DESIGN CONSIDERATIONS FOR THE NEXT GENERATION OF GENERAL AVIAITON DESIGNS

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PRESENTED TO

THE LANGLEY RESEARCH SUMMER SCHOLARSHIP PROGRAM
AUGUST 8, 1995
HAMPTON, VIRGINIA

Abstract

This paper discusses the results of research conducted at NASA Langley Research Center during two summer programs during 1994 and 1995. These programs were the NASA Advanced Design Program and the Langley Research Summer Scholars program. The work was incorporated in a three phase project at Embry-Riddle Aeronautical University which focused on development of the next generation Primary Flight Trainer, as well as in ERAU's participation in the AGATE General Aviation Design Competition. The project was conducted as part of the ERAU/NASA/USRA Advanced Design Program in Aeronautics as well as the AGATE competition. A design study was completed which encompassed the incorporation of existing conventional technologies and advanced technologies into PFT designs and advanced GA aircraft designs. Multiple aircraft configurations were also examined throughout the ADP/AGATE. Evaluations of the various technologies and configurations studied will be made and recommendations will be included.

1. Introduction and Background

Embry-Riddle Aeronautical University has been involved with the NASA/USRA Advanced Design Program since 1992, when the university was invited to participate in the Aeronautics division of the program. At that time, the ERAU aerospace engineering department's design faculty recognized an important role that the Embry-Riddle could play in the program. Although General Aviation had been addressed at times in the first eight years of the program, the subject had been underemphasized. In particular, the topic of Primary Flight Trainer aircraft had been completely neglected. Due to Embry-Riddle's position as one of the leading aviation training schools in the world, the development of a contemporary PFT was of obvious importance to the school. This fact, coupled with the overall plight of the GA industry, prompted the decision to focus the ERAU/NASA/USRA ADP on the development of the next generation PFT.

As part of the ADP structure, each participating university is teamed with a NASA center that shares a focus common to the school's ADP topic. In Embry-Riddle's case, NASA Langley Research Center was chosen. Through this cooperative arrangement, a Graduate Teaching Assistant was sent to LaRC each summer to complete research on topics relevant to the university's ADP. The research gathered by each GTA was then incorporated into the next phase of the ADP design study. Support work from outside of the ADP, including LARSS participation, the AGATE General Aviation Design Competition, and other such programs, was integrated into the overall study. The AGATE program is being conducted by the General Aviation/Commuter Element of the NASA Advanced Subsonic Technology Program in an effort to create a new generation of GA aircraft. Through graduate student participation in the ADP and LARSS, ERAU was able to make it's first ties to the AGATE program. This affiliation has expanded into ERAU becoming a member of the AGATE government/industry/academia consortium on a higher level, and has also included student participation through the AGATE General Aviation design competitions. In this manner, the ADP study does not end with the completion of the ADP, but is to continue into future AGATE, LARSS, and other ERAU program participation.

Phase I of the ADP focused on incorporating existing "off the shelf" technologies and on integrating a true concurrent engineering environment into the ERAU design classroom. Phase II further developed some of the Phase I baseline configurations with more advanced technologies and created a high emphasis on occupant safety and crashworthiness. The goal of Phase III was to incorporate further advanced technologies (such as those still under development) and to summarize the efforts of the entire ERAU/NASA/USRA ADP. Through the overall efforts of the ADP, a design database of technologies (old and new) and configurations specific to GA was created. Throughout each phase of the projects, the utilization of cutting edge technologies as design tools was also a major goal. The manner in which the design classes were conducted and in which the group projects were assigned generated the most successful attempts at CE ever made at ERAU. The use of CAD and FEM at the Daytona Beach campus were highly stressed as design tools in the classroom, as well. Another of the major innovations in undergraduate design course work, due in part to the ADP, was the introduction of rapid prototyping at ERAU. Through a National Science Foundation grant, the university obtained a stereolithography (SL) capability at the same time the ADP was commenced. In Phase III, SL has been incorporated directly into the detailed design curriculum at Embry-Riddle as part of the ADP, AGATE competitions, and other programs.

2. The Need in GA

The GA industry has undergone a severe depression, nearly to the point of extinction. The boom in production of Single Engine Piston aircraft in the 1970's was followed by a major decrease in shipments in the years to follow. The fact that such a sharp dive in production has occurred in the GA industry has been of major concern to the aviation industry, in general. It is GA aircraft that supplies the training necessary in the production of pilots that go on to fly larger aircraft. A number of studies have been conducted to analyze the decline in GA and to try to create a means of revitalization of the industry. The results of the past studies have indicated that the average age of the SEP airplane is 28 years[1], which is a rather long lifetime. The obvious reason for such a high average age is the fact that newer aircraft simply have not been produced to replace the older fleets. However, a demand still exists for the aircraft. The major reason that new aircraft have not been produced in large numbers is primarily the influence of product liability.

Reference 2 states the product liability situation in 1987: "Product liability costs for manufacturers (of GA aircraft) have skyrocketed in the past three years (1985-1987). Huge awards or settlements have driven up costs." The reference states that in 1985 manufacturers and their insurers paid over $200 million in judgments, settlements, and defense costs, up from $47 and $77 million in 1981 and 1983, respectively. "The manufacturers report in 1985 insurance cost averaged $70,000 for each airplane delivered... This amount, if added to the price of small aircraft, would make the price astronomical." It is easy to see why the GA industry entered such a plummet.

The recent passage of the products liability reform bill, known as the "1994 General Aviation Revitalization Act (S.1458)," has created some aid to the problem. However, the bill is far from solving all liability problems, and still allows for many potential suits that could continue to devastate the GA industry. The employees of companies such as Piper Aircraft Company still see a nightmare of liability problems to be solved before a true revitalization of the industry can take place.

One way to alleviate the liability problem is to look to the automotive industry. The last Cessna 152 produced in 1986 was essentially the same aircraft as the original model 150 designed in the 1950's[1]. Yet, the automotive industry continues to make vast improvements in design and particularly in crashworthiness. With added design features such as airbags and 5 mile-an-hour bumpers, automotive insurance prices progressively decrease. A similar trend could be applied to the future of GA design.

During 1980-85, the National Transportation Safety Board conducted a study of GA aircraft occupant restraint and seat systems under the title of the "General Aviation Crash Worthiness Program."[1] The results of this study indicated the need for energy absorbing seats and the use of shoulder harnesses. As a result of the study, major changes were made to the airworthiness regulations for GA.

3. ERAU's Response to the Need

Due to the effect of product liability and its relation to occupant safety upon the GA industry, crashworthiness was a major focus throughout Phases II and III of the ADP, as well as in AGATE design efforts. In order to accomplish this, aspects of FAR Part 23 regarding occupant safety, crashworthiness and the Head Injury Criterion were incorporated into the ADP/AGATE designs. The HIC is an equation, integrated over the time duration of impact, which places a specific upper limit on the integral acceleration of the head's CG[1]. The HIC and the other crashworthiness requirements of FAR 23 were then incorporated into the ERAU designs through the generation of Spatial Requirements Specification Documents.

The SRSDs were documents generated for individual aircraft configurations (for example, a two-seat high wing tractor versus another document for a three-seat low wing pusher). The SRSDs provided cabin volumes for each given configuration which adequately met the HIC and Part 23 requirements. Simultaneously, each provided room for adequate structural volume around the cabin, which was designed to accommodate up to the 95th percentile man. A brief explanation of the spatial requirements accompanying the cabin volume was also included in the SRSDs. These documents were then to be given to preliminary design students for incorporation into future designs. This was to allow for realistic cabin and surrounding structural volumes in the generation of future preliminary designs.

4. Results of the ERAU ADP an AGATE Programs

Throughout the process of generating crashworthy designs, a large database of information regarding a myriad of GA design parameters such as engines, airfoils, and many other topics was created at ERAU. This information was gathered throughout the ADP by the GTA's during their internships at LaRC (through the ADP and LARSS), as well as by the faculty and students at

Embry-Riddle. The following sections discuss some of the observations made and conclusions drawn from the ADP which were also integrated into ERAU AGATE participation.

4.1 Airfoil Selection and Wing Position

In Phase I of the ADP, conventional airfoils were employed in the designs. However, in Phase II it was decided to explore the possibility of incorporating Natural Laminar Flow (NLF) airfoils. The Phase I designs were refitted with NLF airfoils and the new designs generated in Phase II also included them. The study revealed that the NLF airfoils were effective in providing improved performance over traditional airfoils. However, the manufacturing of the NLF airfoils required high tolerances, perhaps even beyond the practicality of aluminum construction. Therefore, composite construction was considered for the NLF designs. Another potential problem with the NLF designs was the effect of debris, such as insects, collecting on the wings. However, NLF performance in this state was, at worst, equivalent to traditional NACA series airfoil performance. The final problem recognized with NLF airfoils was the low speed power requirements, which were potentially dangerous to student pilots. After considering all the advantages and disadvantages of the NLF airfoils, it was concluded that a NACA 6-series airfoil may be the best option for a low cost PFT with safe, desirable training characteristics. Conversely, for advanced GA designs, such as the ERAU AGATE design submittal, NLF airfoils were considered an effective choice.

Wing positions examined in the ADP and AGATE activities varied from low to mid to high wing. The driving force behind this parameter was primarily the general configuration of the aircraft. In other words, the engine and cabin area positions were of major concern to wing position. The structural weight and complexity of each wing configuration was another factor. The mid wing configuration appeared to be the least desirable due to complexities of wing structure at the cabin interface, while maintaining a desired cabin size.

4.2 Powerplant Selection and Position

Several powerplants were explored in the design studies. These included currently certified engines such as the Lycoming O-235 and non-certified engines such as the Zoche Diesel. The non-certified engines considered were engines with potential for near-term certification. Air cooled engines were the most common type of engine used, however, liquid cooled engines such as the Rotax 914 were also examined. For the pusher aircraft, it was determined that a liquid cooled engine may be most advantageous. This eliminated the problem of providing venting to the engine compartment, and thus reduced the associated drag as well. The tractor configuration aircraft would also benefit from the reduced cooling drag of a liquid cooled engine, however not as dramatically as the pusher.

In the course of the design activities, several configurations were considered for engine position. The first designs pursued were originally tractor and mid-engine configurations. Later in the study, a pusher configuration was added. The mid-engine concept was eventually phased out and modified to a tractor arrangement. This was due chiefly to the problem of the drive shaft required for such an aircraft. The drive shaft offered intriguing possibilities in acting as an aid in shock absorption upon impact. Examination was conducted of using the drive shaft to crumple in stages, thereby absorbing impact shock during a crash. However, the shaft added unnecessary weight, cost, and maintenance complexity to the aircraft design and was therefore removed from the design.

The incorporation of a ducted fan into the designs was made towards the end of the ADP and continues into AGATE. In the early stages of the studies, it was decided to first examine designs with more conventional powerplant configurations, even in the pusher configuration. However, upon further assessment of desired performance, safety, and noise characteristics, the ducted fan was considered for the pusher design. The inclusion of a ducted fan for the tractor designs would have been impossible concerning the practicality of both mounting the fan shroud and providing proper pilot visibility. For these very reasons, the pusher design seemed to provide a perfect testbed for the fan concept.

Mounting of the fan shroud was considered in several different configurations including incorporation into the tail boom design, as the booms granted obvious mounting points for the shroud. However, this configuration was thought to possibly cause complications in the operation of the ducted fan. Because a very small tolerance must be included between the blade diameter and the inside of the fan shroud, it is necessary to minimize any possibility of the blades striking the shroud. The mounting of the shroud to the tail booms, with a rigid connection (via a drive shaft) to the engine, could potentially introduce vibrations from the booms. This would thereby creating interference between the shroud and the blades. Therefore, another shroud mounting configuration under scrutiny is to mount the shroud directly to the aft portion of the fuselage. Yet another design being studied incorporates the ducted fan as a self contained unit attached to the tail booms, but connected to the engine through a flexible coupling. This would also reduce the vibration problem at the prop-shroud interface, but may add undesired weight to the design (despite the possible increased maintenance accessibility). The only practicable alternative to the pusher configuration would be a high mounted tractor or pusher configuration, such as is typically designed in amphibious aircraft. However, this type of design would produce undesirable thrust line effects versus the direct thrust line of a more "conventional" pusher engine mounting.

The reasoning behind the inclusion of a ducted fan in the advanced designs was multifaceted. The initial consideration was to improve the noise characteristics of the aircraft. Noise abatement can be addressed by three basic issues: propeller blade number, blade contour, and inclusion of a ducted fan. In the tractor configurations, the only options were to increase the blade number and modify the blade contour until desired noise characteristics were achieved. However, with the pusher, the ducted fan could be used, as well. By including a higher number of blades, the prop cost will increase significantly. Yet, by using a fan concept, the blade number can be kept to a minimum while still attaining favorable noise characteristics.

Admittedly, the fan will also increase the price of the aircraft. However, the price increase is accompanied by more than just improvements in noise abatement. Ducted fans are known to increase thrust due to their effect of increasing prop efficiency. This factor could potentially offset the extra cost of including the ducted fan. Also, in a mass production market, particularly the one projected for AGATE, this and other advanced technologies will be highly reduced in acquisition price (due to supply and demand).

Apart from the increased cost of a ducted fan, Foreign Object Damage may prove a potential problem for such a design. This problem is being considered by examining the spray pattern of debris off the landing gear tires. Corrective action could then be taken, if necessary, but may not be required due to the smaller disk area of the fan versus a regular prop. Additionally, one of the concepts for the self contained ducted fan includes a stabilizing strut from the fan to the fuselage. This strut may aid in protecting the fan from FOD.

4.3 Landing Gear

In approaching the landing gear design, the original decision in each ADP design was to use fixed gear. This was chosen due to the reduced cost (for design, manufacturing and maintenance) and complexity. The drag penalty and resulting performance reduction were not considered a problem with the original design goal of approximately 120 knots (for the ADP). In order to achieve higher cruise speeds (if so desired for upgrades of the design outside the PFT market, or more specifically, as required to achieve AGATE requirements), partially or fully retractable gear become necessary. In the original case (lower speed requirement), the early pusher designs considered oleo struts for both the nose gear and the main gear. Later study considered changing to a damped spring nose gear. This would greatly reduce the cost and complexity associated with oleo type gear. Spring gear could also replace the oleo gear for the pusher main gear, as was originally conceived for the tractor designs. Similar, but somewhat more advanced, concepts were also employed in the AGATE retractable designs which, again, were tailored towards crashworthiness.

4.4 Seating Arrangement

In order to create higher performance in each of the concepts, it was decided to examine the effect of incorporating staggered seating. This was done in both the tractor and pusher designs. Initially, it appeared intuitively obvious that by incorporating staggered seating, the resulting reduction in fuselage cross-section would produce improvement in aircraft performance. In order to check this, a related study was conducted[1] to examine the actual effects of cabin width upon performance. From the study, it was determined that the reduced fuselage cross-section associated with staggered seating actually had very little effect upon aircraft performance. For fuselages with larger length-to-diameter ratios, the change in diameter did not change performance appreciably.

One benefit of staggered seating in the cockpit was more shoulder room for the student and instructor, while still allowing the instructor to view the student at the controls and vice versa. Another benefit of the staggered seating arrangement in the pusher was that it allowed for the reduction of parallax in viewing instruments from the instructor's seat. This arrangement could potentially require a separate set of instruments for the instructor. With an advanced cockpit system of the projected AGATE variety (i.e., a glass cockpit system which incorporates all instruments with an on-board central computer system, displayed on screens in front of the pilot), this would pose little problem. The same central computer and instrumentation would be used to drive both the student and instructor displays. This would also dispose of parallax problems associated with today's instruments as well as the problems of side viewing associated with CRT displays. Using the AGATE type display in conjunction with a fly-by-wire control system would also eliminate problems with control system routing typically associated with staggered seating. However, an AGATE type system is not currently available and may not be for quite some time. The cost and complexities associated with staggered seating may not be worth the benefits in creating a low cost PFT in the immediate future. Therefore, these technologies are reserved for potential applications in the AGATE market to come.

The other major consideration in seating arrangement for the designs was the number of seats to be included. For the AGATE program, the design specifications called out a range of two, four, or six seat aircraft. A four seater was the choice for the 1995 AGATE design as middle ground, and due to the larger potential market (initially at least). However, in future AGATE design efforts at ERAU, it is anticipated that the designs will be expanded to an AGATE family of all seat configurations.

Since the primary mission of a PFT requires only a student pilot and an instructor on board, the obvious choice would be a two-seat configuration. However, ERAU utilizes a training program dubbed "Gemini" in which a second student pilot is to fly on training flights as an observer. This increases the seating requirement to a minimum of three seats. There are very few existing three-seat aircraft. The trend is to step from two seats to four seats. Yet, in order to keep the power and cost requirements to a minimum, it was decided to incorporate no more than three seats into the ADP designs. In the end, a two-seat configuration was seen to be the best for the general PFT market, excluding the "Gemini" program.

4.5 Crashworthiness and Occupant Safety

As stated previously, a primary focus of the ADP and AGATE was to address the issues of crashworthiness and occupant safety. The history of GA has shown little regard for these topics, which has made major contributions to the current nightmarish litigation situation. The goal of these projects was to create a revolution in the thinking associated with crashworthiness/occupant safety and GA. To accomplish this, the first problem to be addressed was to determine exactly how crash safety could be incorporated into all stages of the design process. This began with conceptual design, where students were informed of design attributes which could greatly enhance crash survivability (such as angling the bottom edge of firewalls/bulkheads directly in front of the crew to prevent scooping on impact). The problem was then expanded to include detail design. In this stage, crashworthiness was heavily addressed and fully developed. This was accomplished by determining design constraints that would ultimately conclude in a truly crashworthy design process.

The crashworthy design constraints originated from several sources. Although historically neglected in GA, crashworthiness and occupant safety have been widely researched and addressed by numerous sources such as the NTSB, NASA, the FAA, industry and academia. From the study of this broad database, general points for crashworthy design were selected. Precise design constraints were also determined from the FAR Part 23. From FAR 23.561, the loading conditions at impact were determined to be 9 or 18 g's, depending on the predicted impact scenario for a given component. From FAR 23.562, the conditions to be met were at both a 60 degree impact at 19 g's from the horizontal and at a 10 degree yawed frontal impact at 26 g's for occupant restraint systems and seats. These conditions were incorporated to address emergency landing conditions within the cockpit. From these regulations, the requirements for proper cockpit volume could be determined and the integration of a seat that could withstand a 26 g impact was found necessary. These total loading conditions, from FAR 23.561 and .562 were then to be used as the design guidelines, as they were found to be the worst possible loading constraints for crashes (as determined in the development of the regulations).

The loading constraints were then to be applied to all detail designs. The particular loading conditions applied to a given component were selected from the constraints. This was based on the position of the component in the aircraft. For example, if the component was in the cockpit, it would need to withstand the constraints for items of mass in the cockpit per FAR 23.561. The integration of a seat that could withstand 26 g's played an integral part in this. It reduced the loading constraints in some cases due to the fact that the seat could absorb 26 g's, thereby requiring less severe loading constraints for a related structure. In addition to applying the loading constraints to detail design, multiple features were evaluated for integration into a complete aircraft design which provided the highest level of crashworthiness and occupant safety possible. These included items such as the incorporation of crashworthy seats, restraint systems, and many other items.

Each design for the ADP and AGATE was created with the intent of surviving the worst case impact scenarios determined from FAR Part 23. However, it was worth considering a means of returning the aircraft to the ground in an emergency situation with as little stress as possible placed upon the occupants. To do this, a ballistic parachute was considered for integration into the designs. The pusher design provided a perfect opportunity to explore this option. More than sufficient volume existed in the cabin area behind the occupants for mounting a ballistic parachute system. This location was also directly in the CG range of the aircraft, thus providing for the desired balance upon deployment of the parachute. The package offered by Ballistic Recovery Systems[3] was used for comparison of volume and mounting requirements of a ballistic parachute for the ERAU designs. The particular package used for comparison was the Cessna 150/152 model. Although the incorporation of such a package was found to be possible, it was also determined to add considerable weight and cost to the overall aircraft design. Therefore, it was decided to include the BRS as a design parameter for both the PFT and AGATE designs, but to potentially offer it only as an option at the time of sales.

Crashworthy seats are becoming a reality slowly, but surely. In the development of the ERAU designs, a seat/restraint system developed by the Jungle Aviation and Radio Service was implemented. The seat, commonly referred to as the "JAARS seat," was the only seat available at the time that withstood dynamic testing requirements of FAR Part 23. Although the seat was never certified, it has been flown in a number of JAARS missionary aircraft. With the development of crashworthy seats under FAR 23.562 in the future, it will be possible to redesign the next generation GA aircraft around these alternate seats.

Another technology under investigation for occupant safety was the incorporation of airbags. This is one of many areas in which the automotive industry is far ahead of the GA industry. The integration of air bags into cars has saved numerous lives, prevented many injuries, and has even resulted in the reduction of insurance costs. Obviously, this is an area in which GA could use improvement. Therefore, in Phase III of the ADP as well as in AGATE design efforts, students were challenged with incorporating airbags into their designs. The installation of such devices has proven thus far to be a challenge in GA aircraft. Yet, studies have been conducted by the FAA, NTSB, and NASA in the incorporation of airbags into both GA and other types of aircraft. The student investigations have so far resulted in preliminary suggestions for airbag integration. One configuration considered involved mounting the airbag installation in the top of the instrument panel, perhaps set behind the instruments (requiring slight repositioning of the instruments as a possibility). This configuration is similar to some automotive installations and may reduce obstruction of the instrument panel while preventing an oversized and complex yoke design. Another possible configuration involved airbags installed in the headrests, similar to a design considered in military aircraft. The method employed in the AGATE design was to have the airbag deploy from the passenger side of the instrument panel, instantaneously expanding to cover the pilot's side as well.

Some of the other advanced technologies considered in the studies have included fire hazard reduction schemes and smart structures. Items such as impact activated fuel cut-off switches and fuel bladders have already been integrated into the later ADP designs. Additionally, a workable in-situ fire extinguishing system was designed for installation into the AGATE design. This design has led to the concept of a water spray system in the cockpit, with a chemical extinguishing agent introduced in the contained engine compartment behind the cabin area. Yet, items such as smart structures are still in the early stages of design. This is due primarily to the highly experimental status of such technologies, as applicable to GA. Following future developments in these areas, it may be possible to integrate them into future advanced GA designs in a cost-effective and practical manner.

By enhancing the overall safety attributes of GA aircraft, benefits additional to product liability will be realized. If GA were to appear an even safer mode of transportation to the general public (beyond its already exemplary record as compared to automobiles), then wider interest in the industry could potentially be realized. This would expand the market and thereby truly allow for not only a revitalization of the GA industry, but indeed would create a renaissance within the industry (as is projected for AGATE). Admittedly, the initial production cost of this new breed of crashworthy PFT would be higher than that of existing designs, and would also most likely be higher for AGATE. However, the possible reductions in product liability problems may easily counter this cost increase. The increased fuselage size of a crashworthy aircraft is also of concern at first glance. However, a study conducted at ERAU proved that the increased fuselage size would only affect aircraft weight and performance very modestly (about a 2 pound increase per inch of fuselage width, and a maximum of 5-10 knot decrease in cruise speed versus existing aircraft)[1].

4.6 The Recommended Platform

Of all the designs generated by the ADP, the twin boom pusher configuration was found to be the most successful. Although there were benefits to the other configurations studied, this one provided the best overall platform for integration of the technologies studied. The ADP pusher design has attributes which lend directly to the concept of crashworthy design. Therefore, this configuration was applied to the AGATE design efforts. In many GA crashes, the aircraft is subjected to belly-in landings where the underside of the aircraft sustains extensive damage and the props are destroyed. For fully or partially retractable gear designs (such as for AGATE), this issue is of prime concern. The ducted fan pusher configuration permits higher protection of the prop in such an impact scenario, in addition to the benefits discussed previously. Also, the possibility of a removable shock absorbing nose cone allows for easy replacement and/or removal and repair in the event of a relatively minor crash. The pusher concept was the most adaptable to the application of this and the other technologies discussed above.

5. Conclusion

This paper has discussed the study of the design of the next generation of general aviation aircraft as conducted through the ERAU/NASA/USRA ADP and AGATE design efforts. The various technologies and configurations studied throughout the ADP, AGATE and LARSS programs were discussed and recommendations were made regarding many of them. Certain areas of examination have not yet been completed, as the AGATE program continues, and with it further ERAU research through programs such as LARSS. From the efforts conducted thus far, a large database containing data on a myriad of GA technologies has been assembled at Embry-Riddle. The database consists of information on engines, airfoils, crashworthy related technologies and other items, as well as ERAU student and faculty reports, and external reports and articles. This database is offered as an item of interest for evaluation in the design of future GA aircraft, particularly PFT and AGATE designs.

6. Acknowledgments

The author would like to thank Dr. James G. Ladesic and Professor Charles N. Eastlake for their guidance and support throughout the duration of the ADP and AGATE design programs. Thanks also to Dr. Bruce J. Holmes and H. Paul Stough, III, of NASA LaRC for their support throughout the author's internships (as part of the ADP and LARSS programs). Special thanks goes to the students who participated in the ERAU/NASA/USRA ADP and AGATE design competition from 1992 to 1995.

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