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Aircraft Integrated Design and Analysis - A Classroom Experience

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AAE 451 is the capstone course required of all senior undergraduates in the School of Aeronautics and Astronautics at Purdue University. During the past year the first steps of a long evolutionary process were taken to change the content and expectations of this course. These changes are the result of the availability of advanced computational capabilities and sophisticated electronic media availability at Purdue. This presentation will describe both the long range objectives and this year's experience using the High Speed Commercial Transport design, the AIAA Long Duration Aircraft design and an RPV design proposal as project objectives. The central goal of these efforts is to provide a user-friendly, computer-software-based, environment to supplement traditional design course methodology. The Purdue University Computer Center (PUCC), the Engineering Computer Network (ECN) and stand-alone PC's are being used for this development. This year's accomplishments center primarily on aerodynamics software obtained from NASA/Langley and its integration into the classroom. Word processor capability for oral and written work and computer graphics were also blended into the course. A total of 10 HSCT designs were generated, ranging from twin-fuselage aircraft, forward swept wing aircraft to the more traditional delta and double-delta wing aircraft. Four Long Duration Aircraft designs were submitted, together with one RPV design tailored for photographic surveillance.

Supporting these activities were three video satellite lectures beamed from NASA/Langley to Purdue. These lectures covered diverse areas such as an overview of HSCT design, supersonic aircraft stability and control and optimization of aircraft performance. Plans for next year's effort will be reviewed, including dedicated computer work station utilization, remote satellite lectures and university/industrial cooperative efforts.

Design Education at Purdue

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Basic data for the School of Aeronautics and Astronautics

During the 1987-88 School term the senior level design course, AAE 451, was divided into two groups, each with its own instructor. Enrollment in the Aeronautics Section totalled 76 while 60 were enrolled in the Astronautics section. Groups are organized into 5-6 person teams with responsibilities for

Aerodynamics

Propulsion

Structures and materials

Performance

Dynamics and control

Economics

Project participation for 1987-88 consisted of 10 teams working independently on HSCT, 4 teams working on the AIAA Long Duration Aircraft and 1 team working on an RPV design for photographic missions. This report describes activity in AAE 451 during the past academic year.

Organization of classwork and schedule

The semester is 15 weeks long with an additional week of time for final exams. Final reports are due the first day of the last week of class. Oral presentations are given during the last week of class after the written reports have been submitted. These presentations are limited to one hour for each group with about 30 minutes allotted after the presentation for questions from the audience. All faculty members are invited to these presentations.

Formal lectures are presented during the first five weeks of class. These lectures focus both on philosophical issues that have not been emphasized in the classes before this time and on the subject of aircraft performance.

Performance and the associated aerodynamic terminology and propulsion overview are very important to discuss since no formal course in Aircraft Performance exists in our present curriculum.

Students are assigned written work that outlines the history of their specialty area and its relation to their particular project. In this paper they are asked to discuss issues that they are likely to face during their work during the semester and to review the compromises and conflicts that they are likely to face. This forces them to commit to paper at an early stage of the design their thoughts and ideas.

Oral presentations by the students begin about 6 weeks into the semester. The class meets on Tuesday mornings from 8:30 to 11:20 a.m. and on Tuesdays and Thursdays from 2:30 to 3:20 p.m. During the Tuesday morning session each group must have one member present an overview, complete with overhead viewgraphs, of a certain area of their project.

We begin these overviews with weight estimation using historical, statistical data of the type found in Professor Roskam's books. In addition, the tradeoffs between wing loading and thrust-to-weight ratio for take-off and cruise are examined, together with the interaction between wing loading, field length and aerodynamic characteristics for landing and take-off. The aerodynamics specialist presents an initial planform design and discusses his reasons for choosing it.

Stability and control is next in order of presentation. This person is responsible for the initial sizing of control surfaces based upon the initial weight estimate and the planform design.

Performance is next in order of reporting. The first step is to define the fuel necessary to satisfy the range requirements, based upon initial research by the propulsion specialist and the data available from aerodynamics investigation.

The engine data is next presented and discussed together with its impact upon the performance and range.

The weight data for the updated aircraft is then presented, together with a discussion of the materials and structural forms necessary for construction of the design. Significant problems are reviewed, such as heating or cg shifts during operation.

The economics issues are then outlined to focus on the primary issue, that is, making money for the company.

Design updates are given each week, no matter who is speaking, as part of the regular presentation. These updates primarily focus on weights updates from the computer code used to generate our weights data.

Computer code utilization.

Students are required to research their design to the fullest extent possible. This includes use of empirical relationships such as are found in the literature and use of computer codes that are available on the Engineering Computer Network (ECN) and also available on the small PC's located in our fledgling design laboratory.

Aerodynamic investigations are enhanced by the use of the **Vortex Lattice Method code (VLM) that currently runs on the CYBER 205 computer. This code also furnishes valuable data for stability investigations. Aerodynamic studies also use the Supersonic Wave Drag program obtained from NASA/Langley and a skin friction drag and a supersonic L/D program also obtained from Langley.**

Performance studies have used, in the subsonic regime, a small code written for the IBM PC and similar compatible machines. The FLOPS code for flight optimization and performance was used in a preliminary way during the Spring semester. This latter code is highly sophisticated and as a result somewhat awesome and difficult to use.

Structural analysis codes are now being investigated to bring capabilities on-line that are similar to those in the aerodynamics and performance area.

Computer utilization for the design class

The availability and accessibility of main-frame computers, work stations and personal computers has begun to revolutionize the teaching profession. Because of the ability to simulate the behavior of so many physical systems and processes, the computer is an ideal supplement to the classroom and reading. The computer can literally teach students "what they don't tell you in textbooks" and effectively give students hands on experience of the type that they previously had to wait years to get. The other side of this opportunity is a potential problem. If the computer is not used wisely the student may become overloaded. This will cause him to short circuit to the extent that he uses the computer as a crutch, not a tool.

The computer is particularly effective when used for creating documentation and figures. The ease of use and the exceptional quality that can be obtained for minimal effort and cost make this a revolutionary tool, quite apart from its number crunching prowess.

The efforts during the coming year will **focus on further integration of the computer into the design process.** The course will be used as a laboratory to try to organize tasks in an efficient manner and to create data bases that can be updated rapidly. In particular, the concept of creating design sensitivity information and organizing this information in different ways will be explored. During the next year we plan to acquire several new small PC's to supplement our existing capabilities. We will also be able to make use of the growing number of Sun Workstations within the department. Current remodelling of our building will allow use to create a new, dedicated design room where our PC's, design video tapes and design reference material will be located. We will continue to acquire design material from our industrial affiliates.

Satellite Video Transmission Activities.

During the past academic year, we have pioneered the use of live video transmissions that originate from NASA Langley Research Center. Three programs were presented from Langley: Mr. Corneilius Driver - An Overview of SST Design; Mr. Leroy Spearman - Supersonic Stability and Control; and, Mr. L. Arnold McCullers - An Overview of the FLOPS Flight Optimization and Performance analysis code. These programs were taped for future use in the design course. We are currently reviewing future speakers for next Fall semester. These video lectures are supplemented by visitors to Purdue during the semester.

Summary of HSCT Design Efforts

Ten groups of students participated in the HSCT design effort during the academic year 1987-88. These efforts were greatly aided by **Ms. Vicki Johnson of NASA Langley Research Center**. The present discussion will confine itself to summarizing significant details of this work.

The Request For Proposal or RFP for this project was generated by the Advanced Vehicle Concepts Branch at Langley, in consultation with Purdue University personnel. The RFP (reproduced in the Appendix to this report) requests a design that will fly a 6500 nautical mile mission carrying between 250 and 300 passengers and travel at a cruise Mach number chosen to be somewhere between Mach 2 and Mach 6. The aircraft must be able to operate from a conventional airport infrastructure and be "economical to operate." The anticipated introduction time for this aircraft is in the year 2010.

The requirement that the aircraft operate within the existing aircraft infrastructure is a primary driver of the design, as was indicated by all the design efforts. The reluctance to choose exotic fuels led to a selection of a turbojet propulsion unit and conventional JP-X category fuels. In addition, the fact that heating effects accelerate with increasing Mach number led to the choice of Mach numbers of near Mach 3 in all cases.

During the first semester, there were numerous problems encountered because of the inability to obtain reliable and detailed engine data for this class of aircraft. This led to trouble in meeting the range operational requirements and a number of associated difficulties. These difficulties definitely proved the wisdom of the old adage that the "engine is the heart of the aircraft."

Engine data difficulties led to take-off power problems as well as excessive fuel consumption problems and the associated range difficulties. By the beginning of the second semester, these problems have been overcome to a great extent, by the arrival at Purdue of "rubber engine" data from Langley. This greatly eased the burden and increased the confidence of the engine people. In addition, most groups during the second semester had little difficulty achieving the 6500 nautical mile range requirement.

Most of the designs proposed during the two semesters carried passengers in the 260-290 passenger range. Most made extensive use of NASA wing planform data, and all foresaw the need for titanium, heat-resistant structures, with some utilization of advanced composites. A copious amount of reference material and an extensive bibliography had been collected by the course Teaching Assistant, Jeff Layton, during his time at Langley during the Summer of 1987. During the second semester, four seniors who had taken the course the previous Fall were enlisted to assist the new class. This assistance proved extremely helpful and pitfalls were avoided, even though new obstacles were encountered.

One group broke new ground and investigated an unconventional dual fuselage design. This design showed a great deal of potential as far as carrying large numbers of passengers and fuel was concerned. The significant issue with this aircraft is the distance between the two fuselages and the structural connection between them so as to ensure structural integrity and to minimize flexing between the two sections.

Center of gravity placements was also a significant issue faced by the design groups. The problems created by cg placement and travel were two. First of all, because the aircraft operates both subsonically and supersonically, there is an aerodynamic center shift with respect to the cg when the aircraft goes supersonic. This shift is rearward and creates a large static margin which tends to make the aircraft difficult to trim. To ameliorate this difficulty, fuel sequencing was used in the supersonic flight regime to attempt to control the cg position. In the subsonic flight regime the reverse is true. There is little that can be done in managing the cg position of an aircraft bloated with fuel.

Let's examine some specific data generated by these groups to understand some of the difficulties and possibilities afforded by HSCT design. First we will examine one of the better designs generated by a group during the Fall semester. This design was dubbed "The Wave" by its creators, a six man group with responsibilities as outlined previously.

The Wave

As with the other three design teams who considered HSCT design during the Fall semester, the Wave group faced the problem of learning about the design process, while at the same time attempting to master the intricacies of the computer codes that had been newly acquired for this course. Their design, shown in various views in Figures 1,2 and 3 was an over-under engine arrangement with an arrow wing much like the proposed

Lockheed design. The length of the aircraft measures 220 feet long, while the tip-to-tip span is 95 feet. Wing area of 6530 square feet and a take-off gross weight of 559,000 lbs. provide a take-off wing loading of 86 psf. The take-off thrust-to-weight ratio can be as high as 0.39.

The primary problem encountered by this group and others to follow was that the operational range is very sensitive to the lift-to-drag ratio achieved at supersonic speeds. The desire to use conventional fuels and a turbojet engine led the group to choose Mach 2.8 as their cruise speed. At this speed and an altitude of 65,000 feet, the maximum trimmed L/D attained was computed to be 5.8. This fact, coupled with the overland sonic boom problem, led the group to plan for and to achieve a 5500 nm. range of the type suitable for Los Angeles-Tokyo routes.

A fairly extensive economic analysis was attempted by a **Wave** group member. Two seating configurations were proposed. One configuration had a total of 312 coach sets, while the other had 182 Business Class seats and only 98 Coach seats. The second configuration was preferred for marketing reasons. The cost of the aircraft was estimated to be about 180 million dollars and unless 500 could be sold, it was unlikely ever to return all its costs unless there was some form of subsidy. It was concluded that the efficiency of the HSCT was its own worst enemy. High speed makes it more productive. As a result, fewer aircraft are needed. However, fuel requirements at high speed make the aircraft expensive to operate and very sensitive to the price of fuel.

Some problems that came back to haunt the Wave group were fairly typical of those encountered by all the groups. The desire to fit the aircraft within the existing infrastructure of major International airports led the groups to place constraints on aircraft length and width. These constraints precluded achieving the necessary slenderness to develop high supersonic L/D values. In addition, inattentiveness to c.g. placement at the earliest possible time led to difficulties integrating the landing gear into the design. As a result, all aircraft from the Fall semester had characteristic long, storklike landing gear arrangements to satisfy tipover and ground clearance requirements as well as being able to rotate at take-off. Some designs, because of the take-off rotation requirement, sprouted large canard surfaces to satisfy this requirement and then paid the price in cruise performance.

Spring Semester - The Stork

During the Spring semester, the 6 new groups considering the HSCT design problem had the benefit of the experience of the preceding semester's activities. Some groups chose to ignore certain of these lessons, for reasons unknown, and repeated certain judgmental errors. Two features of the Spring semester designs stood out. The first was the variety of different designs. One design even considered the possibility of a dual fuselage configuration. The second feature that was apparent on the Spring semester designs was the improvement of supersonic L/D performance. This improvement was due to the fact that the best aerodynamicists from the Fall semester had been retained as paid consultants (undergraduate teaching assistants). As a result, the students learned how to use computer codes more rapidly and then were able to try things like fuselage cambering and wing cambering to raise the value of L/D.

Where values of supersonic trimmed L/D were of the order of 6 for designs submitted during Fall semester, these values rose to between 7 and 8.2 during the Spring. Much more attention was paid to c.g. placement and control and to trade-offs between take-off requirements and cruise. An additional factor that made the design process a bit easier and more efficient during the Spring was the availability of "rubber engines" from NASA/Langley. This data made it much easier to reliably size the powerplant and to integrate it with the airframe for take-off and cruise.

Figures 4,5 and 6 show the dual fuselage design proposed by a group who dubbed this design "The Stork." This design was designed to operate at Mach 3 and cruise at an altitude of 60,000 feet. Its maximum L/D was computed to be 8.2 and was the result of optimizing the distance between the two fuselages. One potential problem with this design is excessive flexibility that might allow significant relative movement between the two sections in flight. The group tried to answer this by blending the wing structure and fuselage in such a way as to create significant stiffness between the two.

"The Stork", has a relatively low wing-loading of 68 psf. with a wing area of 9504 square feet. It has the capability to fly efficiently overland at subsonic speeds and can be used on long range routes such as New York-Tokyo. The range is estimated to be 6500 nm. and it can carry a passenger load of 400 passengers. Its length of 226 feet and width of 138 ft. make it suitable for conventional airport operation. In addition, the thrust-to-weight ratio at take-off is about 0.18, making it a low noise aircraft. Curiously, the design team member assigned to do the economic analysis was skeptical of the commercial viability of this or any other supersonic transport design.

Spartacus

Next in order of consideration for effectiveness was a design known as Spartacus. This design, shown on Figures 7 and 8, was the product of a 6 member team, who, interestingly, were all participants in the Purdue co-op program. The Spartacus design weighs 625,000 lbs. at take-off and uses a thrust-to-weight ratio of 0.43, a fact that will be noticeable to the passengers. The use of the FLOPS code showed that the time to climb to 65,000 ft. was 26 minutes and that, at a cruise Mach number of 2.8, the cruise leg of its operation took 4 hours and 10 minutes.

Most noticeable in the Spartacus design is the presence of a large horizontal tail surface for control of the aircraft. The group argues that this is beneficial, particularly at take-off, for rotation. The wing loading is 95 psf. and the aircraft has a range of 6500 nm. due to a supersonic L/D of 7.7. It is projected that the aircraft can seat between 258 and 312 passengers, depending upon the arrangement chosen.

The Hawk

The Hawk design, shown in Figures 9 and 10 uses the NASA AST-205 design as a baseline design. This design seats 276 passengers and utilizes wing and fuselage camber to achieve a maximum supersonic L/D of 6.70 at Mach 3, its chosen operating airspeed at 65,000 feet. This aircraft weighs 561,000 lbs. and has a take-off wing loading of 69 psf. with a take-off thrust-to-weight ratio of 0.32. As with the other Spring semester designs, the NASA ASTM3-1A engine was chosen as a powerplant.

Mercury Mark II

The Mercury Mark II design began the semester as a long, flying fuel tank that more resembled a missile than an aircraft. Once the group began analyzing their design a bit more carefully, the wings became larger and the fuselage shorter, while the cruise airspeed came down. This design, shown in Figure 11, uses a variable sweep feature to overcome the compromises required between low speed landing and supersonic flight, as well as the requirement for overland flight. Passenger capacity is 272 passengers with a range of 6500 nm. Design team members recognized that the variable sweep feature could have a weight penalty associated with it, as well as the requirement that fuel management becomes intricate because of wing sweep configuration changes during flight. The group did not do as detailed an analysis as was done by others in the aerodynamic area. As a result, they achieved only a supersonic L/D of 6.9. However, the aircraft is configured to carry so much fuel that the range requirements were met.

The Dolphin

The Dolphin team used an over-under engine arrangement similar to that used by the Wave design team. The Dolphin design, depicted in Figure 12, weighed in at 520,000 lb. This team claimed the ability to carry 300 passengers a distance of 6500 nm. and cruise at 65,000 feet. Wing loading at take-off was 81 psf. and it was claimed that the total trip time was of the order of 5 hours.

Swallow

The group designing the Swallow HSCT created the design shown in Figures 13 and 14. This design will cruise at Mach 2.7 at 60,000 ft. and is projected to carry 24 First Class passengers and 240 passengers in Coach. This aircraft is somewhat longer than others in that it measures 292 ft. in length, with a wing span of 110 ft. Curiously, the range of this aircraft is on 5545 nm. The design employs a fixed arrow wing with a cambered circular fuselage. The wing loading at take-off is 102 psf. The aerodynamicist did a credible job of achieving a supersonic L/D of 8. This aircraft was one of the heavier designs, coming in at 705,000 lbs. In related matters, this design group made maximum use of computer generated figures and text, primarily from the MacIntosh PC's.

Conclusion

The past two semesters of design effort have revealed a number of areas of improvement over past years and some areas of continuing difficulty. Because of the varied interests of Faculty members and the quick pace of the semester, coupled with continuing high enrollments, there is not a great interest in the design mission in universities. Purdue is no exception. Few faculty members attend the final student presentations. Few are available to provide consultation and guidance in aeronautically oriented endeavors. This is unlikely to change in the future.

One bit of assistance in overcoming this lack of faculty resources and interest has been to use guest speakers from industrial organizations, either in person or on video tape. Purdue University is fortunate to have excellent facilities and studios to make this happen. The positive results of this effort have been previously illustrated.

A second deficiency that must be attended to in the future is the continuing low quality of communication skills of our students. The potential for excellence is there, but it has not been developed. In short, the students do not know how much trouble they are in. At Purdue we have tried to address this shortcoming by requiring frequent written and oral reports. This has worked very well. The most glaring deficiency is in the area of written communication skills. Although mastery of this area is a lifelong endeavor, now is the time to begin. Simply put, if requirements are not precisely stated in black and white, it will not be done. This is particularly true in the area of final reports. At the beginning of the Spring semester we all had a good laugh at how engineering seniors did not know that pages in a report should be numbered or that an index should be part of a report. At the end of the semester, all groups committed one or more sins related to this subject.

The solution to this problem is not something to be achieved overnight. However, next year we will require that all reports be prepared using the Word 3.02 software or its equivalent. This software has extensive capabilities, including pagination, table of contents preparation and ease of editing.

Computational software remains a problem. We need more user friendly codes and an executive code to organize the data base generated. Since the emphasis is on conflict and compromise, we must be able to guide the student in generating sensitivity information and then utilizing it in an efficient manner.

In summary, the design area in industry has undergone substantial change during the past few years. University courses must begin to reflect the results of some of these changes, while still retaining the original design education mission that it has fulfilled so well. To do this we need financial and moral support of the kind only the outside world can provide.

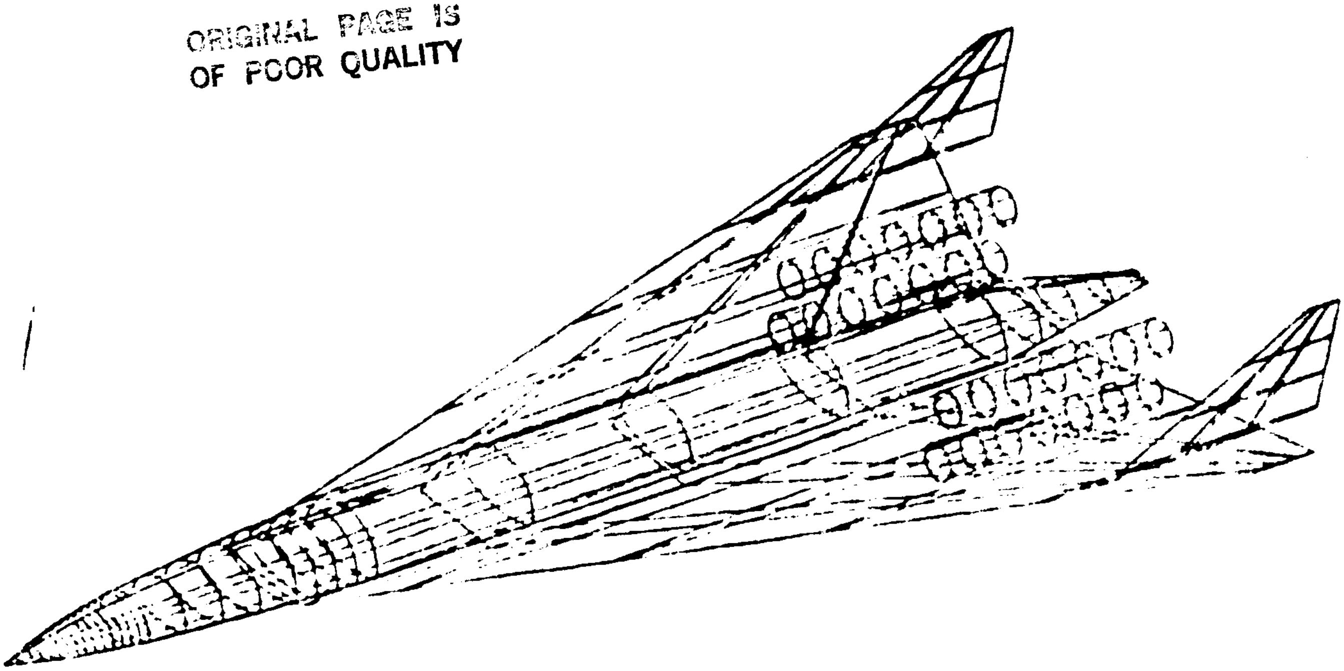


Figure 1 - The Wave Configuration

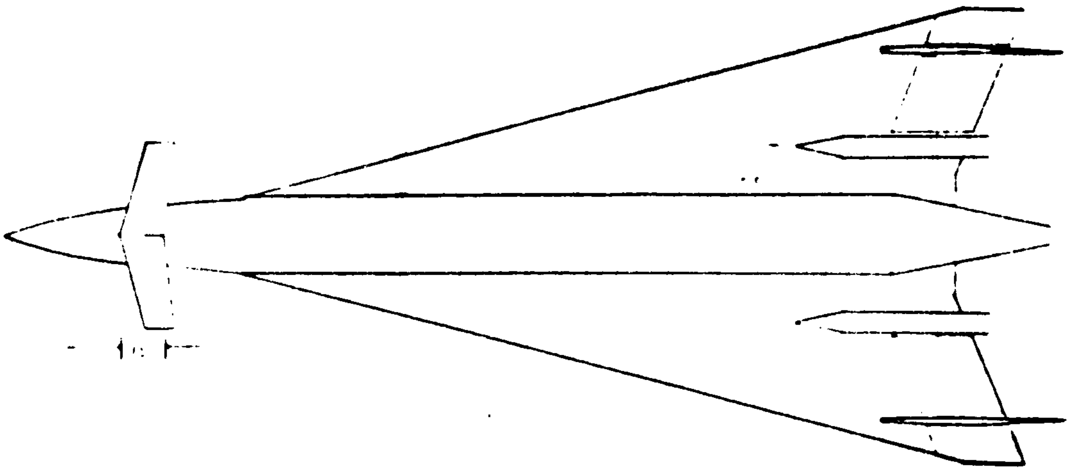


Figure 2 - The Wave planform configuration

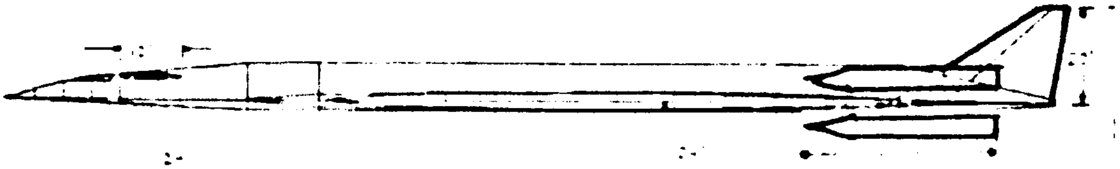


Figure 3 - The Wave - side view

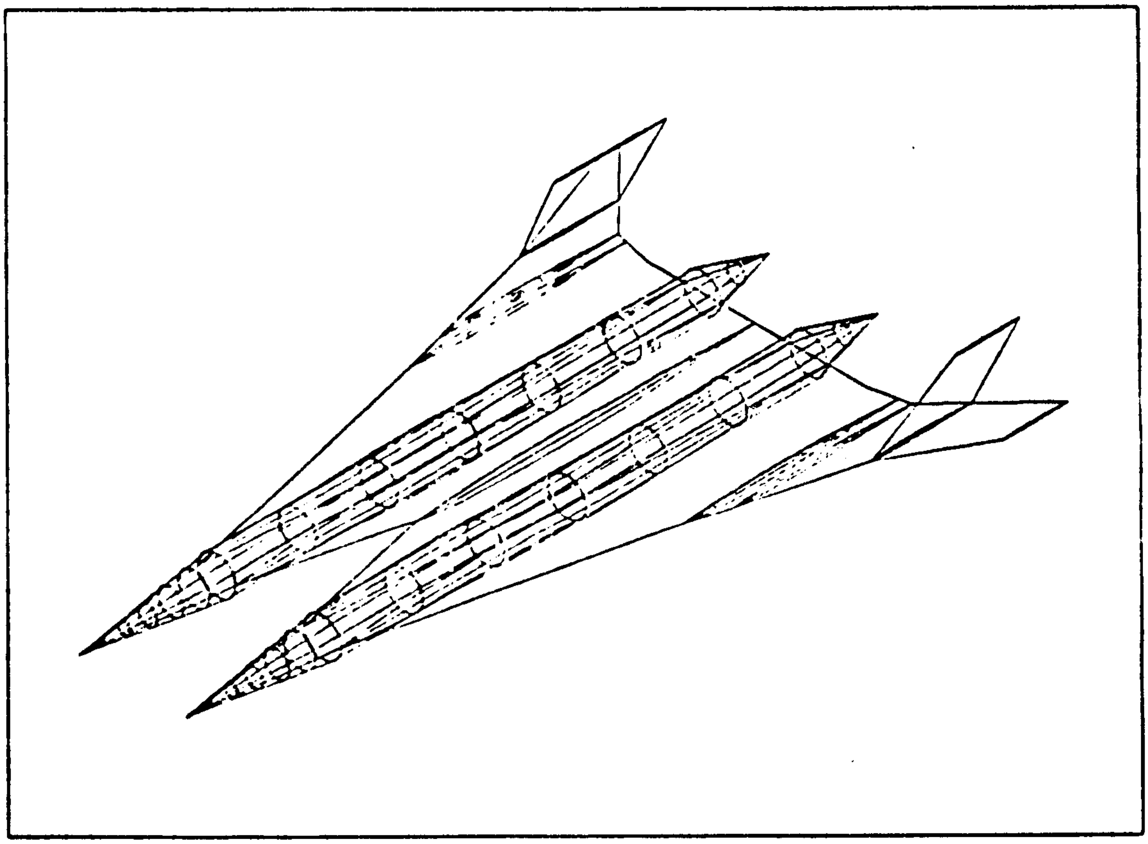


Figure 4 - The Stork

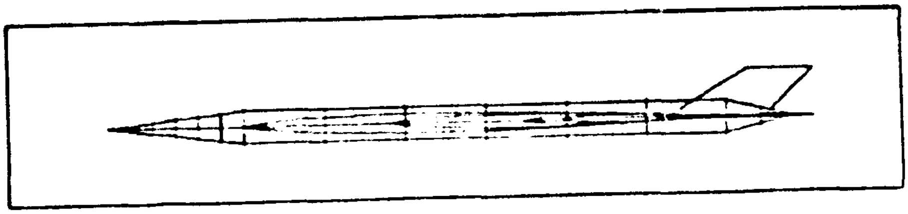
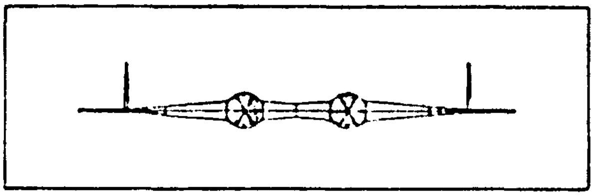


Figure 5 - The Stork -side view



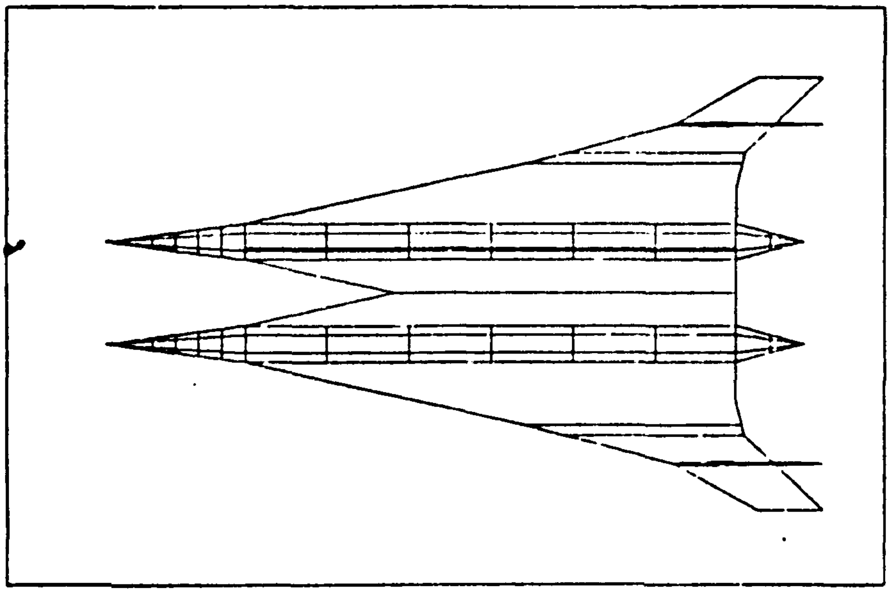


Figure 6 - Planform view of Stork

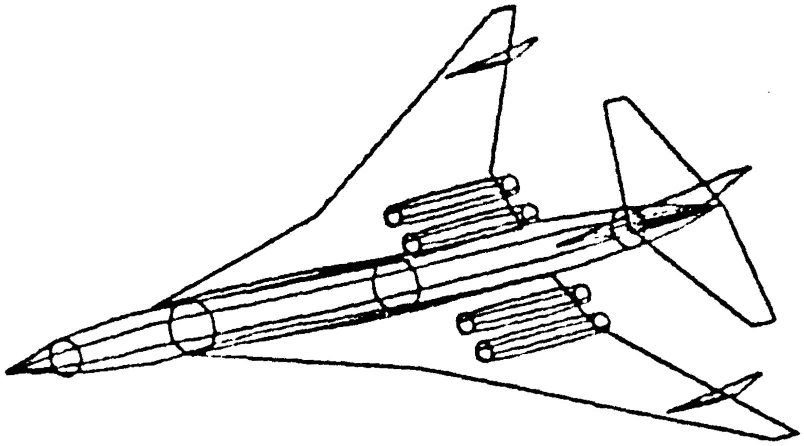


Figure 7 - Spartacus configuration

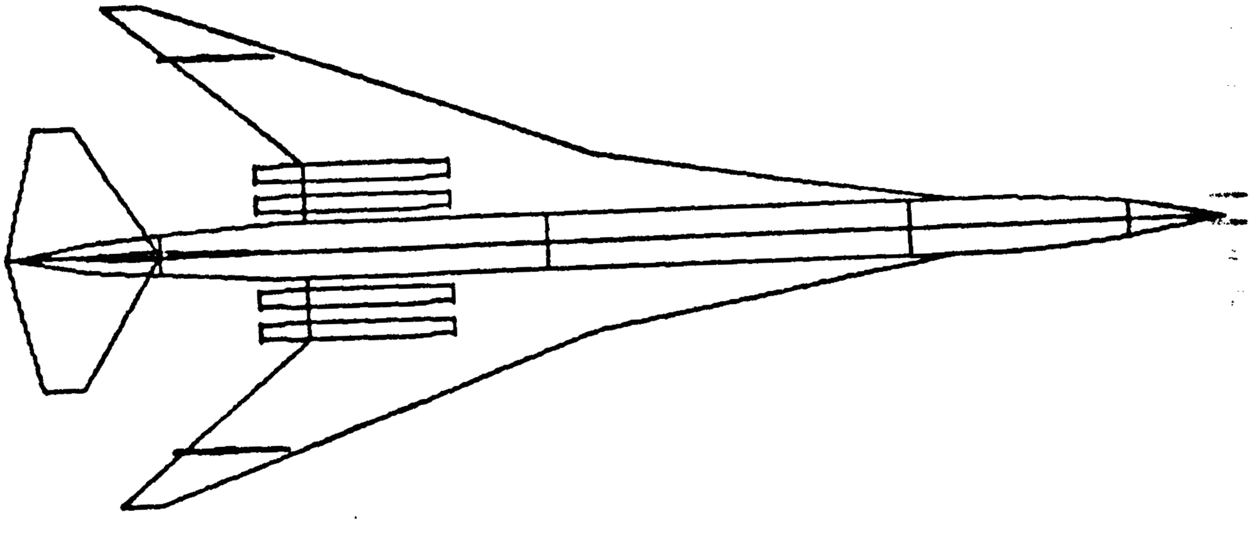


Figure 8 - Spartacus planform geometry

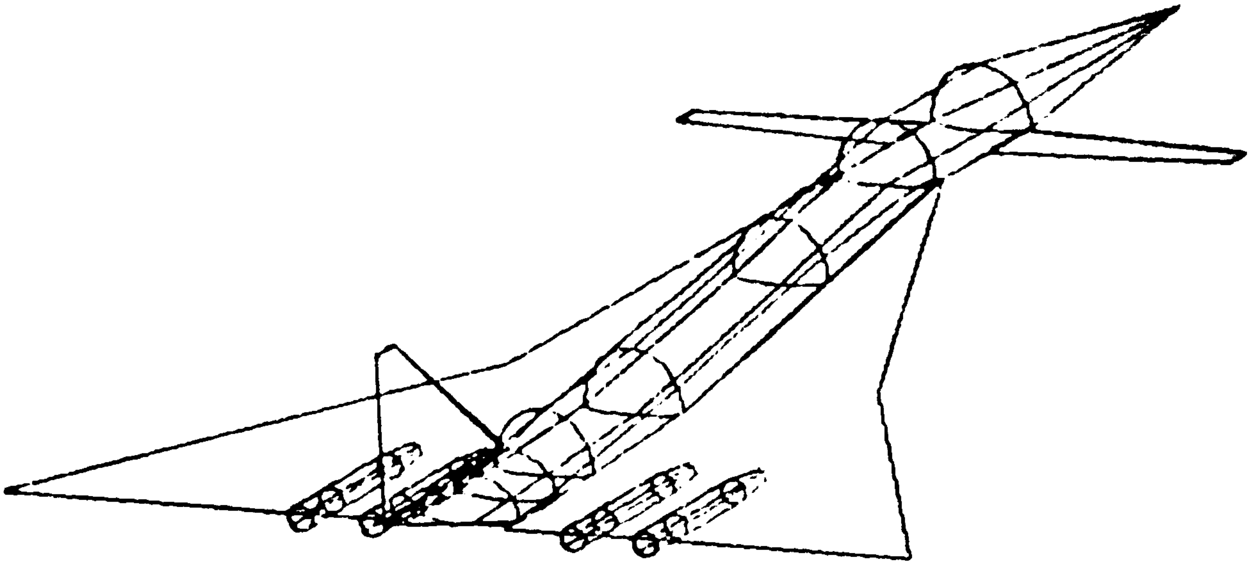


Figure 9 - The Hawk HSCT

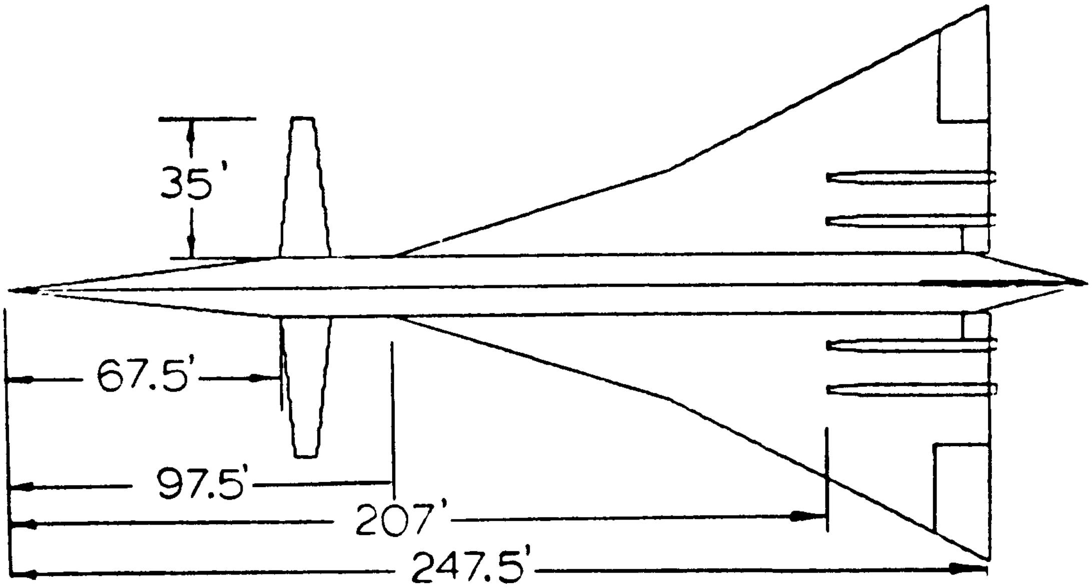


Figure 10 - The Hawk Planform

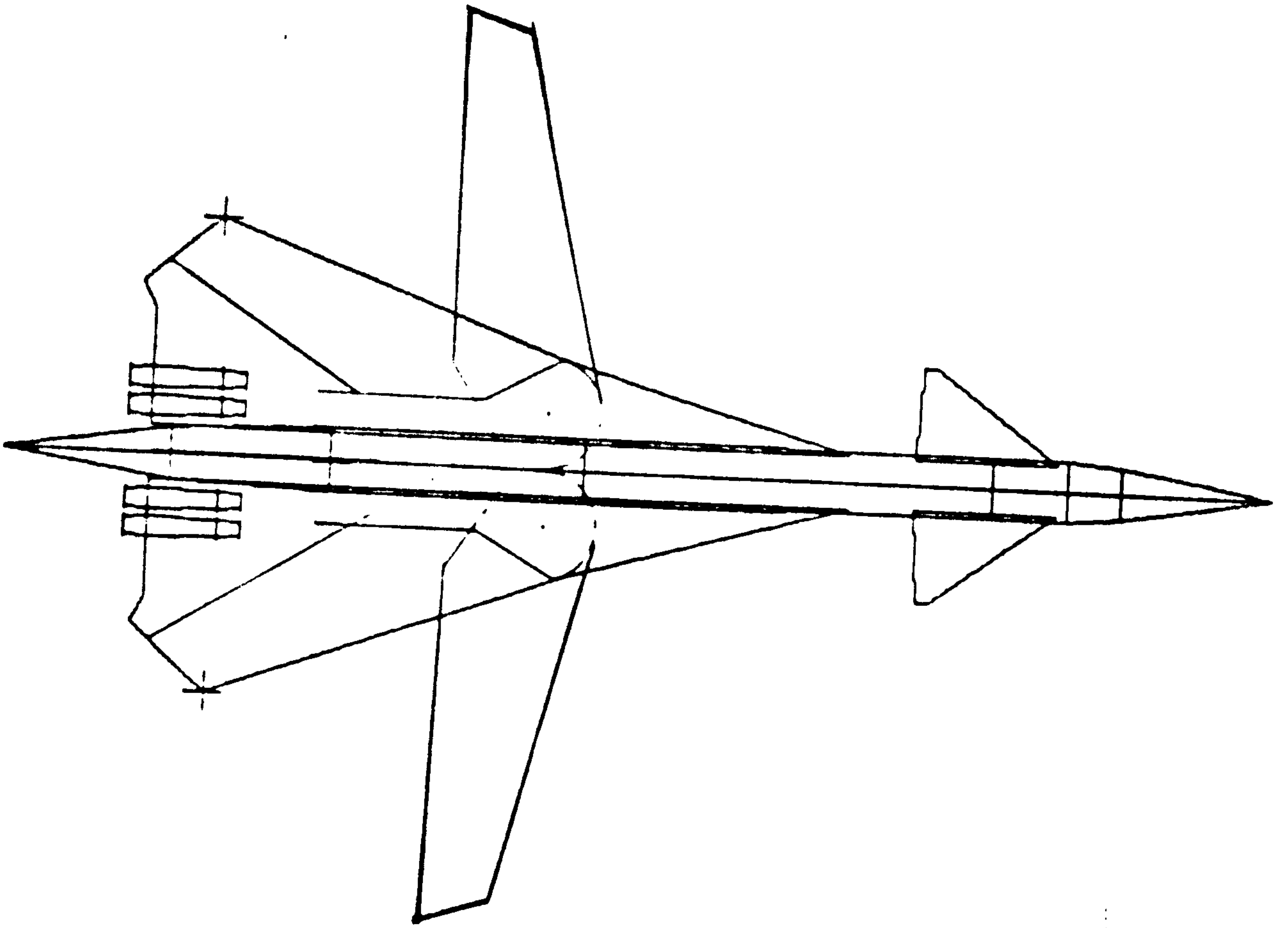


Figure 11 - The Mercury Mark II

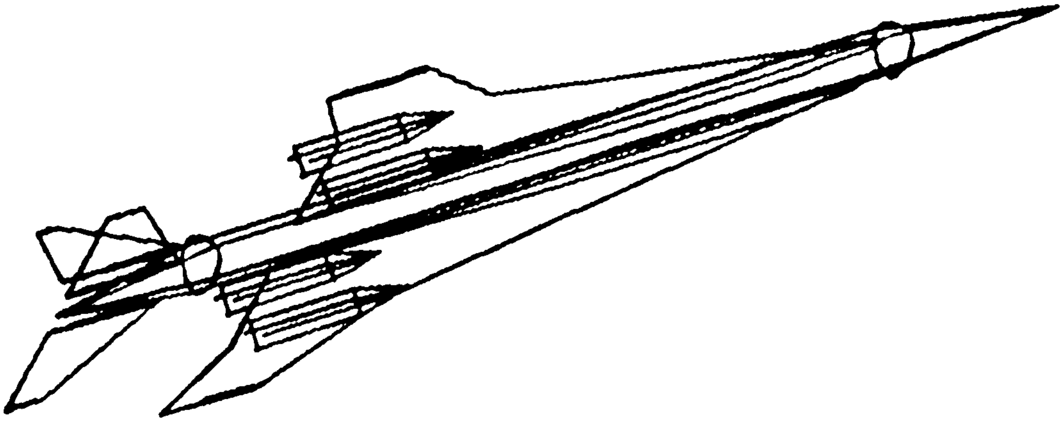


Figure 12 - The Dolphin

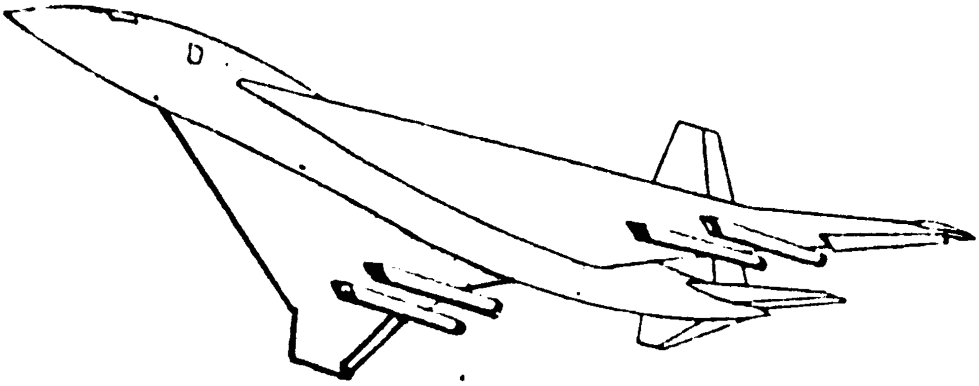


Figure 13 - The Swallow

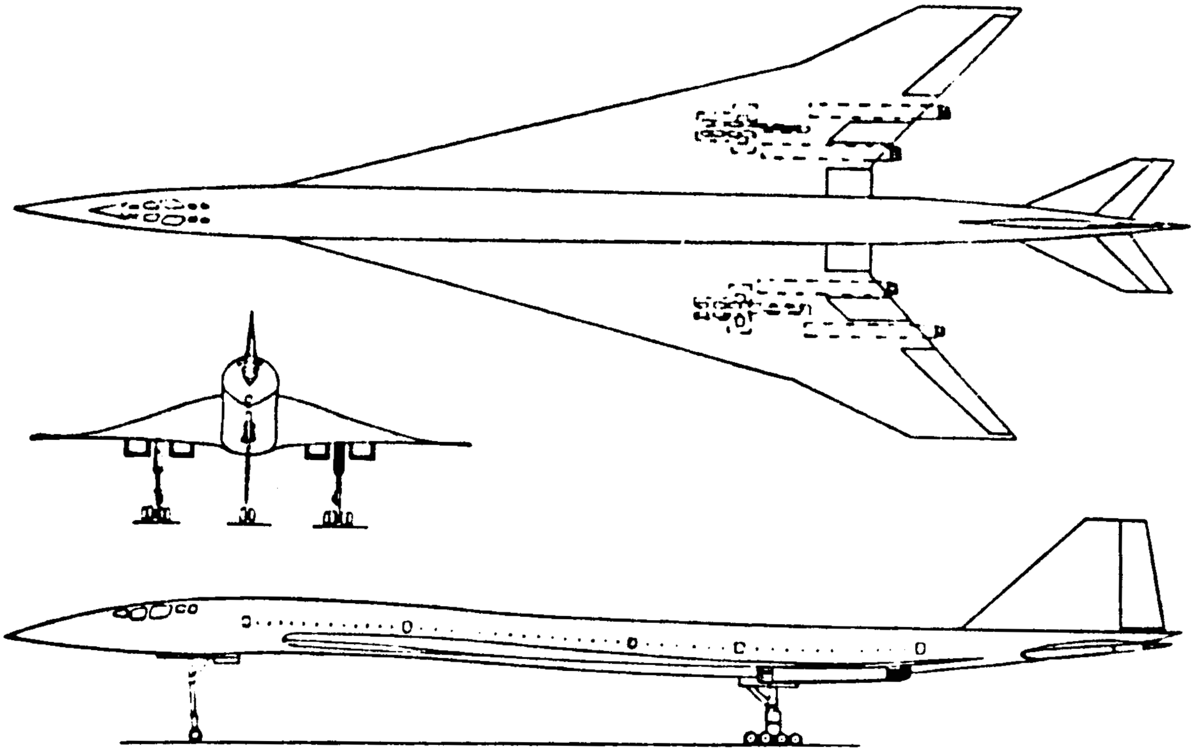


Figure 14 - Three views of the Swallow

REQUEST FOR PROPOSAL

DESIGN FOR A HIGH SPEED CIVIL TRANSPORT

Expanding international passenger markets and advances in technologies applicable to high-speed flight could result in an economically viable high speed civil transport. It is proposed to design such an aircraft with the following characteristics:

Mach number between 2 and 6

6,500 n. mi. range with modified reserves (see mission profile)

250 - 300 passengers

Approach speed less than 160 kts.

Operate from conventional airports (balanced takeoff field length less then 12,500 ft.)

Meet FAR 25 requirements

First flight in year 2010

Other areas of consideration should include:

Airport noise - an attempt should be made to calculate and minimize airport noise to comply with FAR 36.

Sonic boom - sonic boom levels should be calculated and an attempt made to minimize boom to allow the possibility of overland supersonic flight.

Fare levels - the possibility of ticket cost being comparable to that for an equivalent subsonic transport (with fuel at $1.00 per gallon) should be investigated with a surcharge included if necessary.

The design cruise Mach number should be fixed based on appropriate technological and economic considerations. The primary mission considered should be all high speed. An alternate mission should be considered where part of the mission is flown at subsonic speeds (for overland flight and engine out possibilities).

In order to arrive at a final configuration capable of meeting the design requirements, close interactions between all discipline areas will be required. However, there are specific technical areas associated with the various disciplines which must be addressed. The following sections outline the disciplines and their associated technical areas.

Configuration layout - Special consideration should be given to the volume requirements of both passengers and fuel. Fuel type, volume, and location depending on Mach number should be addressed. Physical realism should be included during the configuration layout with particular attention given to landing gear placement and integration.

Aerodynamics - Good high-speed aerodynamic performance is an obvious requirement for this configuration. Takeoff and landing performance, subsonic aerodynamic performance, and stability and control for the entire flight regime should be acceptable. Finally, sonic boom should be evaluated and an attempt made to obtain acceptable boom levels.

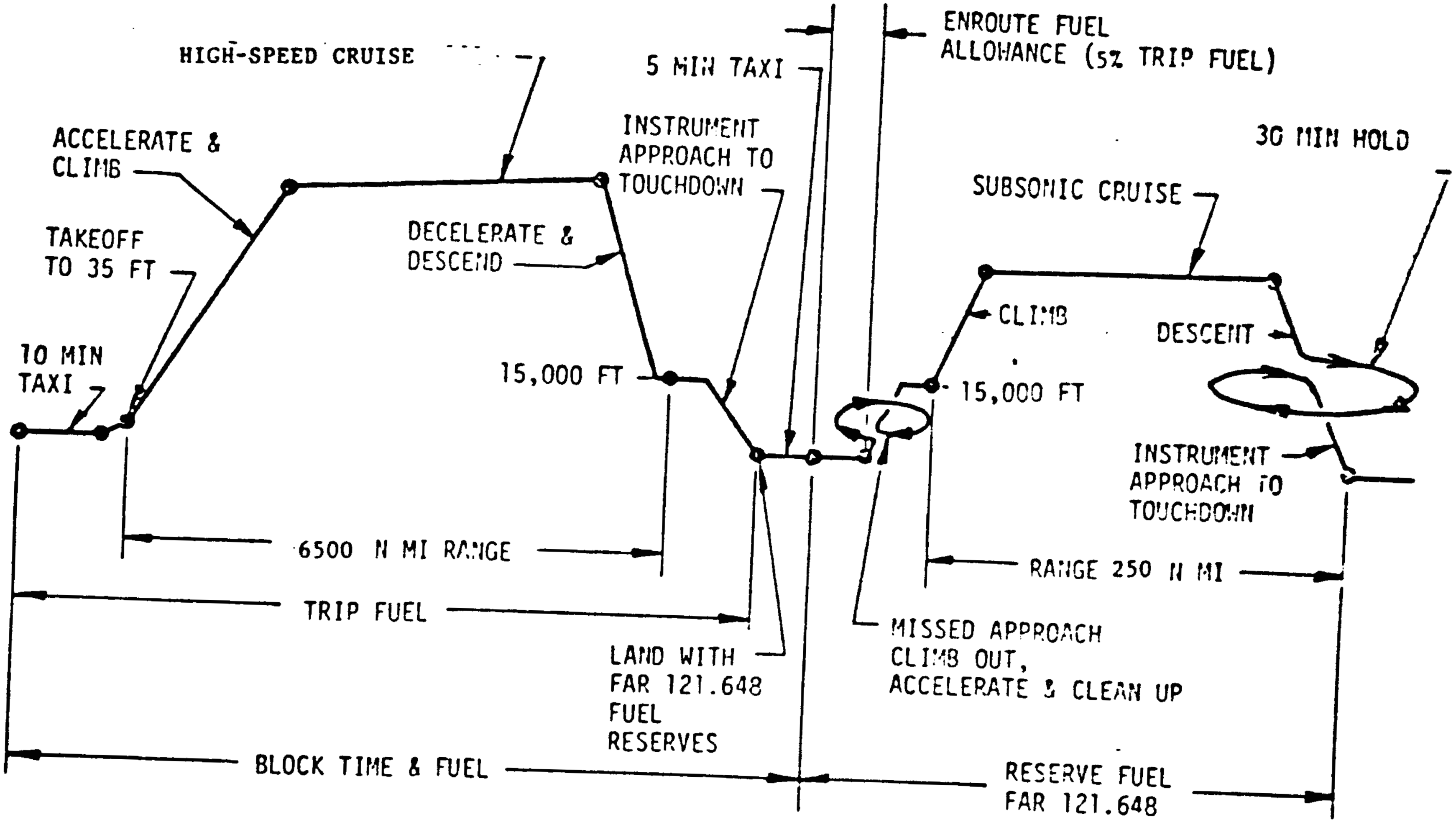
Structures - Expected operating temperatures should be predicted and appropriate materials identified. Additionally, thermal management considerations should be addressed. The effects of all these factors on configuration weight should be identified.

Propulsion - The propulsion system and fuel type should be selected consistent with the design Mach number. Efficient high-speed cruise is an obvious requirement. In addition, off-design subsonic cruise propulsion performance should be evaluated. Finally, terminal area noise should be considered.

Performance - The aircraft should be sized to meet the design mission. Acceleration rates during the entire mission should be estimated and the effects on passengers considered. Additionally, the effect of a subsonic leg during the mission (as would exist with no overland supersonic flight or an engine out condition) should be evaluated. Finally, the sensitivity of the configuration to design range (between 4,000 n. mi. and 8,000 n. mi.) should be evaluated.

Economics - A market study should be conducted to determine the need for this type of aircraft and to estimate the number of aircraft which will need to be produced. Manufacturing costs and operating costs both need to be evaluated. The sensitivity of operating costs to fuel price should be presented. The effects of design choices on the economics need to be evaluated. Also the effect of design range on both the market and economics should be considered. Finally, the effect of no overland cruise on the economics should be identified.

Attachment: Mission Profile



MISSION PROFILE