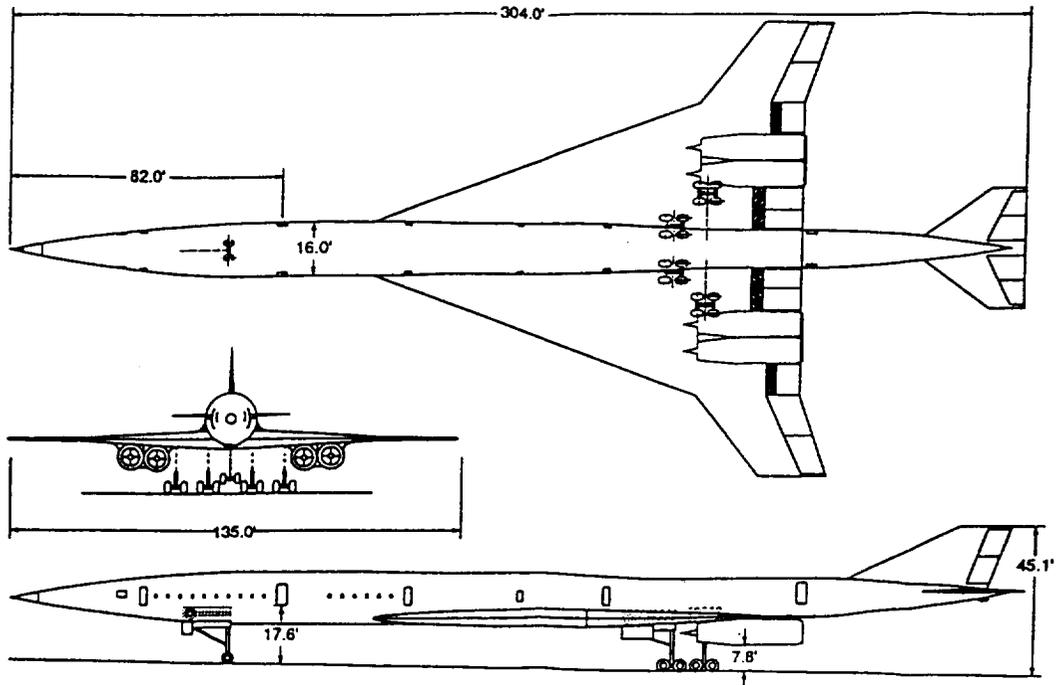


Fig. 8 Three-view of Swift

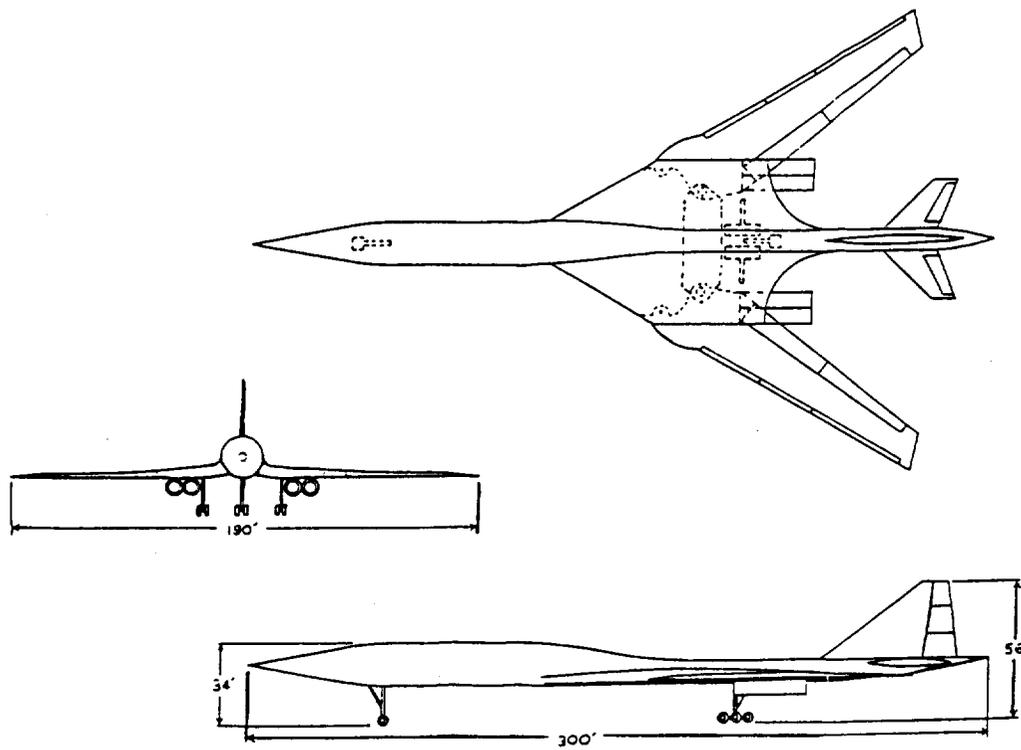


Fig. 9 Three-view of TBD<sup>3</sup>

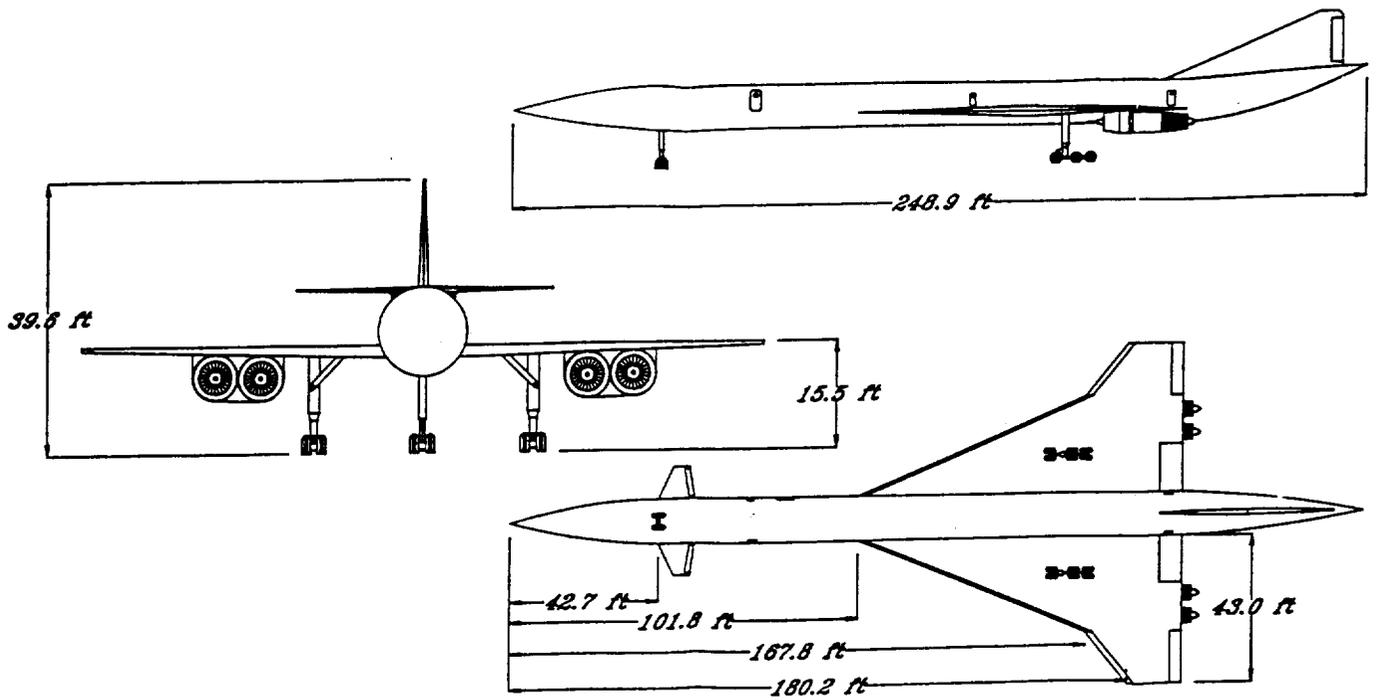


Fig. 10 Three-view of Phoenix

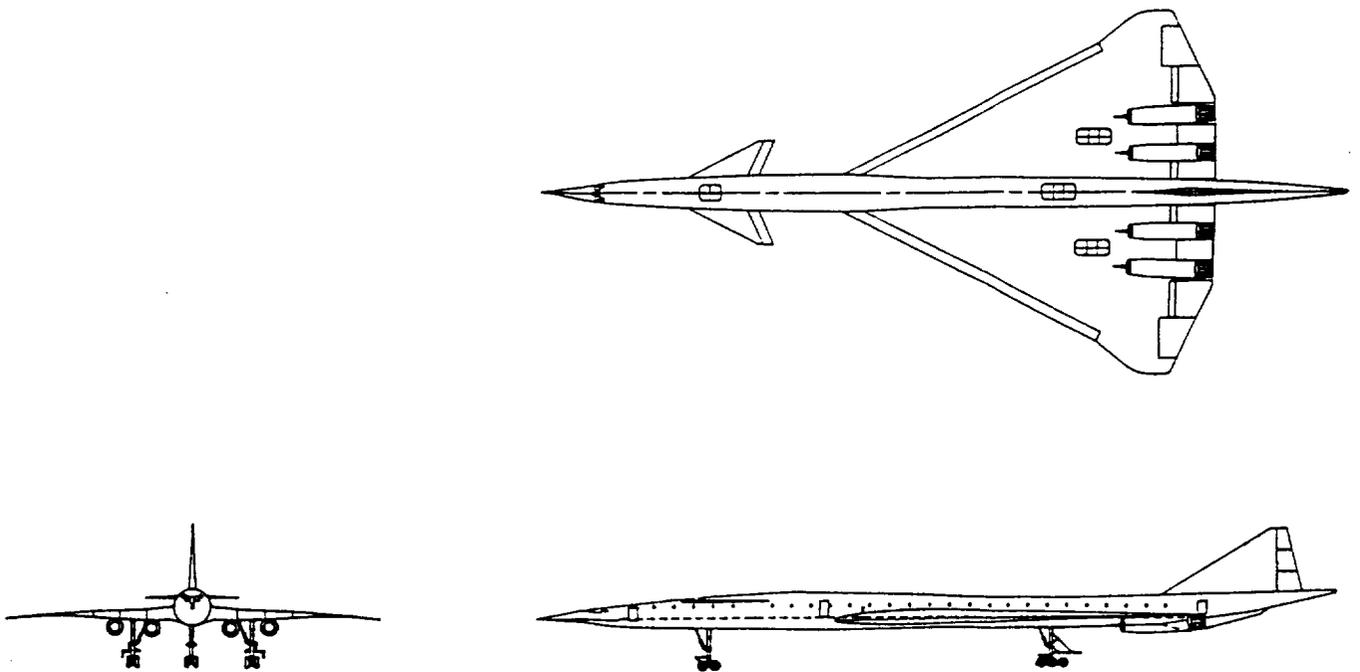


Fig. 11 Three-view of MM-122

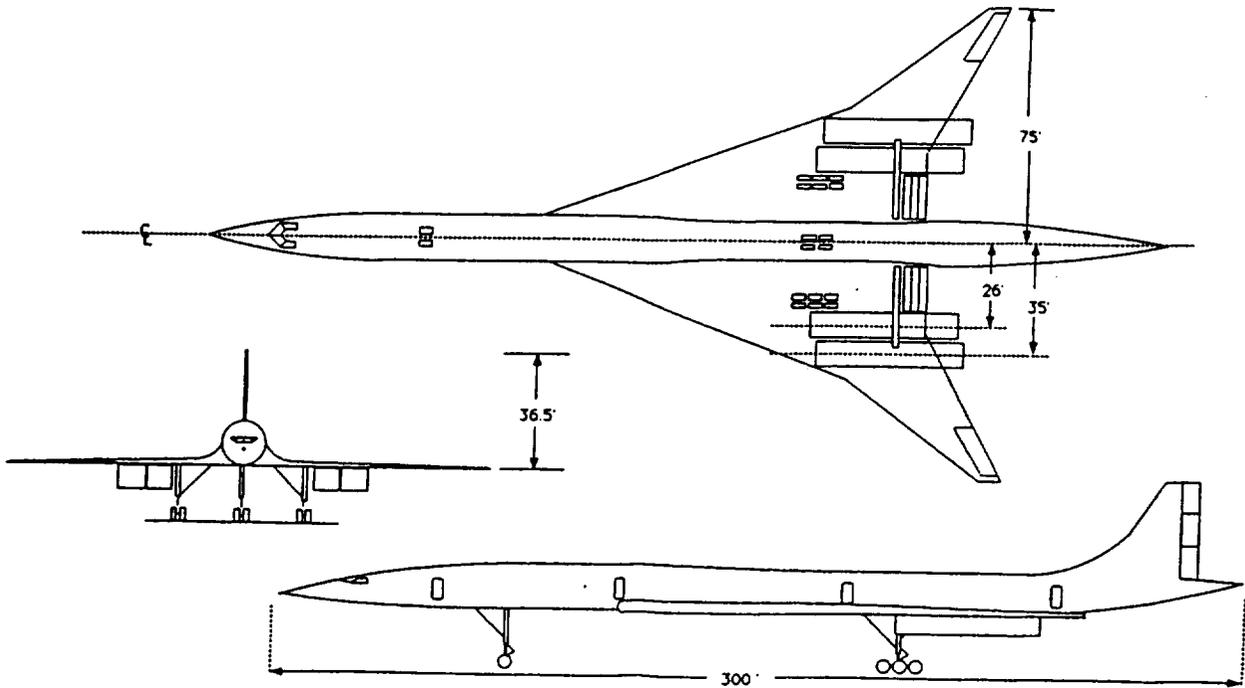


Fig. 12 Three-view of the Trojan

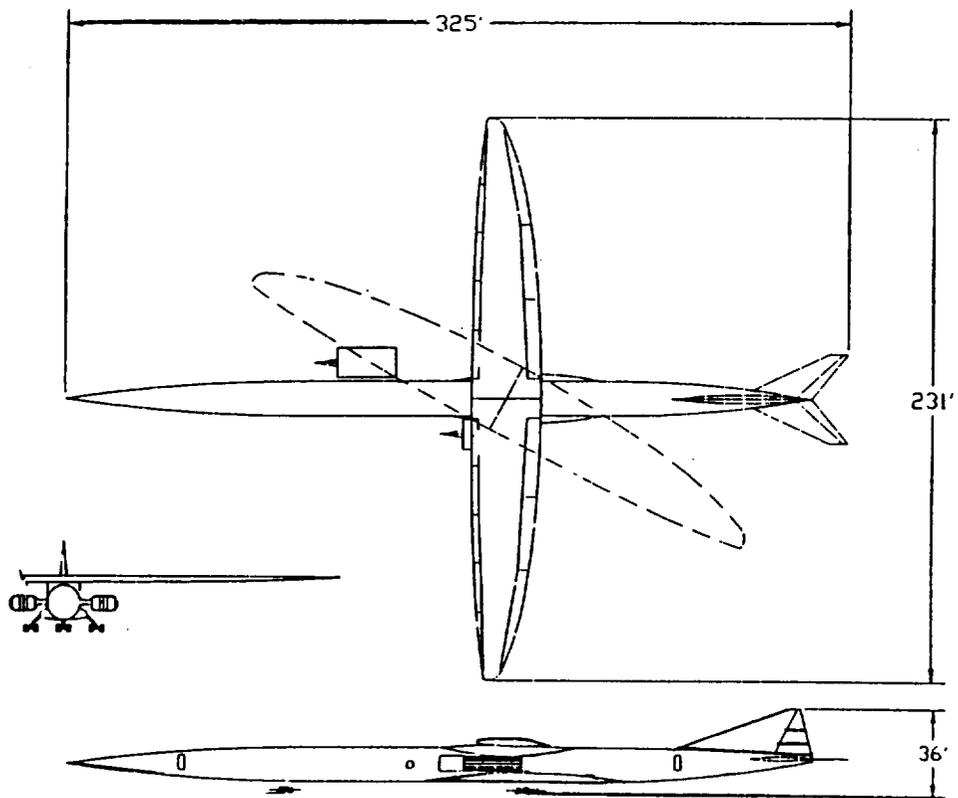


Fig. 13 Three-view of the RTJ-303

design strives to be a realistic solution to the supersonic transport problem.

### **MM-122**

The MM-122 is the answer to the international market desire for a state of the art, long range, high speed civil transport. It will carry 250 passengers a distance of 5,200 nm at over twice the speed of sound. The MM-122 (Figure 11) is designed to incorporate the latest technologies in the areas of control systems, propulsions, aerodynamics and materials.

The MM-122 will accomplish these goals using the following design parameters. First, a double delta wing planform with highly swept canards and an appropriately area-ruled fuselage will be incorporated to accomplish desired aerodynamic characteristics. Propulsion will be provided by four low bypass variable cycle turbofan engines. A quad-redundant fly-by-wire flight control system will be incorporated to provide appropriate static stability and Level I handling qualities. Finally, the latest in conventional metallic and modern composite materials will be used to provide desired weight and performance characteristics.

The MM-122, priced competitively at \$249 million, incorporates the latest in technology and cost minimization techniques to provide a viable solution to this future market potential.

### **The Trojan**

As the name suggests, the Trojan is a very safe and reliable supersonic aircraft (Figure 12). This high speed civil transport aircraft carries 250 passengers over 5,200 nm at a Mach of 2.0. Trojan incorporates unique features such as windowless cabin, low arrow-wing configuration, and no horizontal stabilizer. To be competitive, the Trojan has a unit price of \$200 million.

### **RTJ-303**

In recent years, designs for high speed civil transports have been studied for their feasibility in the commercial market. The oblique, variable sweep wing supersonic

transport configuration (Figure 13) was first proposed by Dr. R. T. Jones, former chief scientist of the NASA Ames Research Facility, who spent most of his life studying oblique aerodynamics. Studies of the oblique wing concept have shown substantially improved transonic performance at Mach numbers up to 1.4 and the elimination of sonic booms (audible at ground level) in flight at Mach numbers as high as Mach 1.2. Also predicted is an increase in low-speed performance, as well as the potential for increased range and/or reduced takeoff weight for a given payload. Further, a reduction of airport and takeoff noise to well within current standards is expected. Data for this rather unique type of configuration is limited, but enough research has been done to demonstrate some of the clear advantages of this type of aircraft. Although no supersonic flight test data has been obtained to date, supersonic wind-tunnel data has been obtained by NASA for Mach numbers up to 1.4 with wing sweep angles up to 60 degrees. Subsonic flight tests have been conducted by NASA using a remotely piloted aircraft and a low-cost piloted vehicle known as the AD-1.

The final payload of 300 passengers was a compromise between length restrictions on the aircraft weighted against the desire to remain competitive in the market with the maximum number of passengers carried for each flight. The range of 4,700 nm was decided upon to include Los Angeles to Tokyo in the city pairs to the Pacific Rim. Three hundred nautical miles are given in addition to this range to account for reserves and a flight to an alternate airport. This resulted in an aircraft sized for a range of 5,000 nm.

### **The Edge**

As the intercontinental business and tourism volumes continue their rapid expansion, the need to reduce travel times becomes increasingly acute. The Edge Supersonic Transport Aircraft (Figure 14) is designed to meet this demand by the year 2015. With a maximum range of 5,750 nm, a payload of 294 passengers and a cruising speed of Mach 2.4, the Edge will cut current international flight durations in half, while maintaining competitive first class, business class, and economy class comfort levels. Moreover, this transport will render a minimal impact upon the environment, and will meet all Federal Aviation Administration Part 36, Stage III noise requirements.

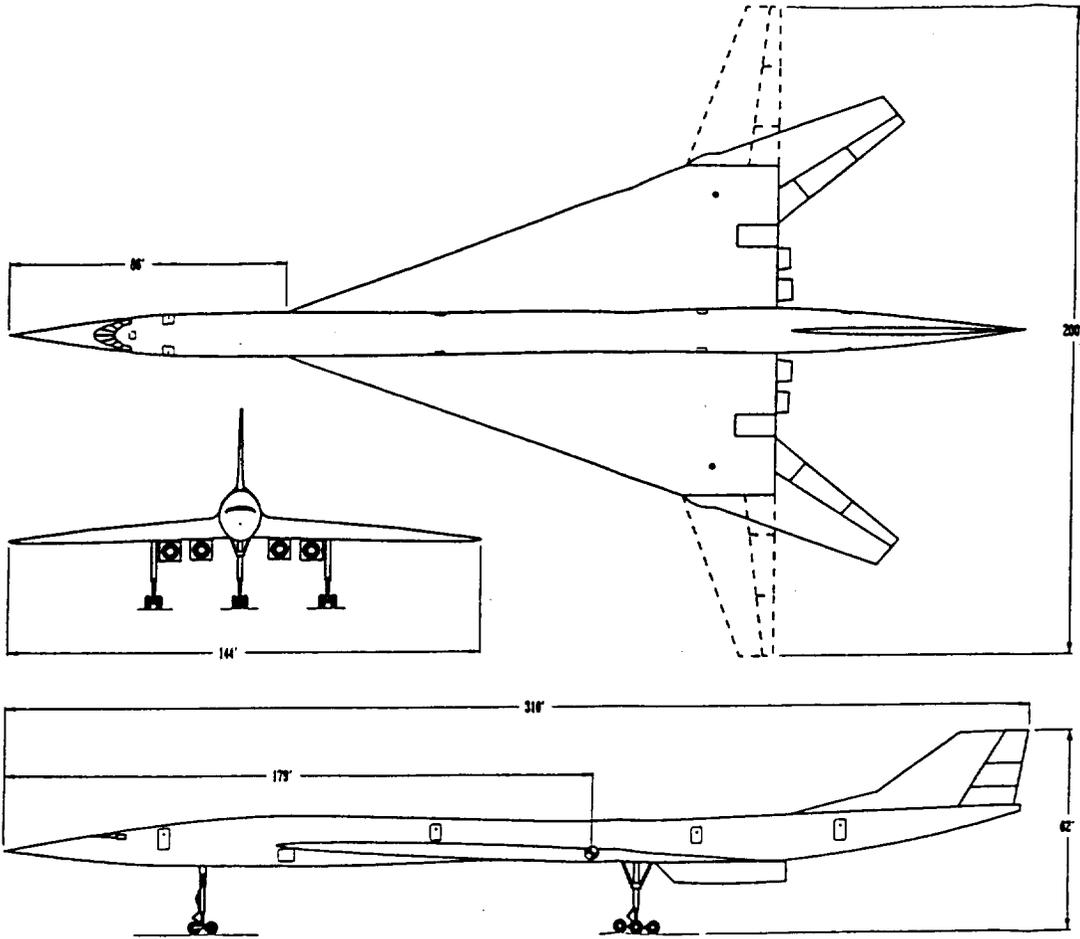


Fig. 14 Three-view of the Edge

The cornerstone of the Edge's superior flight performance is its aerodynamically efficient, dual-configuration design incorporating variable-geometry wingtips. This arrangement combines the benefits of a high aspect ratio wing at takeoff and low cruising speeds with the high performance of an arrow-wing in supersonic cruise. And while the structural weight concerns relating to swinging wingtips are substantial, the Edge looks to ever-advancing material technologies to further increase its viability.

Heeding well the lessons of the past, the Edge design holds economic feasibility as its primary focus. Therefore, in addition to its inherently superior aerodynamic performance, the Edge uses a lightweight, largely windowless configuration, relying on a synthetic vision system for outside viewing by both pilot and passengers. Additionally, a fly-by-light flight control system is incorporated to address aircraft supersonic cruise instability.

The Edge will be produced at an estimated volume of 400 aircraft and will be offered to airlines in 2015 at \$167 million per transport (1992 dollars).

### Conclusions

The nine aircraft design teams at Cal Poly, San Luis Obispo have examined a wide variety of solutions to the High Speed Civil Transport problem. These solutions vary from conservative, realistic approaches, such as double delta wing planforms and the use of conventional materials, to more exotic designs, such as variable planform geometry, application of advanced materials, the selection of canards, and even an oblique wing design. Both Class I and Class II preliminary design analysis were performed on all nine resulting aircraft.

Cal Poly has shown, in these analyses, that a second generation High Speed Civil Transport is technically, environmentally, and economically viable. This viability is strongly dependent on continued advances in the following key areas: improved thrust-specific fuel consumption coupled with a decrease in nitrous oxide emissions, aerodynamic tailoring through increased use of analysis tools such as computational fluid dynamics (CFD) and the use of more advanced materials capable of meeting high strength, high temperatures, and lowered

structural weight requirements. With these advancements on the horizon, the time has come for the second age of supersonic travel - the High Speed Civil Transports.

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