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UNDERGRADUATE STUDIES OF SUPERSONIC TRANSPORT DEVELOPMENT

1. Abstract

The technical and business case for hydrogen-powered supersonic airliners is re-examined as an exercise in multidisciplinary concept innovation by undergraduates at different levels. A progression of exercises is used. A conceptual design exercise in a freshman introduction course was expanded to modify a conventional hydrocarbon fuelled airliner concept to one using hydrogen fuel, quantifying the economic opportunities in the Carbon Market. Sophomores in research Special Problems were tasked with extending the freshman experience to supersonic airliners, as part of a team including senior students. These students explored radical concepts for such airliners. An upper level aerodynamics course was used to develop technical figures of merit for supersonic hydrogen airliners from basic aerodynamics knowledge. The process identified numerous gaps in the comprehension of the students from their courses. The integration challenge of this project enabled iterative refinement of their understanding. The concepts and analysis approaches taught at each level are seen to have become useful only when subjected to integrated use through several iterations. The paper also demonstrates a process to show how some certainty can be achieved in developing an ambitious advanced concept through the notion of a "figure of merit". The results have led to a poster presentation and progress towards peer-reviewed archival publication.

2. Introduction

Weary travelers have long dreamt of flying supersonic in spacious comfort across the world. Yet today there appears to be no immediate prospect of the leading airliner manufacturers developing affordable and viable realizations of this dream. This paper explores the notion of using the hydrogen-fueled SST as the focus of undergraduate projects, thereby raising awareness, debunking superstitions and reducing risk enough to trigger inspired thinking among design leaders. Perhaps, this thinking will blossom at least by the time today's undergraduates rise to decision-making positions in industry. The paper is laid out as follows. The first part defines the issues. The second lays out an approach to address the issues. The third explores the synergy with the aerospace undergraduate curriculum and pedagogy, and the final part reports on technical and pedagogical results from this exploration at our institution.

2.1 The Problem

The Concorde[1] and the Tupolev 144[2] are famous as 1960s pioneers of an age of supersonic intercontinental travel that promised much, but ultimately did not get beyond the niche market stage. The Tu-144 suffered a fatal crash at the first Air Show where it was exhibited in the West, and regular passenger service was cancelled after only 55 flights citing safety issues. The Concorde on the other hand was widely respected as a technological marvel, whether loved or hated. Airport noise and sonic boom concerns killed its prospects of flying across land, and thus of expanding its markets. Though nearly 200 orders were placed initially, only 14 entered commercial service. Lessons abound from these two projects.

How much of the environmental concerns were real, rather than born of commercial competition, may never be resolved. The true lesson was perhaps that failure to resolve the non-technical societal issues could kill even the most elegant technical designs. The sharp rise in oil prices in the 1970s and 80s, and the politics of the Cold War and US-Europe competition, ensured that the Concorde would never be produced in large enough numbers to be economically viable. But there is no doubt that it lit up the dream of traveling across the world faster than the sun. Rising fuel prices, aging aircraft and one fatal crash, ended the First Age of the SST.

Recent efforts to revive SSTs have taken shape with the US High Speed Civil Transport (HSCT) project[3] of the 1990s, and the continuing Japanese interest[4] in a large SST. The NASA HSCT project involved the leading airframe and engine manufacturers in the US, but was finally cancelled[5] in 1999. Since then, several companies have been designing supersonic business jets[6,7] combining concepts from obsolete fighter plane and engine designs and transonic business jet operations.

In 2004, the author spent a summer as a Boeing Welliver Summer Faculty Fellow, and took the opportunity to ask everyone he could find, including former students who worked on the project, why the HSCT was cancelled. The answers are summarized below, of course in the author's words and understanding:

- As a technology exploration, the HSCT project was not intended to develop a commercial SST design or X-plane demonstrator. The project explored issues and solutions in the Mach number range from 1 to 25. A corollary was that no real technical obstacle was identified in the Mach 1.4 to 2.5 regime of expected commercial SST operations.
- The airlines' business model depends on business/first class travelers to make most of their long-distance routes viable. An SST would take away the high-paying passengers, and thus cut the low-risk profit of the established transonic fleet while taking on a huge new risk and investment. There was no business case for doing so.
- The design did not "close". The propulsion, structure weight, and noise/ pollution concerns (in each case according to people in other areas) simply did not all get resolved satisfactorily in a manner that assured sufficient profitability to make the market risk worth taking.

At the time, EADS and BOEING were in a tight race for orders for the A380 and the B787 respectively. There was a battle for public acceptance between the hub-and-spoke economy of the very large airliner, and the point-to-point convenience of the midsize airliner. In this environment, three more significant trends combined into a third, a "killer" for SST dreams:

a. The travails of Airport Security tilted the scales towards Point-to-Point but reduced the speed argument for SST business travel. Passengers now had to report hours ahead for each flight. Those who could afford Concorde fares might now choose to fly in private aircraft, avoiding the harassment and intrusiveness of airline travel.
b. Fuel prices started a sharp rise, with Peak Oil[8] feared imminent. This argued for the best fuel economy as the deciding criterion.

c. The combination of security, fuel cost and market upheavals put most airlines into a mutually destructive spiral ‘race for the bottom’ in cost-cutting, making it very hard to imagine them going in for the huge investment and technology risk of the SST.

Predictably, “serious” studies of supersonic airliner feasibility, conducted by “professional” organizations, focused down on a few low-risk concepts that looked not much different from the Concorde, and concluded the expected: that they could not make money with sufficiently low risk building SSTs. The issue of seeking alternative fuels was explored, but the announced progression was towards synthetic hydrocarbon fuels, bio-derived “carbon-neutral” hydrocarbon fuels and then eventually hydrogen, some 40 years away. Thus the “responsible conclusion” was that SSTs were dead.

We seek to see how to break out of this situation. Given that announced motivation, careful attention must be paid to all the reasons cited for the non-viability of the SST. Determining the truth of each such reason, and exploring ways around them, is a task too risky to be left to professional research organizations, large companies, NASA or even to PhD theses in Aircraft System Design. It is a job for undergraduates and their professors who, by popular definition, have nothing better to do.

2.2 Reviewing Pessimism

The 1999 summary presentation by NASA on the HSCT project is the first reason for hope. It declared that the “3-legged stool” of HSCT feasibility was broken. The two legs of technological feasibility and environmental acceptance were strong in feasibility. However, the third leg, the market prospects, were weak and broken. The chart that accompanied this conclusion, however, showed the routes that had been considered in the study: they consisted of the trans-Pacific and trans-Atlantic routes connecting to the US west and east coasts respectively. The entire western hemisphere was shown, with no other routes. The entire Eastern Hemisphere was missing.

This struck the author as being rather 1970-ish. A brief detour is in order here, realizing that the 1970s were 40 years ago. The Cold War was in full swing. The West and the Soviet Union effectively neutralized each other’s plans for large global advances in travel and communications. There were no viable business destinations in central and southern Africa, and most nations banned travel and commercial links with Apartheid-ridden South Africa and Rhodesia. The People’s Republic of China was not a leading trade/business destination, and their own citizens (except for government/Party officials) were not known or allowed to travel, or to have the means to travel much outside. Plans for the Concorde would have included landing at Bombay (Mumbai) as one of two viable business destinations in India (the other being Delhi which is deep inland), but supersonic overflight of India towards Australia was precluded, just as it was banned over Europe and the continental USA. This explains why there were few viable supersonic routes in the Eastern Hemisphere in the 1970s. On the other hand, the projected meteoric rise of the Pacific Rim economies in the 1980s came to a crashing halt with the currency manipulation crisis of the early 1990s, and the long-running quasi-recession in Japan. Video conferencing also eliminated many excuses for jetting supersonic across the world. It is undeniably more “powerful” to be able to “do” a conference from a hammock in the Carribean than after an 8-hour dash across the world.

The world has changed drastically since then, most notably since the early 1990s. The Berlin Wall is down, and the European Union integrated, with functional relations with the Former Soviet Union nations. South Africa is an open and booming economy. Most dramatic is the rise in the economies of Asia since the early 1980s, and the opening of travel in and to the People's Republic of China. Viable business destinations and international airports abound now in Central and Southern India, with busy air connections throughout India, the Middle East, Sri Lanka, East Asia and Europe. Rising middle class incomes, and millions of expatriates worldwide, have created strong demand for quick, convenient, point-to-point travel. This is especially true among older, relatively wealthy travelers. For many, the rigors of a 20 to 30 hour journey with long 9 or 17-hour flights punctuated by the rigors of airport transit and security lines, are definitely traumatic and potentially fatal. Hence the potential market for supersonic travel may be far greater than that envisaged by the designers of Concorde in the 1950s or by NASA in the 1990s.

Rising fuel prices appeared to put these dreams beyond hope. Experts pointed out the simple (but flawed) logic that required power (and hence fuel consumption) is proportional to the cube of speed, and hence travel at twice today's speed should cost 8 times as much. Damage to the upper atmosphere would be unacceptable. These concerns negated the substantial gains in reducing sonic boom, in composite structures, and in engine efficiency, achieved since the 1970s. Hydrogen-fueled airliners, on the other hand, were rejected for 4 reasons:

- The presumed difficulty in handling liquid hydrogen (the "Hindenburg Superstition"[9]).
- The large volume presumed to be essential due to the low density of liquid hydrogen, and hence unacceptable supersonic wave drag.
- The high cost of producing and storing hydrogen in sufficient quantities.
- The presumed energy inefficiency and carbon footprint of producing hydrogen starting with fossil-driven power plants.

2.3 Reasons for Optimism

The reasons for optimism are summarized below.

- There may be substantially more demand for supersonic airline travel, than has been considered in previous studies.
- The point-to-point airline strategy has gained ground because of airport security and congestion problems. Rising demand for the B787 aircraft shows that several airlines are buying into the point-to-point concept, and many more cities around the world are beginning to offer intercontinental service.
- Point-to-point trips now exceed 17 hours using long-range airliners such as the B777ER, the midsized B767 and the upcoming B787, showing viable demand for long trips with high fuel and low payload fractions.
- The next logical step is to reduce the time for point-to-point travel, increasing trip frequency per aircraft. This requires supersonic flight.
- Given point-to-point architecture, there is little reason to go to high supersonic Mach numbers, since travel time rather than airport ground time dominates total trip time. In fact, going to Mach 1.4 may offer enough reduction in travel time to attract a much larger segment of travelers, and obviate the need for full-stretch bed-seats.

- Aircraft experts indicate that with current aerodynamics, engine and airframe/propulsion integration technology, and some intelligent use of atmospheric winds and density layers, sonic boom will be imperceptible on the ground at up to Mach 1.4 over the Continental United States.
- Concepts such as Boeing's Sonicruiser, the Blended Wing-Body, the Oblique Wing and the B-2 bomber (regardless of their maximum speeds) suggest that ideas for larger-volume, innovative configurations are not lacking.
- Even with large increases in fuel prices, airline ticket prices have not increased much. This suggests that low-supersonic flight with a high-demand market and hydrogen fuel will not require first class ticket prices as has been commonly believed.
- In the longer term, hydrogen being unlimited in supply, fuel costs should come down, so that the cost should settle to make coach-class ticket prices viable.

2.4 Summary of Issues

The problem is distilled to the following questions for consideration by undergraduates:

- What is the drag implication of using hydrogen, given the lower fuel weight fraction?
- How have demographics and economic development altered worldwide market projections for supersonic transport? What are viable destinations, and what are the flight times, curfew implications and business implications of supersonic flight between these destinations?
- What is the impact of Global Warming/ Carbon emission reduction initiatives on the prospects for hydrogen-powered flight?
- What are the noise implications of the hydrogen-powered SST?
- Are there radically different concepts to take advantage of the different features of hydrogen fuel, supersonic flight, and airport logistics?

3. Approach

3.1 Resources

Obviously, the above issues are beyond what we usually cover in an aerospace undergraduate curriculum. A snap poll in our classes indicated that few students had heard of the Kyoto Protocol, and fewer still have any idea of the Carbon Trading Market and the ways in which companies and nations are allowed to "account" for carbon reductions by spending money on carbon reduction initiatives. Economics is covered at best in a Cost-Reduction sense (which drives designs towards the lowest risk, most conventional) than in a Business Case sense where large risk and expenditure are justified by high return on investment. The traditional aerodynamics and propulsion curricula are fragmented, and typically do not include a challenge to integrate the knowledge.

Against these, we had three important resources, built and tested over two decades:

- The Design-Centered Introduction (DCI) to Aerospace Engineering, tested since 1997, showed that freshmen can and do adequately and profitably handle the cross-disciplinary challenges of doing conceptual design of a flight vehicle[10,11].

- Long experience with undergraduate research projects, including the recent institution of Undergraduate Theses, enabled refinement of a system where progress can be continued over multiple semesters by the same or different student teams.
- A treasure trove of advanced technical knowledge from the Boeing Company's High Speed Aerodynamics experts, has been gradually integrated into the undergraduate curriculum, pushing the expectations of advanced aerodynamics courses up a few notches every year. This emphasizes the application of mathematics to identify the ideal performance under given constraints, and the Figure of Merit of a given configuration. Thus today we are able to take students to the point where they can do a credible drag analysis of a supersonic configuration at supersonic and subsonic speeds, and, more importantly, develop figures of merit for actual configurations against theoretical ideals.

3.2 Implementation and Pedagogy in the Freshman Course

The DCI has been taught to freshmen at our institution since 1997. Over time, and with different styles of different senior faculty, several ideas have evolved it. Starting with a safe exploration where the B777 concept was slightly stretched for higher range in 1997-98 (with interns reporting back excitedly that their designs had been amazingly close to the Boeing 777ER under development), the course pedagogy has been refined. The design process tailored to first-semester freshmen, is of course very simple:

- For given specifications, estimate the payload using common sense (e.g., "What is the average weight of a passenger on an airliner? How much weight of food and water should be carried per passenger?)
- From benchmarking against prior designs (using diverse and uncertainty-ridden data from the Internet), guess a Payload Fraction. Find the Take-Off Gross Weight (TOW).
- Use a Wing Loading (W/S) from benchmarking, and find planform area S. Use airport gate or other commonsense constraints, or again benchmarking, to fix span, hence find aspect ratio.
- For a selected cruise altitude and speed, find the lift and induced drag coefficients.
- Guess a value for low speed zero-lift drag coefficient. Hence find total cruise drag, and speed for minimum drag. Find cruise L/D.
- Starting with a thumb-rule (typically, that installed sea level static thrust is 30% of TOW, and that the plane must take off with 1 engine out), select a suitable engine and number of engines.
- For the selected engine, find thrust-specific fuel consumption from published data, and estimate thrust at altitude using either an empirical thrust variation, or assuming that thrust is proportional to air density.
- For specified range, find the fuel weight fraction needed at takeoff, including given fuel weight fractions consumed during climb.
- Given engine thrust-to-weight ratio (or a propulsion weight fraction), estimate the remaining weight fraction with which to build the aircraft (structure fraction).
- Test against a specified absolute minimum structure fraction (typically 0.27 for the newest composite structured airliners), to see if the range can be met.
- Once the cruise point design is shown to close, test the steady flight envelope, using the criteria of aerodynamic stall, or thrust available, to find minimum speed at any altitude. Use the available thrust at each altitude to find the high speed limit. The ceiling is found by

checking against a minimum specified climb rate. Thus the student can check if the design closes.

This is implemented on a spreadsheet, so that the student can practice iterative refinement of the aircraft design and see the effects on the flight envelope immediately.

Students in Spring 2008 were asked to do the conceptual design for a short-haul airliner (1000+ mile range) in teams of two each, and use a steadily-filled-out weekly report template submitted through the "T-Square" web-based course management system, to build their design. By the end of the 12^{th} week of the semester, they had progressed far, and were claiming extreme hardship and fatigue because of the complexity of the calculations. A question on the second midterm test extracted thoughtful answers comparing their impressions of aerospace engineers to what they had reported in the first week's assignment, which had been to write a 500-word essay on "Why I am in the School of Aerospace Engineering". So they were asked to re-do the calculations in 1 week, for the case of hydrogen fuel, mainly as an exercise to demonstrate the wonders of the "Learning Curve" and their own unrealized competence. The primary changes with LH2 fuel were:

- Heating value per unit mass of fuel was taken to be 4 times that of hydrocarbon jet fuel. With present-day engines converted to hydrogen without an increase in turbine inlet temperature, this may be optimistic. However, the net effect of 75% reduction in thrust-specific fuel consumption is justified by the higher thermodynamic efficiency and the higher thrust-to-weight ratio of the engine when hydrogen is eventually used.
- The additional fuel volume needed was to be calculated, and integrated into the aircraft layout.
- The increase in payload fraction was to be used to reduce TOW (meaning recalculate everything), not to go to a larger payload.

In this endeavor, we used the hydrogen airliner concept primarily to build students' confidence, and introduce the notion of a business case. The hypotheses were that if the design were kept small and subsonic, the drag penalty due to increased volume would be small, and in fact the additional volume needed would be minor. These proved to be correct. It is possible that hydrogen usage as fuel may indeed first occur in the case of short-haul airliners than supersonic ones, in order to realize the benefits of fleet carbon reduction.

Finally, students were asked to do an economics comparison against the conventional airliner that they had already developed. A modest fleet size of 500 airplanes was assumed over the life of the project, and each airliner was assumed to fly a given number of passenger-miles per year. The savings in tons of CO2 per year from the fleet was to be calculated, and converted to money using the market price of CO2 credits on the world Carbon Trading Market. This strategy avoided the issue of actually calculating the project cost etc., while providing a glimpse into estimating a marginal revenue source and learning about market valuations and the economic opportunities in the Global Warming issue.

3.3 Undergraduate Research

Two students who had completed the freshman course in Spring 2009 worked as a team in Fall 2009 to explore radically different supersonic configurations. A senior student who had worked with a System Optimization research team and had experience of using the large "professional" aircraft system design codes, worked with our team to develop cost estimates. The research team was asked to use the Concorde to validate their procedures, and then develop a process to go from conceptual design decisions, to estimates of per seat-mile costs under contemporary airline operation scenarios. A 4^{th} student who was pursuing the supersonic airliner topic under the Undergraduate thesis option, was asked to lead the team, and take on the task of exploring the demographics and route-planning to justify a viable fleet. A list of over 100 airports was easily found viable as supersonic destinations.

3.4 High Speed Aerodynamics Course

The most in-depth analysis feasible in the core undergraduate curriculum is in the AE 3021 High Speed Aerodynamics course. The students in previous years had been asked to work in teams of two, select an aircraft that could fly supersonic, and estimate its drag under a subsonic and supersonic flight condition respectively using the aerodynamic analysis techniques that they had learned. The drag estimation was validated by using the published maximum speed of the aircraft, and reasoning out the drag from the installed engine thrust and flight altitude. The subsonic drag estimation included lift-induced drag and skin friction drag (computed for thin strips along the wings, tail and fuselage), and a 10% addition for interference, whereas the supersonic estimation also included wave drag and compressible boundary layer calculations.

In Fall 2009, the project was to choose either to do the above for an existing large supersonic aircraft (which essentially meant the Concorde, but extended to the 5000 mile range specified) or for a supersonic LH2 airliner with the payload capacity of a Boeing 787, and 5000 statute mile range. The specification was biased in favor of those who chose the more risky option. The ideal wave drag calculation was to be based on a Sears-Haack cross-sectional area distribution, for the total volume needed to accommodate all components. Students were asked to plot their final area distribution against the Sears-Haack distribution. The reasoning was that an aircraft design bureau would drive to minimize the difference between the final geometry and the modified Sears-Haack distribution for minimum total drag.

4. Results and Discussion

4.1 Conceptual Design Procedure

The freshman-level conceptual design process worked very well, considering the difficulties encountered by students just 2 more years into the curriculum. This year, the use of the "T-Square" web-based course management system proved very effective. The entire process was laid out as an assignment sheet right after "Drop Day" when it became safe to divide the class into teams of two. The team formation itself is an exciting process in a freshman class, because most of the students do not know each other at all, so that the usual process of asking the students to form their own teams must be accompanied by a "safety net" where the instructor forms teams from those unable to do so. This year this process also brought the excitement of the administration trying to accomodate the strident attempts from a Virginia lawyer, who tried to get advantages for his offspring all semester, in this case by demanding that s(he) be paired with one of the "more successful" students in the class (interpretations left to the experienced teachers reading this). The procedure used was to go down the alphabetical list of students, find the first one who had not found a partner and pair that student with the next down the list who had not found one, before considering any social engineering.

The Project Document for the conceptual design project was laid out in the first week, albeit with mostly empty headings. Each week, each member of every team had to upload their Project Document with the appropriate sections completed, understanding that iteration was allowed later. Each was graded, with no promise that teammates would be graded equally (though mostly there was no reason to do otherwise). The submission form included space for each student to confidentially report "how their team was working". This combination generally brings excellent performance, as long as the few reports of teammates not showing up, are promptly and effectively followed up. Thus by Stage 5, the project was essentially done, and the end-of-project spike in effort and understanding could be mostly focused on technical learning rather than report formatting.

This worked as hoped-for. Most teams had very credible conceptual designs. The final conversion to hydrogen did not go very well for many teams, because they may not have captured all the issues. Some, for instance, came up with extremely large aircraft because they used the same fuel weight as the hydrocarbon-fuelled one, but with no sensible mission, as a labor-saving strategy. On the final exam, one question out of 6 was to do the essential portions of a conceptual design, and most did quite well on that, though they reported that it was a "difficult question". The desired learning had been achieved, and the net result of this iterative process is that students became good at doing something of which their counterparts who had not gone through such a process, made very "heavy weather", in senior courses.

4.3 Cross-disciplinary exploration

Once again, the curious point arises – that freshmen have no difficulty cruising across disciplines and learning about the Carbon Market, but seniors have a tough time with such things, primarily because of a lack of receptivity. The thesis student did explore demographics, but for her, the utility of the simple freshman conceptual design procedure, proved very elusive, as she wasted time and effort in many futile excursions into complexity. The horizontal knowledge integration, in the end, is proving very effective, but it does not come easily.

4.4 Basic knowledge issues

In high speed aerodynamics, the level of performance in such an exercise was quite inhomogeneous. There were of course several excellent team efforts, but there was a sadly large number of students who missed the point of the exercise. Better attention to these aspects will be necessary in the next teaching of the course. At the final integration level, students had difficulty with the notion of finding a "Figure of Merit" for their design compared to the ideal design for the given constraints. This process required, for instance, comparing sonic boom footprints between their own design concept, the Concorde and the HSCT concept of the 1990s.

Developing a metric with the ideal being the maximum of unity, posed problems. So did the much more basic task of finding the root-mean-square error between the ideal body shape distribution and their own design, and expressing that as a percentage error.

4.4 Implementation Experience

1. As the project moved through the year, several lessons were learned. The undergraduate thesis effort failed. The student found that the demands of other coursework and part-time work were incompatible with the depth and breadth needed for the thesis effort. The thesis effort was not carried past the end of the Fall semester. However, this student did a valuable literature search and identified several issues and answers from prior work.
2. The other senior student who came with previous experience of working in System Design, provided good guidance on how to derive cost per seat mile. One lesson learned is that the experience of working with complex formulae and canned “professional” codes that included various secondary factors, inhibited understanding of the simple methods used in the freshman conceptual design, and hence the student had difficulty understanding the common-sense basis of the process. This student too dropped the project at the end of the Fall semester.
3. The loss of these two students was compensated by the two senior students who had taken the senior high-speed aerodynamics course in Fall, who joined the project in January 2010. These students were asked to assume leadership of the team and carried it forward, with detailed calculations. As the semester progressed, their understanding of the concepts taught in high speed aerodynamics became clearer and they became more comfortable with the methods and results.
4. In order to move the learning experience forward, the sophomores were required to educate the seniors on the conceptual design and carbon market techniques. The seniors were required to educate the sophomores on the high-speed aerodynamics drag calculations. Each team member was required to have a working spreadsheet for the whole project and to compare validation cases with the rest of the team. This process did not work well until they saw why it was needed, the hard way.
5. In February, the students decided to enter the AIAA Student Conference by developing a paper[12]. The paper deadline of March 5 fit well with the deadline for making posters for their presentation at the Spring Undergraduate Research Symposium at our institution. The paper became a way to integrate the status and results of the project. The market survey and carbon market revenue projections were done very competently by the sophomores. The high-speed aerodynamics issues were left to the seniors. Unfortunately, this proved to be a bad idea. The March 5 deadline was met, although as of 24 hours prior to that, the seniors had not delivered any results or text to the paper. The paper had to be withdrawn because it turned out that the final version had reached only an “incomplete assignment” level with several key result figures not included. A project meeting analyzed why this occurred, and carried to the level where there was no way to avoid the conclusion that it was poor planning and work scheduling that caused the seniors to fall down on their parts.
6. The students however had two more chances. The first was to present their results in a poster at the Undergraduate Research Opportunities Symposium to other students, faculty, parents and other visitors from all over and beyond the campus. The intense effort triggered by the paper deadline debacle took the results to the level should have been achieved at the

deadline. This made it evident that there were still some major errors of comprehension left to be solved through re-analysis and calculation.

7. With the added experience of the UROP symposium, the paper is then being re-written with substantial input from the faculty advisor, and is being submitted to a double-blind-plus-expert peer-reviewed professional conference later in the year, with their names preceding the advisor's. Thus, what started as a freshman assignment will reach the level of at least being submitted to full paper professional peer review.

4.5 Technical Results

The first overall technical result is that the conceptual design choices have been linked all the way to estimating passenger-seat-mile fuel costs. From here, numbers from airline annual reports allow figuring of the ratio of fuel costs to overall costs, and hence the ticket prices needed. This allows an estimate of the fuel price levels that would make hydrogen fuel a viable choice for supersonic flight. This shows that at current prices of jet fuel, and projected large-scale costs of hydrogen, liquid hydrogen fuel is viable for supersonic airliners. The preliminary estimate of seat-mile costs assumes that fuel cost is 30% of total airline costs. The impact of global carbon reduction programs on the viability of the LH2 airliner was considered and found to provide very strong support for product development.

The students in High Speed Aerodynamics found that the increase in drag due to the move to LH2 was quite small. The move favored the adoption of newer configurations such as the Blended Wing-Body and the Oblique Wing. The 5000-mile range ruled out Concorde derivatives with hydrocarbon fuel, as the fuel fraction was impractical. However, with LH2 this was quite practical. The larger volume of LH2 in fact made it feasible to consider more spacious layouts than those on current transonic airliners – a major improvement over the cramped interior of the Concorde. Even with a very low L/D (due to errors in the drag estimation and failure to use the "Figure of Merit" notion), the use of hydrogen was found to come our with a lower cost per seat mile than using jet fuel.

4.2 Vertical Integration aspects

This exercise required students to integrate everything that they had learned from the freshman introduction to the upper level high speed aerodynamics course. In fact, one of the stumbling blocks was in differentiating between thumb-rules/ empirical expressions from their Senior Design and Aircraft Performance courses, and specific calculation results from aerodynamics. A second issue is that when given a "procedure" for instance in the Capstone Aircraft Design course or Performance course, students fail to link those to the simple procedure given in conceptual design, and thus get needlessly confused (for instance, they get lost in complicated expressions to include the differences between ramp weight, taxi weight and takeoff weight, instead of using a simple factor). Alarmingly, it did not worry students who had just completed the first semester of Aircraft Design that their design came out with an L/D of 3! In the high speed aerodynamics course, some students tried to avoid work by using conceptual design numbers or numbers obtained off the internet instead of doing the detailed drag calculations.

The notion of using the Sears-Haack geometry as an ideal, and benchmarking their own concept's area distribution against it, came very hard for the high speed aerodynamics students. This notion of using applied mathematics to generate a Figure of Merit is obviously something to emphasize in future.

The comments received by the students at their Undergraduate Research Opportunities poster presentation are very revealing. The experienced viewers who came through commended the apt strategy of using the ideal area distribution as a way to estimate minimum wave drag, and then arguing that aircraft designers would come very close to this in the eventual design. They also commended the students for their success in "proving" that there is indeed a new market for supersonic airliners, and strongly encouraged them to go forward, since they (the viewers including some former pilots of supersonic aircraft) were eager to see the age of supersonic airliners come alive. In sharp contrast, the "judges" who were mostly graduate students in engineering, proved to be completely clueless about the points made in the poster, and instead asked the students about the "impact on the upper atmosphere" (if you fly on Mach 1.4 there is no need to fly at extreme altitudes) and about the difficulties of handling hydrogen and of generating cryogenic hydrogen (something that has been done without incident on a large scale at Kennedy Space Center and several other places around the world for over 40 years). This shows again why such vertical integration exercises that also require students to gain perspective, are so vital for a successful education.

All said and done, the result of the project is very positive. The process that we have laid out is iterative as much as it is interactive, and patient but demanding. It has firm and clear, albeit ambitious goals. Through such a process, the very real difficulties faced by students who have just taken various disjointed courses, can be overcome enough for them to make good breakthroughs inside what is ultimately a very short period.

5. Conclusions

1. In this paper, a multi-level process has been laid out, to explore a high-risk, realistic concept using undergraduate participants. Vertical and horizontal knowledge integration aspects are explored, with differing levels of success and difficulty. A simple conceptual design procedure is used at the freshman level to permit students to explore advanced aircraft concepts and see what is needed to make the design close. This process is then used as the starting point to develop configurations in undergraduate research projects and an upper division aerodynamics course, where radical configurations on the one hand, and detailed technical calculations and optimization on the other, are performed.
2. The conclusions on the LH2 supersonic transport are very encouraging. The large rise in engine thrust-to-weight ratio and the decrease in thrust-specific fuel consumption, since the 1960s until the present (for instance the F-35's engines) are obvious reasons why aircraft designs will close better today. As the cost of hydrocarbon fuel rises and the cost of hydrogen production comes down, LH2 becomes an ever more attractive option.
3. With the continuing demands of this advanced concept exploration, the way is opened to continually improve the depth and percentage of comprehension in the core courses. On the other hand, sophomores coming off the freshman design experience are excellent candidates to explore radical designs.

4. Serious difficulties still persist with getting the students to complete a finished product in time to conduct an adequate cycle of reviewing and refinement. The intermediate deadline of an AIAA Student Paper was used to force an integration of the project in the middle of the semester. This, followed by a poster presentation, allowed the student team to gain more perspective and experience. Eventually, the student effort is leading to a paper that will be submitted to professional double-blind peer review, where their undergraduate status will not be visible.
5. The "crunch" of having to do closed-form design analyses involving ideal designs and figures of merit, brings out many sources of confusion and incomplete understanding. Many of these are at a very basic level, which should not be surprising.
6. The real conclusion from this, then, is the demonstration of how the notion of Iteration is brought into the curriculum, and results in a dramatic improvement in real learning and maturity of competence.
7. Next year, this year's radical sophomore concepts will become assignments for the seniors in aerodynamics to validate and optimize using Figure of Merit calculations.

6. Acknowledgements

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