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Assessment of the DARPA Affordable Polymer Matrix Composites Programs

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Assessment of the DARPA Affordable Polymer Matrix Composites Programs

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PREFACE

This work was performed under a Defense Advanced Research Projects Agency (DARPA) task entitled "Materials Science Analyses." The purpose of this task is to document the status of DARPA's Affordable Composites Program and to provide the necessary technical information and technical assessments for DARPA's Defense Sciences Offices (DSO) to make informed decisions on research and development (R&D) requirements and the direction of present and future R&D programs in materials science and materials processing.

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EXECUTIVE SUMMARY

Support for Polymer Matrix Composite (PMC) programs has been ongoing for over 20 years. The Air Force, the National Aeronautics and Space Administration (NASA), and the Navy provided early support for PMC development programs. Later, the Defense Advanced Research Projects Agency (DARPA), the National Institute of Standards and Technology (NIST), and Department of Energy (DoE) provided support. Industry internal research and development (IRAD) programs have also contributed to the advancement of PMCs; however, both government and industry programs were based primarily on performance, with only limited concern for the cost of producing the composite components. Even though the focus of Science and Technology (S&T) programs has shifted to reducing the cost of fabricating PMC components while still maintaining the performance gains enabled by composite materials, PMCs continue to be nagged by high cost. Most of this high cost was attributed to fabrication, tooling, and assembly.

In 1993, DARPA set out to address these continuing cost issues by establishing the Affordable PMC program. The goals of this program were to:

- Develop and demonstrate technologies that would reduce acquisition costs of composites for high-performance air vehicles and other platforms by 30+ percent
- Develop a composite structure equal to or lower than the cost of a metallic structure for transports and other "lower performance" applications
- Reduce prototype tooling costs and lead times by 40+ percent.

None of these projects were involved with significant materials development. Affordable processing was the key focus. The strategy behind the DARPA Affordable PMC program was to focus on technologies that impacted the cost drivers: design, fabrication, assembly, and prototype low-cost tooling. Multiple Phase I projects were funded to determine the most promising technologies. The Phase II projects would develop and mature the technologies. At the end of Phase II, the technologies would be transitioned either directly into weapon systems production or into follow-on Service activities.

However, in June 1995, DARPA management decided to eliminate the FY 1996–FY 1999 funding. Nearly all the projects were impacted by this decision, especially those that depended on the Phase II follow-on to mature the technology into commercialization. As a result, the expected maturation cycle would be delayed. Table ES-1 summarizes the objectives and current status of the refocused DARPA Affordable PMC program projects.

In addition, a 1995 Industrial Base study for PMCs conducted by the Office of the Under Secretary of Defense (Acquisition and Technology) (OUSD(A&T)) concluded that PMC "affordability issues associated with material production volume and component fabrication for military and commercial markets are being adequately addressed" by existing government programs. However, because the conclusions of the 1995 Industrial Base study were partly based on the existence of the DARPA Affordable PMC program, some concerns arose when DARPA decided to eliminate funding for these projects.

In response, DARPA initiated an assessment of the Affordable PMC program to determine how mature the technologies would be when each of the refocused projects ended. Based on the maturity scale developed in this assessment, the maturity of these technologies toward affordable composite usage is as follows:

- Although most of the projects were impacted by DARPA's funding decision in 1995, all the projects will complete a feasability demonstration in their refocused plans.
- Technology developed and enhanced in three DARPA projects—Fiber Placement Benchmark, Cure-form Processing, and the Fan Cowl Door (FCD) task under the Affordable Composite for Propulsion (ACP) project—will be transitioned to production programs.
- The fan blade task and the Fan Inlet Case/Inlet Guide Vanes (FIC/IGV) task under the ACP project will continue to mature to a higher level under the Joint Strike Fighter (JSF) program. Several other projects are being supported in other programs; however, it is uncertain if the amount of funding from these programs will mature the DARPA projects to a significant level. These projects include Precision Assembly, Electron Beam (E-beam) Processing, and Rapid Placement Technology for Affordable Composites (RAPTECH).
- Projects that did demonstrate potential cost savings but remain immature and have not been supported in other programs are WeldTech, Induction Heating, Integrated Airframe Technology for Affordability (IATA), Affordable Tooling, and the Fan Exit Case (FEC) and the Fan Containment Case (FCC) tasks under the ACP project.

Table ES-1. DARPA Affordable PMC Program Projects: Objectives and Status

Title	Objective	Status
Affordable Polymer Composite Structures: E-Beam Processing	To demonstrate the cost benefits and structural adequacy of the e-beam process for aircraft structures	Project is entering end of Phase I with technology demonstration activities progressing.
Integrated Airframe Technology for Affordability (IATA)	To demonstrate the feasibility of design/ process synergism with unitized structures and bonded assembly composite properties	Phase I complete. Results show that weight savings of 33 percent and cost savings of 65 percent are achievable.
Cure-form Processing	To demonstrate the cost benefits and structural adequacy of the process and develop a design guideline	Original project was descoped to focus on producing design and processing guidelines.
Rapid RTM Tooling Project (RaPat)	To use rapid prototyping technologies to reduce the cost and lead time for RTM prototype tooling and verification articles	An F-117 access door and the RAH-66 Transmission support fitting have been selected as demonstration articles.
Induction Heating	To develop and demonstrate the benefits of using an induction heating cell for curing and joining composites	Project has been completed.
Affordable Tooling	To develop and demonstrate low-cost tooling approaches for non-autoclaved and autoclaved material systems	Tooling is being developed. Non-autoclaved materials characterization has just started.
WeldTech	To develop and demonstrate the cost benefits and structural adequacy of induction-welding thermoset and thermoplastic composites for aircraft structures	Data were presented at the 1996 SAMPE Conference.
Precision Assembly	To identify the root causes of assembly cost and develop/demonstrate techniques to reduce these costs. Recommend follow-on projects to improve airframe assembly	Assembly cost drivers have been identified. The program is focusing on reducing the thickness variation in composite parts.
Fiber Placement Benchmark and Technology Road Map	To determine the capabilities of the latest fiber placement machines and prepare guidelines for their use; define additional improvements	Project will complete the design guidelines and fiber placement of more complex part features.
Rapid Placement Technology for Affordable Composites (RAPTECH)	To develop in-situ fiber placement of thermoplastics and verify structural adequacy/cost effectiveness for aircraft structures	Fabrication of panels to verify structural properties has been completed.
Affordable Composites for Propulsion (ACP)	To design propulsion components to take advantage of RTM and fiber placement processes and verify their affordability by building and testing structures	Extensive RTM and fiber placement process maturation has occurred.

I. INTRODUCTION

Support for Polymer Matrix Composite (PMC) programs has been ongoing for over 20 years. The Air Force, the National Aeronautics and Space Administration (NASA), and the Navy provided early support for PMC programs. Later, the Defense Advanced Research Projects Agency (DARPA), the National Institute of Standards and Technology (NIST), and Department of Energy (DoE) provided support for PMC development programs. Industry internal research and development (IRAD) programs have also contributed to the advancement of PMCs; however, both government and industry programs were based primarily on performance, with only limited concern for the cost of producing the composite components. With the end of the Cold War, these programs have become more cost conscious and adverse to technical risk. The focus of Science and Technology (S&T) programs then shifted to reducing the cost of fabricating PMC components while still maintaining the performance gains enabled by composite materials.

Cost reduction concerns in PMC technology, however, have surfaced previously. An assessment by the National Science Foundation (NSF) in 1978 (Ref. 1) identified several cost reduction areas for the then current PMC technology. These areas included raw materials, fiber manufacture, parts fabrication, and assembly. At that time, advanced composites were considered principally for specialized applications where performance requirements were a premium and first-production component cost considerations were secondary. The 1978 NSF study emphasized that this narrow focus on performance had to change and that first-production component cost considerations were important. Finally, this study concluded that advanced composites would find significant commercial use if performance and cost criteria could be achieved simultaneously.

PMCs continued to be nagged by high cost. Most of this high cost was attributed to fabrication, tooling, and assembly, as shown in Figure I-1. In 1993, DARPA set out to address these continuing cost issues by establishing the Affordable PMC program. The goals of this program were to:

- Develop and demonstrate technologies that would reduce acquisition costs of composites for high-performance air vehicles and other platforms by 30+ percent

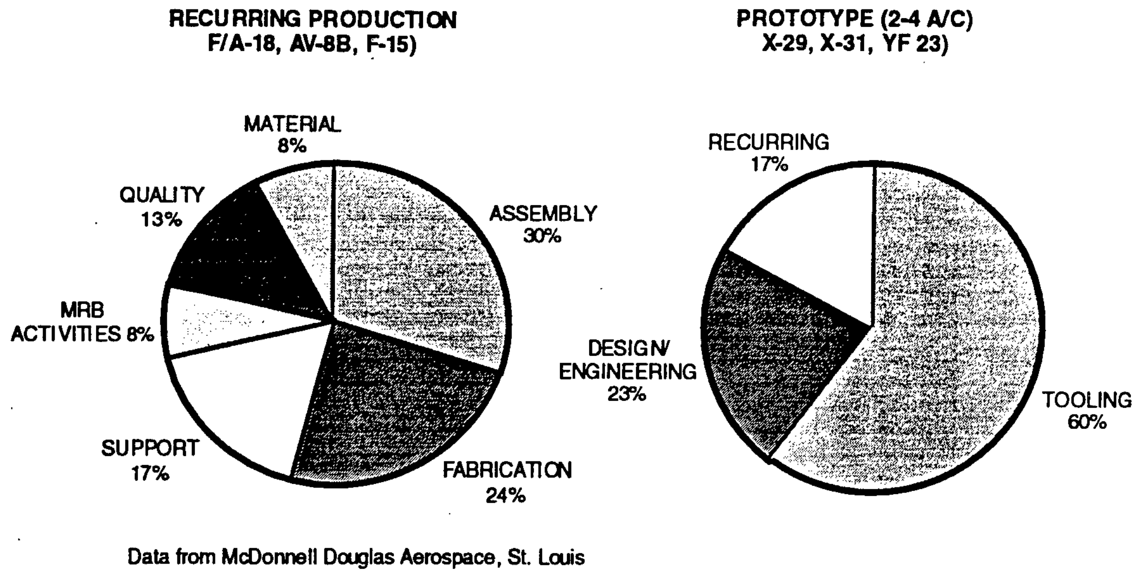


Figure I-1. Historical Cost Data Used to Develop DARPA's Affordable PMC Program

- Develop a composite structure equal to or lower than the cost of a metallic structure for transports and other "lower performance" applications
- Reduce prototype tooling costs and lead times by 40+ percent.

The strategy behind the Affordable PMC program was to focus on technologies that impacted the cost drivers: design, fabrication, assembly, and prototype low-cost tooling (see Figure I-2). Multiple Phase I projects were funded to determine the most promising technologies. The Phase II projects would develop and mature the technologies. At the end of Phase II, the technologies would be transitioned either directly into weapon systems production or into follow-on Service activities.

Three types of projects were initiated to meet the goals.

1. A set of DARPA core projects addressed high-risk, high-payoff areas that the industry would not pursue on its own.
2. The Advanced Materials Partnerships supported tasks to provide near-term (3–5 years) benefits. In this project, industry shared 50-percent of the cost.
3. The Technology Reinvestment Project (TRP) focused on near-term insertion. Again, industry shared greater than or equal to 50 percent of the program cost.

Most of the tasks under these projects started mid FY 1994. The remainder started in FY 1995 (see Figure I-3).

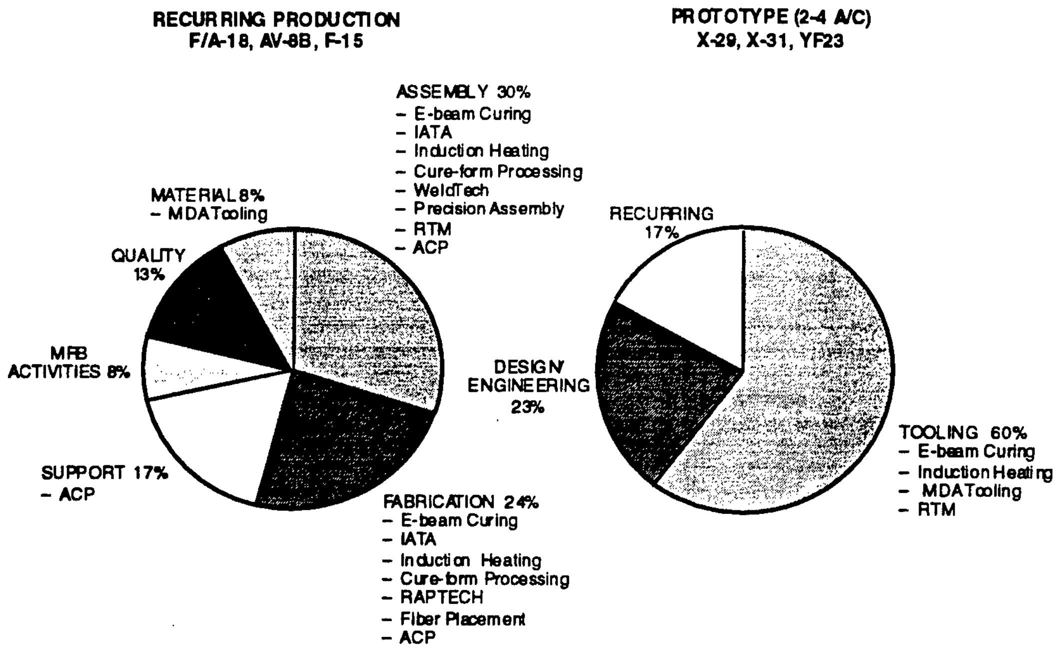


Figure I-2. Major Cost Drivers Addressed by DARPA's Affordable PMC Program

The high-risk, high-payoff core projects were expected to have Phase II follow-on efforts beginning in FY 1997 and ending in FY 2000. The remainder of the projects were expected to finish in the FY 1997/1998 timeframe. The maturing efforts of the Affordable Composites for Propulsion (ACP) project were aligned with the Integrated High Performance Turbine Engine Technology (IHPTET) needs, and the results of this DARPA project were to be added to the IHPTET road map. Transition to Service sponsorship, such as the Composite Affordability Initiative (CAI),[1] was also planned.

In June 1995, DARPA management decided to eliminate the FY 1996–FY 1999 funding. Nearly all the projects were impacted by this decision, especially those that depended on the Phase II follow-on to mature the technology into commercialization. As a result, the expected maturation cycle would be delayed.

1 The CAI objectives are to develop the tools and technologies necessary to enable aircraft designers to design all-composite airframes. These designs would use revolutionary design and manufacturing concepts to enable breakthrough reductions in cost and weight. CAI membership includes the Air Force, the Navy, and industry. The intention of the fast-track demo and pervasive technologies is to develop technology to the point that it can be directly transitioned to the Joint Strike Fighter (JSF) program within the next 2 years.

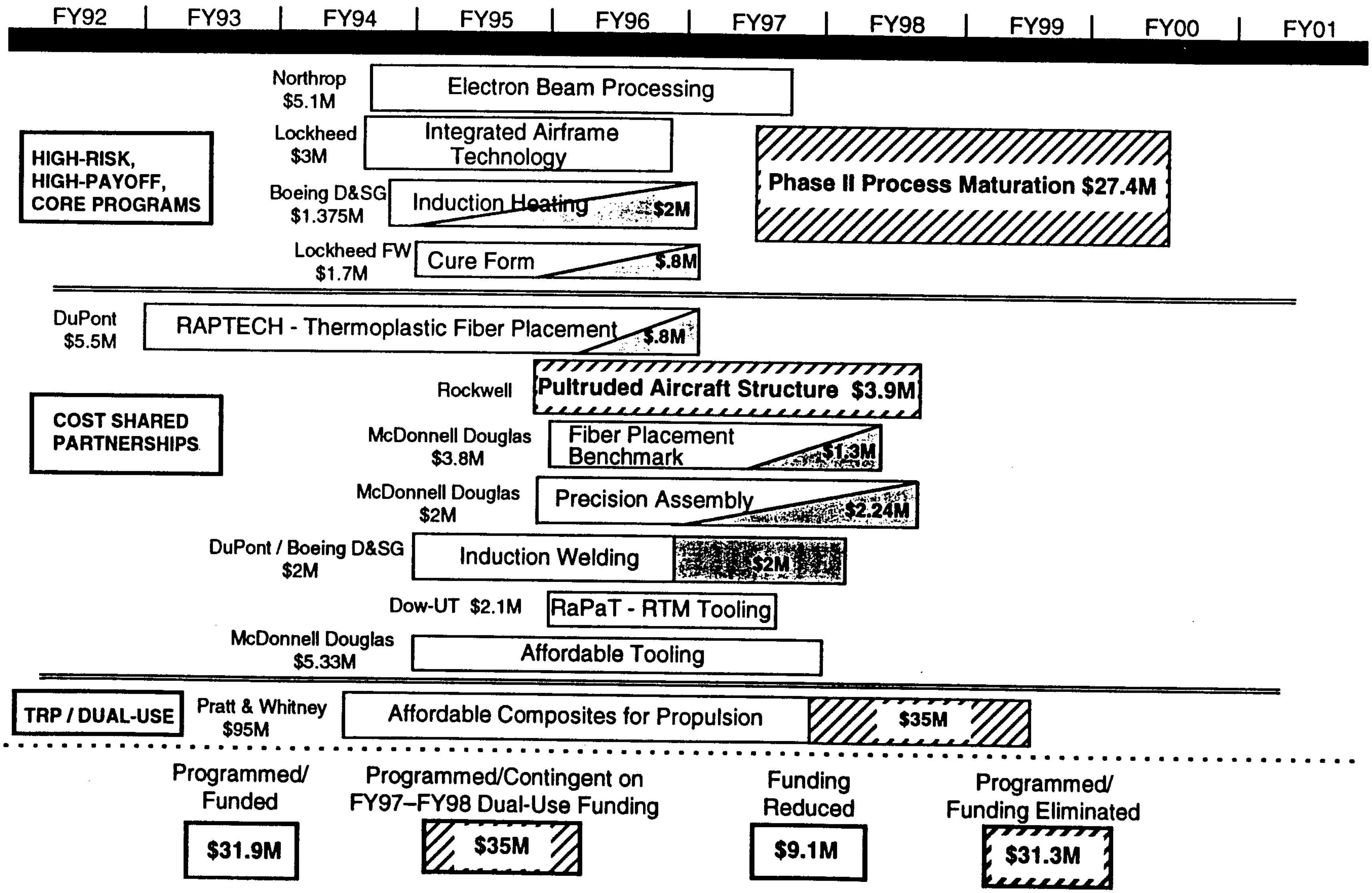


Figure I-3. DARPA Affordable Composites Initiative

In addition, a 1995 Industrial Base study for PMCs conducted by the Office of the Under Secretary of Defense (Acquisition and Technology) (OUSD(A&T)) (Ref. 2) concluded—based, in part, on the existence of the DARPA programs—that PMC "affordability issues associated with material production volume and component fabrication for military and commercial markets are being adequately addressed" by existing government programs. However, because the conclusions in the 1995 Industrial Base study were partly based on the existence of the DARPA Affordable PMC program, some concerns arose when DARPA decided to eliminate funding for these projects. In response, DARPA initiated an assessment of the Affordable PMC program to determine how mature the technologies would be when each of the refocused projects ended.

II. DARPA PROGRAM ACCOMPLISHMENTS

This section summarizes the progress in the DARPA projects and itemizes the major achievements to date. Table II-1 lists the titles, contractors, and objectives of each project. None of these projects were involved with significant materials development. Affordable processing was the key focus.

A. AFFORDABLE POLYMER COMPOSITE STRUCTURES: ELECTRON BEAM (E-BEAM) PROCESSING

In e-beam processing, a stream of high-energy electrons provides the energy needed to initiate polymerization and cross-linking via cationic, anionic, or free radical mechanisms. Chemically active species, such as cationic photoinitiators, are added to resins developed for thermal curing so that these resins can be e-beam processed (i.e., e-beam resins require a different chemistry). Aerospatiale had been using e-beam processing for rocket motor cases and realized a 30-percent cost reduction in tooling and 20-percent reduction in recurring cost over autoclave processing. Although they were using aerospace-grade resins and fiber, the e-beam-processed parts were inadequate for airframe application because of greater than 2 percent voids in the final structure. Before DARPA's involvement in this area, little work was aimed specifically at airframe applications.

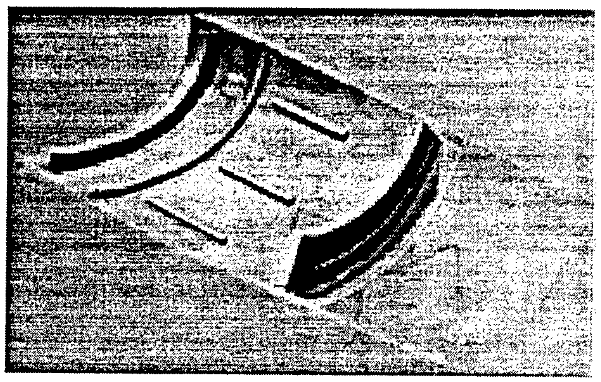
Northrop Grumman was the prime contractor for DARPA's e-beam processing effort. The Phase I objectives were to demonstrate e-beam technology feasibility for low-cost aircraft primary structural components, improve manufacturing processes for enhanced quality and performance of the e-beam-processed parts, and assess cost benefits for e-beam technology related to fabrication and assembly costs. Key accomplishments to date include the following:

- Achieving greater dimensional control using e-beam processing such that the amount of shimming during assembly can be decreased
- Using low-cost tooling materials, such as wood or plaster, and fabricating tools quickly
- Co-curing/co-bonding dissimilar materials, which can reduce tooling and fabrication costs and provide design flexibility.

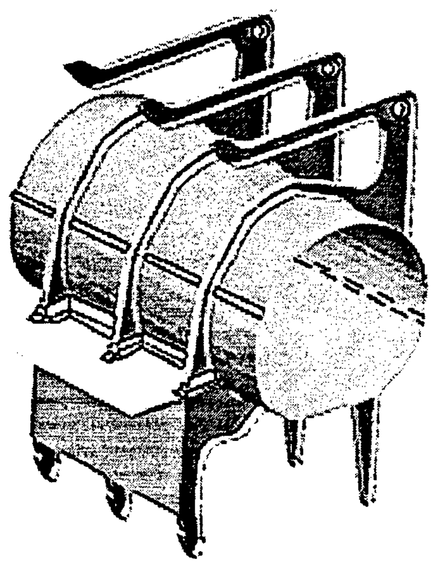
Table II-1. DARPA Affordable PMC Program Projects

Title	Contractor	Objective
Affordable Polymer Composite Structures: Electron Beam (e-beam) Processing	Northrop; Aerospatiale; SRL; FMC	To demonstrate the cost benefits and structural adequacy of the e-beam process for aircraft structures
Integrated Airframe Technology for Affordability (IATA)	Lockheed (Skunk Works); Dow-UT; Alliant; AECL	To demonstrate the feasibility of design/ process synergism with unitized structures and bonded assembly composite properties
Cure-form Processing	Lockheed Fort Worth	To demonstrate the cost benefits and structural adequacy of the process and develop a design guideline
Rapid RTM Tooling Project (RaPat)	Dow-UT; Lockheed; Sikorsky	To use rapid prototyping technologies to reduce the cost and lead time for RTM prototype tooling and verification articles
Induction Heating	Boeing Defense & Space Group (DSG)	To develop and demonstrate the benefits of using an induction heating cell for curing and joining composites
Affordable Tooling	McDonnell Douglas Aerospace (MDA); EDS; Radius Engineering	To develop and demonstrate low-cost tooling approaches for non-autoclaved and autoclaved material systems
WeldTech	DuPont; Boeing DSG; University of Delaware	To develop and demonstrate the cost benefits and structural adequacy of induction-welding thermoset and thermoplastic composites for aircraft structures
Precision Assembly	MDA; Fiberite; Radius Engineering	To identify the root causes of assembly cost and develop/demonstrate techniques to reduce these costs. Recommend follow-on projects to improve airframe assembly
Fiber Placement Benchmark and Technology Road Map	MDA; Northrop Grumman	To determine the capabilities of the latest fiber placement machines and prepare guidelines for their use; define additional improvements
Rapid Placement Technology for Affordable Composites (RAPTECH)	University of Delaware; DuPont; Cincinnati Milacron; Hercules	To develop in-situ fiber placement of thermoplastics and verify structural adequacy/cost effectiveness for aircraft structures
Affordable Composites for Propulsion (ACP)	Pratt Whitney; Northrop Grumman; DuPont; Dow-UT; Alliant; MDA	To design propulsion components to take advantage of RTM and fiber placement processes and verify their affordability by building and testing structures

A paper study by Northrop Grumman also indicated a potential 30- to 60-percent reduction in total fabrication cost over the current vacuum bag and autoclave fabrication processes. When DARPA announced that the PMC projects would not have a Phase II follow-on, Wright Lab worked with Northrop Grumman to refocus its efforts. Remaining resources were reprogrammed to demonstrate large-scale application of the technology. These efforts included two detailed assembly demonstration articles (one bonded with no fasteners and one mechanically fastened to show improved fit-up and reduced shimming) and one full-scale, unitized fuselage section targeted for the JSF. Figure II-1 shows these articles. These efforts, along with an update on the cost benefit analysis, will be completed by December 1997.



"Bonded" Assembly



Unitized Fuselage Section

Figure II-1. E-beam Demonstration Articles

B. INTEGRATED AIRFRAME TECHNOLOGY FOR AFFORDABILITY (IATA)

The overall objective of this project—performed by Lockheed Skunk Works—was to design an airframe structure to take full advantage of composite material properties and low-cost manufacturing processes. This project demonstrated that composite aircraft components had to be designed differently to take advantage of the composite properties. Lockheed finished this effort in July 1996 and accomplished the following:

- Provided a production solution for a 95-percent composite fighter that could be built "affordably"
- Provided clear definitions of required production processes, methods to implement, and development needed to get the technology into production
- Produced full-scale demonstration articles to augment its study
- Constructed an extensive bottoms-up cost and weight reduction database to support its design model.

Lockheed was able to show a 65-percent reduction in recurring production costs for the 100th article produced and a 33-percent reduction in weight of an airframe article. Although some of the non-autoclave processes used to produce several of the full-scale parts were not as mature as the autoclave processes [i.e., e-beam processing, vacuum-assisted resin transfer molding (VARTM)], Lockheed was still able to demonstrate lower manufacturing costs. Lockheed, in its final presentation, recommended that more work was needed to develop resin systems specifically for e-beam processing and to fabricate full-scale parts to qualify these materials and the curing process.

The originally planned Phase II effort was intended to verify the new design approach developed in Phase I by fabricating large-scale structures. Although this Phase I effort generated interest and received much attention, no one has continued support for this effort. One possible reason why IATA has not been accepted is that it was a radical departure from traditional design philosophy and did not have adequate data to support its cost and weight reduction claims.

C. CURE-FORM PROCESSING

The objectives of this Lockheed-Fort Worth project were to demonstrate and validate cure-form processing cost savings and technical feasibility by fabricating selected tactical aircraft composite elements of varying degrees of difficulty. The cure-form process eliminates some of the bagging operations required for autoclaving and allows for low-cost tooling. Figure II-2 shows a schematic of the process.

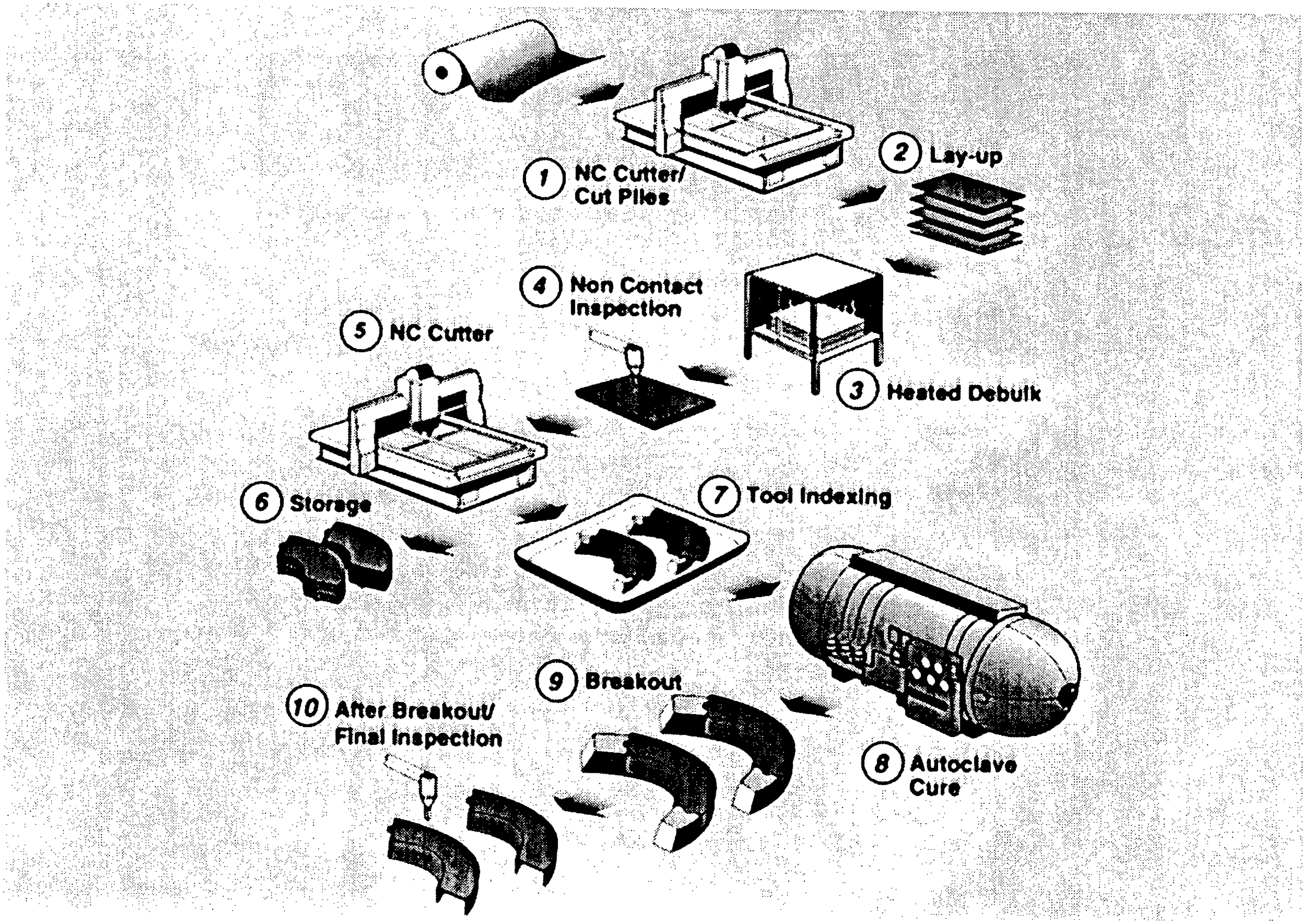


Figure II-2. Cure-Form Processing Demonstrates and Validates Lockheed Martin Tactical Aircraft System (LMTAS) Low-Cost Composite Manufacturing

"Staged" laminates are cut, layed up, and debulked. After non-contact inspection, the debulked material is then cut and can be stored or formed over near-net-shaped, low-cost tools and autoclaved. This project's major accomplishment was the cure-form design guide. This guide documented the relationships of part features, tooling, and process strengths and limits. Data for the design guide were collected from work in the cure-form project and from Lockheed's IRAD work. Elements to be fabricated for demonstrating cost savings include a horizontal tail spar for the F-16 and a fuel tank lower frame for the F-22. At the time of this paper, no data were available on the properties of the cure-formed parts or the estimated cost savings that this process could achieve over resin transfer molding (RTM) or conventional hand lay-up. The impact of DARPA's funding decision was minimal.

D. RAPID RTM TOOLING PROJECT (RaPat)

The long lead time and high costs associated with hard tooling have hindered the use of RTM as a process even though it can produce a consistent, dimensionally accurate part. The objective of the RaPat project was to reduce time and cost of RTM prototype tools and to demonstrate these savings by producing subelement parts made with these lower cost tools.

Dow-UT was the prime contractor for this project. Sikorsky Helicopter and Lockheed Martin Skunkworks were involved in the design and evaluation of the selected prototype RTM tooling used to produce RAH-66 transmission support fittings and an F-117 access panel. Out of the eight tool families, Dow-UT identified two families that were especially high cost and had long lead times: preform tools[2] and mold die tools. Several different materials and process approaches were evaluated for reducing the lead times and costs for these types of tools. Each material and process combination was evaluated for dimensional accuracy, durability, handleability, cost, and fabrication time. Several tool families have been selected to produce the subcomponent parts. Both parts being produced in this project will incorporate a combination of the preform and mold die families. At least three of each part will be produced.[3]

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2 Preform technology is complicated. Many pieces are involved in this process, and the tools require extensive handling. Dow-UT is documenting reasons for using preform tools vs. simpler tools in the applications they are addressing in this project.

3 The preliminary cost data derived from the family of tools studied was somewhat skewed. Several of the vendors had never built mandrels this large. As they gain more experience, the cost and lead time for some of the prototype tooling may decrease.

This project will continue through December 1997. DARPA's decision did not affect funding for this project.[4]

E. INDUCTION HEATING

The primary focus of the PMC program's induction heating project was to establish the process parameters to yield properties equivalent to autoclaved materials and to achieve reduced processing time. Although funding cuts led to an abbreviated project, Boeing Defense & Space Group (DSG) achieved important results with PMCs:

- Developed thermal and electrical models that gave an order of magnitude increase in susceptor efficiency
- Completed thermoset composite process trials using 8552 and BMI 5250-4 resins and transferred the revised 5250-4 cure cycle to the F-22 program.
- Completed a design concept for an all-composite wing tip to be induction heat cured
- Completed baseline joining trials to show weight and cost savings.

The open hole compression (OHC) properties for the IM7 BMI 5250-4 composite material were lower than the minimum values established for this project; however, the mechanical strength was comparable to the goals established by Boeing DSG.[5] A significant decrease in the processing time was realized using induction heating vs. autoclave processing for the same resins. However, the cost savings estimated for the all-composite wing tip were not completed at the time of this report.

Phase II was supposed to demonstrate tooling and overall cost savings that could be achieved with this process. When using induction heating, the real cost savings is the flexible fabrication capability it can provide: multiple parts composed of different materials can be processed in a single induction heating cell. Boeing DSG has demonstrated that super plastic forming/diffusion bonded (SPF/DB) titanium, polymeric composites, brazed honeycomb, and titanium welding can be processed through induction heating. This capability saves on the amount of equipment required for each of these materials and saves processing time. Normally, it takes ~12 hours to cure brazed titanium honeycomb in a

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4 Dow-UT was also involved in two other DARPA Affordable Composites Initiative projects: IATA and ACP. Its participation in these projects involved the RTM process rather than tooling.

5 The minimum desired material properties are given in an interim report by Boeing DSG, September 1995. The origin of these values was not given.

vacuum furnace. Using induction heating, Boeing DSG has been able to decrease this time by a factor of 10.

F. AFFORDABLE TOOLING

The objective of the McDonnell Douglas Aerospace (MDA) Affordable Tooling project was to:

- Demonstrate a range of low-cost autoclave and non-autoclave tooling concepts
- Prove that high-quality, flightworthy composite structures can be produced on a repeatable basis by taking advantage of low temperature/low pressure non-autoclaved materials and innovative tooling designs.

The project approach was to build on the existing MDA IRAD investment and on the Air Force's Low-Cost Composite Processing (LCCP) program.

The Affordable Tooling project addressed tooling costs (Task I) and non-autoclaved materials (Task II) concurrently. Task III was supposed to demonstrate tooling designs for autoclave and non-autoclave processing. Several of the tooling tasks also complement activities MDA had in the Joint Strike Fighter (JSF) Advanced Lightweight Aircraft Fuselage Structure (ALAFS) program. The Affordable Tooling project was set back because of a long strike at MDA in 1996 and, as a result, has analyzed only a limited amount of data at this time.

Work in progress includes:

- Implementing significant design time savings for the C-17 aft landing gear pod fairing tooling using the Composite Tool Design System (CTDS)
- Optimizing low-cost tool fabrication technologies that use spray lay-up chopped glass and graphite tools with subsequent arc sprayed metal coating to improve tool durability
- Evaluating robotic arc spraying for metal coating on tools
- Completing a manual design of the C-17 aft fairing tool and comparing man-hours and cost to those of the CTDS for a similar tool.

Most of the work in the enabling materials task has been delayed because of material availability. Initially, the task was to expand the work in the LCCP by investigating higher modulus fibers—Hexcel IM7, Amoco T650-42, and Amoco G40-800—with the F511 resin.

Hexcel then stopped making the F511 resin, and the project had to find other vendors for a similar resin. Two resins are being evaluated: ACG's modified LTM45EL and Cytec's modified CYCOM-753. In addition to the modification in the resins, MDA has experienced a shortage of AS4 carbon fiber. MDA will be substituting AS4-like fiber (Toho HTA and Amoco G30-500) to complete the project.

G. WeldTech

The objective of the WeldTech project was to weld or join composites without fasteners. According to the airframe companies' cost data, the weight and production time can be reduced greatly by eliminating metal fasteners. Boeing DSG and Dupont worked together on the WeldTech project. Boeing DSG had been involved in welding thermoplastics, but welding thermosets presented a new challenge. By trial and error, they were able to identify a thermoplastic interlayer that was soluble with the thermoset material. The thermoplastic interlayer did not alter the curing properties of the thermoset. Also included in this "glue joint" was a copper mesh—the susceptor required for induction heating. Figure II-3 shows this method.

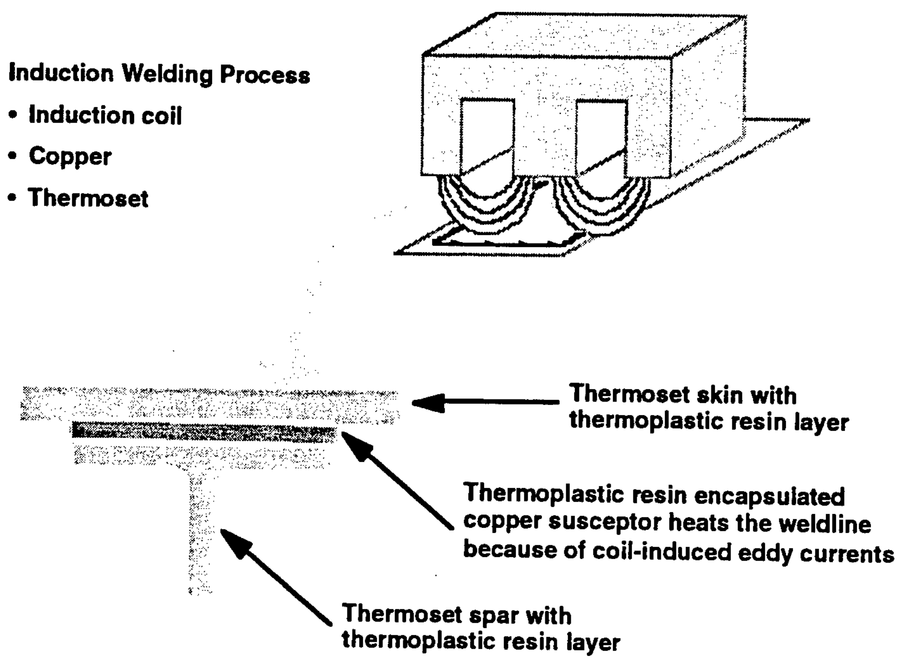

Figure II-3. Induction Welding Process Developed in the WeldTech Project

The thermoset systems that were tried were Hercules 3501-6/IM6 tape and 3501-6/AS-4 fabric; however, halfway through the project, Boeing determined that the 3501-6 system would not work. When joints were tested, failure would occur in the parent thermoset (3501-6) and not in the bond line area. This indicated that the thermoset was the weakest component of this system. Boeing switched to Hercules 8552/AS-4 fabric, a toughened thermoset, but only obtained a limited amount of data before the project ended. Even though none of thermoplastic adhesives investigated—polysufone, polyethersufone, and polyetherimide—were of aerospace quality because of their poor solvent resistance, they were sufficient for proof-of-concept demonstration.[6] To date, most of the data obtained are based on the 3501-6 resin. The initial data for the 8552 resin indicated higher pull-off strengths, with failures occurring at the edge of the weld line.

For proof-of-concept purposes, Boeing welded a 50-in. spar to a skin section using the 3501-6 system. The induction weld head moved at 1.25 in./minute. It took four passes to weld the section together. Boeing also showed that re-welding incompletely joined areas on other smaller samples was possible. Boeing's cost model, based on the A-6 wing, showed a 60-percent cost savings for the assembly of a skin to substructure by using induction welding instead of metal fasteners. This project ended in December 1996. A Phase II follow-on was not funded.

H. PRECISION ASSEMBLY

MDA was the prime contractor for the Precision Assembly project. This project's goal was to reduce the cost associated with the assembly of composites. The project focused primarily on the causes of variability of part dimensions and on fit-up problems, which represented the major cost drivers associated with assembling composites. Root causes—identified early in the project—included in-coming material variability, thickness variations, spring-in caused by residual stresses, and processing variations. MDA studied several materials and processes and documented the variations. These results fed into the variation validation and the cost-benefit analyses. The project's scope was narrowed when funding was reduced. Consequently, residual stress, spring-in, and fit-up were not addressed to the same extent as materials variability. Phase II of the project—to demonstrate assembly variability prediction and control on a part with problem features—was dropped. Since this project was also delayed by the MDA strike, only a limited amount of progress has been made.[7]

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6 The results were presented at the 28th International Society for the Advancement of Materials and Process Engineering (SAMPE) Conference in Seattle, Washington, on November 4–7 1996.

7 The MDA projects will finish ~ 6 months later than originally planned with FY 1995 funding.

I. FIBER PLACEMENT BENCHMARK AND TECHNOLOGY ROAD MAP

MDA was the prime contractor for the Fiber Placement Benchmark project. Northrop Grumman also participated in this project. The project's objective was to determine the capabilities of the latest fiber placement machines and to develop fiber placement manuals/ guidelines. From these efforts, the development of a technology road map was envisioned. This road map would identify desirable near-term modifications to existing equipment and provide guidance for long-term evolutionary development for these systems. The fiber placement applications included several F/A-18E/F structures and several propulsion components from the ACP project. The manufacturers of the fiber placement machines, Cincinnati Milacron and Ingersoll, were not directly involved with the project. Also, because of the reduced funding, this project did not address fiber steering (moving the fiber tows) around airfoils and other odd shapes.

J. RAPID PLACEMENT TECHNOLOGY FOR AFFORDABLE COMPOSITES (RAPTECH)

This project developed an automated, in-situ, tow placement head for thermoplastic impregnated fiber tows. Application of this process was slated for relatively flat areas, such as wing skins, or round configurations, such as rocket motor cases. RAPTECH was a follow-on project to an earlier DARPA-funded program that combined the fiber placement experience of Hercules, process modeling, process simulation, sensing expertise of the University of Delaware, and thermoplastic in-situ consolidation technology expertise of DuPont. The goals of RAPTECH were to:

- Develop the next-generation head technology for automated thermoplastic tow placement by incorporating an on-line sensing and control system
- Demonstrate the ability to produce high-quality in-situ laminates with properties approaching those from autoclave processes.

The tows are pre-coated with a dry thermoplastic resin and fed through the RAPTECH heated head. The resin melts, and the pressure of the head consolidates the resin/tow system to form laminates on a tool. Properties that were obtained for thermoplastic fiber/resin systems IM7/PEEK and IM7/PEKK met or exceeded those obtained for the same materials processed by traditional autoclave processing. For the polyimide fiber/ resin system, IM7/K3B, the mechanical properties were only 85 percent of the same materials processed by autoclaving. To obtain autoclave properties with IM7/K3B, a final autoclave curing is required to achieve full autoclaved material properties. The cost savings for this type of processing should be significant since it eliminates hand lay-up, long autoclave times, and debulk cycles. However, the project did not quantify the amount of these cost savings or produce specific components.

K. AFFORDABLE COMPOSITES FOR PROPULSION (ACP)

The ACP project was designed to develop advanced manufacturing processes and technologies that could reduce the cost and weight of aerospace structures for future ultra-high bypass engines. Pratt & Whitney led this consortium and was responsible for component integration, assembly, and testing. Others involved included Northrop Grumman, who focused on the engine nacelle [mainly the core cowl (CC)]; DuPont, who developed the fan blade containment structures, associated materials, and fabrication processes; MDA, who fiber-placed the skins on the fan cowl doors (FCDs); Alliant Tech, who provided fiber placement knowledge, and Dow-UT, who built the fan exit case (FEC) and fan inlet case/inlet guide vane (FIC/IGV) structure using RTM processing.

RTM and Automated Tow Placement (ATP) were processes used to build the composite structures. Another focus of the ACP project was to accurately define the cost of manufacturing parts by RTM and ATP to enable a "true design-to-cost" approach for future products. The following are accomplishments:

- **Fan Exit Case (FEC).** One of the prototype FEC components was successfully static-load tested to verify the capability of withstanding the dynamic blade-loss loading. Fatigue capability and damage tolerance were validated on 10 of the strut components. Birdstrike resistance, hardbody foreign object damage (FOD) resistance, hail strike resistance, and bending capability were tested on airfoil subcomponents. Because of DARPA's funding decisions, the horizontal containment rig (HCR) test to validate the survivability of the FEC in the event of a blade-out will not be performed, and accelerated durability testing will be dropped.
- **Fan Containment Case (FCC).** Three FCCs were fabricated using the ATP technique to form the overlapping ribs of the isogrid structure. The demonstration cases have successfully met the weight reduction goals of this project. Ballistic tests have indicated that the isogrid stiffener-to-shell interface will successfully withstand the impact of a blade loss. Funding decisions also impacted this part of the ACP project, and no further performance testing is planned at this time.
- **Fan Blade Development.** A baseline fan blade design was completed using a two-dimensional (2-D) fiber architecture. Figure II-4 shows the full-

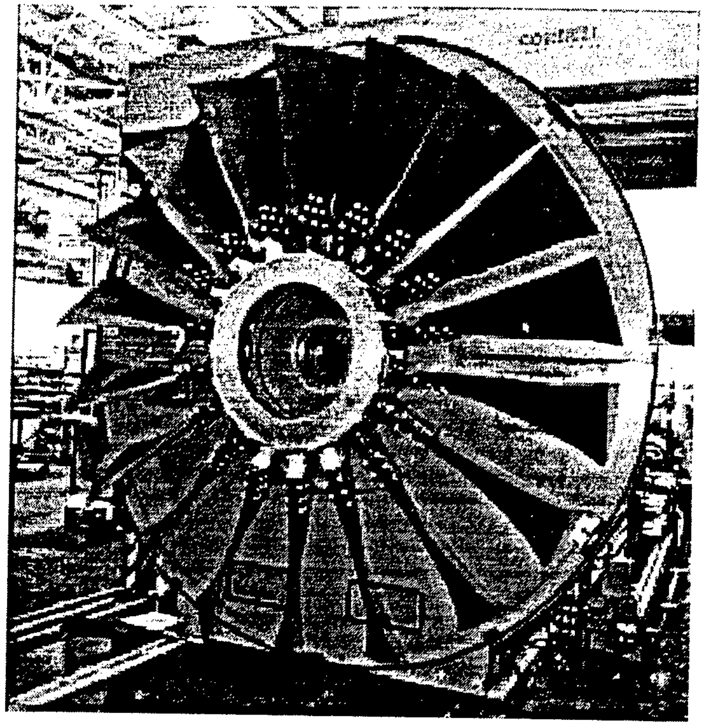

Figure II-4. RTM Full-Scale Composite Fan Blades

scale fan blades on a test stand. This architecture was augmented with through-thickness stitching to improve the interlaminar properties and increase the toughness of the structure. Because of the birdstrike testing, blade architecture modifications are currently being evaluated. These modifications include using additional material in the high-stress regions, changing the root angle and root curvature to soften the transition from the root to the airfoil, and using three-dimensional (3-D) weaves and other fiber architectures to enhance the toughness of the structure.

- **Fan Cowl Door (FCD).** A total of 11 demonstration FCDs were fabricated in this project. The demonstration door skins were made using the ATP method at MDA. Northrop-Grumman fabricated the hat-section stiffeners and completed the assembly. Materials characterization, impact damage assessment, thermal cycling, and a preliminary assessment of the effects of defects (EOD) have been completed.

- **Fan Inlet Case/Inlet Guide Vane (FIC/IGV).** Figure II-5 shows a composite FIC/IGV for the F-119. This FIC/IGV had been designed and fabricated to demonstrate the potential feasibility of applying composites to this component. It has been determined that this component could yield as much as a 32-percent reduction in cost and a 44-percent reduction in weight over the metallic baseline.

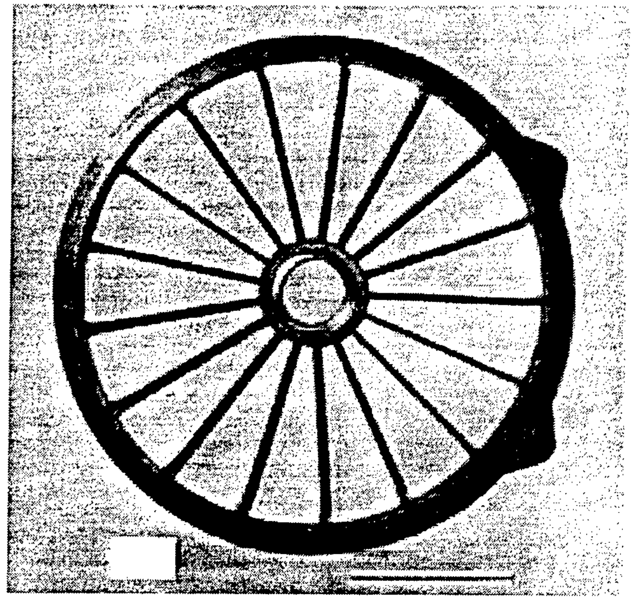

Figure II-5. Pratt and Whitney Composite F-119 FIC/IGV

- **Core Cowl (CC).** Implementation of the the ACP project technologies—including fiber placement of the skins, use of pitch-based graphite core, improved acoustic skin fabrication and perforation techniques, and co-curing of the final bondment—is currently projected to save approximately 15 percent in weight and 30 percent in cost over the baseline. The ACP CC technologies include commercial and military applications.

III. ASSESSMENT OF THE TECHNOLOGY MATURITY

Although the DARPA funding cuts affected many of the projects, most of these projects did achieve many of the goals of the refocused effort and have been "adopted" by a Service and/or another agency to advance the technology. In this section, each of the DARPA program projects will be discussed in terms of their maturity and industrial application. Table III-1 summarizes the status of these projects, lists the source of funding for those projects that are being continued, and shows the impact of the DARPA funding reduction. Table III-2 lists the resin/fiber systems and demonstration parts included in each of the projects. Most of these projects are still in progress and have not yet completed their cost savings estimates. An assessment of the technology maturity follows.

A. DARPA PROGRAM PROJECT STATUS

1. Affordable Polymer Composite Structures: Electron Beam (E-Beam) Processing

This process has cost-savings potential through the fabrication of large, integrated structures with high dimensional tolerances. However, without a characterized material process system, e-beam processing is high risk. No one has developed a satisfactory resin, much less understood the mechanisms involved in e-beam processing.

Recently, the NASA High-Speed Civil Transport (HSCT) program has invested some funding in Northrop's e-beam technology for developing e-beam processed thermoplastics. Oak Ridge National Laboratory (ORNL) secured DoE funding to rehabilitate an e-beam facility to accommodate large components. This facility will be available as a processing center. Also, ORNL has completed a resin development program through its DoE Cooperative Research and Development Agreement (CRADA); however, the material data results from this program were not available at the time of this assessment.

2. Integrated Airframe Technology for Affordability (IATA)

This project was to have been the basis for the CAI; however, the role of the IATA in this program is still being debated. Lockheed Skunkworks may use this study in its

Table III-1. DARPA Affordable PMC Program Project Status

Project	Status	Continuation	Impact of DARPA Funding Reduction
Affordable Polymer Composite Structure: E-Beam Processing	Project is entering end of Phase I with technology demonstration activities progressing.	NASA HSCT support.	High
IATA	Phase I complete. Results show that weight savings of 33 percent and cost savings of 65 percent are achievable.	No additional support. May be used in the CAI study, but this is to be determined.	High
Cure-form Processing	Original project was descoped to focus on producing design and processing guidelines.	Mature and will be used by Lockheed in the F-16 program.	Low
RaPat	An F-117 access door and the RAH-66 Transmission support fitting have been selected as demonstration articles.	Matured and continued support from JSF. May also be supported in the CAI.	Low
Induction Heating	Project has been completed.	Boeing IRAD no longer continuing, and no additional support is forthcoming.	Medium
Affordable Tooling	Tooling is being developed. Non-autoclaved materials characterization has just started.	Support from the CAI to be determined.	Low
WeldTech	Data were presented at the 1996 SAMPE Conference.	No additional support. for thermostat welding. Boeing will support thermoplastic welding.	Medium
Precision Assembly	Assembly cost drivers have been identified. The project is focusing on reducing the thickness variation in composite parts.	Air Force is incorporating this project in its dimensional control program.	Low
Fiber Placement Benchmark and Technology Road Map	Project will complete the design guidelines and fiber placement of more complex part features.	Support for fiber steering from GLCC. Also, support from the JSF program.	Low
RAPTECH	Fabrication of panels to verify structural properties has been completed.	Support from the NASA HSCT program.	Medium
ACP	Extensive RTM and fiber placement process maturation has occurred.	Support from JSF, Joint Dual-Use Program Office (JDUPO) programs.	Medium

Note for Table III-1: *In column 1,* ***boldface*** *indicates some form of continuation towards maturation.*

Table III-2. Composites Systems Studied

Project	Resin/Fiber System	Parts Produced
Affordable Polymer Composite Structures: E-Beam Processing	RB48/AS4 and CATB RB46/IM7 and CATC RB47/IM7 and CATM	Bonded assembly and mechanical fastened assembly Aft-aft center fuselage structure
IATA	PR500/IM7 plus CATB PR500/IM7 plus CATC	RTM bulkhead 5 ft × 5 ft × 5 ft wing section VARTM keelson Upper and lower fiber-placed skin
Cure-form Processing	976 epoxy/T300 5250-4BMI/IM7 977-3Epoxy/IM7	F-16 horizontal spar F-22 fuel tank lower frame
RaPat	PR500/AS-4 & IM7	RAH-66 transmission support fitting F-117 access door
Induction Heating	8552/IM7 5250-4/IM7	Panels
Affordable Tooling (autoclave and non-autoclave)	Modified LTM 45EL/HTA Modified CYCOM 753/ G30-500 F511/AS-4 F511/T650-42 F511/G40-800 F511/IM7	C-17 aft landing gear pod tool ALAFS wing skin tool Test Specimens
WeldTech	8552/IM6 3501-6/IM6	Panels and joints
Precision Assembly	3501-6/AS-4 3501-6/T-300 977-3/IM7 977-3/AS-4	Joints only
Fiber Placement Benchmark and Technology Road Map	3501-6/AS-4 977-3/AS-4; 977-3/IM7	Contoured surfaces ALAFS wing skin
RAPTECH	AVIMID K3B/IM7 PIXA/IM7 PEEK/AS-4 PEKK/AS-4	Panels
ACP	5250-4/IM7 5250-4/IM7 PR520/IM7 PR500/AS-4 3501-6/AS-4 8552/AS-4 5250-4/AS-4	FIC/IGV (RTM) Fan blades (RTM) Fan blades (3-D Preform) FEC (RTM) Containment case (Modified ATP) Cowls/inlet (ATP) CC (ATP)

internal PMC work. Lockheed Fort Worth has considered using an updated version for some of its work in JSF. Validation is needed for the conclusions from this effort, but no organization has stepped forward to do this work.

3. Cure-Form Processing

This Lockheed Fort Worth project will produce the design guide for cure-form processing and use it in the F-16 program. It may also be transitioned to other programs, such as JSF. Although this particular cure-form process is proprietary to Lockheed Fort Worth, other companies use similar cure-form processes. The design guide will be available to other PMC users and producers. Funding cuts had little impact on this project.

4. Rapid RTM Tooling Project (RaPat)

The RaPAT project will complete demonstration articles (see Table III-2) using the tools developed in this project. The RTM process is mature, and other demonstration pieces have been fabricated in the ACP project that also illustrate RTM's maturity. The CAI is interested in continued development of low-cost tooling but has not yet committed support to this area. Dow-UT will be producing RTM composite engine components for the JSF program. It is not clear whether the experience gained in this tooling project will be incorporated in the JSF engine program.

5. Induction Heating

Little was accomplished by way of maturing the induction curing of PMCs. Areas that still need to be addressed are demonstration of this technology with prototype parts and nondestructive evaluation (NDE) techniques for characterization of the joints. Boeing IRAD will continue to invest in induction heating of metals but not in PMCs. It is still questionable whether the CAI will support induction heating technology since it is not a near-term technology (compared to RTM). Other than the CAI and Boeing, this project has not received any support.

6. Affordable Tooling

Through some support from the Air Force and work that is being done in the JSF ALAFS program, MDA's Affordable Tooling project will continue to refine low-cost tooling and non-autoclaved materials. Additional support may come from the CAI, but this support remains an unknown at this time. With the many changes that have been made in the type of fiber and resins that were to be evaluated, the low-temperature materials evaluation part of this project is not a true follow-on to the Air Force's LCCP; instead, it is another materials development project.

7. WeldTech

Many issues (i.e., NDE techniques for evaluating the weld, a resin for the bondline that is suitable for aerospace applications, and thinner bond lines) could not be addressed in the abbreviated project. The bondline material used to show proof of concept for joining thermoset components was not resistant to solvent. The maturity of this project is limited and would require an effort in materials development and in NDE technique development.

Another issue that needs to be addressed is the long-term environmental effects of having a metal susceptor incorporated in the bondline. What is the effect of the susceptor on fatigue properties over time? Even though this technology does have potential in saving weight and cost by not using fasteners to join composite materials, no funding source has come forward to support this technology. Boeing will continue to pursue thermoplastic welding in the JSF program.

8. Precision Assembly

The Air Force is embracing this effort in its Processing for Dimensional Control program, which is intended to address the issue of composite part fit-up and assembly costs. The specific issues identified for each of the areas in precision assembly will be addressed. Also, industry is currently submitting a precision assembly effort to the CAI.

9. Fiber Placement Benchmark and Technology Road Map

After the funding cuts, this project focused on the fiber placement machine. Both fiber placement machines were well characterized, and a document describing their capabilities will be the final product of this project. Demonstration parts produced in the ACP project further supported the capability study. The Great Lakes Composite Consortium (GLCC) will support the fiber steering areas that were dropped from this effort. Ongoing work in the JSF ALAFS program will also address fiber steering issues.

10. Rapid Placement Technology for Affordable Composites (RAPTECH)

This project was to have finished in 1996. NASA's HSCT program is continuing to support this technology but not at DAPRA's level. NASA Langley also has an internal effort with its own in situ tow placement system. Although the RAPTECH system is a gantry-type system vs. NASA's movable arm, similar technical issues—which include porosity, uniformity, and material control—are being addressed.

11. Affordable Composites for Propulsion (ACP)

ACP completed almost all the demonstration parts and will now be involved in the JSF program's engine demonstration. The ACP components transitioned to the JSF program will be the FIC/IGV and fan blades. Two fan blade configurations are being studied to determine whether the complex fiber architectures being used to enhance the birdstrike tolerance of the advanced ducted propeller (ADP) blades will be needed in the military blade configurations, and, if so, how to adapt the architectures to the military blade envelopes.

The ACP core cowl technologies include both commercial and military applications. The design features and processes developed and proven production-ready can be implemented on thrust reverser core cowls for the C-17, 747X, and the A3XX airplanes. Northrop Grumman is pursuing the C-17 application. A possible application of the CCs to the JSF program includes the weapons bay doors and the inlet where hot acoustic environments may require a high-temperature composite material; however, the JSF program has not supported this application.

B. ASSESSMENT OF THE TECHNICAL STATUS OF THE DARPA PROGRAM PROJECTS

To assess the maturity level of the DARPA PMC program, an approach that was described by Lincoln in the article "Structural Technology Transition to New Aircraft" (Ref. 3) was used. Lincoln identified five factors that were necessary to transfer structural technologies from the laboratory to full-scale development:

- Stabilized material and/or material processes
- Producibility
- Characterized mechanical properties
- Predictability of structural performance
- Supportability.[8]

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[8] Supportability was defined as the ability to repair the structure in the field and inspect the structure during manufacturing and service.

Lincoln did not rank these factors but stressed that a deficiency in any one factor would not lead to a successful transition.

Lincoln's approach was taken from a structural designer's point of view. Although this approach involves the importance of materials and their properties, more detail was needed to describe key material parameters maturity for the DARPA program projects.

In addition to material and structural parameters, affordability is also an important area addressed in the DARPA program projects. The Institute for Defense Analyses (IDA) added the following maturity factors to Lincoln's original factors to address more fully the materials and cost parameters:

- Availability of characterized materials
- Favorable design trades and cost studies
- Development of quality assurance procedures
- Demonstrated affordability.

In this assessment, a maturity level has been assigned to each of the factors for every DARPA project.[9] The maturity level is determined by the amount of unavailable information or experience that impedes technical progress. The maturity levels, defined in Table III-3, range from 1 to 10. The lower maturity levels (1–2) indicate that a technology was deficient in all aspects of materials characterization and testing as well as subcomponent[10] and full-scale development. Maturity levels between 3 and 4 indicate that only coupons were produced and additional tests and larger components are needed to validate the material properties. Maturity levels between 5 and 7 suggest that cost models need to be validated. Also, full-scale and subcomponent scale components need to be tested in order to validate the cost models. The higher maturity levels (8–10) indicate there are minor deficiencies but that the technology is mature enough for production.

Based on these maturity level definitions, Table III-4 shows the maturity level of each factor for each project in the DARPA program. Table III-5 itemizes the major reasons why the technologies in the DARPA program did not advance to a higher maturity level.

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9 The tooling programs were rated on the tooling they developed and the composite components or subcomponents they built from the tools. Most of the tooling compounds were readily available and developed.

10 For this assessment, a subcomponent is defined as a part having more geometry than a flat plate and is larger than a coupon.

Table III-3. Maturity Level Definitions

Maturity Level	Definition of Maturity Level
1–2	Materials are not available and need development. No complex parts were built. No test data were available.
3–4	Properties are not reproducible. Testing is not complete. No subcomponents or full-scale components built. No cost models were validated with full-scale parts.
5–7	Limited data are available, with large error bars. Subcomponents built but testing is incomplete. Full-scale components built but not tested to design loads. Cost models validation is incomplete.
8–10	Materials and processes are well characterized. Solid database is available for different conditions. Reproducible subcomponents and full-scale components built and tested to design loads. Cost models have been validated.

Part of the limited advancement in these projects has been attributed to DARPA's funding decision; however, technical issues also impacted progress in these technologies. For the E-beam and WeldTech projects, appropriate resin materials—materials that had to be developed before subcomponent test data could be obtained—were not available before the projects began. Despite these major deficiencies, the WeldTech project was able to show that thermosets could be induction-welded—but not with aerospace-quality material. A large component was produced in the E-beam project, but this component was not tested to verify that it met design requirements. Also, the e-beam processing mechanism was not fully understood, and the process was not always consistent in what it produced. The IATA project introduced a new design paradigm but did not have the Phase II resources to prove the cost savings for composite components using the IATA design and cost models.

DARPA's funding decisions had a low-to-medium impact on the maturity of the RAPTECH, Induction Heating, and Precision Assembly projects. Despite funding impacts, some progress was made in these technologies. The RAPTECH project cost model showed a 33-percent cost savings using the heated-head tow placement but was not validated by a full-scale component. Induction Heating had characterized materials and processes but did not produce subcomponents or full-scale components to validate its cost

Table III-4. Technology Maturity Assessment of the DARPA Affordable PMC Program

Project	Maturity Factors							
	A	B	C	D	E	F	G	H
E-Beam Curing	1	1	4	1	2	2	2	2
IATA	4	4	7	2	4	2	2	2
Cure-form Processing	8	8	8	8	8	8	7	7
RaPat	7	8	7	8	7	8	3	7
Induction Heating (Thermosets)	7	7	4	4	4	2	2	3
Affordable Tooling								
– Tooling	7	6	7	6	7	8	5	6
– Low-Temp Cure Materials	2	3	2	2	3	2	2	2
WeldTech (Thermosets)	2	2	4	2	2	2	2	3
Precision Assembly	4	3	4	5	5	2	3	5
Fiber Placement Benchmark and Technology Road Map	9	9	9	8	8	8	8	8
RAPTECH (Thermoplastics)	7	7	2	4	4	1	3	1
ACP								
FCD	9	9	9	8	8	8	8	9
FCC	8	8	8	7	7	6	5	4
FEC	8	8	8	8	6	6	5	8
FIC /IGV	8	8	8	7	6	6	5	5
Fan Blade	8	6	8	7	5	7	5	5

Note for Table III-4: For the columns under Maturity Factors, the following apply:

A = Characterized Materials Available
B = Stabilized Materials and Processes
C = Lab Scale Subcomponents Fabricated With Equivalent Geometric Complexity
D = Life Prediction Model Available and Mechanical Properties Valid for Components and Subcomponents
E = Design Trades/Cost Studies Are Favorable and Quality Assurance Procedures Developed
F = Producibility of Full-Scale Components and Test
G = Supportability
H = Demonstrated Affordability

Table III-5. Maturity Level Explanations for the DARPA Program Projects

Project	Reasons for Maturity Level
Affordable Polymer Composite Structures: E-Beam Processing	Little understanding of resin curing mechanisms Limited mechanical data and life prediction models Cost/affordability only predicted Full-scale component not tested
IATA	Mechanical data/life data not available Some of the processes proposed to contribute to affordability were immature Full-scale parts were not built or tested Did not validate that the cost model was reasonable by producing a demonstration part(s)
Cure-form Processing	Cost analysis was abbreviated and not substantiated with proven parts
RaPat	Full-scale component tests not completed Cost model validation not completed and will be based on only two pieces Inspection of the parts during the process and in-process controls not studied
Induction Heating	Did not address inspection Full-scale parts were not built or tested Cost/affordability only predicted
Affordable Tooling	
Tooling	Validation of affordability and cost model incomplete Tooling processes still have shortcomings (nozzle erosion for spraying graphite fibers on tooling surfaces) Testing of full-scale tools and components incomplete
Low Temp Cure Materials	Earlier materials from the LCCP program were no longer available and a new materials database had to be developed Components fabricated but not full-scale Cost savings not supported by demonstration parts
WeldTech	Materials development work is needed since materials used in the weld were not aerospace quality Mechanical properties of subcomponents were not characterized Long-term durability properties of the weld not addressed Cost model not supported by demonstration parts Unable to inspect the weld without destroying the part Full-scale parts not built or tested
Precision Assembly	Limited database developed and no components produced to support cost savings
Fiber Placement Benchmark and Technology Road Map	Fiber steering on curved surfaces not demonstrated
RAPTECH	Cost savings not quantified No complex parts or full-scale parts produced Post autoclave curing was necessary for some materials to achieve desired properties Inspection and repairability not addressed

Table III-5. Maturity Level Explanations for the DARPA Program Projects (Continued)

Project	Reasons for Maturity Level
ACP	
FCD	Full-scale tests not complete
FCC	Not all the full-scale tests will be completed in the project Cost models were not validated Engine demonstration test will not be done Inspection of full-scale parts not addressed
FEC	Full-scale HCR test and engine demo test will not be done
FIC/IGV	Full-scale testing will not be done Repair data not available Life prediction studies will not be done
Fan Blades	Fan blades failed the birdstrike test and required a new design Test data on new design not available Cost and repair data not available

model. In one task under the Precision Assembly project, MDA is developing a material variability database for only one material. It is unclear whether these data will apply to other material systems. Also, validation of the MDA assembly model will be based on production parts. No complex parts or subcomponents will be produced from the material studied in the material variability task.

Projects that matured to a higher level include tasks under the ACP project, the RaPat project, and tooling tasks under the Affordable Tooling project. Full-scale testing was not complete for the RaPat project or the Fan Blade task under ACP. Even though full-scale testing was dropped from the FEC task under the ACP project, several FECs were built and did demonstrate cost savings when compared with conventional metal FECs. Other tasks that had not completed validating cost models include FIC/IGV task, the Fan Blade task, and tasks under the RaPat project. The FCC task did meet the lower weight metric but not the affordability metric. In all these more mature projects, a limited amount of effort was given to component repair and inspection.

The most mature technologies were in Cure-form Processing, Fiber Placement Benchmark, and the FCD task under the ACP project. Only minor deficiencies were noted for these technologies. The cure-form design guide will be transitioned to production in the F-16 program at Lockheed Martin. Eleven FCDs were built in the ACP project. MDA is interested in incorporating these doors into its C-17 program. Fiber placement technology—with maturity scores of 8 or higher—was the most mature technology in the DARPA program. However, fiber placement has been maturing for over 15 years and has already been used in several aircraft production programs, including the F-18 E/F. Between the suggested machine modifications from the Fiber Benchmark project and funding from the GLCC and the JSF program, this technology will continue to develop and become more feasible with less risk to the industry.

In general, two maturity factors in each of the DARPA program projects—supportability and demonstrated affordability—were assigned low-to-mid scores. Repair and inspection were not explicitly addressed in any of the projects, except for the ACP FCD task and the Cure-form Processing project. Use of composite materials will be hampered if reliable inspection tests and repair processes are not available. Fabrication and testing of full-scale demonstration articles are essential to demonstrate affordability and producibility.

Most of the revised projects did not have the resources to build full-scale components much less test them. For the ACP project, some of the components will be incorporated in an engine demonstration test for the JSF program. Without this full-scale data, however, the author's assessment is that many of the technologies in the DARPA program will remain immature and high risk even though they have lowered costs and have increased system performance. It is unknown whether sufficient funding from other sources, such as the CAI, will be able to push many of these technologies ahead and gain industry's acceptance.

IV. CONCLUSION

The DARPA Affordable PMC program was established to address the high cost related to PMCs. Based on the maturity scale developed in this assessment, the maturity of these technologies toward affordable composite usage is as follows:

- Although most of the projects were impacted by DARPA's funding decision in 1995, all the projects will complete a feasability demonstration in their refocused plans.
- Technology developed and enhanced in three DARPA projects—Fiber Placement Benchmark, Cure-form Processing, and the FCD task under the ACP project—will be transitioned to production programs.
- The Fan Blade task and the FIC/IGV task under the ACP project will continue to mature to a higher level under the JSF program. Several other projects are being supported in other programs; however, it is uncertain if the amount of funding from these programs will mature the DARPA projects to a significant level. These projects include the Precision Assembly, E-Beam Processing, and RAPTECH.
- Projects that did demonstrate potential cost savings but remain immature and have not been supported in other programs are WeldTech, Induction Heating, IATA, Affordable Tooling, and the FEC and FCC tasks under the ACP project.

GLOSSARY

2-D	two dimensional
3-D	three dimensional
ACP	Affordable Composites for Propulsion
ADP	advanced ducted propeller
ALAFS	Advanced Lightweight Aircraft Fuselage Structure
ATP	Automated Tow Placement
CAI	Composite Affordability Initiative
CC	core cowl
CRADA	Cooperative Research and Development Agreement
CTDS	Composite Tool Design System
DARPA	Defense Advanced Research Projects Agency
DoE	Department of Energy
DSG	Defense and Space Group
DSO	Defense Sciences Offices
e-beam	electron beam
EOD	effects of defects
FCC	fan containment case
FCD	fan cowl door
FEC	fan exit case
FIC/IGV	fan inlet case/inlet guide vane
FOD	foreign object damage
FY	fiscal year
GLCC	Great Lakes Composite Consortium
HCR	horizontal containment rig
HSCT	High-Speed Civil Transport
IATA	Integrated Airframe Technology for Affordability
IDA	Institute for Defense Analyses
IHPTET	Integrated High Performance Turbine Engine Technology

IRAD	internal research and development
JDUPO	Joint Dual-Use Program Office
JSF	Joint Strike Fighter
LCCP	Low-Cost Composite Processing (Air Force)
LMTAS	Lockheed Martin Tactical Aircraft System
MDA	McDonnell Douglas Aerospace
NASA	National Aeronautics and Space Administration
NDE	nondestructive evaluation
NIST	National Institute of Standards and Technology
NSF	National Science Foundation
OHC	open hole compression
ORNL	Oak Ridge National Laboratory
OUSD(A&T)	Office of the Under Secretary of Defense (Acquisition and Technology
PMC	Polymer Matrix Composite
R&D	research and development
RaPat	Rapid RTM Tooling Project
RAPTECH	Rapid Placement Technology for Affordable Composites
RTM	resin transfer molding
S&T	Science and Technology
SAMPE	Society for the Advancement of Materials and Process Engineering
SPF/DB	super plastic forming/diffusion bonded
TRP	Technology Reinvestment Project
VARTM	vacuum-assisted resin transfer molding

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This document is a technical assessment of the Defense Advanced Research Projects Agency (DARPA) Affordable Polymer Matrix Composite (PMC) program. The projects under this program were initiated to develop and demonstrate technologies that would reduce the acquisition costs of composites for high-performance air vehicles and other platforms by 30+ percent, develop a composite structure equal to or lower than the cost of a metallic structure for transports and other "lower performance" applications, and reduce prototype tooling costs and lead times by 40+ percent. The projects that were originally planned had to refocus their efforts and/or finish earlier than planned. This document summarizes the technical achievements of these projects, assesses the readiness of the technologies for systems applications, and discussed the process and exit criteria that were developed to assess the technology readiness.

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