The Creation and Use of a Manufacturing Process Development Strategy in the Aerospace Industry

by

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Submitted to the Alfred P. Sloan School of Management and the Department of Mechanical Engineering in partial fulfillment of the requirements for the Degrees of

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and
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Abstract: This thesis describes the development and use of a manufacturing process development strategy to develop strategic long term manufacturing process technologies for industries that produce large assembled products such as commercial aircraft. The goal in the creation of this strategy is to increase the amount of innovation in these industries through a focus on developing the fundamental manufacturing processes. This strategy differs considerably from the current "product-focused" methods to develop manufacturing processes, as is documented in this thesis.

The use of a Process Development strategy requires that new manufacturing technologies can be made ready for factory implementation within a timeframe that future market opportunities can be reasonably forecast. With process technology development projects requiring over a decade in the aerospace industry, a significant acceleration of these projects is required before this strategy will become fully effective. The thesis contains several strategies to accelerate process development activities within a multifunctional environment. This thesis proposes the creation of process development teams as an upfront adjunct of concurrent engineering and product development teams to increase the speed of development of new processes and amount of innovation in complex assembled products. A group of Charter Parts Councils is also proposed to manage a firm's technology development efforts by taking a longer term view of product development and decoupling a certain percentage of research (25 to 35%) from direct product considerations.

The effectiveness of the proposed development strategies was demonstrated with a project on the In-Situ Roll Consolidation process for thermoplastic composites. During this effort, upfront process modeling, followed by designed experiment manufacturing experimentation was used to understand and improve the process. The major process variable determined during the testing was the head velocity of the composite lamination head, which strongly controlled the strength of the panels. The strength of In-Situ consolidated (+/-45) panels was found to be about half of autoclaved material. The modulus of the In-Situ consolidated panels was measured to be 30% less than expected due to fiber waviness in the tapes created during In-Situ processing. Substantial improvements in this process are required before it could be used in production. The effectiveness of this development approach is that the exact problems with the process are known with some certainty after the first round of development is complete. The next round of development can concentrate on solving these problems. A list of recommendations for the next round of process experiments is included at the end of the thesis.

Thesis Advisors:
Paul A. Lagace, Associate Professor of Aeronautics and Astronautics
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Chapter 1
Introduction

This thesis is the result of a six month internship within the Operations Technology organization of the Boeing Commercial Aircraft Group, and the subsequent work of the author at MIT in the Leaders For Manufacturing Program. Operations Technology, and its subgroup, Manufacturing Research and Development, have a mission to develop the new manufacturing processes for the Boeing Commercial Airplane Group. The key topics in this investigation were to look at the practices and culture of this organization and allied organizations within Boeing, to understand the issues and difficulties which lead to long development times of new manufacturing technology in the aircraft industry and then create potential solutions to the difficulties identified. The specific examples given in the thesis are all from the Boeing Company, but point to generic problems in new manufacturing technology development in the aerospace industry in particular, and in other manufacturing industries which produce large assembled products in general. Although the work applies mainly to these industries, the results apply to other manufacturing industries as well.

The three major questions to be answered in this thesis are:

1.) Can a strategy to develop fundamental new process technology be successful to innovate new complex assembled products, such as aircraft, to create strategic advantage for the firm?

2.) Can new methods of process development be undertaken to more rapidly develop manufacturing technology?
3.) Is it possible to form new multidisciplinary organizations of design and manufacturing engineers capable of developing new processes more rapidly?

To answer these questions, new methods of organizing for fundamental technology development along with new methods of process development engineering are proposed in this thesis to increase organizational learning rate and to decrease the development time of new processes.

The intent of these proposed organizations and practices is to shorten the time it takes to develop and implement new manufacturing technologies into the American aerospace industry. By shortening the development cycle, it would then be possible to effectively use a Manufacturing Process Development strategy as part of the corporate development and technology strategy, to enable completely new types of aircraft or to attain higher levels of performance and reduced cost in existing aircraft. This process development strategy differs from that presently in use by focusing loosely on the parameters of future aircraft programs at a time horizon far enough in the future to allow new manufacturing processes to make these products possible. The current paradigm in this industry uses product development to drive technological development while this strategy allows the technology to evolve or enable the product. The manufacturing process development strategy proposed in this thesis focuses the technological development activities of a firm on the development of new processes for its future products. This is in contrast to the current manufacturing technology development organizations who are chartered to develop processes for current aircraft programs under development or to support current factory manufacturing processes which together are inherently short term focused activities. With this strategy it will be possible to increase the amount of innovation in the next generation products and create technological
competitive advantages over competitors. The arguments given in Chapters 2 and 3 will show that this strategy will become increasingly important to maintain the competitive technical edge for future subsonic and supersonic aircraft.

The thesis will demonstrate, using historical models of technological innovation (2, 75 and 76), why new competitors in the commercial aircraft industry have chosen composite structural technology as an area of innovative competition, and the organizational structural problems that established firms in American commercial aircraft companies have in dealing with these challenges. These models will explain why process development does not currently play a major role in the strategy of the mature firms in this industry.

Finally, the thesis will conclude by demonstrating the proposed development practices showing their potential to accelerate the learning rate of new processes and for cutting the development lead time to implement them. The specific technology chosen, In-situ Consolidation of Thermoplastic resin matrix composites was selected for two reasons;

1.) the relative immaturity of this process, where the development strategies proposed in this thesis have their greatest applicability and;

2.) the potential long term strategic importance of this process to the American aerospace industry and to Boeing.

This process is the type of long term technological development project that would be undertaken by a firm utilizing a long term process development strategy. The technical work in this thesis was undertaken to demonstrate the tools and philosophies of a manufacturing process development strategy.
Use of Multi-disciplinary Teams for Product Development

The Boeing Company, like many large American manufacturing firms, has historically performed its development of manufacturing processes, materials and new aircraft design in a very functional organizational environment. To break down these traditional barriers in the design and fabrication of its newest jetliner, the 777, Boeing has implemented the concept of Design-Build teams (DBT's) to bring manufacturing process and cost input early into the design process and prevent the traditional "throw it over the wall" engineering design release to manufacturing. This design release practice is a common practice in many manufacturing firms whose products are internally complex, (PR,81,84,10) and whose manufacturing and engineering organizations are separate functional organizations. These traditional methods of product development have been shown in these references to lead to longer lead times for product development and a larger number of expensive Engineering and Manufacturing Change Orders late in the development cycle. Through the use of DBT's and computer aided design and engineering integration, Boeing hopes to avoid these problems with the 777. They also hope to shorten the development time and reduce the cost of developing a new commercial aircraft. The use of simultaneous engineering in new product development is the topic of much discussion within the aerospace industry (4) and the American manufacturing community in general (13,14). Experimentation in methods of program organization such as the use of DBT's is currently underway to achieve its goals.

Hayes, Wheelwright and Clark,(30), Clark and Fugimoto(10), Cusimano(17) and others(84), all propose such reorganizations of product development to include simultaneous engineering and manufacturing development practices to cut the product development time of new assembled products. Inherent in their arguments is the assumption that manufacturing process development and its implementation in a manufacturing plant occurs concurrently with engineering design within a 2 to 3 year time frame. In the aerospace industry, where fundamental process development currently takes
a decade or more (68, 37), these practices, while helpful to cut new product development time, are not sufficient to bring new innovation into the aerospace industry and complex assembled products in general. This slower development time in process R&D is described by Clark and Fugimoto (10) as a problem area in automobile development as well. The organization and practices to rapidly develop process technology in advance of new product development is not described in their book. The purpose of this thesis is to propose new organizations and practices to accomplish this goal.

**Current State of Long Range Materials and Process Development**

The development of advanced manufacturing processes at Boeing and within the aerospace industry is still characterized by the traditional pattern of functional hand-off between the major organizations participating in this task:

1.) Manufacturing Research and Development/ Operations Technology
2.) Materials Technology
3.) Structures Technology

The functional organization of the long range process development projects is in sharp contrast to the use of multifunctional team concepts described in the previous section for the new development of new products.

The use of simultaneous engineering principles to accelerate these technology development projects is currently in the early stages of implementation within some Defense Advanced Research Projects Agency aerospace manufacturing technology development projects (18, 19, 4), but the use of these principles in process development activities of major aerospace firms is still in the embryonic stage. To break down the barriers between these key organizational stakeholders in the development of new manufacturing processes and cut the development time to implementation, a new type of multifunctional team to concurrently develop manufacturing processes, materials and structural technology, is proposed in this thesis. With such a team, the concepts of
concurrent engineering and simultaneous materials and manufacturing process
development could be performed together in an aligned fashion.

The enhanced sharing of information between the three functional specialties is one
reason for the enhanced learning rate and faster development. Kanter (38) proposes that
groups organized around a common goal, (such as the development of new process
technology) "aids (in the) activation of innovation by producing structural integration at
the micro-level". She also adds that, "Cross fertilization (of ideas) across disciplines and a
focus on users is built into the structure (and culture)." This proposed Process
Development team concept would then be capable through the cross fertilization and
integration inherent in its structure to achieve the goal of the reduction in time to develop
and implement new manufacturing processes. At the conclusion of the development
activity, Process Development Teams, (PDT's) would be more capable to transfer the
technology throughout the company's operations and into its new products.

The proposed PDT concept is consistent to that proposed by Rosenthal (63) to
bridge the cultures between engineers involved with design and manufacturing activities.
He points out the major challenge to the formation of such a team, is the blending of the
innovation culture of the designers with the production efficiency culture of the
manufacturing engineers. He states that the successful implementation of this team
structure requires management attention to create a new culture which values both
innovation and efficiency, and uses technological complexity as a catalyst to creation of
integration, rather than being a formidable barrier. Schein (65) describes the difficulties of
getting people from different parts of an organization to work together effectively by
stating, "...people start with different assumptions, different languages, (and) different
world views -in short, different cultures. Roberts (62) and Goldman (28) point out the
integration of development activities, with those of manufacturing, has been a major
barrier to the implementation of new technology in mature American manufacturing firms.
Roberts (62) proposes that the cultural and organizational barriers to creating the bridges
between development and manufacturing are the most difficult challenges to the creation of a multifunctional development team approach to either product or process development. He also states that so-called "liaison" or "integrator" individuals or staffs have generally been ineffective in the transfer of technology from R&D to manufacturing. The transfer that occurs from a "holistic" multidisciplinary team hopefully will be superior in this respect.

Prototype organizations which resemble some of the attributes of the proposed PDT team concept have existed, or are currently in existence, at the Boeing Company. Each of these prototype organizations have brought together in one central location each of key functional specialists, but have not made the last step of creating multifunctional development teams, in a direct analogy to the established Design-Build teams. The final step is the most difficult one because it involves the bridging of cultures. Clearly, of the major tasks to create and manage the proposed development teams is the creation of a new culture and incentives to make the team concepts work effectively. The operation and strategy of the proposed PDT concept is contained in Chapter 6 and 7 of this thesis.

This thesis will explain how the focus on product R&D activities within aerospace companies in particular and American manufacturers in general has led to a situation where, as Thurow (47) has stated, "when it comes to process technologies, Americans have been slow to invent and slow to adapt". Mansfield (47) agrees with Thurow on this topic and adds, "Many studies indicate that process R&D has a bigger effect on productivity than does product R&D." Mansfield's research on fifty large American and Japanese firms has shown the predominant emphasis of product R&D in American manufacturing firms, where 66% of the their total R&D funds are devoted to product R&D. His research has also shown the exact opposite is true in Japan, where 66% is devoted to process development. For example, whenever team-based organizational structures have been established within Boeing, their goal has been focused on the
development of new products. Rarely have these teams had the explicit goal of
developing a new manufacturing technology to enable a new generations of products, or
to increase the performance and/or lower the cost of existing products. The thesis will
give several case examples where this lack of a process focus, especially in the early stages
of product development efforts, has stifled innovation in new products.

The present emphasis on cutting development time in new products through the
use of simultaneous engineering organizations and practices, cuts the "time window"
available to develop new manufacturing technologies during the product development
project. To implement new manufacturing technologies on new products, firms will need
to undertake up front technology development to stock the technology "pantry", before
the new product program is begun. This de coupling of process technology from product
development and the creation of a technology "pantry" is proposed by Clark and Fujimoto
(10) in their study of the world automotive industry. The auto industry is similar to the
aerospace industry because autos are another complex assembled product with long
product and process development times, so their conclusions are valid for aircraft as well.
The old paradigm of using the product development projects to drive new process
development, will not yield an acceptable amount of innovation with the new accelerated
product development cycle strategies proposed for industrial competitiveness in the
following references. (30,84,10,71).

Development of a Manufacturing Strategy

Clark and Fujimoto also describe the fundamental paradox between
"technology push" projects where the technology development precedes the product, and
"technology pull" where the product development drives the technology. They propose a
solution to this paradox by the establishment of long range process technology
development plans which are closely co-ordinated with the long range vehicle (product)
plan. Hayes, Wheelwright and Clark (30) suggest that it is necessary to develop a process
development strategy that is explicitly oriented to the development of the long term design
and manufacturing capabilities of a firm. The lack of a long range process development
strategy on strategic manufacturing processes was pointed out by Henderson (31) in a
report on Operations Technology at Boeing. The creation of such a strategy and the
organizational structure to support it for the aerospace industry is proposed in Chapter 6
on the organizational goals and missions of the proposed Charter Part Councils, and
Process Development Teams.

The strategies proposed in this thesis to derive competitive advantage from
the rapid development of strategic manufacturing processes, are just one aspect of an
overall manufacturing strategy which seeks to transform the firm into a World Class
manufacturing company, whose manufacturing facilities, people, organization and
processes are all parts of a complete core competence in manufacturing. To create new
and growing competencies in new technologies, the proposed multidisciplinary team
approach is required because simultaneous transmission of the technology throughout the
entire organization is required before the technology can become a growing competence.
(58) After the technology has been fully transmitted throughout the entire organization,
the new competencies are then capable of being used for strategic advantage within the
next generation of products. The smaller the total development time, the faster the
diffusion of the technology throughout the organization, and the greater the potential
benefits from the strategic technology over the current state of the art, allows a firm or
industry to capture greater competitive advantage.

Demonstration of Rapid Process Development Strategies

To demonstrate the utility of a PDT organization, an ad-hoc multifunctional
development team was created informally within Boeing's MR&D organization to
investigate a specific advanced manufacturing process technology, In-Situ Consolidation of thermoplastic composite materials. The chapters on the development of this process will capture the strategy, methods and learning of this team. The learning rate of such a team is an important metric of a process development team's performance, because it dictates the speed in which a new process is developed and implemented. Strategies and tools to enhance this learning rate were investigated and their results are reported in Chapters 8, 10 & 11.

The amount of organizational learning which is accomplished during development projects is never talked about in traditional functional organizations involved with process or product development. In the development of the roll consolidation process of this thesis, this was found to be the most important factor in managing a process development activity. Organizations whose development organizations are capable of learning rapidly about new technology are capable of creating strategic advantage from their development activities and fielding new core competencies in their products and factory processes. The new competencies give companies a first mover advantage in relation to their competitors. The strategies proposed in this thesis (to some extent demonstrated) to hasten the development of a structural composite technology, are generic enough in principle that they can be used for other structural and non-structural technology development projects in the aerospace and other complex manufactured products. In principle these strategies are not specific to the composite process that was investigated in this thesis.

Chief among these strategies are the simultaneous development of the manufacturing process and the materials of construction, and the use of process science modeling of a manufacturing process to hasten the early learning about a new process. The scientific model of the process (developed for roll consolidation in Chapter 9) allows the interpretation of problems encountered during early development trials, and allows the team to simulate potential solutions. Without the development of this model, much of the
work performed in this thesis simply could not have been accomplished after failures were experienced during the initial processing trials.

The use of designed experimentation by varying the key processing variables has been proposed as a method (50) which can be used for manufacturing process development to optimize the process under development. The chronic problem experienced with designed experiment testing, especially in the formative stages of advanced, complex processes, is the critical processing parameters are not known before the testing begins. Large screening, designed experiments to determine the critical parameters are costly and time consuming to perform. The use of process science modeling of the process allows the process development team to simulate the effects of the critical parameters, so that when tests are performed, realistic values of the critical parameters are used. This simulation removes the gross empiricism from designed experiment testing and allows much of the time consuming screening experimentation to be skipped. When the designed experiments are performed for process optimization, they are more effective because the test parameters are carefully chosen to yield the best probability of finding the optimum processing conditions. The time required to find the optimum through progressive experimentation is reduced. This follows with the theme of this thesis to reduce process development time.

**Organization of the Thesis**

This thesis is organized into three parts around a central theme of manufacturing process development. The first part, consisting of Chapters 2 through 5, will establish the current approaches used for manufacturing process development with the difficulties, structural problems and limitations inherent with these approaches. These explanations will be approached in different chapters from three different perspectives; company strategy, organizational and cultural structural problems, and from industrial evolution.
These perspectives give an overall picture of the current approaches and the underlying assumptions that create the present difficulties with process development.

Chapter 2 will introduce in a brief fashion the key competitive strategies that allowed the Boeing company to become the most successful company in the commercial aircraft industry. In this chapter, the entry of the Airbus consortium and their competitive challenge to American commercial aircraft manufacturers in the area of technology development will be described. The emergence of composite materials and their progressive substitution for aluminum in the aerospace industry will be presented and analyzed.

Chapter 3 documents many of the generic industrial problems with process development in U.S. industry. Specifically, the difficulty justifying process development with financial investment analysis procedures, the smaller share of R&D resources devoted to process development, and the ineffectiveness of long range research are described. This chapter concludes with the introduction of a Process Development Strategy to overcome the difficulties that have been described, with the experiences of two firms in other industries who have attempted such a strategy.

Chapter 4 will establish the key linkage between the manufacturing process technology and the product technology, which become tightly intertwined in mature industries. When this occurs, it is impossible to develop innovative new products without first developing innovative new manufacturing processes. This chapter will document that new manufacturing technologies take longer to develop than the development of new products and the current approach to drive new technology development with product development programs in a concurrent fashion generally does not yield fruitful results.

Chapter 5 uses a generally accepted historical model of industry innovation to describe why process development subsides in mature manufacturing industries, after a dominant design is established. The history of process development in the commercial aircraft industry is compared with this innovation model and specific instances will be
noted when the industry has used manufacturing process development to enable its new products. This model of industrial innovation will also show the vulnerability of dominant players in mature industries to new competitors with new, state of the art manufacturing technologies.

The second part of this thesis, contained in Chapters 6 through 8, will propose the use of manufacturing process development as a key part of a World Class Manufacturer's manufacturing strategy. Chapter 6 will propose two new organizational forms, the Process Development Team and the Charter Parts Council. The goal of the multifunctional, Process Development teams will be focused upon developing strategic new process technologies to a state of refinement so that they are capable of selection onto a new or existing product. A major goal of Process Development Team concept is to substantially improve the development and implementation of new technology. Reductions in the total development time by a factor greater than 1.5 are needed which may be achieved through accelerated learning and concurrent development to allow the process development strategy described in this thesis to be effective in achieving the goal of creating strategic advantage and to enable new product lines. The organization, goals, skill mix and development strategies of this multidisciplinary organization will be discussed. This chapter will propose the creation of several Charter Parts Council's to manage a company's technology base and to align its long range process development on strategic technology development, as a mechanism to focus long range process development on future market opportunities. These proposals and the subsequent discussion will take place with the hypothesis that manufacturing process development is a key component of an overall manufacturing strategy to create a World Class Manufacturing firm.

Chapter 7 will describe the methods of process development that the process development members will utilize to speed the development of the process technologies.
These methods will be used in the development of In-Situ Consolidation of Thermoplastic materials process in the final part of this thesis.

Chapter 8 will describe the attributes of In-Situ Consolidation and Thermoplastic Composites to justify its selection as a strategic, next generation process and material, worthy of development by a Process Development Team.

The final section of this thesis, contained in Chapters 9 through 12, is to demonstrate the utility of the proposed new process development techniques presented in the previous chapters through the development of one strategic manufacturing process, In-Situ Consolidation of thermoplastic resin matrix/graphite composites. Specifically, Chapter 9 describes the development of a process science model of this process and the derivation of the key equations used in its makeup. Chapter 10 builds upon the process science model developed in the previous chapter, by using the model as an analysis tool to create a designed experiment (DOE) test matrix and to form an understanding of the effects of the key processing parameters. Chapter 11 follows up on the analysis section through the presentation and analysis of the mechanical test and panel warpage results from the designed experiment test panels. The results and analysis of Design of Experiments (DOE) test matrix were to determine the effects and the optimum values of the process parameters in this process. Chapter 12 completes this section by describing the simultaneous materials/ manufacturing process development and the role of analytical modeling in this methodology. This chapter is concluded with the identification of basic materials science properties for selecting suitable candidate materials to use in the In-Situ Roll Consolidation process. Once this has been accomplished, materials can be developed with suitability in a given process in mind.

A summary of the major effects determined by the testing and analysis of this project is given in Chapter 13. This Chapter also contains recommendations for a new process control system to maintain a constant consolidation temperature during processing and the conditions of future test matrices to better optimize the process. Chapter 14
concludes this thesis by tying together the rapid process development theme of this thesis with the enhanced learning rate organizations and the proposed development methods demonstrated in the analytical and experimental test programs. This chapter uses the data presented in the thesis to answer the three questions posed in this chapter on the viability of process development strategies in large mature manufacturing organizations.

Overall, this thesis will present the problems inherent with the attitudes, practices and strategies in use with regard to new process development in the American aerospace industry, and then propose new organizational forms and practices to overcome these difficulties. The thesis will conclude by demonstrating the proposed strategies and tools on a specific strategic process technology, In-Situ Roll Consolidation. To develop this infant technology, a process science model was created to be used as a learning tool to overcome the initial problems encountered with the process, then was used to define a process window to perform an optimizing DOE. The thesis will conclude with the test data from the DOE program and recommendations for further development of this process.
Chapter 2
Why Does the American Aircraft Industry Need A Manufacturing Process Development Strategy?

This chapter will attempt to describe the need in American aircraft industry for a manufacturing process development strategy by describing the current strategy of the Boeing Company and their future needs and challenges as a representative company within this industry. The need for manufacturing process development strategy for future competitive success will be illustrated with the emergence of the Airbus competitive challenge, the substitution of composite technology on commercial and military aircraft and the technical requirements of future commercial aircraft. Each of the changes in this industry point to the future where competitive success will be determined by the development of new process technologies to feed into new products. The substitution of composite materials points to the need for new manufacturing technologies to make these materials economical for the manufacture of more and larger components of an aircraft. The new materials, manufacturing processes and design concepts will change the basic dominant design in this industry as they progressively make older aluminum structural technologies obsolete. This dynamic substitution when coupled with future aircraft requirements that demand much higher performance efficiencies to compete against existing airliners, along with the emergence of well financed foreign competitor(s), leads to the conclusion that a manufacturing process development strategy is vital for long term survival in this industry.

Current Aircraft Industry Company Strategy

To illustrate the company strategies used within the commercial aircraft industry, the strategy of the Boeing Company will be used, as the industry's largest and most
successful competitor. A major tenant of their strategy has been the development of new commercial aircraft to fit existing or emerging airline market niches. To accomplish this strategy, most of its process development activities have been focused on developing processes to manufacture the next aircraft then in development. Long term process development to enable completely new types of aircraft has not been a hallmark of the commercial division or group of the company, since the 1930’s¹.

Boeing has achieved market dominance in the commercial aircraft market with a current market share of approximately 60%, by focusing on the following strategic areas in competition with their competitors:

Excellence in the design of their aircraft to achieve technical performance in areas of aircraft economies such as fuel burn per passenger seat mile, which have consistently outperformed their competition (73). This has been achieved through good design, aggressive weight reduction, good project management and vehicle integration efforts, and superior aerodynamics technology. The result of this focus has created a dominant product engineering culture within the company and has relegated other functions, such as manufacturing, to play support roles in this strategy.

Creation of a high quality product which has given the airline customer an aircraft with a long life of safe operation (greater than 20 years of operation life and 100,000 takeoff and landing cycles) with a high reliability of aircraft availability (above 99%). This has been achieved with damage tolerant (recent designs) and multiple load path design philosophies and a focus on achieving low risk, but efficient structural designs through extensive allowables and component testing. The safety record of jet aircraft has continually improved over the past 40 years due in large part to excellence in the design of

¹ For a description of the process development that accompanied the emergence of a dominant design in this industry, see Chapter 5.
safe aerostructures and the high compliance quality of the manufactured aircraft. High compliance quality is achieved in many cases through 100% inspection of critical parts. Damage tolerant design philosophies require manufacturers to work with customers to continually inspect aircraft in the fleet to continually assure safe operation of older aircraft. This emphasis on safe operation of Boeing's product has also reinforced the dominance of the product engineering culture to assure safety through careful design and testing. It has also created a risk averse decision making structure when dealing with risky new process or product technologies.

Marketing their product with a strategy of achieving economies of scale in their production of aircraft. By outselling their competitors in numbers of comparable aircraft, they have been able to aggressively move down the production learning curve of each aircraft, amortize the development cost over larger numbers of airplanes and create a production cost advantage over the competition, to attain high profitability. One study of labor efficiency between two manufacturers showed that Mc Donnell-Douglas required as many labor hours to assemble a MD-80 series aircraft as did Boeing for a much larger 747.

Creation of a family of compatible aircraft to fill all an airline's market size needs ranging from short range intercity jet aircraft,(737-500) to long range, large capacity aircraft for international travel (777A and 747-400). The compatibility of some aircraft parts and systems, such as the compatible Flight Management System on the 767 and 757, has allowed airlines to save on spares, logistics, training and flight crew costs by owning two Boeing aircraft types for different market segments. The 737 family of small jetliners ranging from the 107 seat 737-500 to the 157 seat 737-400 allows an airline to tailor the aircraft to its route structure, while maintaining parts commonality in one aircraft. This is another example of this strategy to capture customer sales through a product "family".
Boeing also customizes many of its aircraft models to fit the unique needs of an airline. Because of this customization, Boeing maintains a design team in place to perform this aircraft tailoring, long after an aircraft has gone into production. Because of the cost, size, complexity and customization of each aircraft, commercial aircraft can not easily be compared to other mass produced products like automobiles, but have more similarities to engineering projects such as the construction of buildings. (see Figure 5.2 for a comparison of aircraft manufacturing to two other manufacturing industries)

Creation of an extensive organization to support their airline customers with economic analysis, technical advice, repairs and spare parts to maintain their aircraft in a profitable operating condition. Boeing has been known to go to heroic measures to fix an aircraft in a state of AOG.(Aircraft on Ground) Customer support has become a strong motivating factor in the minds of their customers to purchase a Boeing aircraft, even if that means waiting in line for delivery, due to Boeing's current long backlog of customer orders. Close customer contact has also included incorporating customers desires for new aircraft into the product development and family strategies. Key customers have been instrumental in the design of all past Boeing aircraft development programs such as Pan Am for the 707 and 747, and United/Eastern for the design of the popular 727 (64). This practice has continued with extensive user input of United, British Airways, and JAL on the 777.

Employment of a financial strategy of conserving large amounts of liquid assets within the firm to essentially self finance its development projects. Because of the long term payback and high managerial, technical and market risks associated with development of commercial aircraft (87), it is uncertain that financing of these large projects could be performed with outside financing (55). During the high interest and discount rate years of the 1980's, which created a shorter term perspective on the part of
most American managers, Boeing engaged in only two low market risk, relatively low cost, fast payback modification programs, the 747-400 and the 737-300, -400 and -500 family (85). No completely new commercial aircraft programs were initiated during this time, though the one which was contemplated, the 7J7, never materialized(5).

From the above discussion, no one point indicates that Manufacturing or manufacturing process development are a central part of Boeing's strategy, but act to support these other strategic activities. A key cultural assumption in this organization and within this industry, is that product development and engineering are the most important activities of the firm and process development is to be performed in support of new products only. This discovery was made through a process described by Schein (65) through interviews of insiders on this topic by the author (who is also an insider to this culture). The underlying assumption has been in use since the 1950's, but it is never explicitly stated. This implicit assumption results in the continual use of a "technology pull" strategy, using new product development projects to develop new technology. This underlying assumption is not unique to Boeing, as the artifacts of this assumption have been detected throughout the aerospace industry in other companies and within the U.S. Air Force. A fallout of this assumption is that all process development activities must support an ongoing product development activity. With this assumption, the converse is also true, without a ongoing product program as justification, a new process development effort can not proceed.

New Competitive Challenge

During the 1990's, the Airbus consortium has emerged as Boeing's chief competitor in the commercial aircraft industry, eclipsing Mc Donnell-Douglas in this role. Like Boeing, Airbus has begun its own product family which eventually will compete in all market niches of this industry. Airbus has also drawn upon the substantial internal
the Boeing Company, believe Airbus has an unfair subsidization advantage in the 
competition between the two firms.

Early Airbus jetliners like the A310, which was developed in the mid 1970's, were at 
a substantial performance disadvantage to the similar sized Boeing aircraft like the 767-200, 
due mainly to poorer aerodynamic excrescence drag\(^2\) (73) and were perceived to be of 
inferior technology and quality. However by the late 1980's, with the introduction of the 
latest Airbus aircraft, the A320, perceptions had begun to change and this aircraft was 
regarded as a high tech, high performance airplane. The A320 was equipped with state of 
the art fly-by-wire controls, an airfoil design which many concluded was better in its drag 
performance for a given degree of lift than comparable Boeing designs, and most 
significantly, a higher total percentage of total aircraft structure was fabricated from 
composite materials than the Boeing competitive airplanes. (10% versus the 4% for the 
767). (49 & 41) Some of this difference could be explained by the fact that Boeing did not 
launch a completely new commercial aircraft in the 80's, but it was clear that Boeing was 
now behind its competitor in the level of technology on an aircraft in production. Unlike 
the 767 aircraft, which used composites for low load-bearing "secondary structures" like 
fairings, radomes, access doors, ailerons, flaps, and rudders while Airbus used composite 
materials for a primary load-bearing structure, the horizontal stabilizer, and developed it as 
a "wet" tailed\(^3\) aircraft at that. To innovate the tail structure of the aircraft, composite 
process development was required to manufacture this tail from a new material, quite unlike 
the aluminum alloy sheet which is the predominant material of construction of previous 
commercial jetliner tail sections.

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\(^2\) Excrescence drag is a parasitic drag term which is a function of the smoothness of the airframe. Rough surface finishes, poor aircraft 
sealing, non flush riveting or poor fairing between two airframe sections, all contribute to excrescence drag.

\(^3\) A "wet" tail includes fuel in the horizontal stabilizer. This design choice makes the structure more difficult to manufacture because 
it must resist fuel leakage. The Navy's A-6 rewiring project, a "wet" composite structure illustrated the difficulties in manufacturing such 
designs.
Unlike the aluminum alloy sheet which is the predominant material of construction of previous commercial jetliner tail sections.

Airbus also implemented a robotic drilling and joining process to fabricate its fuselage sections in an automated fashion. The result of this automated process is more consistent quality and tighter dimensional tolerances of its aluminum fuselage sections and less labor, rework, shimming and inspection, which lowers the cost, weight and excrescence drag of its major components. It is clear that with this aircraft and the incorporation of these new process technologies, Airbus has shown that it intends to compete with advanced technology that is not confined to avionics, engines and electronics alone, but also includes structural components and technology.

Composite Substitution in the Aircraft Industry

A modified Fisher-Pry (21) substitution model was used to analyze the substitution of composite materials in the aircraft industry. Figure 2.1 shows the composite substitution for military aircraft in terms of a ratio, \( \beta \), the weight fraction of the aircraft structure built with composite materials to the maximum weight fraction that could potentially be fabricated with composite materials. (primarily those components currently fabricated from aluminum). The modified Fisher-Pry expression used for this analysis is;

2.1 \[
\ln \left[ \frac{\beta}{1-\beta} \right] = (2\alpha f_{\text{max}}) \cdot t + (-2\alpha f_{\text{max}} t_0)
\]

where \( \beta = f / f_{\text{max}} \), \( \alpha \) is the mean substitution rate, \( t_0 \) is the year where half substitution of the new technology for the old occurs, and \( f_{\text{max}} \) is the maximum percentage of the structural weight fraction that composites could potentially replace.

As time has progressed from the initial introduction of composite materials on the F-111, progressively higher weight fractions of new military aircraft structure has been fabricated with composite materials (60). A similar substitution curve for commercial
aircraft is shown on Figure 2.2. These figures each use 1967 as the base year with the introduction of composites on the F-111(60). Comparison of these two figures shows that the rate of substitution in the commercial aircraft market segment has been roughly 40% as fast as the military segment, and the time to half market substitution, $t_0$, is 2.5 times longer. This slower substitution is due mainly to the lower life cost savings for a pound of weight savings on commercial aircraft as compared to military aircraft\(^4\). The increased value for weight savings by improving performance and survivability, allows the military designers to utilize higher amounts of the expensive composite materials in their aircraft. Figure 2.2 also shows that during the 1980's Airbus aircraft incorporated a larger percentage of composites on their newly introduced aircraft than did similar Boeing aircraft. However the projected composite substitution for aircraft introduced in the 90's shows similar levels of usage on competing aircraft. Finally, this figure shows that in the next two decades substantially higher weight fractions of composite materials are projected to be used on the future products in this industry.

\(^4\) The additional cost that may be incurred to save a pound of structural weight for commercial aircraft ranges between $100/lb and $350/lb. The underlying rationale for these costs are the airline's life cycle cost savings in fuel burn with a reduced weight. For military aircraft, this figure may range between $500/lb and $2000/lb depending on the range and speed characteristics of the vehicle being designed. These figures take into account both the life cycle savings, the multiplier effect of reduced structural weight in reducing fuel and further structural weight, and finally the improved performance increases survivability and allows for a smaller fleet size to perform the same mission objectives. Each of these factors makes the designers of military aircraft willing to spend more for a pound of weight saved and therefore more likely to utilize high cost, but lightweight materials or structures. These cost figures that are used in trade studies vary over a range much like an futures option contract. If an aircraft is overweight and the deadline for releasing engineering drawings is nearing to support the first aircraft rollout, the cost to reduce a pound of weight progressively increases because of the penalty clauses in new aircraft performance guarantees. The actual cost figures used to evaluate weight reduction projects at any given point in time is proprietary information of the commercial and military aircraft manufacturers, because this figure gives a strong indication of the design strategies likely to be employed at any given point in the development project. These cost ranges and the organizational dynamics which contribute to the selection of materials and technology for commercial and military aircraft was obtained from several interviews with Weight and Structures Technology Managers. The literature on this important subject does not contain firm values of this cost metric.
Figure 2.1  Substitution of Composite Materials in Military Aircraft Structures
Figure 2.2  Substitution of Composite Materials in Commercial Aircraft Structures

Modified Fisher-Pry Curve
Alpha = 0.06943
t0 = 43.51 yr
fmax = 0.72

Data Derived From Following Sources:
Mr. Johannes Kohorst (41); Airbus Data
Mr. Al Miller (49); Boeing Data
The process of substitution of composite materials and the new structural concepts which may potentially be produced from them, constitutes a new dominant design in the commercial aircraft industry. This transition will be similar to the transition that occurred in the 1930's with the introduction of aluminum\(^1\). The Abernathy and Utterback model for industry transformation \(2\) for the introduction of new technology and the change in the dominant design predicts that survival in transforming industries requires a large investment in process technology and introduction of several generations of rapidly evolving manufacturing processes to compete. A process development program then is strategic to a firm's survival in transforming industries. As illustrated on Figure 2.2, the utilization of composites in commercial aircraft has had a relatively long, slow incubation time. Substitution is projected to proceed at an accelerating rate throughout the next two decades. To achieve the large structural weight fractions projected for composite materials in this figure, their introduction into wing and fuselage structures will be required. The manufacturing processes presently used for production of composites will not likely be capable of manufacturing these additional components economically without additional process development. Most likely the introduction of totally new processes that are optimal for these new components will be required. \(3\) Hilton and Kopf \((33)\) conclude that "greater penetration \(\text{(of composites)}\) in the \(\text{(aerospace) market will depend on improved fabrication technology and reduced costs.}\)" The ability to cost effectively introduce this technology will require substantial expenditure in new generations of process technology.

As shown on Figure 2.1, substitution of composite materials in military aircraft will shortly reach completion. The ability of military aircraft companies to manufacture composite structures has become a key requirement for the surviving firms. For example, one secret military aircraft project, the A-12, is rumored to have foundered because one of the prime contractors for this aircraft simply could not manufacture the composite
structure of the design. Therefore, along with the change in dominant design that has accompanied this materials substitution, a wave of exit from the industry should occur in accordance with the industry transformation models (77). A similar industry dynamic would be expected as substitution proceeds in the commercial aircraft segment.

New Technology as a Competitive Weapon

Airbus entered into the commercial aircraft industry relatively late, well after a dominant design was established. Entering mature manufacturing industries late requires that the entering firm overcome the barriers to entry through the investment of a large amount of capital to replicate the specialized processing equipment of their established competitors. Utterback and Suarez (77) state that firms which attempt late entry into a mature market usually have short and competitively painful lives, unless they have better product or manufacturing technology than their established competitors. In light of this discussion, the Airbus competitive strategy of attempting to compete with advanced structural technology in the area of composites and the use of large government subsidies is not surprising. Airbus’s emphasis on competence destroying, new composite technology, would be an effective strategy to compete against established rivals such as Boeing, whose capital and technological competence were tied up with the existing metallic structural technologies. Henderson and Clark (32) add "New entrants with smaller commitments to older ways of learning about the environment and organizing their knowledge, often find it easier to build the organizational flexibility that abandoning old architectural knowledge and building new (technology) requires."

In a mature, stable industry, as commercial aircraft had evolved to by the early 1980's, one of Boeing's key strengths was in its functional specialists, who were able to continue designing and producing their current aircraft models with the existing metallic technology. These specialists would not be ideally organized or trained to exist in an environment of dynamic technological change(51,75). The transition of industries from a
period of dynamic product innovation to one of stable cost competition, occurs after a dominant design. This transition also involves a change from the flexible, "organic" organizations of the fluid period to a stable functional hierarchy.\textsuperscript{(75,77)} The learning rate of these organizations also evolves from a rapid rate in the fluid state, to one of slow incremental progress. Klein \textsuperscript{(40)} states that this transition from the "fluid" state to the mature "specific" state appears to be highly irreversible, putting older organizations at a distinct disadvantage when new technology reverts an industry back to a fluid state.

To meet the competitive challenge of radical innovation in structural technologies from Airbus, the American aerospace firms will need to reverse this process of specialization of individuals in functional bureaucracies to create generalists who can adapt to the changing technological environment and able to develop and utilize newer, state of the art, technologies.

**Challenges in the Development of Future Boeing Jetliners**

Another problem facing the Boeing company in the near future is that with the development of the short and long range 777 aircraft (A&B variants) and a potential stretched version of it in the future, all of the market niches between the commuter sized aircraft and the jumbo subsonic aircraft have now been filled. Opportunities for future new aircraft become limited to those where substantial performance advances are required to justify the cost of new airplane development. Without substantial advances in aerodynamic performance, engine performance or structural weight performance, new aircraft with their higher price tags will face aggressive competition from older aircraft, with their long product lives. This sorry state of affairs plagued the 757 in its competition with the older 727-200 models of roughly the same size during the mid 80's, when the price of jet fuel dropped \textsuperscript{(85)} and with it the 757's chief competitive advantage over these older planes. The three potential future market opportunities for the commercial aircraft industry in order of their first flight are outlined in the following paragraphs:
1.) The New Large Airplane, NLA, is a very large subsonic aircraft to fit into the 600-800 passenger category with long overwater range for introduction in the 1998-2000 time frame. Initial plans for this aircraft show it to dwarf even the 747 in size. To achieve the size and long range goals of this aircraft, the high bypass turbofan engine and composite empennage technology developed for the 777 should be capable to manufacture this aircraft and provide much of the needed performance. The very large size of this new aircraft, whose size nearly dwarfs even the 747, makes radical new composite and metal forming technologies cost effective over the life cycle of this aircraft. The performance advantages and reduced fuel burn afforded by weight savings through the extensive use of composite primary structures, such as a composite wing, may be needed to help justify the high cost of this aircraft's amortized development cost to each airframe, for cost effective competition with the smaller capacity 747-400. Such a huge composite wing structure would require completely new composite manufacturing processes to meet the cost and size goals of this project. For example, the long length of this wing would not fit into any existing or proposed autoclaves which are used for consolidating and curing composite structures. Due to the recent push forward of the expected first delivery of this aircraft, it now seems unlikely that a composite wing will be included on this aircraft, because the time to develop these new processes is no longer available. It is likely that the NLA will have a composite empennage, just like its predecessors, the 777 and A320. It would appear that the choice of the technology for this aircraft will be dictated by the development time for new manufacturing processes. The development time for entirely new manufacturing processes that currently ranges to well over a decade for composites and would rule out the use of this material in certain applications where effective manufacturing processes do not presently exist. Organizations and strategies which cut the development lead time of new manufacturing processes would enable new products and make others, such as the NLA, more competitive.
2.) The High Speed Civil Transport, HSCT, is a large supersonic aircraft capable of carrying 300 passengers (nearly the same as a 777) over trans-pacific ranges at speeds above Mach 2. The aggressive goals for this aircraft include a premium ticket price for this aircraft of only 20% of the equivalent 747 fare and limited ecological side effects.(ozone depletion, hydrocarbon emissions, noise on takeoff and landing, and sonic boom generation) Obviously, the achievement of the goals of this aircraft require advanced engines and a lightweight composite airframe. The composite materials used for this aircraft must also be capable of a sustained 300 F exposure, which rules out all currently used composite materials, and all but the most brittle, high temperature, aluminum alloys. To achieve the manufacturing capability to produce the huge high temperature composite structures for this aircraft, a sustained materials and large scale manufacturing process development must be undertaken to enable this aircraft to be designed and built in the 2005-7 time frame. Without this up front technology development, it simply would not be possible to build this aircraft with today's technology and meet the cost and performance requirements set for this aircraft.

3.) The last, relatively near term, project is an efficient, small, short range, subsonic aircraft with a capacity to carry from 100 to 150 passengers. This aircraft would replace the aging 737 and MD-8X/DC-9 families. Boeing tried in the mid 80's, unsuccessfully, to find a market for an aircraft that fits this description, with the 7J7 project. At that time, they were unable to find enough customers with similar desires to choose one configuration and launch a program. This aircraft size class includes the late model 737, A-320 and MD-8X/DC-9 aircraft, and all the older 727 aircraft before them, together totaling over 5500 in total aircraft sales over a 30 year period. Because of the large market for aircraft in this size range, it is nearly certain that firms within the commercial aircraft industry will need to launch new aircraft in the future to capture this
valuable market segment. Once again, substantial operating performance advantages over
the 737-400 or A-320 will be required to allow a high tech aircraft to compete against
these older airplanes. This is possible through the use of very high bypass ducted
turbofans and a primary structural composite wing. To attain the goal of a composite
wing, a much higher level of manufacturing efficiency and a lower level of composite
materials cost will be required to maintain the aircraft's cost in a competitive region. Here
again, aggressive process development is required to enable this aircraft.

Conclusion

This chapter documents the key industry trends that make a process development
strategy and a manufacturing strategy essential to competitive survival. Three major
trends were identified that will impact airframe manufacturers over the next 20 years. The
first is the progressive substitution of composite materials for aluminum in aircraft
structures. Although these materials have initially been incorporated into structures which
have utilized similar design and assembly concepts as the traditional structures, this will
not always be the case. For the progressive substitution of composites to take place
according to the substitution curve that was presented, new processes will be required to
make these expensive materials more economical and suitable for more components of the
airframe.

Driving this substitution is the requirement for substantial improvements in aircraft
efficiency, over the current state of the art, to pay back the large expenditure in capital to
develop new aircraft. Large increases in petroleum prices as have occurred in the 1970's
would only accelerate this trend. Certain aircraft types, such as the HSCT, and its military
derivatives, will be in essence enabled by fundamental new process technology. Finally,
the existing competitors in this industry cannot stand still with regard to new technology,
because new entrants may appear emphasizing the new manufacturing technologies, as
they are not organizationally wedded to the old.
In an industry that has reverted back to a transitional stage in its development through the introduction of new technology, the established firms will need to develop and implement several generations of state of the art technologies to remain competitive. Utterback and Suarez (77) state that after a change in the dominant design (created through a fundamental change in technology) that the once dominant players in the earlier industry usually are minor players or have disappeared altogether in the transformed industry. Competitive survival in technological transitions requires a process technology development strategy and organizations that are flexible enough to develop the technology rapidly and outdevelop their competitors.
Chapter 3
Generic Industry Problems With Process Development

The purpose of this chapter is to illustrate many of the generic industry problems which occur in the development of new process technologies, accompanied by discussion to analyze and identify the underlying causes of these problems. Two examples from other industries (outside of aerospace) that have pursued process development strategies are documented to show the mixed results from the use of this strategy and potential difficulties to be avoided. Potential organizational concepts, strategic investment decision making and development strategies are proposed to overcome these difficulties. These concepts are presented as solutions to some of the difficulties presented so they can be built upon in successive chapters of this thesis.

As an industry reaches maturity and a dominant design has come forward, the manufacturing process and the design of the product become tightly intertwined, as was shown by Abernathy (1) in his study on innovation and productivity in the automotive industry. To illustrate this point, Abernathy describes the case when the Ford Motor Company tried unsuccessfully to downsize their large V-8 engine to put it into a smaller, sporty automobile during the 1930's. At this time, Ford wanted to expand its product line to compete with GM and to have the resulting products fit within its existing underutilized production facilities. They found that the existing production line was so tightly linked to the full sized V-8 product, that the costs to build the smaller engine and auto were nearly the same as the full sized product. It was therefore uneconomical to build the new auto with the existing manufacturing process and this small car had to be dropped, even though it fit within Ford's strategy to expand its product line. To produce this new car economically, Ford would have had to build new factories with new manufacturing processes optimized to build small autos inexpensively. This case illustrates one example
where the product has become tightly linked to the process used to manufacture it. Ford would have needed to undertake up front process technology development to enable the product it wanted to produce.

The current use of design for manufacturing tools (81) and the trend to form Design-Build teams in the aerospace industry to get manufacturing input early on into design teams and to build manufacturable products (81), should increase this tendency to create products that fit exactly into the capabilities of the existing process technology, in the most efficient manner possible. Therefore the product and process will become so tightly intertwined that it will become impossible to innovate the product without innovating the process first. As companies pursue methods such as integrative design-build teams to cut the development cycle of new products in half or more, it will also become increasingly more difficult to implement innovative new processes within this system. With these accelerated development projects, very few new process development projects will fit the shrinking time "window" (described in Chapter 4), . Continued use of product development to drive new process development in parallel with product development, will result in all process and product improvements becoming mainly architectural and incremental in nature1.

Through the choice of the manufacturing process in the design-build team, 80% of the cost of the manufactured item is determined. Rolls Royce(15) and GM (81) found this rule of thumb was true for the manufacture of aircraft engine parts and truck transmissions, respectively. As was shown by Abernathy, this rule was learned (but not so specifically stated) by Ford in the 1930's. Therefore the only way a company can reduce the large structural costs inherent in the selection of the material, and manufacturing or

1 Architectural innovations are those which occur through the rearrangement of basic components through creative new designs (Henderson and Clark Definition) or through the bolting on of new component technologies (Utterback Definition.) Incremental innovations come through continual improvement of existing products and processes. Continuous improvement makes a substantial impact on the competitiveness of a firm through a series of small advances compounding upon each other. Each of these innovative processes can be undertaken within a short time frame but will not yield a discontinuous jump in either performance or cost that fundamental, (the so called "radical") innovation yields.
assembly process, is to undertake up front process development that either lowers the cost of the present process, or replaces that process with a newer process which is less expensive. Alternatively, a company may desire levels of design performance in its new products, that is not capable of being achieved with their present processes. Up front process development is then required to enable the desired product design. These are the rewards for company that undertakes a process development strategy.

Pratt & Whitney Aircraft, a major producer of gas turbine engines for commercial and military aircraft, has performed a study of its R&D funding and discovered that only 25% of the total is devoted to process development, while the remaining 75% is devoted to product development (16). This number at first seemed surprising, because Pratt & Whitney is known throughout the industry as pioneer in new process technologies2, but perhaps that reputation reflects their past history. Several interviews with technology managers at the Boeing Company resulted in a general consensus that the percentage of funds devoted to product development substantially predominates over those allocated to process development. The 25% figure probably is an upper bound for the Boeing Company, when one considers that even a large percentage of the resources allocated to MR&D goes to support product development and is not directed toward new process development. Henderson (31) in a study of Boeing's Operations Technology Pre-Capitalization budget showed that only 13% of these requests were to introduce new capabilities into the company.

An overall survey of the aerospace industry's R&D spending from World War II to 1982 by Mowery and Rosenberg (52) found that a very small amount of the total industry's R&D resources were devoted to basic research (less than 10%) and of the total

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2 Pratt and Whitney Aircraft pioneered the use of many of the advanced technologies used to fabricate today's high performance turbine engines. Examples of these processes are: 1.) casting process of single crystal turbine blades, and before that the development of directionally solidified turbine blades; 2.) the development of superplastic forming/ diffusion bonding to produce hollow titanium compressor blades; 3.) the development of hot isostatic pressing and isothermal forging to produce fatigue resistant compressor disks from superalloy powders; 4.) The creation of a centrifugal forging atomizer process to develop new titanium and superalloy powders with advanced chemistries and microstructures.
the commercial aircraft industry sponsored only 10% of this work (the government
sponsored the rest). The commercial industry did support a substantially greater
percentage, 30%, of applied research (which would include new process development)
which accounted for roughly 25% of the total R&D expenditure. They found that
Product development always claimed the predominant share of the funding, as it never fell
below 60% during all the years of the analysis. These funding patterns appeared to be
quite stable over the nearly 40 years of their study and were not recent trends. Mowery
and Rosenberg conclude by stating that the commercial aircraft industry has only
contributed about 30% of the R&D in the aerospace industry during this time period with
the remaining 70% coming from U.S. Government sources, chiefly the Department of
Defense and NASA/NACA.

Mansfield's (47) study of 50 American and Japanese firms has shown that the R&D
funding devoted to process development in American based manufacturing firms averages
33%, while their Japanese counterparts spend 66% on process research and the remaining
33% on product development. This is particularly worrisome as Japanese firms on
average, invest about 6% of sales into R&D, while American firms average about 3.5%,
so not only is the percentage devoted to process development larger, but the size of the
pie devoted to R&D is larger as well. Clearly, the Japanese manufacturing companies are
operating with another paradigm in mind in their investment in new process development,
and R&D in general. Mansfield states that the reversal of these proportions in their
portfolio of R&D projects is one reason why Japanese firms get a higher rate of return on
their R&D investment, and increases their willingness to invest more in this critical area.
The Presidential Commission report on Industrial Competitiveness in 1985 (47) stated, "It
does little good to design state-of-the-art products if within a short time our foreign
competitors can manufacture them more cheaply."
Interorganizational/Cultural Problems with Process R&D

To manage the diverse activities of each of the diverse groups involved in the development of new structures, advanced materials and processing technologies and to create an environment where these functional skills can grow, many American companies with process focused, multi-plant systems who are generally involved in the manufacture of large, complex, assembled products (as opposed to single plant, product focused companies like Hewlett-Packard) have organized these staffs of engineers into functional organizations. These functional organizations are excellent in the mature, "specific" (75) industries where standard products and economies of scale are the norm, but have difficulty dealing with the uncertainty created when new technology is inserted into old industries. The large hierarchical structures created in these firms have been characterized by Morgan (51) with a "machine" metaphor, where each group can be compared to a cog in the total company machine, each component optimized for its specific function and each emphasizes functional competence. This division of labor has an analog in the organization of the factory operations of these companies; where the work flows between "clusters" of like machines (66) organized by process type (all milling machines, drill presses, etc. are organized together) creating a disorganized factory flow, usually including long manufacturing lead times and high inventory. The hierarchical, functional organization of process development creates a serial development process (71,30) in an environment where information flow and learning is impeded, much as the material flows are on the factory floor. The result of this serial development is a long "cycle time" (71) to complete the development, much like its manufacturing plant analog in factory flow time.

The current development of technology in a functionally divided organization allows work to proceed on some areas of the technology, but not on others concurrently because of different sets of priorities in each organization, creates a process of serial hand-offs. This type of organization will have chronic problems in fielding the technology into
its product line and into manufacturing, because the unfunded work in one functional area
becomes a roadblock which prevents further implementation until this area is brought to
the same level of maturity as the other areas which have completed their tasks. Serial
development is partly responsible for the long process and product development time
which occurs in functionally organized companies(71).

Kanter (38) describes the organizational life of individuals within these functional
organizations by indicating that "they spend most of their time with others just like
themselves who share their beliefs and assumptions." This type of corporate culture
encourages an orthodoxy of beliefs and idea generation is discouraged. She adds that
"when departments or specialties are segmented and prevented from contact , (or) when
career paths confine people to one function or discipline for long periods of time",
communication between the fields becomes difficult and "creativity is stifled."

With a change in the competitive environment, where technological development
becomes a strategic activity, requires a more fluid organization, with better transfer of
shared skills and information to deal with the new technology. Morgan (51) would
characterize this new type of organization with an "organism" metaphor. The
organizational structure which best exemplifies the "organism" metaphor is the formation
of "ad-hoc" teams in response to competitive environmental pressures. These teams exist
as long as they are needed, then dissolve when their tasks are complete. These fluid team
formations and dissolutions allow a firm a great deal of flexibility in dealing with
turbulence in the technological or competitive environment. Within most large firms,
these team structures exist within a matrix management organization, so the teams can
form from a group of specialists held in a functional staff organization. Unfortunately, in
many companies (specifically aerospace companies), the functional staff organizations
predominate in long range R&D, so these projects tend to operate as modified
bureaucracies. In a turbulent technological environment which occurs during the change
in the dominant design, team based R&D is required to create the new technological competence needed for survival in a changing environment.

If a firm desires to become a "learning organization" (51,67) that is adapted to exist in a turbulent technological environment, the eventual goal is to transform the original "organic" team of functional specialists into another type of team typified by the "hologram" metaphor. An organization or team typified by the "hologram metaphor" has members with overlapping or redundant skills, so that each member can perform the required tasks of the team. Such a team is extremely flexible in its makeup and is capable of undertaking a broad range of tasks (within limits). In an "organic" team structure, only that part of the technology that falls within an individual's area of specialty is captured by the individual, so technology transfer frequently entails the transfer of the entire group. By contrast, the "holographic" team structure with its overlapping skills allows the entire technology to become embedded in each individual, making technology transfer easier, especially if it needs to be transferred to several locations. This transformation of a team to a "holographic" model occurs as the technical expertise of the specialists begins to diffuse amongst the team members through long term association and cross training. As this process of forming a "holographic" team proceeds, the members of the team pick up skills in several of the necessary areas. The formation of a "hologram" model team culture includes the creation of the team's own language and methods, which increase the rate of learning amongst the members and further increases the rate of technological development. When the transition to "hologram" team based culture is complete, each member of the team has captured the entire technology and is capable of transferring it in its entirety at the conclusion of the project. The result is a growing interconnected organizational competence diffused by these team members.

The manufacturing analog to these new types of development organization is the organization of machines on the factory floor into balanced cellular lines, where the
product flows smoothly and rapidly with a high amount of information transfer between the workstations which have been integrated together. This analogy also holds from the standpoint that the cycle time for a product (manufacturing process development) is cut substantially with such an organization. The transition to these new types of organizations are essential for older firms in a "specific" pattern to remain competitive in the industry where technology innovation becomes a strategic concern to the survival of the firm (75).

The boundaries between the functional staff groups of the traditional development organization have created a major barrier to the implementation of new technologies, because each of the skills required to develop a new process are not focused on the technology at the same point in time, as development proceeds in a serial, time consuming fashion, as in the machine shop analogy. This same problem has been addressed in product development, where it leads to a "throw it over the wall" mentality, as the project transitions from research or Preliminary design, to engineering design, to manufacturing.(81,10,64(at Boeing),71,50,61) The result in product development has been longer product development cycles, with many engineering changes coming late in the development cycle(81,71). These changes are created because the designs prove to be unmanufacturable; don't fit with other parts of the system; are incompatible with the overall goal of the product concept (10); or are inefficient to manufacture. A similar set of circumstances occurs in process development and leads to the Catch-22 like dilemmas in the development process.

Because the different organizations with responsibilities to develop new process technology have different priorities and missions, they do not fund the development of process technology in their functional area at the same time to support the development of technology in other areas. To illustrate this point, two cases of this that were observed during the internship will be used. One MR&D (Manufacturing Research and Development) process technology group has invested nearly a decade in the development
of Resin Transfer Molding, an attractive process for the fabrication of previously hand laid up, complex, composite structures. Because this process requires the use of less viscous thermosetting resins and graphite fiber woven preforms which are fundamentally different than those used in the fabrication of 2D laminate composites made with tape, significant work is required in other functional areas to accomplish the implementation of this technology on commercial aircraft secondary and (possibly later) primary structures. First of all, a specification for the new less viscous resin system(s) and the woven fiber preforms needs to be developed by the materials technology organization. With this specification, the structures technology organization can then procure panels or components from vendors or from the MR&D laboratory, to create a set of allowable materials properties for this materials system and manufacturing process. Additionally, structures technology will need to learn how to design composite structures with woven fiber preform reinforcement, which is significantly different than cross plied 2D, composite laminates that they are now familiar with. Until a set of allowables and design analysis techniques exist, schedule driven and risk averse design engineers on a aircraft development program cannot attempt to use this attractive process as a baseline for a component's design.

The materials organization's mission is to develop new materials specifications and also to police the old ones at the vendors and within Boeing, and as such has its resources stretched in performing both these duties. To develop a materials specification,(in Boeing lingo an X-BMS) or for structures to create a set of allowables for this new material or process, a customer must be found (new aircraft program or existing aircraft program) that is willing to use the process and fund the work. Because an aircraft program is generally under tight schedule constraints, the data from the specification and allowables program could not come in time to support the program. Therefore a program would be unwilling to fund work that they are not going to use. Even a design trade study to show the practicality of the new material/process cannot be performed without a set of
preliminary allowable mechanical properties being available, so interesting a customer to fund the work is also highly unlikely. Under this functional organizational development, with "pay as you go" funding, a Catch-22 exists where the process and its implementation is stopped from further progress; because no allowables program will be run without a program customer; and no program customer will select a new material or manufacturing process as a candidate without design allowables and a materials specification being available. For all intents and purposes, under the structure of this problem, the manufacturing process development done in house on RTM might as well not have been done. A similar problem currently exists with the X-BMS for APC-2/IM-7, a thermoplastic resin composite material used in the In-Situ Consolidation development program, to be described in the later part of this thesis. The independence of the organizational subunits have made it increasingly more difficult and costly to achieve radical innovations in new materials or processes. Although these examples were taken from Boeing's composite development programs, these Catch-22 impediments created by the development system are generic within the defense aerospace industry for new materials.

The major problem with this type of serial development, is the long period of time that it takes to implement new process technology into established firms. The implementation of graphite composite primary structures in the Boeing Company took roughly 12 years from the initial development effort, until it was fully in production on a product. Similar results of decade plus development times have been observed in the superplastic forming of titanium in other aerospace companies. Shuster (68) discusses many of the chicken and egg dilemmas in the introduction of new materials and fabrication technologies into the aerospace industry specifically with regards to discontinuously reinforced metal matrix composites. He documents that it took the DuPont Company 20 years to break into the black with its Kevlar aramid reinforcement fibers. Project
HINDSIGHT (37), a mid 1960's Department of Defense program to retrospectively ascribe the major process and product innovations that enabled the (then) current generations of military systems, showed that 31.5% of the innovations required 10 or more years of development to ready for their first systems applications. From a non systematic observation of the 603 innovations listed in this report (not all of the innovations were itemized) those innovations which required longer than 10 years were primarily process rather than product innovations. This report also shows that the long process development times in the aerospace industry have existed (at least) since the mid 1960's, and is not a recent occurrence.

Clearly, a new type of organizational structure is needed to span the functional organization's boundaries to develop all the fundamental skills around a new process to a state of readiness that it can be used on an aircraft program. This thesis proposes the establishment of a Process Development Teams concept (PDT), similar to the aforementioned DBTs, but will contain individuals with all the functional skills present to develop, scale-up, and qualify both a new process and its associated materials technology for use on future products. For example, structural analysis representatives would be present to learn how to design structures with the new processes (like with the wovcn fiber preforms in RTM) and to perform trade studies to evaluate the structural performance of the new technology and establish performance goals for its development, as data from the initial experimentation is completed. They also would be able to continually evaluate the current state of the materials and manufacturing technologies to determine how far these new technologies are from efficient implementation. This provides a performance "scoreboard" to assess the maturity of the process for funding and implementation decisions. Other functional specialists would be present with other skills in manufacturing process development, quality assurance, industrial engineering and materials technologies, as will be described in Chapters 6 and 7.
These multifunctional team structures should enhance creativity and innovation in technology development. Kanter (38) describes this enhancement in creativity process by stating that: "Cross-fertilization of ideas comes from cross-boundary contact. Creativity often springs up at the boundaries of specialties and disciplines, rather than squarely in the middle."

**Net Present Value (NPV) Financial Justification of Process Development**

One potential explanation for the current use of new product programs to drive all new process development activities is the difficulty that process development groups have in justifying process development in the first place. If these groups can justify that the process will be useful to produce the next forthcoming product, then it ties a set of revenues to the development project and allows an NPV investment decision to be made on the development of the new process.(30) To justify the development, optimistic projections of the total development time are made, which makes the NPV a positive value and allows the process development to meet the new product's introduction schedule(30). Using NPV calculations to decide highly uncertain investment activities like process development is a misapplication of this decision tool. This tool is only well suited to help make decisions on activities where the cost, implementation/development times and future revenue streams are reasonably well known or can be estimated with some degree of certainty(30). In new process development, none of these can be estimated within any precision at the outset of the project, so the NPV tool will yield answers which have little validity.

Gold(27) states that there are," very serious obstacles to estimating the effects of profitability even after the actual outcomes of the production operations are known." For most process innovations, the use of the NPV
capital allocation process requires data on profitability "before any experience has been gained."

This makes the use of NPV decision making with new process technologies nearly impossible. Henderson(31) has documented that the use of financial justification and ROI hurdle requirement (a less sophisticated and less accurate financial decision tool than NPV) is being used to evaluate Pre-capitalization Budget requests for process machinery development at Boeing. One of the conclusions of the study was the high hurdle rates selected, (much greater than the underlying company ROI), caused Boeing to systematically underfund process development.

Another drawback to the use of the NPV tool for technology investment decisions is the problem of the base case (30). In most NPV calculations, the base case assumption (called the status-quo condition) is the company’s revenues and profits will continue in the future, as they are now, even if the company decides not to invest in new technology. Even the most casual observer will realize that nothing in the business world is static and the continuing use of old manufacturing processes, whether putting the company at a cost or performance disadvantage to their competitors, will likely have an adverse effect on the revenues and profits of a company in the future. It is likely that any firm that uses a formal financial justification for the funding new process development and innovation will likely underfund new process development.

The final problem with the use of the NPV decision model for new process development is the practice of using high discount rates in the evaluation of these activities due to the risk associated with new technologies. In the early eighties, discount rates as high as 25 to 30% were commonly being used (27). Hurdle rates in the high teens (31) are still being used, indication that a very high risk b (8) is assigned to these projects. Gold (27) states that this, "heavy discounting of future returns from some newly emerging
major technology innovations seriously underestimates their contributions to long term competitiveness." Gold goes on to add, "discounting expected profits back at the usual (high discount rates) over the several years usually required to achieve effective operation often fails to yield net present values attractive enough to warrant their adoption." From his argument, the types of process development which are done would be incremental process changes which could be performed in a short period of time with very little risk, but would not include long range, fundamental process development which have a greater long range strategic impact on the operations of a company. This was another of the major conclusions provided by Henderson (31) in her study of Boeing Pre-Capitalization manufacturing development projects. The long development times that presently occur in the aerospace industry on fundamental process development, when coupled with an implicit (mental) or explicit Net Present Value decision rule calculation, create structural barriers to prevent firms from investing in fundamental process development at all.

**Profitability of Investment in New Process Technology**

The long period of time to develop new process technologies creates a vicious downward spiral in the willingness of a company to undertake this type of development. Using a conventional discounted cash flow investment analysis procedure, the longer it takes to develop a new process technology, the less one would value the potential benefits derived from the R& D expenditures. Long process development times that produce NPV's which are small or negative, make it less likely that a firm will engage in process development in the future. Process development is essentially a learning activity, the speed of this learning and the rate of development is based upon the skill and prior knowledge of its practitioners within a company. If process development is not undertaken often because it does not appear to yield acceptable returns on the R&D dollars invested, little or no skill in hastening the development process is acquired. Future process development activities will not improve and may even slow down. As a result, the
NPV’s of these projects will continuously degrade in a downward spiral fashion and even fewer development projects will be undertaken.

Concerted effort to cut the development time of such projects will raise the NPV of these projects by bringing the benefits closer to the time of investment, lowering the uncertainty of the investment and allowing the company to capture a greater market share and profitability by being first to market with their developed technology. A shorter development time also lowers the total cumulative cost of each new development project, and allows more development projects to be undertaken for the same budget. In contrast to the earlier vicious downward spiral, concerted effort to reduce development times creates a virtuous cycle leading to the increased use of process development as a competitive weapon. Such an occurrence will make a company more willing to invest in future development projects and perhaps more important, less risk averse in their investment decisions.

To attain these benefits, the development time metric must be compressed from the current 10-15 years to 5-7 years. With this compression, the development time is brought into the range where long range market and technology forecasts can reasonably be made. With similar time scales, strategic choices of process development projects can then be made. Finally, the more rapid development of new technology will yield a competitive advantage in the marketplace by fielding technology ahead of the competition, increasing the payback on the investment in this technology.

**Accounting System Problems with R&D and Process Development**

Research and Development in general and process development in particular are accounted for under American FASB rules as expenses of the period rather than fundamental investments in the competitiveness of the company like capital equipment. Kaplan (39) states that return on investment (ROI) measure of profitability was developed earlier in this century to help corporations engaged in multiple activities evaluate the
efficiency of each of the diverse operations, and as an overall measure of the profitability of the entire company. With senior managers graded on their divisional ROI profitability, a strong incentive exists to reduce expenditures on discretionary expenses and intangible investments like R&D, whenever sluggish sales or growing costs make profitability targets hard to reach (39). Kaplan adds that, "The immediate effect of such reductions (cutting R&D expenditures) is to boost reported profitability - but at the risk of sacrificing the company's competitive position." When R&D budgets are cut, the short term, product directed R&D usually has the highest priority, because it is essential to create the companies strategic new products, so the longer range, fundamental process research is frequently the target of such cutting.

The effect of these periodic cuts on development projects is to cause the periodic disbandment of the research group or their redirection onto new tasks. In a year or two the funding is restored and the members of the team have to be reassembled and the project has to go through the slow initial startup phase once again. The result of the periodic nature of funding (quite common at Boeing and other companies) is the development efforts take much longer. It is also difficult to maintain technical competence in the development staff, as individuals are continually being redirected into new career paths, due to budgetary constraints. Cyclical funding also makes it difficult to enter into long term joint development efforts (described in the next chapter as the preferred way to develop technology with a vendor) because management is unsure as to the long term commitment to the effort, as it may be a target for cutting during the next budget crunch.

Clearly new methods of accounting for long term investments in technology need to be created to remove the incentive from financially oriented senior managers from periodically axing process development projects, if a firm is to successfully implement a manufacturing strategy and become a World Class Manufacturer.
Strategic Process of Selecting New Process Development Projects

A new approach to this dilemma of different time scales is to make process development a strategic decision rather than a financial one. Gold (26) recommends replacing the NPV project evaluation process with the following set of three questions.

* What will happen if we adopt/develop it and our competitors don't?

* What will happen if they adopt/develop it and we don't?

* What will happen if we adopt/develop it and they do to?

To answer these questions and to fund strategically new manufacturing processes that provide a competitive edge in the firm's future new products requires a whole new approach to finding and evaluating potential manufacturing processes for their strategic value. This approach begins with a high level marketing study of the products that will be desired in the marketplace 7 to 10 years from the time of the study. At this time horizon there is enough time to complete fundamental process development. At further time horizons, beyond 10 years, it becomes difficult to predict what new products will be needed to fill emerging needs. From this market study, a group of process and product experts will study its recommendations and come up with a list of potential process improvements or innovations, which will enable these new products to be produced with either lower cost or improved performance. The senior managers of the company will next rank the market opportunities on the basis of size, risk, capital requirements, etc. and decide which ones are the best opportunities for the company to pursue. Those processes which were needed for the high ranking, strategic market opportunities will be funded to enable those products for the future. This simple method for selecting new technologies strategically, allows a firm to manage its technology base and chart its direction for the future. This will be one of the key assignments for the proposed Charter Parts Council in
its management of the technical base for major components throughout a firm's product line.

The strength of this strategic approach to new process development is it removes financial justification from the "go-ahead" decision and aligns the process development projects to the long term strategic goals of the company. Process development becomes a strategic activity that is the first step to achieve the vision of the future set forward for the corporation.

**Enabling New Products With Process Development**

Figure 3.2 shows a diagram of the development process using such a process development strategy. In this diagram, process technology creates new manufacturing processes and causes the design space for new products to grow outwards (perhaps from null space) allowing the designers more freedom to design high performance aircraft which will compete strongly in the market, at an economical cost. The expansion of the design space allows the generation of new parameters for new types of aircraft. (parameters are the product focused requirements for new aircraft). By expanding the design space envelope, new products are enabled and newer requirements will emerge. This creates a learning loop in the feedback arrows between design space and requirements generation. Requirements generation has traditionally been done by Preliminary Design (PD) groups in the aerospace industry. A tight relationship of PD with the process technology created by a Process Development Team (PDT) will accomplish the work of this diagram.
This type of innovation has been characterized by Utterback and Kim (76) as a "process-product discontinuity" where a fundamental innovation in process essentially makes the product completely new. Examples given in their paper of this type of innovation include; synthetic gem processes, the Hall Process in Aluminum, and the continuous float glass manufacturing created by Pilkington.

**Process Development Strategy; The Electronics Industry**

In contrast to the aerospace industry, the electronics industry is an example of a manufacturing industry which has followed the process development strategy to create innovative new products, and they have invested heavily in process R&D. The
competitive edge of this industry is in the creation of ever more dense and more rapid integrated circuits, which are created by better photolithography and ion implantation process technologies. These firms tend to work with vendors on the photolithography equipment (32) but they also have extensive, internally developed, proprietary processing equipment in the attempt to create strategic advantage. This equipment is highly technical and is based upon state of the art electronics and optical systems. The scale of this process equipment used in this industry is much smaller in size and cost, but more advanced in electronics and optics technologies, than the huge processing equipment needed in the aerospace or automotive industries.

Not all of the firms in this industry have had complete success with their process development strategy, because they have ignored the needs of the marketplace and have lacked a consistent product strategy to serve their customers needs. The key conclusion that can be drawn from the electronics industry is the use of a process development strategy cannot stand on its own, but must be aligned with a long term product development and marketing strategy to be successful.

**Black and Decker; Process Development for Competitive Advantage**

During the 1970's the Black and Decker company examined its consumer power tool business and decided to undertake the development of a new process to manufacture electric motors (46), a key component of power tools. By combining design with the manufacturing process development, they were able to develop a process to make motors with 50% fewer parts than their previous designs. The flexible process they created allowed all motors of varying power levels (for different sized tools) to be fabricated on the same automated line simply by adding more stacked layers into the motor assembly. The result of this development was to cut the cost of the motor from $0.50 to $0.30 and allowed Black and Decker's manufacturing costs to remain constant during the high
inflation years of the late 1970's. The modularized design they created in concert with this process removed the impediment of having to design a new motor for every new product introduction. Without this impediment, the rate of product introduction was increased dramatically by the development of this new process. The result for Black and Decker has been a growing market share in both the U.S. and foreign markets, with an expanded product line. The development of Black and Decker's competitive advantage in scale, scope and flexibility created a shakeout in their industry and left them pre-eminent in the consumer power tool market.

The question remaining to be answered is, "Can this strategy be as effective in large, complex, assembled products as it was for simple assembled products?"

Creation of Proprietary Capital Equipment as a Source of Strategic Advantage

The internal creation of proprietary equipment in the electronics industries and at Black and Decker, is in deep contrast to the aerospace industry, where nearly all of the processing equipment is externally supplied, as will be documented in the next chapter. Figure 3.3 shows a systems dynamics diagram, after Senge (67), of a firm facing the fundamental problem of an eroding technical base in process technology. To solve this problem, they may either purchase the technology from a vendor, which is a symptomatic solution, or internally develop new technology as a fundamental solution to create competitive advantage. The purchased technology loop is a much faster solution to the problem and allows the solution to fit a product dominated strategy. The fundamental solution loop of this figure includes a delay of 5 to 10 years, which it takes to develop and field new technology. This delay lowers the attractiveness of the fundamental solution from a schedule and financial standpoint. Also shown on the figure is the use of the symptomatic (top) solution of purchasing the technology from vendors has the side effect of lessening the internal technological competence. As the organization's manufacturing process development and equipment design skills atrophy from in-use, makes the
fundamental solution even more difficult and time consuming to implement in the future. For such a system, Senge (67) would argue that a leverage point exists to this "shifting the burden" type problem structure. The delay on the fundamental solution is such a leverage point. A concerted effort to reduce the delay through new organizational structures and methods of development and technology transfer will make the fundamental solution a more viable option to solve the fundamental problem. Use of the fundamental solution to this problem creates the potential to create manufacturing strategic advantage.

Tyre (47) argues that the symptomatic solution is based upon the misguided assumption that manufacturing equipment can simply be purchased off the shelf. She cautions that the expectation with "turn-key" vendor supplied manufacturing systems, that you will simply need to learn to "push the right buttons", is not borne out in practice.
Conclusion

This chapter documents several of the problems that occur in manufacturing industries to decrease the amount of longterm process development and implementation of these processes into the factories of these industries. The first problem presented was the predominant focus on product development in most American Firms. This focus is the outgrowth of short time horizons created by high discount rates and the result of the investment decision process in use by these firms which requires the revenues of a product to justify a project. Justifying a process development activity with such a methodology is much more nebulous because it is difficult to tie a revenue stream to this type of project.

The other major problem discussed in this chapter was the functional organization of mature American companies which slows learning, inhibits information transfer and promotes serial development of new technology. The net effect of this organization is to create slow process development projects which add to the financial disincentive to invest in process technology. With the evidence presented in this chapter it is not surprising that the U.S. has a much smaller percentage of its R&D funds devoted to process development when compared to Japan.

To overcome many of the difficulties documented in this Chapter, the concept of a "holographic", multidisciplinary, Process Development Team was introduced in this Chapter. This proposed concept will be built upon in succeeding chapters.
Chapter 4
Structural Problems With Process Development at Boeing and the Aerospace Industry

This chapter will build upon the generic problems of American industry with manufacturing process development by focusing on those difficulties which are unique to the aerospace industry. Several systemic problems presently exist within the aerospace industry which impede the development of process technologies and make implementation of these technologies into new products more difficult and time consuming to accomplish. Although the problems presented in this chapter are concrete examples from the one company in this industry that was studied, these problems are generic enough that other aerospace and manufacturing firms would suffer from similar, if not the exact problems presented here.

The examples presented in this chapter were obtained from general discussions and interviews with numerous engineers and managers at Boeing during the internship of the author. The individuals interviewed came from Operations Technology, Structures Technology, Boeing Materials Technology, the corporate research centers and from both the commercial and military divisions of this company. The individuals interviewed ranged from laboratory technicians and hourly workers, to engineers, scientists, labor leaders (Seattle Professional Engineering Employees Association), first level supervisors in Operations Technology, project and program managers, and one Vice President, to get a multidimensional viewpoint of product and process developmental activities in this firm. The interviews were both structured and unstructured (some were telephone conversations), lasting from 30 minutes up to an hour and focused on the current development system and the difficulties that resulted in low amounts of innovation. The individuals selected were identified due to their participation in key current or past development projects to the technological needs of this firm. These individuals were then
able to identify the strengths and weaknesses associated with current development strategies or approaches. Typical questions asked during these interviews are shown on Figure 4.0.

**Figure 4.0 Typical Questions Asked During Interviews**

- Which technology were you working on? Why were you working on this technology?
- How long did it take to develop your manufacturing technology from the initial work until it was implemented into a production environment? What were the major impediments to the implementation of the technology?
- How much interaction occurred between engineers from manufacturing, structures and materials?
- What was the relationship between yourselves and the engineers from supplier companies? Was this a co-operative joint development project with a large amount of information sharing or were they just providing hardware deliverables to a preset schedule?
- How much of the manufacturing capital equipment was developed at the Boeing Company?
- Was this technology required for the needs of a program? Would this project have been funded if it there was not an immediate program as a customer?
- Was the schedule to develop the technology set by a program? Was there enough time to develop the technology and still meet the schedule? Did the schedule lead to a downselection of the process technology? Did process technology development and funding continue after the downselection?
- How was the development project organized? Was it by engineering/manufacturing function? Were the engineering and manufacturing development engineers co-located? How much interaction and information sharing took place during this effort? Could a tighter co-ordination of functional engineers have been more effective in development of this technology? Would cross functionally trained engineers be even more effective?

As presently configured, the Boeing Company would have a difficult time implementing a process development strategy until many of these issues presented in this chapter are resolved through their ongoing cultural change efforts and through
reorganization and realignment efforts. This statement would be true for other manufacturing firms with similar problems.

The Boeing Company presently uses its new product development programs, (such as the 777 or HSCT) to develop the required new process technologies for these programs. The program controls the funding for the development activity, and is the "customer" for the development activity. As the customer for the effort, the program generally gets to decide which direction the development activity will take to meet its schedule and cost goals. The advantage of such a system is that it keeps the technology development focused upon the goals of tangible product needs and prevents the tendency towards "blue-skies" or "hobby shop" research. Unfortunately, this system tends to bias the majority of Boeing's technological development towards short term process improvement projects, which have little long term competitive advantage in the marketplace. The following examples will document many of the weaknesses of the current paradigm of product-driven process development.

**Product and Process Development Occur on Different Time Scales**

The development time of new manufacturing processes in this paradigm must fit within the schedule of new aircraft programs, which currently takes about 4 years to complete, from the kick-off of the project until the roll out of the first airplane. This is the goal of the 777 program. The time allotted to develop new processes must fit within a much smaller time "window", because the manufacturing processes must be committed to at an earlier point in the program time schedule to allow time to build or modify facilities for these processes and to allow time in the schedule to build the first aircraft. Therefore, all process development must fit within a two year window of opportunity as shown on Figure 4.1 , a representative time schedule of a typical new aircraft development program. This figure illustrates the fundamental discrepancy in time scales between the aircraft
manufacturing processes has historically taken up to a decade or more in the past. Only under
the most optimistic conditions will a fundamental process development project fit within the
allotted time "window" of these programs. At the point where the manufacturing process
commitment decision is made, promising new technologies that do not fit the time scale of the
program are down selected and work on these technologies stops for lack of a funding vehicle.
Down-selection of the hot drape forming process for the horizontal stabilizer spars for the 777
was observed by the author, when technical difficulties were encountered after a major change in
the design. This process, in its present state of development, was not able to form the contoured
spars without compression buckling occurring. After its down-selection, the funding on this
process for future applications was reduced and technical progress slowed.

Recent competitive pressures have led the Boeing company to implement
organizational practices and information technology networks to reduce the development time
of its new airplanes to less than 4 years. As an integral part of this effort, Design-Build
Teams have been formed for the development of the 777. Improvements in the efficiency of
development effort will cut the time to market of the new aircraft, so that emerging market
needs can be better served. Cutting the aircraft project's development time will lessen its
expense and bring the revenues from production forward in time, to improve the profitability
of these development efforts. (Our old friend, the project's NPV) Additionally, Steiner (52)
has stated that when the market is ready for a new aircraft, the manufacturer has to go (his
emphasis), because the eventual prize goes to the company that is fast on its feet.

Unfortunately, this reduction in time to market will also have the effect of cutting
further the "window of opportunity" for new processes. At some point this will require that
those processes which are selected be mature before the program begins. As the time which is
allotted for manufacturing process improvements continually shrinks, this will allow only the
most incremental improvements to be completed.
The Design-Build team structure may also have an unintended consequence in limiting the amount of innovation in the aerospace industry. In the old system, engineering would propose an innovative design with little or no consideration of whether it would be a challenge to manufacture. After the design was transferred "over the wall", manufacturing would have to do whatever is necessary to produce the design. Through this sequence of activities this old system may have at times acted to spur technology innovation or process changes in manufacturing. In the new DBT system, a design which does not fit within the existing manufacturing technology can be vetoed by the manufacturing representatives on the team. This raises the question as to whether the DBT team structure provides sufficient incentive to innovate new manufacturing technology, which the old system may have (at times) promoted. A manufacturing representative on a critical component DBT for the 777, admitted that the designs for this component that were driven by the manufacturing representatives were usually overweight and agreed that it was the manufacturing input that constrained this design effort to select heavier options.

The foregoing argument supports the earlier conclusion that the DBT's will create a tighter linkage between the product design and the manufacturing processes. Without an up-front investment in new process technology, such a product development system may slow future innovation in manufacturing processes.
The reason that Process development takes longer to accomplish than the development of new products is because it takes more time to innovate the process; work out the bugs; optimize the process: scale up the process; facilitate and transition the process to the manufacturing floor; run manufacturing trials and designed experiments with full scale equipment; then transition and ramp up to full scale production. The more complete the initial work in this procedure and the greater the knowledge of the process captured in working out the bugs, and optimizing the process, the smoother the downstream scale up and manufacturing trials will proceed. These basic steps are not unique to the aircraft industry but are generic to all manufacturing industries. The development process takes longer in the aircraft industry for three main reasons;

1. Large Scale Equipment and Manufacturing Facilities Require Substantial Time to Scale-up a Process
2. Empirical Cost Models of New Manufacturing Processes Need to Be Generated Before a New Process Can Be Accepted For Utilization on a Aircraft (Catch-22; how do you get cost data before you are in production)

3.) A Large Materials and Component Test Database Needs to Be Generated Before a New Process, Material or Design Can Be Accepted For Inclusion into an Aircraft to Assure Safe Operation of the Product.

Each of these reasons act to make process development slower in the aerospace industry than in other industries with lower acceptance criteria for new materials, component designs or processes. One could argue that the more severe cost constraints in the auto industry make process development of new technologies slow in that industry as well because a process needs to progress further down its learning curve to be cost competitive with existing processes before it can be effectively utilized.

It is clear from these different time scales of development that it is extremely difficult to develop a fundamentally new process around the schedule of a new product. The one benefit of this "product-driven" approach is that it focuses the development group to meet the needs of a potential product, which they might not otherwise do if they were just developing the process with no specific product in mind. Therefore, the trick is to decouple the process development from the product's rigid time scale, but maintain some degree of focus of the effort to the future needs of new products.

As described in the previous chapter, the bulk of R&D money in the aerospace industry is spent on new product development, and generally not enough money is available in non product designated R&D to develop new processes to a state of maturity in the intervening years between aircraft programs. This funding pattern is an artifact of the underlying cultural assumption of this industry (described in Chapter 2) that process development is not performed without a valid product development project that it
supports. There is not a long term funding mechanism to continue process development on promising new technologies until the next aircraft program rolls around, which may be a half decade or more. Without aggressive investment in the new technology between aircraft programs to stock the technology "pantry", the in-house developed technology is generally not mature enough for the next aircraft program. This usually results in management decision to;

1.) buy the technology from a vendor (if available) or;
2.) offload the manufacturing of the components to a subcontractor who has developed the technology independently or;
3.) down select the technology because it cannot be developed in-house in time to support the schedule of the next aircraft program.

Similar problems with using a "technology pull" strategy for integrating new process technologies with long term product development are described by Clark and Fugimoto (10) from research on the auto industry.

During the internship, the reliance on vendors for new process technology was documented by the observation that the development of every single advanced composite manufacturing process in the Boeing Commercial Airplane's MR&D Group was being performed out of house, at a vendor1. With the development occurring in outside laboratories, the Boeing process development engineers had assumed the role of a program manager, to manage and coordinate the efforts of outside vendors to a statement of work. Due to a lack of laboratory scale, new process technology equipment in their own laboratory, they were not able to work on new processes in house. From this

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1These advanced composite development programs included efforts in thermoset resin tow placement, and in-situ tow placement of thermoplastic composites. In each case, the development activities of all the candidate next generation composite processes were taking place in vendor's facilities. This observation is not confined to just composite processes but also includes next generation metal forming processes. Until recently, no laboratory scale equipment existed at Boeing to develop any of these processes.
observation, the conclusion that one is forced to reach is the development of core
competence in the critical next generation composites technologies is seriously suspect.

Going along with this "out-of-house" development is the mindset among many
Boeing managers and facilities engineers that all the capital equipment should be
purchased from outside vendors, even if Boeing has to design it for them. The result of
this mindset, is the lack of Boeing developed proprietary process capital equipment to
create a competitive edge over the competition. Therefore little in house manufacturing
competence is being developed through these development or capital procurement
programs. The structure and incentives of this problem create a system which encourages
the "hollowing out" of Boeing's future manufacturing capability.

This type of system is common in American manufacturing industries, where
"product pull" of technology is common to insulate the product divisions from the
disruptive influence of new technology in the factory and also insulates product
engineering from the risk of failure associated with these new technologies. General
Motors organized into product groups in 1921 (1) to create this "product-pull" type
system, after their experience with a "technology-push" program to develop a copper, air
cooled automotive engine which nearly wrecked the young company.

Materials Development Strategy of Airframe Manufacturers

Boeing has an implicit policy in the core assumptions of the organization that it
does not develop materials in its own laboratories, even though many of its materials
engineers have the skills and inclination to do so. Therefore, Boeing prefers to purchase
its materials from outside vendors, as it has procured aluminum sheet from the aluminum
industry. This policy is likely the result of several poor past experiences with attempts to

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2 During 8 years of observation at Boeing, the author has only observed 3 instances where laboratory scale process development
equipment were developed at the Boeing company. Development of proprietary capital equipment in house is far more difficult than the
purchase of the equipment from a vendor. This was especially surprising even in the research laboratories where processing equipment can
generally not be purchased from vendors.
develop materials in their laboratories. They may also fear a potential loss of management focus with materials development or manufacture which dilutes them from their primary mission to develop, sell and manufacture aircraft. The downside of this policy is competence in materials and processing technology has not fully blossomed. However one positive aspect of this policy is it creates good relations with materials suppliers, because their is no threat of tapered or complete backward integration.

This policy is especially problemsome with composite materials, as the structural performance is dictated by the "design" of the material, through its lay-up. The compromise that has been made with these materials throughout the aerospace industry, is the manufacture and supply of a generic prepreg tape from the materials suppliers. The manufacture of the materials is then completed at the component manufacturer through lay-up and consolidation of the prepreg tape. Composite materials have changed the rules of the game such that final materials fabrication and component manufacture now occur simultaneously. With this compromise, the aerospace companies have in effect backward integrated one step into what had traditionally been their suppliers domain, but have not completely backward integrated through the entire value chain. The one exception to this is the Hercules Company, which has completely backward integrated to include fiber and prepreg manufacture. In the effort to capture more of the value which results from their composite materials, composite manufacturers, such as DuPont, have begun to fabricate components from their prepreg materials. These moves provide a threat of forward integration of the suppliers into airframe manufacturing with these materials.

**Strategies to Develop Technology with Vendors**

During the development of the in-situ consolidation panels and the observation of two other composite processing development projects during the internship, it became obvious that two strategies are in use to develop new manufacturing technologies and materials with outside vendors. The most common strategy employed is a "vendor"
approach where the vendor develops the technology on its own and the manufacturer initially buys test panels or coupons for testing purposes. In this approach, the manufacturer purchases the panels from the vendor to a defined project schedule and statement of work, then later performs structural tests upon the test panels. The second and less common approach (used during the In-situ Consolidation test panels portion of this thesis), is a joint development project where the vendor and manufacturer co-develop the material and/or process in a collaborative fashion. The largest difference between these two approaches is the mental goals of the participants at the outset. In the "vendor" approach, the manufacturer's goal is to obtain test panels and perform the testing to meet a project schedule, and have little care as to how the test panels were made, or the capability of the process to fabricate quality panels in a manufacturing environment. In contrast, the goal of the joint development approach is to learn about and improve the process to a point that acceptable test results are achieved. Figure 4.2 shows the attributes of these two development approaches.
The problem with the "vendor" approach is that product focused engineering groups often use it with process or materials technologies which are not mature. A common result of such development efforts is the panels that are procured do not live up to their structural performance expectations, after they are tested. Without the intimate knowledge of the process that comes during a joint development program, the non-performing technology is quickly written off from further consideration at the company. The long term problem through the use of this approach is the residual bias that exists against the new process or material when it eventually is perfected by its vendor. At this point it is then capable of meeting the performance expectations of the manufacturer, but may not soon get a second chance. This "once burned, twice shy" bias leads to slower adoption of the technology or may prevent the new technology from being considered again. A famous quote within the materials community is, "The best thing you will ever hear about a new material is the first thing you will hear about it!", summarizes the
feelings of development teams which have tested materials before they have become mature. With the vendor approach to new process or materials development, the manufacturer who begins to investigate a new technology first, is actually at a competitive disadvantage to those firms which begin later, when the technology is more mature, because of the lingering bias that results from the initial investigation.

The "joint development" approach overcomes the difficulties inherent with the "vendor" approach, because its goal is to first develop the process, then obtain structural test data. This test data comes after the process has been optimized and is capable of producing good quality panels. With this latter approach, there are no early public failures which lead to project cancellation. This approach creates a competitive advantage for the firm which begins joint development first, because they continue to work with the vendor throughout development and are then ideally positioned to capture the technology first as it matures.

With either approach to development of technology with a vendor, the manufacturer runs the risk that the technology will be subsequently transferred or sold to their competitors at the conclusion of the development project. With the "joint development" approach to process development, the firm has (or should have) captured the technology in-house during its development. The "vendor" approach is possibly the worst in this respect, because it allows the vendor to develop his technology on the funding of the prime contractor, without having to share or transfer the technology after it has been developed.

Boeing and other commercial aircraft manufacturers have used new manufacturing technology on their new aircraft products only, but have never re-designed their older aircraft's structure with new manufacturing technologies to either lower its cost or improve its performance. Modification programs usually consist of stretching a fuselage or refitting the aircraft with new components like avionics, flight management systems,
engines or perhaps some secondary structural composite components like ailerons or rudders all of which can be "hung" on the existing structure. With this strategy, the aircraft industry misses the opportunity to keep older aircraft up to date and provide a lower risk opportunity to introduce new technology into the product line. This introduction strategy is the norm in the automotive industry, where introduction of new process technology on older vehicles exposes the company to technology risk on the modification projects, and market risk only on their completely new products, but not to both on their new products. By proving new manufacturing processes on modification projects, the technology is matured in a low risk manner and is then ready for the next new aircraft program. Another advantage of this strategy is the modification program can always go back to the old technology, if the new technology does not work out or is judged to be too risky to meet either the re-qualification criteria or airframe life constraints. Managers from General Motors claim that this paradigm is commonly used within the auto industry, although implementation of new processes on entirely new products (such as the lost-foam engine casting process and new high impact polymer body panels on Saturn automobiles) are not in line with this claim.

Difficulties With Long Range Research

There is a definite bias against long range research within managers in Boeing's operating divisions. To some extent this bias seems understandable, because much of the long range research performed at the old Boeing Scientific Research Laboratory, (disbanded in 1971) and now at the High Technology Center, was and is the "blue sky" orientation of the projects performed at these centers. A review by the author of the topics of the research performed at these centers led to the conclusion that little of it was connected to the existing Boeing businesses, and none of it on long-range process or structures technology development. The focus appeared mainly to be on technologies 15 to 25 years in the future and mainly on electronic and computer technologies. These
laboratories were located on "college campus" like settings, far away in distance and culture from the rest of the company which added to the bias against them. Consequently, with the location of these laboratories, there is little interaction with the operating divisions of this company. Furthermore, other than in aerodynamic computational modeling, no one can point to a technology developed at these laboratories that is currently in production or use at Boeing. The attitude of many divisional managers towards these laboratories is to either shut down these operations or to completely reorganize them, if they were allowed to. Chan (11) found, in a study of R&D managers in 4 aerospace firms, that these managers are highly cost and time conscious, therefore they prefer low cost and short duration research or development projects. Consequently, managers with these attitudes would not care for long term projects like those at BSRL/HTC. Another reason for these negative attitudes towards these long range research laboratories, is the violation, of the "product-focused" underlying cultural assumption in this industry. (Chapter2) Finally, there is an honest belief of division managers that the work performed in these laboratories does not add to future competitiveness in the core businesses.

Roberts (61) in a thorough study of American central research laboratories found with few exceptions (3M), that managers were dissatisfied with the amount of technical work performed in their laboratories that has ever reached the marketplace and generated a profitable payback for the firm. Goldman (28) in an anecdotal account of the R&D work performed in four corporate research laboratories that he was associated with explained the poor performance of these laboratories in implementing new technology into a business was due to three main reasons:

1.) the poor cultural fit of these central laboratories to the mature firm;
2.) the misunderstanding of the work that is performed in them by the manufacturing and marketing functions;
3.) the risk averse, financial driven executives make improper decisions regarding the newly developed technologies.

The difficulty in creating new organizations to engage in long range process development is to maintain a focus on the future product line, without going "Blue-Sky" with a lack of a clear market or product focus. Kanter (38) states that, "R&D units that remain isolated are less creative than those that maintain close integration in the search of exploration stage." Kanter continues by allowing that the physical isolation of these labs is necessary to allow the development work to proceed undistracted, but it is necessary for the department members to immerse themselves in the concerns of the firm or its customers, outside of the laboratory, to generate productive new ideas. The creation of ownership of the long range development activities in the divisional product groups also needs to be established to enhance the technology transfer, as the developmental process nears maturity and manufacturing implementation. Maintaining a focus on the long range product needs of the firm and emphasis on technology transfer are two key priorities of organizations formed to create a manufacturing process development strategy. With these priorities these organizations will avoid the current difficulties with long range research at Boeing and other companies. This is not to say that some basic research should be undertaken by a high technology firm on leading edge technologies, but a better mix of basic and applied long range projects in the firm's development portfolio will serve the firm's technological needs in their existing businesses better. This balance of programs and the closer interaction of the labs with the needs of the firm will also increase the amount of innovation taken from these laboratories and put into production, a chronic weakness identified for R&D labs.

The two methods proposed in this thesis to establish this long range product focus and ownership of the development project in the product divisions are the Charter Part Council management of the Process Development Teams and the intended rotation of engineers from the product divisions into the team structure for approximately a year to
capture the technology and diffuse it back to the product division. The majority of individuals on the "core" team will be assigned to it for longer periods to maintain continuity. Technology transfer at the conclusion of the effort is one of the key managerial objectives to speed its implementation into the company's operations. As mentioned in the previous chapter technology transfer is one of the key strengths of a "holistic" team structure and one of the primary incentives to attain this type of team structure.

Risk Averse Decision Making

Engineers in the commercial aircraft industry have relegated composite materials to secondary structures on earlier jetliners\(^3\), because of the relatively brittle nature of these materials (relative to aluminum). The relatively brittle nature of these materials raised the perceived risk of a catastrophic failure of a major component such as a wing to a higher level over the life of the airframe, than was judged to be acceptable. This risk is a definite violation of one tenant of Boeing's strategy (Chapter 2) and was therefore unacceptable in their mental frame. A second problem with the use of composite structures on these earlier aircraft, was the unfamiliarity of commercial aircraft designers with a anisotropic material.

To cut the risk of implementation of primary composite structures, Boeing has chosen the low risk approach of changing the material, but leaving the basic structural concept of built up skin-stringer and spar construction used for aluminum, intact. This is a

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3. These aircraft include the 757 and 767 where the technology was available but was not used for primary structures. On military aircraft of the same vintage composites were being used extensively in wing and fuselage components. Military aircraft exist in a much less rigorous regulatory environment, and require a much shorter vehicle life of 10,000 hrs versus 50,000+ hours for commercial aircraft. Another consideration requiring additional conservatism on the part of commercial aircraft designers is the extensive amount of pressurization of the commercial aircraft fuselage when compared to its military cousins. A final consideration in the choice of a material or structural concept is the much more constraining structural cost of commercial aircraft. For military aircraft, designers are presently willing to spend up to $1000 for a pound of weight saved, so expensive composite structures can be economically considered, while the figure for commercial aircraft is much lower, around $300 per pound of weight saved so the design could tolerate composite structures which cost about $350/lb, provided that it is able to save 25% of the weight of an aluminum structure which normally runs $200/lb. The severe weight sensitivity of the future HSCT allows these designers to pay nearly what military designers are willing to pay for weight savings, so they are willing to tolerate composite structure that costs nearly $1000/lb compared to the alternative material, titanium at $500/lb in completed structure.
classic example of the use of an incremental innovation strategy. The alternative, a radical innovation strategy would use innovative new structural concepts which take full advantage of the directional strength of composite and minimize the use of stress concentrating, fasteners through the use of large panel structures, co-curing and adhesives to fasten the structure together. This latter approach developed on the ATCAS program (35) has shown the potential to design and manufacture structures that weigh considerably less (20 to 30%) than comparable structures fabricated from aluminum at roughly the same cost. These innovative designs coupled with new manufacturing techniques have shown promise of cutting the cost of these structures considerably when compared with conventional composite structures (35).

The incremental approach that has been taken on many early composite implementation projects in the aerospace industry is partly to lower manufacturing risk, and partly to make analysis of the structure possible with existing methods. The primary reason appears to be the avoidance of performance risk in the area of structure, (by poor adhesive joints in a radical innovative design for example,) while accepting the risk only in the area of new materials. The materials performance risk can be managed through 100% NDE inspection, extensive allowables testing and the use of conservative knockdown factors on the fiber strain-to-failure which insures that each design would meet its performance specifications. The use of quasi-isotropic laminates eases the requirement for analysis of non-isotropic laminates and cuts down the required amount of allowables testing for each tailored lay-up. The advantage of this strategy is you are able to implement new structural technology onto an aircraft and obtain operating experience with it, while minimizing your exposure to supportability or product liability claims. The structural and manufacturing performance of this approach has been dubbed affectionately as "black aluminum", where the structure is difficult to manufacture, costs a great deal to manufacture due to many complex part details to save weight, does not save part count and does not live up to the high expectations of weight savings expected
of composite materials. Burt Rutan, a maverick, innovative composite structural aircraft designer, whose aircraft include the world circling, all composite, Voyager aircraft, recently shamed his fellow American aircraft designers at a SAMPE conference for their needlessly complex, overweight, composite structural designs, which are based upon extreme design conservatism (56). He went on to warn that such practices threaten to endanger America's technological lead in composite materials. These poor first experiences in the implementation of composites on commercial aircraft due to the underlying design conservatism may likely cool the ardor of risk-averse project managers for the second use of these materials on a second project. These experiences may slow the transition of these materials from the rear horizontal stabilizer to the larger and much more highly loaded wing structure.

The conservative, risk-averse decision-making style on a large commercial aircraft program is to some extent understandable when one realizes that the development of a new aircraft to be a "you bet your company" proposition (87). Because of the high financial stakes involved, (~$4 Billion) a poor major technical decision is extremely expensive. These decisions may jeopardize the whole program and the future financial health of the company. Whenever possible, a high risk technology will be backed up by an older, lower risk technology should the high risk approach turn sour. During the development of the 747-100, the first generation, high bypass, JT-9D turbofan engines kept experiencing compressor stalls during test flight and initial customer service, holding up deliveries of the aircraft in the production pipeline. The resulting inventory balloon nearly bankrupt the Boeing Company in 1971(64). These lessons of new technology implementation are quietly tucked away in the corporate culture and within each of their program manager's mental decision models. These lessons and mental models become real when decisions about new technology are made.

A long range approach of new manufacturing and materials development in concert with extensive innovative structural design and test is necessary to lower the risk
of radical structural innovation ahead of a project launch so that the technology can be judged acceptable for the second generation of composites in commercial aircraft.

Conclusion

This chapter built upon the information contained in the previous chapter by documenting additional difficulties with process development that are specific to the aerospace industry. The major problem documented in this chapter was the use of a product development strategy to drive process development even though the "time window" for process development on an aircraft development project is too short for fundamental process development to occur. Other difficulties presented in this chapter were an (industry) bias against long range R&D, near exclusive dependence on suppliers for process R&D and processing equipment, and extremely risk-averse technology decision making on new products (with good reason). Each of the difficulties act as barriers to new technology implementation into its production aircraft or prevent a firm from capturing strategic advantage from the creation of unique manufacturing capabilities. These difficulties would make it difficult to implement a process development strategy without a major realignment of the organization and change in the culture. This comes from the general finding that organizational realignment is relatively easy when compared to changing the basic assumptions of a culture.(65) A proposed solution to the difficulties of this chapter is the increased emphasis on process development by performing manufacturing development up front of product development in a multidisciplinary, advanced technology organization. This organization would be uncoupled to a specific product, but aligned to future market requirements, to enable future products.
Chapter 5

Historical Development of Process Technology in the Commercial Aircraft Industry

This chapter will demonstrate, using specific cases, where process development has been used within the aircraft industry to innovate new products. This chapter will document three cases in Boeing's history and one in Lockheed's, where fundamental development in process technology enabled generations of new aircraft. Abernathy and Utterback's model of technological innovation will be used as a framework to describe the development of process innovations in this industry. This framework will show that the aircraft industry has evolved technologically very much as have other manufacturing industries; with the emergence of a dominant design; a wave of fundamental process development; followed by the growth of a functional bureaucracy and incremental product and process improvement as the industry matured. This technological evolutionary framework provides one explanation for the current low amount of process development in the aerospace industry. This model would characterize this industry, in its current state of development, as in the mature "specific" state, not unlike that of the auto industry in the late 1970's. The "machine " like organizational metaphor, described in Chapter 3, would fit the firms in an industry in this mature state.

This Chapter also presents a comparison of the commercial aircraft industry along the key dimensions of size, complexity, factory organization and cost to other assembled products industries to yield an understanding of their similarities and differences. The purpose of this comparison is to generalize the proposed organizations and practices of this thesis to other industries. The conclusion of this discussion indicates that the proposed organizations and practices of this thesis will apply mainly to those industries
with complex assembled products, with long development lead times, and complex process technologies.

Model of Industrial Technological Innovation

The standard model of industrial innovation, developed by Abernathy and Utterback (2) and later by Utterback (75) and Utterback and Kim (76), describes the rate of major innovations in a manufacturing industry as a function of its maturity, as shown in Figure 5.1. They have shown that the resources devoted to Research and Development in the industry also exhibits a similar functional dependence with its maturity as the curves shown on this figure. The initial emphasis in the embryonic industry is on product development, with ever increasing resources being expended on development in this area as the market grows, until a dominant design appears1. After this design, the product approaches a state of relative maturity and progressively less resources are expended on further product development. Eventually all the potential product innovations become exhausted. Utterback and Kim (76) describe the industry and organizational transition that occurs just after the appearance of the dominant design, where the amount of resources devoted to process development becomes much greater, as the manufacturing strategy moves from flexible, multipurpose machinery to expensive, product related, fixed automation. After this transition, cost reduction, experience curve learning and economies of scale become primary motivations for the manufacturing organization. As shown on the figure, the large emphasis on process development which occurs during industry transition, fades as the industry becomes mature, and is replaced by incremental product

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1 The definition of a dominant design is that which includes all of the essential features which all succeeding products in the industry will include. All successive products will be in essence derivatives from the dominant design. For example, the dominant design in the early commercial aircraft industry was the DC-3 (1934) which had a semi-monocoque aluminum skin structure, a low monoplane design with retractible gear, flaps and nacelled radial piston engines. All later versions of piston powered aircraft were derivatives of this aircraft with one major innovation, which was the inclusion of a pressurized cabin on the Boeing Stratoliner (1940). A new dominant design was established in commercial aircraft with the emergence of jet propulsion on aircraft. The second aircraft designed in this category, the Boeing 367-80, and its derivatives, the KC-135 and the Boeing 707 family formed the new dominant design. These jetliners established the norm for subsonic aircraft with pressurized cabins, engines in nacelles and low wing designs with slotted fowler flaps.
and process development. A tight intertwining of the process and product design, as described by Abernathy (1) occurs in the mature industry. This stage of industry development was described as the "specific pattern" by Abernathy and Utterback(2). Only a few of the original competitors remain in the mature industry who have successfully made the transition in their process technology to manufacture the dominant design efficiently.

Figure 5.1 Dynamic Model of Industry Innovation

A. this mature stage of the industry development, all of the process or product innovations become primarily incremental in nature. Radical product or process innovations are resisted internally, as competence destroying, by the culture of the mature companies. These firms become so entrenched in their present product or process technologies that they convince themselves of their superiority of these even in the face of the technological challenge from new entrants, and may redouble their efforts to keep it

2 The "specific pattern" terminology used by Utterback and Abernathy (2) also describes the prevailing culture in these functionally organized mature firms in a way that is very similar to the "machine like" metaphor of organizations used by Morgan (51) as described in Chapter 3
so. These mature firms will rarely adopt the new technology early, even when it would appear rational (in retrospect) for them to do so.

Even when radical innovations are adopted by the dominant firms in a mature industry, they are usually adopted into their products as incremental innovations, without fully utilizing the power of the new technology. The cultural disincentives to radical innovation put the established firm at a disadvantage to smaller, new entrant competitors with the application of new technologies. An organizational/technological system as described in Utterback and Abernathy and later articles (2,75,76,77) would explain the development of the "black aluminum" composite designs for aircraft in the previous chapter. This is similar to what occurred in the introduction of the first transistor radios,(32) where the newly developed, small, lightweight transistors were plugged into the same sockets of the massive heat sink structure formerly used by the radio's tubes. The introduction of radical new technology as an incremental change occurred in this case because it fit the established culture of the established firm. Using a radical innovation route to develop a circuit card to miniaturize the assembly and allow the radio to become lightweight and portable requires a new culture in the innovating company. Similar conclusions could be drawn from the creation of "black aluminum" composite aircraft structure described in the previous chapter.

**Historical Development of Commercial Aircraft From Process Technology Innovation Standpoint**

The industrial evolution of the commercial aircraft industry will be analyzed in this section using the framework of the Abernathy and Utterback's industrial evolution model. As mentioned in the discussion of the concept of a dominant design, most of the significant process improvements in the commercial airframe industry came about in the early 1930's through the 1940's, just before and after the dominant design in this industry
appeared. In the early 30's, a vision of an all-metal, semi-monocoque, low wing aircraft drove the industry \((48,64,9)\) to substantial improvements in product performance. To achieve this vision, the Boeing and Douglas Aircraft Companies, along with Jack Northrop experimented with skin and spar construction of aluminum airframes \((70)\), by manufacturing structural components and performing structural tests on these concepts. Boeing utilized some of these structural concepts on the B-9 Bomber and P-26 Fighter in the early 30's, which were the first all metal aircraft produced, yet they lacked retractable landing gear and a closed cockpit which would complete the dominant design for multiengined aircraft. Up to this point, the aircraft industry could be characterized by the fluid pattern typical of young industries with a great deal of product experimentation and very general, flexible manufacturing equipment. By 1934, Boeing introduced a new commercial transport, the Model 247, with a closed cockpit, nacelled radial piston engines, retractable landing gear and an all metal, semi-monocoque structure, along with a low monoplane wing, for its sister company, United Airlines \((9,48,64)\). This aircraft revolutionized the commercial aircraft industry with its performance and was the first to be developed with the concept that passengers were the primary cargo, with the delivery of mail, secondary. The demand for airplanes of this performance in other competing airlines, caused the Douglas Aircraft Company to develop the DC-3, which incorporated all of the features of the 247, but added a split flap for low speed landing and a low wing carry through structure to remove all the effects of the wing structure from the passenger cabin. These additional advances enabled this aircraft to become the dominant design in the embryonic commercial aircraft market. From the success of the DC-3 and its later derivatives, the Douglas Company became the established market leader in the piston powered aircraft industry to the mid 50's. All commercial aircraft after the DC-3 would incorporate all of its basic features into their designs. The only major product innovations to occur during this pre-World War II era, were to come with the introduction of the Boeing Stratoliner in 1940, which incorporated turbo-supercharged radial engines and a
pressurized cabin for higher altitude flying performance (64). These latter innovations completed the basic dominant design for piston powered commercial aircraft.

To achieve this rapid advance in airplane performance, the process technology evolved to enable these achievements. The primary process technologies evolved from the ability to fabricate a spruce airframe with fabric skin, where the core competencies of a furniture manufacturer and dressmaker were needed in the early 20's, to a welded steel frame with fabric skins by the late 20's. During the 1930's, the manufacturing competence changed once again to require the ability to machine long, aluminum, I-section spars and the technology to assemble these spars by riveting to produce wings. The use of new assembly processes to manufacture fuselage sections on fixture tooling was also required. During this same timeframe, Lockheed developed a process to hand lay cross plies of spruce veneer onto mandrel tools, then water pressure tanks were used to cure the plywood laminates to produce fuselage halves for their Vega aircraft (22). In essence, this process is the same which was used for the original fiberglass radomes and fairings introduced on aircraft in the 50's, and forms the basis for the manufacture of graphite/epoxy composite panels of today. Not only did the fundamental manufacturing processes change during the 30's, but the scale of the processing equipment also increased rapidly to accommodate the increasing size of the aircraft and continued to do so until the late 60's. This increase in scale has formed most of the incremental process development which has occurred since the 30's. These incremental process improvements are primarily equipment and facilities related and can be performed to the time scale of a new aircraft program, because there are few unknowns associated with their development other than some uncertainty of the tolerances that the larger scale equipment can provide. These incremental advances and the low risk process development activities associated with each product development project formed the mental model that process development is
performed in concert with product development projects, as documented in Chapters 2 and 4.

To accomplish these rapid changes in the process technology, the young organizations in the 1930's were small and very flexible with very little distance separating the manufacturing process engineers, the aircraft designers and the skilled workers\(^\text{64,48}\) who assembled the aircraft. These individuals all worked in close proximity in one small factory. This closeness was captured once again at the Lockheed company's A-12/SR-71 project in the late 50's and 60's. Kelly Johnson's Skunk Works concept of concurrent engineering in product and process development with a small group of highly trained and motivated engineers and craftsmen forms the ideal for the concurrent engineering teams of today and the inspiration for the Process Development Teams of this thesis. The rate of learning and innovation in such an environment was rapid, in what today would be characterized as a "high tech startup". By creating an environment where innovation could occur in a mature company, this project was able to develop in a relatively short period of time the titanium joining and fabrication technologies that enabled the A-12/YF-12A/SR-71 series of Mach 3 aircraft. Morgan\(^\text{51}\) would characterize such team structures with the holographic organizational metaphor, which is proposed for the PDT team concepts. Although the process development performed concurrently with the design of this series of aircraft was the fundamental enabling technology, most historical accounts\(^\text{22}\) of this pacesetting program focus exclusively on the design challenges of dealing with aerodynamic heating, propulsion and aircraft stability at high Mach numbers. On this aircraft, two of the more difficult challenges were the creation of new lubricants and jet fuels to withstand elevated temperatures and the sealing of the fuel tanks. These historical accounts reflect the underlying cultural assumption that product development drives innovation in this industry (Chapter 2).
After Boeing lost market share to the DC-3 in the commercial industry, it was able to transition the aircraft manufacturing process technologies it had developed and their design skills to the manufacture of large bombers (YB-15, B-17, B-29) for the U.S. Army Air Corps (64, 48, 9). With the B-29, Boeing was able to build a large, multi-engined, pressurized aircraft which had the capability of high altitude and long range. After the war, Boeing was able to continue with its manufacturing and engineering core competencies of building large, long range, multi-engined aircraft from aluminum skin, stringer and spar construction in the B-47 and B-52. These jet aircraft allowed Boeing to acquire the knowledge of how to integrate the newly developed jet propulsion systems and high speed, sweptback wing designs into their large, multi-engined aircraft. By 1954, Boeing was ready to re-enter the commercial aircraft market with its core competencies of being able to design and build large multi-engined aircraft with long range and a pressurized fuselage. The 707 became the new dominant design in this industry, and its performance was truly revolutionary when compared to the piston powered Constellations and DC-7s of the mid 1950s. From an innovation standpoint however, this new design would be classified as a product discontinuity (76), because the process technology to produce the airframe was sufficiently similar to that already in use on piston powered aircraft. The advances on the 707 and subsequent aircraft came in the product design area, with the incorporation of swept back, high speed, wing designs and the use of new turbofan engine technologies, which are architectural innovations in nature. The substantial increase in performance of the 707 over its piston powered competitors and the advantages in today's high bypass turbofan aircraft over the earlier jets, come mainly from changes in the critically important propulsion system. Because the change in the dominant design came from an architectural change in the propulsion system, no significant changes in basic underlying manufacturing or materials technology were required (other than changes in component size) to enable the innovation. Therefore the change in the dominant design was accomplished without another surge in process development.
Innovations that are classified as product discontinuities have been shown by Utterback and Kim (76) not to require another surge in process development.

The aircraft industry differs from the Abernathy and Utterback innovation model in one critical aspect, the emphasis on product development in this industry has not waned after the first two dominant designs appeared, even though the advances became incremental in both piston and now jet powered commercial aircraft.

During World War II, the airframe manufacturers transitioned from job shop enterprises to a scale of production that would be called mass production for this industry. Boeing was one of the leaders in this transition in creating a line flow manufacturing process for the assembly of over 20,000 bombers in a three year period. This line flow process remains in place today for the assembly of today’s jet transports, but at a scale which has never approached that of World War II. During the war, the company grew substantially to accommodate this large jump in production and incorporated into its workforce many unskilled assemblers (stereotyped as Rosie the Riveter (64)) to accomplish the task of fabricating the aircraft. The work within such an organization became much more routine and would be characterized with the "machine" metaphor of an organization (51). Serling (64) even claims that Boeing was "military like" and "spartan" in its culture during this time and remained so throughout the decades of the 50's and 60's. These organizations become very efficient at performing the work exactly as it is specified but are capable of learning only in a continuous improvement mode, as it moves down the learning curve of an aircraft's production. On the negative side of the ledger, such an organization becomes incapable of radical change. During this growth phase of the industry, the company organized along functional lines to manage the production and design work within a multi-tiered hierarchy.
The close co-ordination of specialists from different functional areas during the development of processes and products, which was easy in the formative days (48,64) of the aircraft companies, was no longer possible. These large, functional organizations have difficulty creating or accommodating radical change, and as a result of this, the design and process technologies become tightly linked in these mature organizations. Neither the product or the process is able to change radically without first changing the other. This conclusion could also be drawn from the work of Abernathy (1) on the American auto industry in the 70's. The creation of design-build teams at Boeing in the mid 1980's was the first attempt to bridge the functional organization barrier for the design of new products, but no attempt has been made to create small learning organizations for process development in commercial aircraft.

Two of the most significant incremental advances in process technology related to structural fabrication that have occurred in the decades past the original dominant design, were created to accommodate the substantial size increase of the 747's wings. The first innovation was the implementation of shot peen forming technology to form wing skins to provide the curvature required by the wing's aerodynamics. This process creates differential residual stresses onto the machined aluminum wing skins which cause them to curve to their proper shape without the use of expensive tooling or forming presses. In essence shot peen forming is a "toolless" process which easily scales to allow the manufacture of large components, or in this case wings. Conventional forming processes such as Stretch forming or Creep forming, require large tools and presses or autoclaves. These processes become impractical for the large sized 747 wing panels. The elimination of the huge forming tools that would be needed for stretch or creep forming could be viewed, in retrospect, as an enabling process development program. The second major process innovation for the 747 was the implementation of Gemcore riveting machines to automatically rivet the stringer stiffeners to the formed wing skins for this large aircraft.
These process advances enabled the large wide body transports (747, 767 and 777), whose large wing sections would have been difficult and costly to produce without these new process technologies. However, very little mention of the contribution played by these process developments can be found in the company's history or culture. (64, 9)

By the late 1970's the Boeing Company was predominant in commercial aircraft, but had become a marginal competitor in the military aircraft business. Once an industry has reached the "specific" period of its maturity, new innovation in materials or manufacturing processes is likely to come from outside the industry or from a new entrant. In Boeing's bid to become a competitive military aircraft company once again, they in essence became a new entrant in this market. To enable this re-entrance into the market, Boeing's strategy was to emphasize the creation of design and manufacturing capability to build Graphite/Epoxy composite structure. To create this new core competence in composite materials, Boeing created a multidisciplinary process, materials and design concept development team on a one time basis in the Commercial Airplane Company. This ACDP team existed for 5 years to develop the generic technology in a "white world" environment, then it was disbanded to allow its members to join the military airplane programs utilizing the technology that required their skills. The flexible environment of this team was needed to develop the new process technology and would fit well with the new entrant military airplane company, but did not fit at the time with the Commercial Airplane Company, where it was organizationally located.
Comparison of the Commercial Aircraft Industry with Other Manufacturing Industries

To compare the commercial aircraft industry to other manufacturing industries, it is first necessary to compare the production rate and size of commercial aircraft product with other mature manufactured products. Commercial aircraft are the largest and most complex manufactured products ever produced. In the assembly of a given jet aircraft there exist from 2 to 6 million parts. A major undertaking in this industry is the logistical effort to bring together this large number of parts from subcontractors all over the world to assemble each aircraft. A Boeing 747, even with its fuel tanks empty, weighs 550,000 pounds and has 6 million parts in its construction, dwarfing the automobile in both size (4000 lbs for an average passenger vehicle) and complexity (10,000 parts in an automobile). A given model of aircraft will be produced in numbers between 20 and 200 in a year and may continue in production with modifications for up to 30 years, for a cumulative production of from 1000 to 3000 units in its product life. Conversely, automobile models are produced in quantities from 100,000 to 500,000 units each year and will remain in production for much less than a decade\(^3\). The slow production rate and high cost of a commercial aircraft, $25 million for a 737 to $150 million for a 747, compare more favorably to a production process to manufacture standardized high rise office buildings (if one existed) than to mass produced automobiles or electronic goods as shown in Figure 5.2. The value breakdown of a commercial airliner consists of roughly three major items; 25% for the cost of the avionics, flight controls and software; 25% for the propulsion system, and the remaining 50% for structural airframe and interiors. For the smaller military aircraft with high performance engines and advanced avionics, this breakdown runs to roughly three equal thirds. Over time, the cost of the electronics and software included in new aircraft has increased in percentage of total value at the expense

\(^3\) 4 years for some producers and up to 8 years for others (MTCW)
of the airframe percentage, and has attracted a larger share of the Research & Development expenditures as well (52). It is primarily the value created during fabrication of the structural portions of the airframe that is captured by the manufacturing done within the large airframe manufacturers. Figure 5.2 shows the comparison of the commercial aircraft industry with two other manufacturing industries along the dimensions presented above.

Both the automobile and commercial aircraft are produced in a plant system organized by process focus and assembled with a line flow process⁵. In this production system, the components are fabricated in process specific plants then shipped to a final assembly plants where the components are assembled with the parts procured from suppliers, into the final aircraft. Products produced in this multi-plant, multi-stage process are more complex to build than those which can be fabricated in total in one plant, such as consumer electronics. With a process focused plant system, each company must devote a significant number of staff members to co-ordinate each of the plant's manufacturing schedules, so that the desired production rate can be obtained and delivery dates achieved. The aircraft industry can be characterized on a traditional grid of product complexity as internally complex to the highest degree, along both the dimensions of product design (many parts, high and exacting performance, with a high reliability required) and in their manufacturing operations. (huge components, long lead times, multiple plant system with interplant co-ordination required, supplier co-ordination required.)

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⁵ In the automotive industry metal casting facilities feed engine plants, or metal stamping plants feed assembly plants. The analogs in commercial aircraft are metal forging and rolling subcontractors who feed the sheet metal facilities and skin and spar mill fabrication plant, both of which in turn feed the final assembly plants.
<table>
<thead>
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<th>Attribute</th>
<th>Commercial Aircraft</th>
<th>Automobiles</th>
<th>Consumer Electronics</th>
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<tr>
<td>Size (weight)</td>
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<td>2,000 to 5,000 lbs</td>
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<td>10000</td>
<td>50 to 200</td>
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<tr>
<td>Price Range</td>
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<td>$10,000 to $40,000</td>
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<tr>
<td>Yearly Production</td>
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<td>100,000 to 500,000</td>
<td>&gt;1,000,000</td>
</tr>
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<td>4 to 8 years</td>
<td>1 to 2 years</td>
</tr>
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<td>Product Development Time</td>
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<td>4 to 5 hrs</td>
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<td>Process Technology</td>
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<td>5 + years</td>
<td>2 to 3 years</td>
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<td></td>
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<td>Both Internally and Externally Complex</td>
<td>Externally Complex</td>
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Although a commercial aircraft is very highly internally complex according to Clark and Fujimoto's criteria (10), it is not as externally complex as a automobile. The customers of commercial aircraft, the airlines, are much fewer in number than automobile customers and usually have similar demands for given market segments which results in a less externally complex product. The airlines also have professionals who procure their equipment for them and their needs can usually be translated into engineering performance
specifications, so the job of designing the aircraft is made somewhat easier. Therefore the need to anticipate the customer's latent demands in the design process is much less than in other industries such as automobiles or consumer electronics. The two areas where latent demands do play a role are in the ergonometric layout of the cockpit and the design of the cabin interiors. In the military segment of the aircraft business, styling and image are more critical parameters, going along with the commonly held belief of the customers of these aircraft that "If it looks good, It flies good!" (sic) (64). Even in this market segment, the external complexity is still much less than for mass produced commercial products because there are only a few (or one) customer(s).

The most difficult part in designing new aircraft is to develop common denominator designs which can accommodate the conflicting demands (non-latent) of the different airlines, to create an airliner with the broadest possible customer appeal to justify its development expense.(52)

Following Clark and Fujimoto(10), the complexity grid for the commercial aircraft industry is shown on Figure 5.3. This figure contrasts aircraft to other manufactured products on the two dimensions of internal and external product complexity.
Therefore the results of the research in this thesis are specifically targeted to industries whose products are highly internally complex assembled products, take a long time and expense to develop both the product and manufacturing processes, and whose product performance and capability is directly related to the materials of construction and the manufacturing processes which allow the design to be fabricated. The process technologies to be developed are also large in scale and the machinery involved is physically complex.

Boeing, like most aerospace manufacturers, employs a matrix management system for the development of its new products. One of the strengths of such a system is it creates a group of heavyweight project or product managers (in the Commercial Airplane Group, these managers have vice-presidential status) to manage the development projects. This system, has been shown to be lacking in the American automotive industry.(84,10) Heavyweight program managers are able to command the resources of a firm to the
development of a new product without having to beg for resources from each of the functional staff managers of the firm. These managers have been able to manage the severe internal complexity of commercial aircraft and has been able to direct the legions of functionally organized engineers towards a common product goal and maintain the projects on schedule. This method of organization for product development is one reason for the same development time for commercial aircraft and automobiles, despite the large differences in internal complexity between the two products.

The investment to produce a new jetliner is roughly of the same order of magnitude as that for a completely new automobile\textsuperscript{6} and amazingly it takes about the same length of time to design both a car or an airplane, 4 years, considering the vastly larger number of parts in a airplane. The low production rate and the same capital expense provides a high incentive to allow an aircraft to remain in production as long as possible to provide payback for the upfront investment. Boeing has been fortunate to have been the producer of nearly all the jet aircraft models which have been in production long enough to have "broken even" in this "sporty game" (87) and have contributed a net positive NPV to the company. According to independent sources (87) only the 707, 727, 737 (not necessarily all derivatives yet), DC-9/MD-80 series and 747-200, have turned the corner on profitability. Other competitors in this field such as the DC-8, DC-10 (85), Convair 660 and 880, BAE-111, VC-10, Lockheed 1011 and all Airbus aircraft are yet to break into the black for their producers or never will. (The first 7 aircraft named are out of production) To fund these risky development projects, a company requires a "nestegg" of liquid corporate assets created from retained earnings. Airplanes that fail to break even lower the future ability of the firm to compete by not replacing their development funds in the corporate coffers.

\textsuperscript{6} The Taurus developed by Ford in 1987 cost roughly $2 billion to design and facetize for, while the 777 is expected to cost Boeing roughly $4 Billion in 1992 dollars for its development.
The cyclical nature of the airline industry since airline deregulation, fueled by under and over industry capacity, leads to frequent industry shakeouts and has made the airframe manufacturing industry cyclical as well. Recently, the cyclical nature of the airframe industry has partly gone away, as the airlines are replacing their first generation jetliners, leaving each manufacturer with a large backlog of orders. Boeing, the largest manufacturer with a market share of over 60%, has a current order backlog worth over $90 billion. Some airlines such as Kuwaiti Airlines have purchased models in this market based upon when they can get an aircraft, rather than on the traditional metrics of cost, performance or commonality of spares. Therefore, this large backlog is both a blessing and a curse to the manufacturers. On one hand it assures industry stability in employment and profits for the next 5 years, but it also indicates that the present manufacturers are not able to serve current customer's demand. This state of affairs gives indications that new entrants may appear in this industry.

A major difference between American players in the commercial aerospace industry and their automotive industry cousins is their participation in a global market. The Boeing company currently sells 54% of its jetliners to foreign airlines and this trend will continue, as the growth segment of the airline market is on the Pacific Rim.

The concentration in the automotive industry in the late 1970's, before the Japanese invasion began, and the present commercial airplane industry are roughly the same, or about 2.5 equivalent companies (1). This level of concentration is consistent with a mature industry. In such an environment, market shares are relatively stable, before the entrance of new competitors.

The Japanese invasion into the automotive industry has brought new innovation in process technologies, marketing strategies, and manufacturing policies to this industry. The invasion has brought with it a shuffling of the relative market shares and a decrease in
the relative market concentration. As the aerospace industry tends to lag the automotive
industry by roughly 20 years in its historical development, recent trends\(^7\) in this industry
would point that entry of far eastern firms may be occurring in the commercial aircraft
industry as well (24,25,57,69). As one Boeing factory worker put it in a letter to the
company newspaper, "(The) wolves are howling at the door!" (6)

**Conclusion**

This chapter presented a brief historical perspective of process development and
technological innovation in the aerospace industry. In this discussion, two cases were
documented where a basic investment in process technology and the creation of a core
competence in the manufacturing and design technologies around it, have enabled Boeing
to develop 2 generations of bombers, the first successful commercial jet airplane and their
entire family of commercial subsonic aircraft from the first investment during the industry
transformation just after the dominant design, and the ability to manufacture the wide
body transports from the subsequent incremental advances. These core competencies (58)
are the primary reason that the Boeing company survived the cyclical downturns which
occurred in this industry after World War II and its predominance in the market today.
The third case presented was the development of composite process technology, which
was instrumental in creating the A-6, B-2, V-22 and F-22 products of military division and
the development of the 777 horizontal stabilizer.

This discussion also demonstrates in three instances, (aircraft industry in the 30's,
Lockheed Skunk Works and ACDP) that small flexible organizations were able to learn
and innovate process and design technologies much faster than is possible with the
hierarchical organizational structures in place today. Although these team structures have

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\(^7\) The proposed purchase of 40% of McDonnell-Douglas's Douglas Commercial Aircraft business by Taiwan Aerospace (24) and the
recent moves by Toyota and Mitsubishi (57) are also signs that new competitors are emerging in this industry.
accounted for a small minority of the effort devoted to process and design technologies in this industry, their contributions in these three instances have been significant.

Finally, this case illustrates throughout its history, the Boeing Company, has been able to transition their workforce and facilities back and forth between military and commercial aircraft as market demands dictated. These two complementary markets have allowed Boeing to transition the technology and competencies developed in one field to another. This presence in both fields of aircraft manufacture has also served as a method of diversification for the company to buffer it against the cyclicality of these two markets and prevent the loss of critical skills during downturns in either market. This cyclical, coupled with large layoffs of professional product and process engineers has been a chronic problem for other aerospace companies trying to capture value from long term investment in new processes, and serves to reinforce the product dominated culture of this industry, as only those firms which have product development programs in place are able to capture the skills of individuals laid off from other firms\(^8\).

The aerospace industry should be prepared for new entrants in their industry stressing low manufacturing cost, high quality, new manufacturing processes to enable low cost production or enhanced product performance, innovative new designs, rapid product development and a flexibly organized workforce (10, 30, 34, 66) as their main competitive strategies. Based upon the American automobile manufacturers experience with the Japanese invasion, American airframe manufacturers should be mobilizing now to meet these new threats. When evaluating the strategies to fight off such a competitive attack, it must always be remembered that the loss of the financial "nestegg" is potentially fatal.

\(^8\) They only are able to utilize these skills as long as they have product development programs in place, the itinerant engineers move on to other firms and projects as the project on which they are presently employed ends. This describes the employment culture of much of the aerospace industry.
Chapter 6
Creation of a Manufacturing and Process Development Strategy

This chapter will use the characterization format of Wheelwright and Hayes (80) to describe the four types of a manufacturing strategy that may be employed by a firm. To achieve the most advanced strategy, their Stage 4, World Class Manufacturer classification, it is the hypothesis of this thesis that a process development strategy is required. Previous chapters of this thesis have described the generic problems in the aerospace industry with the development of manufacturing processes and have proposed team based development organizations with long range charters to create a manufacturing process development strategy. This chapter will fully describe the organization and responsibilities of the proposed Charter Parts Council and Process Development Team concepts.

Characterization of a Firm's Manufacturing Strategy

Wheelwright and Hayes (80) have developed a characterization format to classify manufacturing firms into four categories according to the manufacturing strategy that they employ. The range in this strategy runs from a "don't upset the apple cart" strategy (Stage 1) to those of World Class Manufacturers (Stage 4).

Firms which are characterized with a Stage 1 strategy under this format regard the manufacturing operation as entirely neutral to the success of the company and try to minimize any impact that it may have on their success. The Stage 2 strategy is an advanced form of the Stage 1, manufacturing neutrality strategy, where the firm not only does not want manufacturing to "upset the apple cart" as Stage 1 firms focus on, but also strive to maintain "parity" with their major competitors. In this strategy, they follow industry practice with regards to human relations policies by following industry-wide
"pattern" bargaining. These firms are normally completely unionized, with major unions representing both blue collar and professional workers. They also avoid major, discontinuous, changes in either product or process; therefore any changes that occur in the industry, if they come at all, usually come from the efforts of outside suppliers. Stage 2 firms treat capital investments in new plant and equipment, procured from outside equipment suppliers, as the most effective means for achieving temporary competitive advantage. Finally, Stage 2 (and also most Stage 3 firms) view economies of scale, and the movement down an experience curve as the most important sources of manufacturing efficiency. Each of these attributes of a Stage 2 firm, fit Boeing and the rest of the aerospace industry to a large extent in their manufacturing strategies.

Using Wheelwright and Hayes classification format for a manufacturing strategy, Stage 3 firms can be distinguished from Stage 2 firms by including in their strategies three other main attributes;

1.) Screening manufacturing decisions to make sure that they are consistent with the division's competitive strategy

2.) Formulation of a manufacturing strategy complete with plant charters and SBU mission statements to guide manufacturing operations over a significant period of time.

3.) Being on the lookout for long term trends and developments that may have an impact of manufacturing's ability to respond to the needs of other parts of the organization.

From evidence observed during the internship these additional attributes were observed at the Boeing Company. For this reason, they have been characterized as a Stage 3 firm. As a group, Stage 3 companies have made some progress in formulating a manufacturing strategy, when they are compared to Stage 1 or 2 firms. However, they
have not completed the process to create a strategy which would enable the firm to become a world class manufacturer.

Most Stage 3 firms regard innovation as making one or two bold moves, such as the introduction of CAD/CAM, or the introduction of flexible machining systems into their plants. These bold moves may also include the formation of "model" manufacturing centers in one or two isolated plants or MBU's¹, but the effects of the technology or policies do not run throughout the Manufacturing organization. Few efforts are made to tie manufacturing more closely to other organizational units. Stage 3 firms do, however, see technological progress as a natural response to changes in business strategy and competitive position, but have not yet become proactive about it. Stage 3 company manufacturing managers are expected to support the firm's business strategy, but not become actively involved to formulate or lead it. Other than the above policies, most Stage 3 companies continue to operate the majority of their operations very much like Stage 2 firms.

From the discussion on Boeing's competitive strategy in Chapter 2, it is apparent that Boeing like many American manufacturing firms has not made the complete transition to a Stage 4 manufacturing strategy, where the competitive strategy of the firm rests to a significant extent on the company's manufacturing capabilities and technologies.

Process Development and Organizational Learning

Those firms characterized with Stage 2 and 3 strategies, mainly source all plant processing equipment from outside suppliers of manufacturing equipment and rely on these suppliers for most of their information on new manufacturing technology. These firms usually have significant Research and Development budgets and facilities, but most often these laboratories are largely product-oriented, with only small efforts devoted to

¹ Boeing nomenclature for a focused manufacturing business unit and is similar in concept to similar to a strategic business unit, SBU
process development. Consequently, a very small amount of the processing equipment found within their factories was either built at the company or significantly modified to fit their precise needs. From the evidence presented in Chapters 3 and 4, this is very much in evidence at the Boeing Company, but perhaps less so at other aerospace companies. This strategy has the self fulfilling result that investment in new plant or equipment yields only short term competitive advantage, because a competitor could equal their performance with a similar investment. One manufacturing technology manager interviewed during the internship stated nearly exactly this conclusion. With the dynamics of such a system, it is little wonder that firms with these policies strive only for manufacturing parity.

Additionally, the managers of the Stage 2 firms are uneasy with the concept that manufacturing is a learning process that can create and expand its own capabilities, and is therefore uncontrollable. Stage 3 firms may realize this, but are uncertain in how to achieve it.

Stage 4 Firms; World Class Manufacturers

Therefore, a wide gulf separates the strategies of Stage 2 or 3 firms from those of a Stage 4 firm with a World Class Manufacturing Strategy, by their differing philosophies and policies. Stage 4 firms develop long range business strategies in which manufacturing capabilities are expected to play a significant role in securing the strategic objectives. The manufacturing function is therefore regarded as a strategic resource for enhancing the performance of other functions within the organization and encourages the interactive development of business, manufacturing and financial strategies to obtain alignment.

These firms anticipate the potential of new manufacturing processes by tapered\(^2\) in-house development and seek to acquire expertise in the technology before the implications of are

\(^2\) Tapered development means acquiring in-house laboratory expertise while participating in joint development activities with outside suppliers. The tapered development truly makes the projects joint in spirit and in fact because each firm can contribute experience and learning to the effort. This tapered in-house effort allows the manufacturer to capture the knowledge of the joint project and build competence in the new technology. The goals of a joint development project is described in Chapter 4.
fully known. To exploit this in-house expertise, these firms position themselves to capture the benefits by developing new processing equipment at the firm, and therefore always lead the industry in technology.

**Transitioning a Firm To Stage 4 Status Through a Process Development Strategy**

To overcome the cultural, organization and structural problems with a manufacturing strategy in general and a process development strategy in particular, (discussed in the Chapters 3 and 4), along with the arguments of Wheelwright and Hayes (80), a company needs to make several changes in its engineering and process technology organizations to enable a strategy of process development, and allow the transition from Stage 3 to a Stage 4 strategy to take place. In the Wheelwright and Hayes format, World Class Manufacturers do not just appear, but evolve over time from the earlier stages by continuous attention to the development of the manufacturing operations, people and the underlying technology. The creation of proposed process development teams concept is one step which will help accomplish this strategy. To implement these concepts and to transition the manufacturing strategy requires a change in attitudes about long range development and the funding of process technology at the expense of product development. Additionally, changes in organization and the tactical methods needed to implement a process technology will be necessary.

A company should pursue a process technology development strategy because its goal is to enable new product innovation by creating the underlying process technology for the future. As stated in Chapter 4, the selection of the process technologies to be developed should fit with the long range business goals of the company and its business segments, at a time horizon far enough in the future so that the technology can have an impact on that strategy.
First, a company needs to loosely couple its process technology development efforts to its product development efforts, except in the area of the incremental process improvements/modifications to existing processes that are needed for ongoing new product developments. The selection of the incremental improvements to a given project should be made on the basis if the technology fits the "product's window of opportunity". All fundamental, revolutionary process improvements should not be associated with a given product, but guided by the expected requirements of aircraft (products) 5 to 15 years in the future. These requirements will guide all future decisions regarding the development of the process, with the goal of making the process meet the market opportunity at some point in the future. Decoupling the process technology from the product development programs prevents the down selecting of a promising new processes, because the process development does not meet a short program schedule. This strategy allows the technology to mature at its own pace. Stated in a different way, process technology should be characterized as either a near term, incremental development or as a long term strategic development. Technologies which do not fit either characterization probably should not be contemplated for development.

Second, a company should begin to implement two new organizational structures to create an environment where process technology is created. The first organization is a group of Charter Parts Councils (CPC). The CPCs will have the authority to create the second new type of organization, Process Development Teams to develop key strategic technologies which impact the component areas of the CPCs. The Charter Parts Council idea is one method to manage the core technologies of a business, an idea borrowed in this thesis from Pratt & Whitney Aircraft. The CPC is based upon the idea that after a dominant design, many manufactured products are made up of several key assembled components. In an aircraft, these components would be the 1.) fuselage, 2.) wings, 3.) engines and nacelles, 4.) landing gear, 5.) rear empennage (horizontal and vertical
stabilizers, aft pressure bulkhead, and tailcone assemblies), 6.) cockpit and avionics. Since these components are produced with common manufacturing technologies and engineering philosophies throughout the company's product line, the charter parts council's mission is to manage the product and process technology of the specific component area, throughout a company's whole product line. This mission is for both current operations and to provide long term direction for the future. This long term mission proposed in this thesis for this organizational structure is for it to assure that state of the art technological competence to design and manufacture these components is provided for in future products.

Charter Part Councils would be made up of executive representatives from each of the product divisions, the support manufacturing divisions and the preliminary design/advanced concept marketing functions, as shown on Figure 6.1. One of the key tasks assigned to the CPC's is the review of each of the new product proposals in the 5 to 15 year time frame. With the help of technical experts\textsuperscript{3}, they would identify new product or process technologies required to meet the technical or cost requirements of the proposed future aircraft concepts. The process technologies identified become the strategic technology development projects to be initiated by the CPC. In their mission to manage the firm's technological development, the CPC's must continually remember that their organization is to guide the long range process development of the firm and not to constrain the research to a short ranged or overly focused agenda of projects. Some fraction (25 to 35\%) of the advanced development projects should be available to explore exciting new technologies that are not mature enough initially to stand the review of a typical executive council. It is intended that through the mixture of loosely coupled new technologies with some higher risk, longer term projects will come the breakthroughs

\textsuperscript{3} Such as the Senior Principle Engineers or Technical Fellows in both the Engineering and Manufacturing Staff organizations. These senior engineering specialists aided by younger engineers in emerging technologies and outside experts in the government and universities provide a large pool to identify the emerging technologies which can significantly impact the performance of the next generation of aircraft.
which will enable the advanced performance innovations in the firm's future product line and provide it with technological competitive advantage. If the work of the Process Development Teams evolves into a short ranged portfolio of projects to support existing product development projects, as may likely occur in the existing culture, a manufacturing process development strategy will not yield the anticipated benefits. With these types of projects, this structure is just a more sophisticated version of the current "product-driven" system.

If process technologies are identified that have significant impact on two or more core components, collaborative efforts between CPCs, would allow for multi stakeholder input into the development process. These collaborative efforts in common technologies prevents duplication of development effort in new technology, yet assures that the needs of each component area are met. To simplify reporting arrangements, one CPC should be designated as the prime CPC to provide management direction to the communal PDT.

In summary, the CPCs play a key role in identification of key technologies required for the future in each of their component areas and provide market and product direction to the PDTs reporting to them, making sure that the process technologies developed, fit with the emerging market opportunities. This structure provides a solution to a chronic weakness with long range research in general and process development in particular, to keep the development effort focused toward an eventual product or strategic goal. The creation of these councils is an important first step to allow a firm to manage its technology base in a strategic manner just as it manages its finances and product lines. More management emphasis has typically been put into these latter two areas and is a major reason for the technological competitiveness problems of American manufacturing firms. As shown in Figure 6.1, the individual Process Development Teams will report to the CPC which has created the it and will provide its development budget. This figure also shows the functional tasks of the PDT and the current organization which provide
individuals with those skills. The charter part council is shown as being made up of representatives from the product divisions, component manufacturing and preliminary design. (from which the new product concepts come)

Goals in the Creation of Process Teams

A key objective in the formation of Process Development Teams is to cut the time that it takes to develop a new manufacturing process and implement it from the present 8 to 15 years to 4 to 8 years for the reasons stated in Chapters 3 and 4. The multidisciplinary team avoids many of the functional innovation barriers that Boeing and other companies have experienced in new process development (38). The use of new techniques of process development within these multifunctional organizations increases the learning and speeds the development project. The use of parallel process and materials development and cross functional learning of the multifunctional team, also speeds the development process. Together these methods and philosophies allow the time objectives to be met. When the development time objectives are met, process development can be accomplished in a time where new market opportunities can be reasonably forecast. Process Development can then act as an enabler to new products, the primary goal of this strategy. Halving the development time also makes process development more attractive from a financial standpoint, thereby increasing the willingness of corporate senior management to invest in new process technology in the future.

Attributes of Process Development Teams

Figure 6.1 shows the functional skills required on a Process Development Team. The three main functional skills required are in the following areas:

1. Structures Technology
2. Materials Technology
3. Manufacturing Technology

A brief description of the duties of the members of the team from these primary areas of skill are described in the following paragraphs.

The structural technology representatives on the team are assigned a task to create new design concepts of the future target product that fit with the new process's capabilities. Some of these concepts should be high risk, aggressive designs that are difficult to manufacture with its current or projected capabilities. These designs will act to "push" the process developers to remain innovative to make these high risk, high performance concepts a reality. Through constant interaction with the manufacturing process development representatives on the team, the structures designers and analysts will continually update the concepts to reflect the present knowledge of the process's manufacturability and the capabilities of the materials after they have been processed.

The materials representatives on the team will select, develop or modify materials so that they are capable of surviving in the intended product environment, work well in the manufacturing process, and whose structural performance yields lightweight designs. To perform this task, they will need to have constant interaction with the structural engineering and manufacturing process engineers on the team. The materials and structural engineers will determine the best screening and optimization testing procedures for the DOE processing trials run by the process engineers.

The manufacturing engineers will specialize in the development of the innovative process technologies. They will be responsible for running screening process trials, process-designed experiment optimization, process machinery and control system design, and the development of innovative tooling concepts and designs. As a process is maturing through the designed experiments, the process equipment designers will begin to scale up the process and prepare for its implementation into a production environment. As the
process reaches maturity, machine runtime data will be incorporated by these engineers into cost models of the process so that intelligent cost trades can be performed against competing processes, so that intelligent process choices can be made by subsequent design teams on the developed technology. These cost modeling efforts should commence in this team structure as soon as practical to create process economic metrics to assess the new processes economic performance.

During the initial and subsequent processing experiments, the mechanical test data from the panels fabricated will create a preliminary materials and structures database which will be used by the structural analysts in trade studies to determine the best structural concepts, materials and processes from an engineering performance standpoint. The multifunctional nature of this development team allows the selection of these concepts for further development based upon cost, performance and risk, rather than on performance alone. The existing design concepts, production processes and materials used on existing products will be included in these trade studies to create a baseline comparison to the new process and/or materials. A plot of the process's improvement on critical performance parameters will be made by the team to estimate the point when the new technology surpasses the old on cost or performance. A schematic of hypothetical performance curve, Figure 6.2, shows the typical S-shaped behavior of a technological performance trajectory. S-curve and learning curve cost trajectories exist in multiple dimensions, such as materials cost, structural efficiency, manufacturing productivity, etc., where comparisons of the new technology to the old must be made on each dimension.

From the preceding discussion, continual interaction of the representatives is required to jointly achieve the tasks set out for the team. The above discussion describes the development task breakout of an early "organic" multifunctional team before skill diffusion amongst the team members has taken place. As the teams remain in place for extended periods of time, skill diffusion through cross fertilization (38) amongst the
members will make each member more efficient. This occurs because each member can anticipate the needs of their peers and provide each other better support. Skill diffusion, along with cross training and experience will transform the PDT into a team structure typified by the holographic, learning organization model. This model was proposed as the ideal for such a technology development organization in Chapter 3 and is the eventual goal for the PDTs. The creation of this type of learning organization is essential if the development time compression target is to be met.
Figure 6.1 Charter Parts Council and Process Development Team
Organizational Structure and Functional Makeup

Charter Part Exec. Council (Wings)

747 Representatives
767 Representatives
777

Decisions to develop generic new technology and to implement mature technology

Materiel-Vendor Qualification

Structures Technology
Structural Design
Structural Analysis
Structural Test

Process Development Team

757
737
PD {HSC1, NLA}
FAB DIV

Finance
Activity based Accounting
Cost Modeling

Materials Technology
Materials Development
Materials Specification

Manufacturing Research & Development
Tool Design
Process Development
Process Science
Manufacturing Integration
Cost Modeling
The results of the continual trade studies will provide a scoreboard on the structural efficiency of the resulting structure and will prevent performance surprises, when a technology is selected for an aircraft project. Lowering the risk of selecting new structural technologies for new or existing aircraft is one of the major goals of a PDT. If a new technology is continually inferior to older, established technologies for the projected applications and whose performance curves are not projected to cross the old technology
on critical performance parameters, the PDT approach allows it to be down selected before the bulk of the development cost is expended at the scaleup and factory implementation stage.

The Process Development team extends the concurrent engineering/TQM approaches of Hauser and Clausing (14), the DARPA Initiative in Concurrent Engineering, (4,19) and Clausing (13) for use in long term process technology development. Implicit in the concurrent engineering literature is its use for rapid product development. The principles described in these references can also be useful in long range process development. The customer input which typifies the use of concurrent engineering approaches is provided by the PD groups and the CPC, to focus technology development to long range user needs. A concurrent engineering approach to the development of composite structures using a team approach of both generalists and specialists, while incorporating user or customer input has been proposed by Wilkins and Karbhari (82). They state that "Concurrent Engineering is an ideal tool for composite product development, to the extent that (if this concept) were not established in other fields, it would have been developed for composites out of necessity." They also claim that the large number of choices the team faces, makes it imperative that design, manufacturing and process economics be integrated during the development process. The PDT concept of this thesis embodies the principles presented in this paper into an organizational format to accomplish its vision.

A key strength to this concurrent method of developing new processes, is the inclusion of structural analysts on the team who will be tasked to create new analysis techniques or codes to analyze the unique structural concepts or material architectures, if these are created by the new process. This analysis is presently done in a sequential fashion at the conclusion of materials or process development, so that process and materials developers are never certain that the new technologies they are developing have
utility in a product, until much of the initial development is complete. Such a development system can be compared to an open loop control system, where the developers suffer from a lack of timely feedback. The structural analyst's skills in the area of solid mechanics can also be utilized in combination with those of the process development engineers to create process science models of the new processes for a better understanding of the physics occurring in the process.

The cost modeling efforts of the PDT will take on increasing importance as the process matures. To accomplish this task, industrial engineering and finance representatives will be incorporated on the team so that integrated, parametric cost models and factory flow simulations can be created while the process is in the latter stages of development, before scaleup. This effort should help the downstream implementation of the process in the DBT's by creating a database for cost comparisons of the new technologies with existing processes, and to provide directions for additional process development if cost reductions are needed. The lack of established and accurate cost models has impaired the selection of new technologies on new airplane programs throughout the industry (33) from a standpoint of risk (Chapter 2 and 4) and has created a credibility problem for the manufacturing engineering team members on the DBT's.

Core Competence in New Technology Development

To properly field new technology into new or existing products, requires competence in a wide variety of functional activities around the new technology. For example, to properly field a composite wing onto a new, small jetliner, each area of the organization must be capable to support this radical innovation. This requires that Manufacturing be capable to build composite wings in an efficient, cost effective, manner with processes that are in control. Engineering must be capable of designing, analyzing and testing the wing, and Quality Assurance must be capable of inspecting the hardware
and assuring that it meets the requirements set by engineering. The Materials Technology function must be capable of specifying how to purchase and qualify the materials from the vendors, and Materiel, the procurement organization, must be capable of qualifying the vendors and component subcontractors for the new technology. The competence in the organization cannot end at this point, because the Customer Support organization must be knowledgeable enough about the new materials, structure and processes to help the customers maintain the aircraft, throughout the life of the airframe.

Each of these organizational functions must be capable of performing its mission around a given innovative technology before the technology can be successfully fielded. When each of these organizational strengths are in place, a growing new core competence is created around the new innovation. For large integrated enterprises like aircraft manufacturers, producing huge manufactured and assembled products, new technology innovation really means the development of new core competencies within the whole organization. (58) These developing competencies are required to successfully introduce the technology into a product. The use of a Process Development Team approach speeds the development and implementation of new process technology, because the technology is developed in a manner which builds competence in each functional area, in a concurrent manner.

Companies which possess the organizational capabilities of being able to develop, integrate and field new technologies in a rapid fashion and can create growing competencies around the new technologies, will be the most successful using a manufacturing process development strategy to create competitive advantage.
New Incentive Structures Required for Engineering Teams

The creation of Process Development Teams along with the Design-Build teams already in existence, will require a new incentive structure to reward the engineering professionals and technicians that staff them. Currently, all members of Boeing's engineering professionals are grouped with others who perform the same skill/function in skill code totems. Within these totem groupings, Boeing is able to assess the performance of its engineering workforce and distribute merit raises in an equitable manner. Boeing is currently reinforcing this system with a new Pay for Performance system, which increases the merit raises for their very best performers and provides mutually agreed upon yearly objectives for each employee. This system is not unlike the management by objectives incentives system used for managers in most American companies. This system was put in place to remove some of the subjectivity's in performance evaluation of the old system, and to create a better system to signal what performance is expected from each engineer. Additionally, the new system has higher performance incentives to better motivate the high performance engineers and creates financial incentives for engineers not to leave the firm after 5 to 10 years experience. One major inequity of the old system was the skill codes that were predominantly populated by manufacturing engineers and engineers from the Commercial Airplane Company (old corporate structure before groups) were paid lower than those in engineering skill codes and the military companies, which created an incentive to transfer from certain functions and divisions to other skill codes or divisions.

The problem with this skill code system is that it rewards those who devote their efforts to becoming functional specialists within the narrow skill codes. This incentive system was first put in place in 1948, when the company was trying to create functional specialists to fit into their functional organization. Both the new and old system create strong incentives to prevent engineers from multiskilling and changing their skill codes, because those that officially change their skill codes, in the act of multiskilling, are likely to
enter the new skill "at the bottom of the totem". Being rated on the bottom is likely to have an adverse effect on the engineer's future salary growth. If multiskilling occurs within this system, it does so unofficially.

In creating product and process development teams, new skill codes should first be created for project integrator engineers with skills in a multitude of skill codes. These integrator engineers (42) will provide the leadership and multidisciplinary technology integration to the team. The creation of this class of "best and brightest" engineers to integrate the manufacturing technology development was one of the key recommendations of a Society of Manufacturing Engineers study (42) to maintain American technological competitiveness in manufacturing industries for the next century. These individuals should be evaluated (and perhaps some of their teammates as well) on a Pay for Knowledge basis, where the emphasis is no longer on unidisciplinary competence, but a working knowledge of several disciplines to tie the work together. Serling (64) indicates that the aeronautical design engineers in the formative stages of this industry would have fit this description well. Groups of these individuals are legendary for designing and producing aircraft in record time by today's standards. This is not to say that these individuals will be a "jack of all trades, but a master of none", but rather an individual with a primary skill in one particular area, but through team activities, classes or training programs and experience (42) have acquired the skills and knowledge in other areas to be effective integrators. Kanter (38) proposes that a company through the introduction of a Pay for Skill incentive system, encourages broader perspectives within development engineers and scientists by its rewards for people learning new disciplines. In an interview with a SPEEA⁴ labor negotiator, the author found that this type of incentive structure would be accepted by the union, if it was voluntarily accepted by the engineers in the integrator or team roles.

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⁴ Seattle Professional Engineers Employees Association, an unaffiliated union representing Boeing's engineers and technical employees in collective bargaining with the company. SPEEA has played a full partner role in the creation of the new Pay for Performance Structure.
These project integrator individuals would provide an excellent pool to draw from to create the next generation of program chief engineers and program managers, creating an attractive career path as an incentive to undergo the additional training this role entails. The management objective in selecting individuals for the team structures is to create the proper mix of skills for the anticipated development program, and the proper mix of specialists and generalist/integrators.

**Technology Forums**

By transitioning to team-based development projects, Boeing and other companies are beginning to isolate their functional specialists from each other, so that much of the information sharing and informal one-on-one training of engineers in the same skill that used to occur in functional organizations, will not likely continue. This is because these engineers are assigned to different projects and are not located in the same building or site. To maintain functional competence in a decentralized team based culture and to promote cross fertilization knowledge transfers (38) between the separate DBT and PDT teams, functional-based, technical forums should be established. Managers in charge of these teams should encourage the engineers that report to them to belong and take part in the presentation and educational activities of these forums.

Technical forums are a central part of the knowledge transfer and educational policies for the scientific/engineering communities at 3M and Monsanto, two decentralized, product focused, divisionalized companies with reputations for innovation in mature company environments. The technical forums in place at these firms has become the glue that holds their decentralized community together and has established a tight informal network, essential to the innovation in these entrepreneurial firms. These forums will work to help create a learning environment that will improve the performance of the teams and provide for knowledge transfer from one team to another.
Early Examples of PDTs at Boeing

Boeing has a prototype of a process development team into place within its Defense and Space Group, where the goal is to develop new manufacturing technologies to enable the next generation of military fighter airplanes. With this organizational charter, this team-based organization meets the definition of a process development team. This group shows an attempt to transition from the Stage 3 manufacturing strategy to a Stage 4 as mentioned earlier, but organizationally it has not made the full transition. The reason for this incomplete transition, is the engineers who make up the team still report to a functional manager in the aerospace industry pattern of skill-based functional organizations. In this project, each development project is broken down into functional pieces. This arrangement still allows a team effort because the whole group is physically arranged in one large bay and the informal network creates the transfer of information necessary for the simultaneous development needed on a PDT.

To complete the transition to a Stage 4 manufacturing strategy and enhance the performance of this group, the engineers need to be arranged by the process technology that they are developing rather than their function. The managers in this new arrangement would play a dual role in the matrix management structure within the teams. In the first role, they would be responsible for a multidisciplinary project team and would report in this role to the project manager of the PDT. Their second role would consist of providing the skill code management in the assessment and assignment of the engineers to the teams in the project. In this second role, he would report to the functional staff group manager in charge of the skill code. The project manager would provide the skill code management responsibility for the manufacturing process integrator skilled individuals. The key reference to this approach to the organization of the teams is that the managers of this project would be responsible for a multifunctional group of employees, not a functional staff. Another major difference to this organizational approach is the managers would be
hardlined to the project manager as their primary source of direction, not to the staff group manager. The goal of such a practice is to create managers who are skilled at leading and coaching a team to solve multidisciplinary problems, rather than managing a group of functional specialists.

Having all the PDT's located in one building, as with this experimental PDT, with its laboratories in the same building and across the street, is also ideal from a knowledge transfer standpoint between the teams. Although this is logistically hard to accomplish with Boeing operations spread throughout the Puget Sound region, the accomplishment of co-location of laboratories and PDTs will enhance the learning rate, cut the development time and hence increase the strategic value of these laboratory assets to the company. Allen (3) has shown that the amount of communication that occurs between pairs of individuals or groups is inversely proportional to the distance that separates them as is shown schematically on Figure 6.3. The amount of communication is in direct proportion to the learning rate. Recent advances in information transfer technologies may have made this figure somewhat less applicable, but it is still true that the majority of problem solving and technology transfer occurs through face to face communication, which requires the co-location of the team and their laboratories. A great deal of thought in facilities planning and building design is required to facilitate the creation of a learning organization and efficient process development teams.
The Boeing Commercial Airplane Group does not, at present, have any team in place which resembles a PDT with their internally funded development programs. They do have a project that could greatly benefit from the strategy and methods of process development practiced by a PDT, in the High Speed Commercial Transport program. This program currently is organized with a Design-Build Team structure, as though this aircraft could be manufactured with incrementally better manufacturing processes or materials used on subsonic aircraft. The developmental laboratory work for this project is done in the separate functional laboratories in widely disparate locations, so that individuals from different skill areas cannot share in the learning of their teammates. The large physical distance between the manufacturing development engineers and the design staff (17 miles) would indicate that the communication necessary to develop the advanced structures technology for this advanced airplane is severely impeded. The focus of a DBT development team is on the product and therefore must have a shorter term vision than a

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1 One externally funded engineering and process development project, the Advanced Technology Composite Structures (ATCAS) program, has an organizational makeup which embodies many of the organizational and development concepts of a PDT. This program is funded by NASA to generate structural concepts and processes to design and build composite commercial aircraft structures.
PDT, which focuses on enabling a product through the next generation manufacturing processes and materials. The functional DBT development of this project has been compared by one Boeing manager to "meeting at the bar when the work is done!" Each of these two types of teams have their place (DBT & PDT), but the proper team structure must be chosen, so it will match the development needs and time scale of project. When fundamental longrange process development is required to enable the product, the PDT team concept should be chosen in preference to the product-focused, shorter term, DBT concept.

Along with the product-dominated nature of all development projects, the functional skill based organization is also an ingrained part of the culture throughout aerospace industry. The creation of the new organizational structures proposed in this thesis will not be fully effective in creation of a world class manufacturing strategy until these underlying assumptions have changed through dialog and personnel turnover.

**Conclusion**

This chapter begins by using the format of Wheelwright and Clark to characterize the firms of the American aircraft industry as either Stage 2 or Stage 3 with regards to the manufacturing strategies that they employ. These firms have not transitioned in their strategies to those of a World Class Manufacturer, where the firm uses its manufacturing operations as a chief source of competitive advantage. The method proposed in this thesis to achieve WCM status is through a process development strategy on strategic new technologies. This strategy will give an established firm an advantage in both cost and performance over their established competitors and able to compete against potential new entrants which appear during industry technology transitions.

The Charter Part Council and Process Development Team structures introduced in earlier chapters were fully developed in this chapter. Their organizational structures, skill
makeup and technology transfer responsibilities and culture are proposed as solutions to the structural difficulties outlined in previous chapters. Successful implementation of these team-based structures will require management focus on the incentive structure, skill mix, interteam and corporate technology transfer and the evolving culture. Over time the "ad-hoc" formation of PDT's can be held within a central, multidisciplinary, advanced technology development organization, made up of groups of these teams. Two examples of team-based, longrange, development programs were presented showing the divergence in fundamental goals of these two organizations and a potential lack of alignment of longrange development projects with a "product" focus.

The specific proposals made in this Chapter for the CPC's and PDT's are:

* Creation of Charter Part Councils to manage the technology base of the company in component areas.

* Use the CPC's to evaluate long range market opportunities and implement strategic process development project teams to enable these new products.

* Perform long range process development in multiskilled team structures to cut development time and increase innovation in structural technology.

* Use TQM / Concurrent Engineering principles on long range process development projects through PDT format.

* Implementation of Pay for Knowledge / Skill incentive structure to encourage the creation of multiskilled technology integrators for team-based structures.

* Creation of functional technology forums for inter team technology transfer, and continuous training of engineers.
* Create an environment of close proximity of team members in laboratory facilities to maximize communication and learning rate.

* Managers in team-based structures lead multi-skilled teams and are not functionally organized in staff groups.
Chapter 7

Methods of Rapid Process Development in Process Development Teams

This chapter outlines the major tasks to be accomplished within a Process Development Team to bring processes and materials under development to maturity. The proposed tools and methods to achieve the goal of cutting the development time for new processes are detailed in this chapter. None of the methods proposed here are new in and of themselves, as most are practiced at some place within a traditional functional corporate structure, but become truly powerful when practiced together in a multifunctional, team based, learning environment.

Initial Process Development Laboratory Experiments and the Development of a Process Science Model of Process

The concurrent use of process modeling with the initial process laboratory experiments will enhance the learning rate of process development efforts on processes that are in their infancy. The use of these methods with the In-Situ Consolidation Process to be described in Chapters 8 through 10, was undertaken to prove this assertion. Initial laboratory experiments with the new process will establish the basic feasibility of the process and provide information on the magnitude of the relative forces, power inputs, pressures and processing times required to run the process. These initial feasibility conditions will be by no means optimal, but will provide a general idea of the processing conditions and the physics, so that a process model can be built around them. The model of the manufacturing process should capture the geometry, processing velocity, the forces or pressures on the machine and material/component, and finally the heat and or mass transport occurring during the process. The process model will then be used to: 

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1.) Add physical insight into additional laboratory processing experiments to overcome processing difficulties.

2.) Establish a "process window" of feasible processing conditions for process optimization. With this "window", it will aide in the creation and analysis of designed experiments to further optimize the process.

Two different routes can be chosen to create these process science models:

1.) The first approach is to use readily available, nonlinear, Finite Element Analysis packages such as Abacus, Nike-Topaz or COSMOS/M which run on the current generation of engineering workstations. (Sun Sparcstation, IBM RS6000 or equivalent computers) In large manufacturing enterprises, with large engineering design and analysis groups, these packages and workstations are already quite available, therefore these assets can be used repetively to explore the effects of process variables or design changes in a preliminary analysis mode with a minimum of additional expense per run.

2.) The second approach is to build computer models based upon analytical mechanical or heat transfer derivations of the geometry's and boundary conditions posed by the process. The advantage of this approach is the increased physical insight gained about the process during the development and use of the model.

In this thesis, the second route to create an analytical computer model was chosen for modeling of the In-Situ Roll Consolidation process for thermoplastic composites. This approach was chosen because it is difficult to capture nonlinear material characteristics, such as the power law viscoplastic deformation which occurs during consolidation processing of thermoplastic matrix composites, with the existing materials models in the Finite Element packages currently available. Another consideration in this choice was the
computer run time for the model. Nonlinear Finite Element Models require substantial amounts of time (often greater than 1 hour) to compute the solution for a model with complex geometry, a tight mesh, temperature-dependent materials properties, and time-varying heat inputs or pressures. Because many different combinations of materials and processing variables need to be screened by the model, rapid analytical computer models are the preferred route if an analytical solution exists for a given simple geometry, while nonlinear finite element models are acceptable for complex geometry processes where no such analytical solution exists or is possible.

An optimal strategy to model a manufacturing process may include a FEM model to analyze some of the microlevel details of the process geometry, while the analytical model provides a less detailed macrolevel model suitable for process screening and understanding most of the physics of the process. This strategy allows the macrolevel analytical model to be used in a preliminary process design mode to identify major issues involved with the process and major trends in improving the quality through changes in the processing variables. The more detailed microlevel FEM models are used to provide a final analysis of the process once the final operating conditions with near optimal performance are approached. This two-step approach speeds process development with the integral use of process modeling by avoiding the use of costly and time consuming detailed, "micro" level modeling until the process has begun to approach maturity. At this level of process maturity, the "micro" level modeling will have their greatest impact on further process improvements.

Analytical computer models also have the advantage of the flexibility of adding new sub models to the "core" model, as process experiments proceed, so that new learning can be captured in the model. A demonstration of the learning which occurred with the development of a process model for the In-situ Consolidated, Advanced Tow Placement Process will be documented in Chapters 9, 10 and 11. In the development of this process
model, the author intentionally chose a strategy of creating a "core" model prototype rapidly to compare its output against laboratory process data to adjust and refine its assumptions, before continuing on to include the more advanced sub models in its makeup and its solution algorithm.

**Organizational Environment of In-Situ Consolidation Development Effort**

The modeling effort was performed was in an *ad-hoc*² process development team of composite manufacturing process development engineers at Boeing, in close coordination with ICI Composite Structure's engineers and technicians. ICI Comosite Structures had the facilities and skilled employees in place (in 1991) to fabricate the test panels with In-Situ Consolidation.

The development of this model is in sharp contrast to other process science modeling efforts at the Boeing Company, where the work is generally performed in a functional group of numerical analysts in a facility far removed in locality and culture from the development and manufacturing efforts of the Boeing Commercial Aircraft Group. It was found that models developed by these groups were not regarded highly by their counterparts in the Fabrication Division or Operations Technology communities because the models were either too complex to set up, run and analyze, or because they were developed with little or no customer input from the manufacturing community. The result was little or no ownership of the resulting models. The choice of location for developing the model in a manufacturing development community was the best one made during the internship from the standpoint of overcoming the perception barriers that come with process modeling and from the standpoint of hastening the learning process about in-situ

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² This Team was not an official Process Development Team, (presently no teams of this sort exist in BCAG) but the interaction of its members and the skills of its members fit the description of Process Development Teams found in Chapter 6 & 7. In this team the majority of the members had primary skills in Composite Manufacturing Process Development, but interestingly two members had skills outside this area, one in materials development and thermal/mechanical analysis of structures and processes, while the other had primary skills in airframe structural analysis and Finite Element Analysis. In an expanded form this, "ad-hoc" PDT forms the prototype of the future teams of this sort in BCAG.
composite technology. It was also fortunate to find a group of individuals with interdisciplinary backgrounds within one functional organization, for this added to the learning process and allowed the realization of the PDT-enhanced development strategies within the *ad-hoc* team.

In the present work, it was observed that the learning about the process that was incorporated into the model was related to the amount of interaction that occurred between the processing technologists and the model's developer(s). Ideally this would be maximized if the manufacturing engineers developing the process have the skills to build their own models. Recognizing that manufacturing engineers (42) have traditionally lacked a heat and solid mechanics analysis background, with the ability to create computer programs, requires that process modeling will be a multidisciplinary activity (at least initially). In the team environment of a PDT, the analysts creating the computer models should not be shy in donning their lab coats and assisting in the initial process development laboratory experiments. Exposure to the process experimentation overcomes the "sticky data" (86) difficulty with transmission of implicit technical data by allowing the modeler(s) to get a first hand knowledge of how the process works. This was found to be helpful in the creation of the process science model of the In-Situ Roll Consolidation process. Observation of the laboratory process resolved for the model's developer several of the uncertainties about geometric arrangement and position of heat input. In the "holographic" environment of a process development team, the diffusion of information and learning between the team members will enhance the complementary skills in each of the member's backgrounds, such as analytical or laboratory skills to make the model creation a team activity.
Creation of Designed Experiment (DOE) Test Program

The initial laboratory process experiments and the results of the computer modeling will identify the primary processing parameters. Using computer simulation of the process with the model, a designed experiment should be created using values of the primary processing parameters which are within the feasible "process window" of the process, but not optimum test conditions. Stated another way, the process model serves the purpose of screening experiments in traditional DOE experimentation methodology. The DOE testing on the panels will help identify the optimum processing conditions within the" process window", or point with a vector in process parameter space to where more optimal processing conditions can be found. The second purpose of the DOE tests is to confirm the results of the model and build confidence in its predictions for its subsequent use in process control, processing variation simulation, and problem-solving activities during process scaleup.

Simultaneous Materials/Process Development

With the process model, a wide variety of existing and potential candidate materials can be simulated for their utility within the developmental process. Screening the candidate materials to find those which can be fabricated with the developmental process will save a lot of time screening materials for their suitability in the process. The eventual goal is to determine the underlying materials science characteristics of candidate materials which allow them to fit into the process, so that a rapid evaluation of the suitability of new materials can be made as they become available. This was demonstrated for the In-situ Consolidation process and is described in Chapter 11. With the basic material science characteristics, it is then possible to develop new materials that are optimal for the process using a "materials by design" philosophy.
Attractive potential materials for a process or application identified through the materials by design philosophy, should be rapidly screened through environmental and mechanical tests to confirm initially that the candidate has the potential for use in the intended thermal, mechanical and chemical environment of the projected application. This suitability screening should be established as soon as is possible, to confirm that these potential materials are viable candidates, before any further processing or materials development is performed. Once the viability of a material is proven, then it can join the other candidate materials in the processing experiments.

Simultaneous materials and manufacturing process development will insure that the new processes will be qualified with state of the art materials. This practice removes the dilemma of creating state of the art manufacturing processes with obsolete materials. It also gives the materials development community an excellent opportunity to design an optimal material to fit both the intended application and the process.

DOE Panel Testing and Analysis

This phase of the project should be begun by the identification of discriminating materials and structural property tests to adequately assess the quality of the DOE panels. These tests should try to measure the residual effects of the processing on properties, so that the effect of processing parameters on quality can be determined. In addition to mechanical testing, microstructural evaluation of voids and defects, NDE methods such as through-transmission ultrasonic testing, TTU, or computer aided tomography, CAT, and warpage measurement technologies such as surface profilometry may be employed for quality\(^1\) measurement of the experimental panels.

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\(^1\) Quality measurements for composite panels include the identification, location and density of voids, laps and gaps along with the panel's dimensional tolerance and warpage. These quality parameters need to be controlled within a defined tolerance range. Panels that are fabricated with defects or tolerances outside these tolerances will likely have lower mechanical or structural performance. These quality inspection tests need to be run during development projects to understand the residual defects in the materials after processing and the effect of the processing parameters on removing these quality problems. Finally, the use of quality tests during development makes it easier to write inspection criteria for the process when it transitions to production. With these internal inspection techniques quality is defined as the deviation from perfection in the internal microstructure, from flatness and from the target dimensions of the panel. Similar quality
The team should set goal levels for the properties of the material after processing. The attainment of these goal values will be an indication that the process is nearing maturity. For composites, these goal values could be based upon a percentage of the theoretical strength and modulus values obtained from the micromechanical calculations, or a percentage of the material's properties obtained with conventional processing technology. Also, a minimal acceptable set of mechanical properties and quality ranges should be established, that if a process persists for a significant length of time (a subjective judgment), a downselection of the material or process should occur. Up front identification of the goals for the process will make the decisions to accept a process or to downselect it, a scientific, rational process and removes much of the subjectivity from such decisions.

The strategy for development of the process through modeling, processing experiments and materials substitution, followed by materials and processing optimization, prevents the tendency for an engineering group to rush out and build panels for mechanical property evaluation and design studies before the process is fully mature. This conventional type of development in product-focused organizations can lead to a negative assessment of an adolescent material/process, which may prejudice the organization from continuing its development further, as described in Chapter 4.

Refinement of the Model and Optimizing DOE

After the DOE panels are tested and the statistical results are analyzed, an optimum range in process parameter space will be established within the process "window". The use of the process model to establish a feasible "window" increases the probability that the optimum established in the first round of designed experiment testing

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measures could be generated for NDI quality inspection of components produced with metallic structural process technologies. Non destructive Inspection provides derived measures of panel quality. These derived measures must be related to the structural or physical performance of the fabricated components which are the ultimate standards of quality which must be obtained and controlled.
is the global optimum of the process. A second round of DOE testing may be initiated with this new set of processing parameters as the center of the test matrix, to further optimize the process to a narrower region of process space. The results of the first round of testing should be used to modify the process model to reflect the knowledge gained during the testing and analytical procedures.

The initial material used for the first DOE trials may only be a "model material" which only simulates the behavior of the desired candidate materials, but is not intended to be used in the projected application. This strategy would be employed if the desired candidate material is still a developmental material and has not yet become available in the desired form (e.g. pre-preg of Ultem 5001/IM-7 for the test program of this thesis). When the desired candidate material becomes available, the modified process science model should be used to predict the process window for this new material and a second round DOE test should then commence using the computer model predicted optimum for the new material as the center point for a full factorial experiment. With this strategy of alternating experimentation backed up by process modeling, a new material, in a new process, can be brought to a state of maturity much faster, than with traditional development techniques. The traditional techniques include successive DOE experimentation, but the process development screening then optimization must start over from scratch each time a material is changed.

After the optimizing DOE trials with the prime candidate material is complete, enough is then known about the process that preliminary factory layout simulation and cost modeling studies can commence. At this time, the team should bring in individuals with skills in industrial engineering and accounting to assist with these tasks. The cost model must be parametric in the sense that it takes into consideration the learning effects in production; complexity, size and shape effects on cost; and the initial materials cost. These models will be every bit as difficult to develop and to generate data for as the earlier
process science models. Cost data from the manufacturing trials and scaleup experiments, will be fed into the evolving cost models, so that accurate predictions of initial manufacturing costs of the developed process can be made. The lack of valid cost models was found to be a risk element that slows a manufacturing technology from being accepted in a design cost-performance trade study. This was found to be a major impediment to the acceptance of new process technology during several interviews of manufacturing representatives on design-build teams. Without a valid cost model, the fully developed and optimized technology never gets through the front door.

Scale-Up and Sub or Full Scale Demonstration Articles

As a process matures, it will be scaled up from a laboratory process to pilot or full scale processing equipment. While the scale-up effort is proceeding, it can be focused to provide facilities which are capable of producing sub-scale and full-scale demonstration articles and later (hopefully) commercial manufacturing. The parallel design effort on the team produces design for demonstration articles provides input of the size, part geometry's and features likely to be included in the components etc., so that these can be included in the manufacturing equipment. After the scaled-up equipment is complete, a final designed experiment will be run with the optimum parameters from previous DOE's (run on smaller sized manufacturing equipment) as the center point of the new test matrix to adjust the process parameters for the larger sized equipment.

At the conclusion of this effort, the certified process will be used to make realistic components from which the materials allowables specimens will be taken. The materials and manufacturing members of the team will complete the effort by writing a joint preliminary materials/manufacturing process specification for the certified process. The allowables test components and coupons will be fabricated to this specification. After the
experimental specification is written, it should be continually updated during the subsequent testing and development activities of the PDT, before the process/material is finally implemented into production. When materials/process specifications are held too rigidly, they calcify the process and prevent continuous improvement of the material and process. A final materials and process specification should be completed only before the process/material combination goes into production.

Risk Reduction

One of the major reasons for performing process development in teams de coupled from a specific product is to perform much of the mechanical allowables testing up front, so that selection of new process, materials and/or design concepts do not entail a large risk in their selection by subsequent product development teams. The completion of the allowables program and the creation of a process and materials specification removes two of the major roadblocks to the use of the new process/materials, as documented in Chapter 4. With the completion of the statistical allowable materials and component design tests, the design of the full scale demonstration article can be completed. The demonstration article will be fabricated with the optimized process/material combination and will utilize the best candidate design concepts for the material/process combination. The successful fabrication and test of the demonstration articles removes two other risk elements in the implementation of the process into the next generation aircraft designs. The demonstration article test program can be expanded to include flight demonstration articles, to obtain operational data on the new designs/materials/structures involved in the demonstration tests.

For very high risk projects, the natural extension of flight demonstration articles is the fabrication of a full scale prototype aircraft, utilizing the design and manufacturing concepts developed by the PDT and PD. Prototype flight test removes much of the
uncertainty from high risk designs before production aircraft are committed to. This approach of producing a prototype aircraft with the use of high risk technologies was recently demonstrated most successfully with both of the competing ATF flight and avionics demonstrators, before the commitment to the production of the F-22. After the prototype aircraft and flight test program is complete, the risk of the new technologies on a new aircraft has been reduced to a level that it becomes a rational decision to proceed with the production airplane. This approach should be used again with the first subsonic airplane with a composite wing and any future supersonic commercial airplane programs that may be committed to.

Technology Transfer

At the point where a manufacturing technology is judged to be mature, the PDT is disbanded in a controlled fashion to insure that the technology generated is transferred into the operations of the company. This is accomplished by accepting the model that technology is best transferred through the transfer of individuals and not only by the publishing of reports. The important strength of a team-based structure in transferring technology is parts of the whole technology will reside within each individual on a holographic team (51) as each member is cognizant of the development efforts of all the members of the team. Therefore the engineer who transfers into a design-build team to develop a next generation aircraft carries not only the structural concept and analysis procedures, but also the design limitations and optimum conditions imposed by the process. Similarly, the manufacturing process development engineer may transfer to perform the integration tasks of another PDT program or transfer to the factory to manage the production area of the newly implemented process. With the development experience on the PDT, the manufacturing engineer will understand the requirements that the design engineers are likely to make on the process in the future. This strength is also important in
case some of the team members leave the firm, because key pieces of the technology are not lost to the firm.

Their previous experience together on the PDT will also create excellent channels of communication between manufacturing and engineering professionals for the future when they have transferred into more traditional functional jobs. The creation of lines of communication is another key requirement to the establishment of a World Class manufacturing company by integrating manufacturing personnel with other functions. The PDT members (both engineering and manufacturing) that transfer to a aircraft DBT will carry the entire technology with them and make it easier to design the product with the new technology. The major concern in this technology transfer is that the individuals understand that with their transfer to DBT’s, the focus has shifted from the development of a process with a generic product goal, to the design and manufacture of a specific product.

Conclusion

This chapter outlined the key strategies and methodologies for the interdisciplinary development of advanced manufacturing processes. The goal of these strategies is to accelerate learning on new process technologies throughout the organization and to lower the risk of this technology so that it can be accepted on a future new aircraft. The narrative shows how the development effort will transition as it matures from a laboratory demonstration to full scale demonstration article or flight prototype. Because of this transition, new skills and disciplines will be required throughout the development to solve the critical tasks at each stage of development. The initial development strategies presented in this chapter will be followed in Chapters 9 through 12 on the early development of the In-Situ Roll Consolidation Process. The specific strategies and methods that were proposed in this chapter are:
* Initial process experimentation to demonstrate basic feasibility and requirements of process

* Creation of a process science model to define process "window" of likely process optimal conditions

* Designed experiment testing to create optimal set of process conditions

* Use of process science model and "model" materials to develop materials then feed advanced "candidate" materials into process.

* Creation of a parametric cost model to predict cost of components fabricated with new technology for first applications without an existing manufacturing cost database.

* Development of preliminary and possibly full allowable properties to allow first applications of new process.

* Demonstration component tests and possibly flight tests to establish production and actual design feasibility.

* Take advantage of "holographic" team structure and culture to transfer the technology fully to the design and production operations.
Chapter 8

Demonstration of Advanced Process Development
With In Situ Composite Consolidation

To demonstrate the utility of the formation of the Process Development Team and rapid process development concepts developed in the previous chapters, an "ad-hoc" process development program was put in place to look at a promising, new, composite manufacturing process. With its capability to laydown and consolidate thermoplastic composites in one continuous process, In-situ Roll Consolidation fits the earlier definition of a strategic manufacturing process with the potential to revolutionize the cost and factory performance associated with the manufacture of composite aircraft structures. This process utilizes a heat source and roller on a gantry lay-up machine to heat, laydown and consolidate thermoplastic resin composite materials in one operation, eliminating the need for the bagging and autoclave operations in conventional composite manufacture thereby revolutionizing the production process. Figure 8.1 shows a photograph of the In-situ Consolidation laboratory prototype machine used to manufacture the panels of this thesis. In addition to the cost benefits of the elimination of two process steps, this process also shows promise in its size scaleability which when coupled to the increased temperature capability of the materials used within the process, may enable completely new designs of aircraft that would not presently be feasible. This is the type of high leverage development program that a Charter Part Council would put in place to create a manufacturing process development strategy with next generation, enabling processes.

Because multidisciplinary process development teams do not presently exist within the Boeing Company, the environment of a Process Development Team was simulated by having the work performed within the MR&D organization with individuals whose
backgrounds included the necessary skills that are required for such a team. These individuals possessed skills in the following areas;

1.) structures technology;
2.) composite and polymeric processing;
3.) materials processing (metallurgical and ceramic technologies);
4.) analytical modeling of materials and manufacturing processes.
5.) materials science and testing.

This group, although functionally reporting to one organization, has the proper mix of skills to be classified as a Process Development Team (PDT). This group will be referred to as an ad-hoc PDT, to demonstrate the effectiveness of the process development strategy and new type of organizational structure proposed in this thesis. It should be remembered that this group would not fit the formal description of a PDT, with official representatives from each of the functional skill areas.

**In-Situ Advanced Tow Placement Consolidation Process**

The In-situ, advanced tow placement process is an emerging lay up and consolidation process which is both an incremental advance in the technology to lay-up composite materials as well as a revolutionary advance, in terms of the consolidation process of these materials. When this process is used with conventional thermoset prepreg tape materials, the advanced tow placement process functions by laying up several narrow width, (1/8" to 1/4") composite tapes simultaneously, rather than laying just one, wide (3", 6" and 12") tape as the current CTLM (Composite Tape Lamination Machine) process does. This allows the ATP process to steer these narrow tapes across the natural path of complex contoured tools, without the tapes buckling on the compression side of the arc. The buckling of the wider tapes used in a CTLM limits the amount of contour that can be designed or manufactured with this process. Advanced Tow Placement
accommodates the curvature of the part by allowing the intertape gap width between the tapes to vary as the head traverses across the curved tool. The use of the ATP head in place of a CTLM on the existing gantry layup machines using conventional thermoset resin composite prepreg is an incremental advance in the state of the art, because it still requires an autoclave processing step to consolidate out the intertape gaps and bond the lamina together, forming a composite laminate.

Even on a flat panel, intertape gaps are required to prevent the lapping of the tapes due to tape width variance or the slight variability of the tape head as it passes over the tool. On curved panels, the gaps in ATP processed panels must be even larger, for it is this property of variable intertape gaps, coupled with the use of thin tapes (1/4" to 1") which allows this process to lay-up panels over tight bend radii without buckling of the tape.

The In-situ ATP consolidation process differs from the thermoset ATP process (just described) through the inclusion of a pressure transmitting stainless steel roller and a inert gas torch to heat, laydown and consolidate the composite tape in one combined process. A close-up photograph showing the consolidation roller, inert gas heat torch, composite tape and composite laminate is shown on Figure 8.1. During the time that the tape being laminated spends under the roller it must bond to the underlying laminate and flow under the pressure exerted by the roller to fill the gaps between adjacent tapes. After the lamination head has passed over the material, the goal is to obtain a laminate which is completely bonded with no residual gaps or voids. When this goal is achieved, no further autoclave processing is required.
As the gap width increases in the curved regions of a panel, the temperature of consolidation must also increase (or the head velocity must drastically decrease) to close these larger gaps in the consolidation process. A gap closure process model is required in the process controller to vary the heat flux in the fusion zone as a function of the bend radii and intergap spacing to successfully consolidate non-flat panels. Wider width consolidation heads (wider consolidation rollers and larger force actuators) which are designed to function with wider tapes, can be utilized for parts whose curvature is fairly gentle. These heads would be used to maximize the material laydown rate, for optimum process economics.

Figure 8.1 In-Situ Composite Consolidation Head and Lay-up Tool
Advantages of In-Situ Consolidation Process Over Current State of the Art Processes

This process differs from conventional composite lay-up processes by being optimized for thermoplastic\textsuperscript{1} rather than thermosetting resins. The consolidation and lay-up in one step and process has profound implications for the factory producing composite laminates. In-Situ Roll Consolidation would eliminate both the bagging and autoclave processes currently used. The bagging operation, although not a cost driver in the cost breakdown of the present composite processes, does introduce significant variance to the overall process in the form of broken or leaking bags. This unhappy occurrence contributes to schedule upsets, off-line repair or loss of yield. A broken or leaking bag with a thermoset composite part usually results in a scrapped part.

The autoclave consolidation and cure process is the largest and most expensive piece of capital equipment in the total composite manufacturing process. This process is commonly the bottleneck limiting throughput of the manufacturing facility (7). The size of the autoclave vessel also places size constraints on the design of the composite components, because all designed components and their lay-up tooling, must be capable of fitting within it. The result of this constraint requires the building up of composite structures from smaller components which is not optimal from a weight or structural efficiency standpoint, and increases the part count and the use of fasteners. The large, 90 ft by 25 ft diameter autoclaves used on the B-2 and 777 program cost roughly $50 million to put on stream. The cost of a new autoclave vessel will increase as a function of the radius squared\textsuperscript{2} and linearly with the overall length of the vessel. Larger autoclaves to

\textsuperscript{1} Thermoplastic polymeric resins are viscoelastic solids which melt and flow at elevated temperatures when heated above their melting point. True thermoplastic resin systems can be heated to temperatures above their melting point an indefinite number of times without loss of their property to flow under applied stress. In contrast, thermosetting polymeric resins cross-link and cure when exposed to elevated temperature. After curing has taken place in these resins, viscous flow at elevated temperatures is no longer possible.

\textsuperscript{2} The thickness of the steel pressure vessel must increase as the square of the radius to maintain a constant hoop tension stress in the autoclave pressure vessel. The time to weld and assemble the vessel should scale with the amount of material used. Additionally, the pumps required to pressurize the vessel also scale with the square of the vessel. Only the furnace size and cost would scale linearly with the radius.
process whole composite wing sections in the future would cost considerably more, especially if the diameter is increased to accommodate the wing root. For example, a 120' X 40' autoclave is estimated to cost ~$170M, by scaling the present capital cost for these new dimensions. Processes that eliminate these huge capital expenses would be a major improvement if additional composite manufacturing capacity is required or larger single piece, component size capability is needed.

The use of thermosetting resins in an autoclave consolidation and cure cycle, also contributes a significant variance to the resulting materials properties in components of different thicknesses. This occurs during the autoclave cure cycle, because the thermosetting resin gives off heat (exotherms), causing localized heating and the creation of localized thermal stresses in addition to the thermal stresses set up by the thermal differential that occurs during the heating of a part to the cure temperature. If the autoclave cure cycle thermal ramp rate is not developed properly, a phenomenon of cure cycle "running away"\(^3\) will occur in localized thicker sections of the part. The result of this phenomenon is thermal degradation of the resin, and/or part warpage. Process trials with full sized composite parts under conditions of different thermal ramp rates, must be run to understand this effect and to control it, which add to the development time and expense of introducing composite parts into manufacturing.

Elimination of the autoclave in the total process system, will cut the capital requirements for additional capacity, remove the size limitation for the projected large size HSCT or NLA components, decrease the variability introduced by the process and potentially cut the development time to introduce new designs into manufacturing.

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\(^3\) The term "running away" is used to describe what happens if a rapid heat up rate is used with thick section laminates. This phenomenon occurs when the resin begins to cure and liberate its latent heat which can not be conducted away fast enough in the thick sections. The rapid temperature increase from the liberation of heat increases the kinetics of the reaction and causes additional liberation of heat. This results in a situation where the the temperature gets out of control and a ruined part is the result. Because of this phenomenon curing autoclave cycles must be run slowly with thick section parts.
The projected In-Situ ATP processing head will fit onto the existing gantry systems of CTLM lay-up machines with a few modifications. From this standpoint, it is an incremental innovation, in that it fits within the existing manufacturing infrastructure. It has been shown that innovations that fit within existing industry infrastructures are more readily adopted (76). It is projected that this new process could be implemented with the expenditure of \( \sim \$1 \text{Million} \) of additional capital\(^4\) per gantry system to modify the existing capacity. Additional capacity would cost roughly the same as a new CTLM. The major advantage when adding capacity is additional autoclave capacity is not required. The only potential drawback to the In-Situ Consolidation from a cost standpoint is the additional expense in the manufacture of hot tooling for part manufacture. Hot tooling may be required to decrease the significant thermal stresses involved with this process to prevent panel warpage. The addition of calrod electric heaters into the INVAR tooling is needed to create the hot tooling. This would be required if the designed experiment on this process in Chapters 10 and 11 show that a significant advantage is gained through use of elevated temperature tooling.

In-situ ATP becomes a revolutionary processing change in its ability to change the factory organization from a clustered flow process to a unitary workstation process (66). Through the elimination of all upstream or downstream processes in the manufacture of a composite laminate with the implementation of the In-Situ ATP process, this process paces the throughput through the total factory. This process is a natural candidate for JIT production, with a minimum amount of Work in Progress Inventory, in the factory. With this factory production policy, shipsets of composite components would be "pulled" by the assembly factory,(66) as they are needed to fabricate the aircraft. A small safety stock of

\(^4\) This cost is estimated from a size scaleup of the $400k cost of the laboratory In-Situ Consolidation units. A full scale unit would include multiple heads and more sophisticated feedback control system on consolidation temperature than current laboratory units.
one or two shipsets (depending on the small variance of this process) would account for
the total inventory. Finally, the composite manufacturing factory floorspace is much
smaller than the present facilities through the elimination of the bagging, autoclave batch
queuing and the autoclave processing steps. The smaller composite manufacturing facility,
without the huge autoclave, could be located next to the start of the wing assembly
process to better tie the two processes, allowing the wing assembly to "pull" parts from
the In-situ Consolidation workstation.

As the substitution of composite materials on aircraft primary structures proceeds,
(Figure 2.2) substantial increases in the capacity to produce structures from these
materials will be required. The preceding discussion on the process economics of this
process makes this a cost effective route to create the needed additional capacity and also
to convert some of the current capacity. The major question remaining to be answered is
whether the throughput of the unitary flow In-situ machines is capable of matching that of
the current composite fabrication system. (CTLM, Bag, Autoclave, NDI). To answer this
question requires knowledge of the maximum head velocity that the process can be run at
to yield acceptable mechanical properties. The Designed experiments test program
described on this process described in Chapter 10 and whose results are presented in
Chapter 11 was undertaken to provide this data.

Advantages of the Use of Thermoplastic Resin Matrix Composites

The advantages of the use of the In-Situ Consolidation process are not confined to
those of the process alone, because the use of thermoplastic resins as the composite matrix
provides additional value to the combined material/process when compared to traditional
resin matrix composites.

The first attribute of thermoplastic resins which make them useful as composite
matrices is their inherent ductility as compared to thermosetting resins, such as BMI's or
straight epoxies. Resin matrices with ductility translate into composite materials with an ability to resist impact damage and a potential to improve compression strength after such an impact. A literature review of these materials, (7) states that thermoplastic resin composites have a smaller and more localized zone of cracking and delaminations after impact than current thermosetting materials. To increase compression after impact strength of state of the art thermosetting resins, the epoxy resins have been blended with thermoplastic additions into the matrix. The increase in the toughness of these blended resin composite matrices has raised their compression after impact strength and has been responsible for the decrease of the structural weight in conservative, commercial aircraft designs. From interviews with Boeing structural engineers, this increase in resin toughness and increased compression after impact strength, has been a major factor in the risk reduction that was required for the use of composite materials in commercial aircraft primary structure. The only commercial aircraft, primary composite structure uses such a matrix.

The inherent resin toughness\(^5\) of thermoplastic resin composites would allow them to be candidates in this application also without additions. The use of In-Situ consolidated thermoplastic composite materials will have larger through penetration translaminar damage tolerance than conventional thermosetting materials (36). The damage tolerance exhibited by In-situ consolidated thermoplastic materials in large notch (cracks > 1") should be similar to that of 2024 Aluminum in thin sections (plane stress). A hypothesized mechanism for the good damage tolerance exhibited in some laminate configurations is due to the ductile thermoplastic resin providing plastic relief in the notch tip zone, blunting the crack, and increasing the material's resistance to crack propagation (36). The resulting

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\(^5\) Toughness of resin material can be defined in two ways: The first definition is the energy under the stress-strain diagram to deform a material to fracture. The second definition is the energy required to obtain critical crack growth in a material, \(G_c\). Each of these definitions correlate together in a qualitative way. The improvement in resin toughness has been shown to increase the toughness in the transverse, out of plane direction and therefore improve the delamination resistance of the composite under impact. Because of the constraining effect of the graphite fibers which limit total in plane deformation of the composite laminate to less than 2% no increase in toughness of thermoplastic composites over thermosetting materials is expected or found in in plane directions (7, 43)
fracture surface reveals matrix yield and fiber pullout, more like a metal matrix composite, than a thermosetting resin matrix composite (36).

Thermoplastic composites also have the additional advantage of denting after an impact, so that ground inspectors are more likely to find a significant damage site, than with thermosets. When dents are detected, NDI inspection and potential repair can be undertaken. Thermosetting resin composites are less likely to dent after incidental impacts. These materials create internal microcracks upon impact with no external indication of damage. The combined properties of easier damage detection and greater compression-after-impact strength make thermoplastic composites low risk candidates for commercial aircraft primary structure.

Thermoplastic resins also can be reheated to above their glass transition temperature several times without degradation to the polymer resin. This robustness allows the possibility of field repair of delamination or impact damage using a heat gun and roller. The ability to reheat the composite panel also allows the possibility of localized or general reprocessing if quality defects in consolidation are found during subsequent or on-line6 NDI inspection. This attribute prevents the possibility of having to scrap a complete panel. Because thermoplastic materials do not cure during their processing, they do not require cold storage. They also do not have a "freshness date" which they must be used by. With thermoset resin composites, exposure times beyond the expiration date requires the entire prepreg batch must be scrapped. The elimination of the freezers is another capital cost reduction for additional capacity. The removal of the material's property variance caused by its age is another important consideration in the adoption of In-Situ ATP technology with thermoplastic composite materials.

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6 On line NDI inspection with feedback is a possibility with In-Situ Consolidation
The repairability advantages of thermoplastic composites also run throughout the value chain, and will make the introduction of use of composites in primary structure more attractive from the airline's maintenance perspective. The elimination of the freshness date allows the operating airline to buy one batch of thermoplastic composite tape to hold for potential repair purposes, instead of having to periodically repurchase and stock new batches of thermoset tape as their freshness dates expire.

However the present cost to produce thermoplastic matrix composites is at a significant disadvantage to thermoset matrix materials. A cost modeling study by Gutowski and Wang (79) has shown that using conventional lay-up, bagging and autoclave processing, of a flat, 24 ply, composite part, produced in a total quantity of 2000, is projected to cost ~$2400/part, while the same part fabricated from graphite/epoxy prepreg costs $1650/part. The majority of the cost difference ($750/lb) is due to the increased manufacturing cost of thermoplastic materials ($500/lb), rather than the increased cost of the materials ($250/lb). Therefore a new process which eliminates the bagging and autoclave operations and their associated costs is required to make this material system cost competitive. Additional cost savings could be realized through the development of new thermoplastic resins whose cost is significantly less than the $70 / lb of APC-2 (PEEK).

Simultaneous Development of Materials With The New Manufacturing Processes

The most common thermoplastic resin matrix material is based upon the PEEK (poly-ether-ether-ketone) chemistry (APC-2 produced by ICI Fiberite) which provides slightly better resistance to temperature than epoxy based thermoset resins (the most common thermoset resin matrix materials) at roughly 200F. Two other thermoplastic resins, HTA (ICI Fiberite) and Ultem 5001 (GE Plastics), provide candidate materials systems with extended use temperatures above 300F, for use on supersonic aircraft.
Thermoplastic materials have the toughness, strength, ductility, chemical resistance and thermal resistance to meet the requirements of existing and projected aircraft. From the foregoing, it is apparent that a new manufacturing process should be developed in close co-ordination with the composite material to be used within the process. A key goal of the "ad-hoc" PDT was to maintain this simultaneous materials and process development internally through its members.

Previous attempts to utilize thermoplastic composites at the Boeing Company involved trying to modify the materials properties to fit into the existing CTLM/ autoclave process system in an incremental fashion. This approach was used rather than simultaneously developing the material and the manufacturing process together to create a process which optimally fits this material system. Thermoplastic composites have three major drawbacks from a processing standpoint to the use of the conventional composite manufacturing process. These are;

1.) the thermoplastic prepreg tape is stiff or "boardy" and will not freely drape over the lay-up tool;

2.) The tape lacks "tack" and will not stick to the laminate it is being layed on;

3.) The consolidation pressure and temperature in the autoclave are much greater than those used for thermosetting resins, requiring temperatures of 750 F and pressures of 200 psi as compared to 350F and 100 psi for epoxies.

To overcome the lack of tack and boardiness problems, this initial program developed a "wet" thermoplastic prepreg, where the tape consisted of a resin matrix in a solution of an organic solvent. During consolidation in the autoclave, the resin was baked out to leave the thermoplastic resin "dry". Because of the operational requirement that thermoplastic resin matrices be capable to resist common organic solvents found around aircraft (such as
Skydrol, JP-4 and Acetone), the only solvent that is capable to create the "wet" prepreg is a very powerful, noxious, chemical which caused a great deal of concern about personnel exposure to it. Because of the use of this "wet" prepreg, the autoclave process cycle must be designed to be slow enough to pump off all the solvent in the resin to prevent gas bubbles in the composite structure from occurring. Incomplete "debulking" will result in deleterious bubbles in the thicker sections of the laminate. The autoclave required for this incremental approach is significantly more expensive than one for themoset processing, because of the higher temperature furnacing requirement and the higher maximum pressure requirements.

The difficulties encountered with their incremental attempt to make a new material fit an existing process are symptomatic of product schedule driven approach to this process development project. Process Development Teams should avoid by this approach by creating new processes to fit the new materials, not trying to force fit new materials into existing processes.

**PDT Development Efforts With In-Situ Consolidation Process**

To hasten the development efforts of this process, the "ad-hoc" PDT utilized the generic strategy for process development outlined in Chapter 7. The specific tasks undertaken during the process development of in-situ ATP consolidation are described below. Each of these tasks will be detailed in the final chapters.

1.) Creation of Thermal-Mechanical Process Simulation Model

2.) Prediction of Process Limitations and Thermal Boundaries With Processing Model

3.) Use of Process Model to Determine Candidate Regions of Processing Space to Design Manufacturing Experiments
4.) Use of Processing Simulation Model To Understand the Effects of Processing Parameter Variability on the Consolidation Process

5.) Designed Experiment Test Panel Fabrication, and NDI Inspection

6.) Concurrent Materials and Manufacturing Process Development

7. Use of (+/-45) Mechanical Tests to Understand the Effects of Designed Experiment Processing Parameters and the Determination of Optimal Processing Conditions.
Chapter 9
Process Science Model of the In-Situ Composite Consolidation Process

Introduction

The In-situ, Advanced Tow Placement Composite Consolidation Process is a complex thermo-mechanical process using a heat source input to melt the polymeric resin of a pre-pregged composite tape, then through the contact pressure of a cylindrical roller consolidates this tape to the underlying composite laminate. During this melting process, the resin must attain a desired temperature so that the thermoplastic resin has the desired viscosity to flow laterally under the roller pressure to close the gaps between the adjacent tapes. When the heat flux incident onto the tape is set at the optimum level, the temperature in the fusion zone yields the proper resin viscosity so that the tape will just close the gap spacing.

The difficulty in using this process is the large number of potential controllable process variables which have a definite effect on the quality of the resulting laminate. While studying the geometry and heat transfer physics of the process, during the mathematical formulation of the process model, it was determined that fifteen process variables can affect the consolidation and gap width, which in turn control the resulting mechanical properties of the laminate. These variables are listed on Table 9.1
Table 9.1 Major and Minor Process Variables of In-Situ Consolidation Process

**Major Process Variables**
1. Head Velocity
2. Radius of Roller
3. Load on Roller
4. Thickness of Laminate
5. Gas Temperature
6. Mass Flow Rate of Gas
7. Width of Gas Impingement on Surface
8. Gap Width
9. Width Variation of Laminated Tapes
10. Distance Between Roller and Gas Torch Impingement
11. Position of Heat Impingement on Tape Surface (Top or Bottom)
12. Tool Temperature
13. Thermal Conductivity of Material

**Minor Process Variables**
14. Width of Tape
15. Position of Consolidation Head on Panel (left, right, center)

This large number of process variables makes the use of a pure Design of Experiments methodology very difficult, expensive, and time consuming to perform even with a two level, quarter factorial design. With these DOE screening experiments, the experimenters are never sure they have chosen the proper range of each of the unknown factors. The results of the first experiment yields only the identification of primary process variables and a direction of where to look in process space for more optimal processing conditions. The primary theme of this thesis is to establish a manufacturing process development strategy through substantial decreases in the time it takes to develop manufacturing processes and to implement them into factory use. The use of DOE experimentation in the development of new manufacturing processes is a slow process which eventually leads to an optimal set of process conditions after a slow, costly and time consuming process. DOE testing finds a great deal of use with nearly mature processes,
already on the factory floor where major processing variables are already fairly well
known, but does not achieve the goal of rapid process development.

Another method of investigation of new manufacturing processes is to shift from
initial experimentation to analysis, using the emerging tools of Process Science. To
demonstrate their utility in the development of manufacturing processes which are in an
embryonic state, this route was chosen for In-situ Composite Consolidation process.

To investigate the underlying factors determining the quality of the laminate panels
from the primary processing conditions, six separate analytical models were taken from
the literature, rederived for the conditions of this process, then coded into ATProcess, a
FORTRAN computer code developed in this project. This code was then used to
investigate the primary processing parameters in a designed experiment, as will be
described in the next chapter. This computer program accomplishes its task by first
determining the required temperature of the resin in the fusion zone to close the intertape
gaps. The heat flux applied to the panel is then adjusted to obtain this temperature under
the consolidation roller where gap closure occurs. Finally, the model outputs the thermal
profile of the tape layer being laminated, the gas temperature and mass flux required to
attain the desired heat flux and the thermal stress that results from the large thermal
excursion that occurs in this process. Each of these calculations are performed in the six
separate sub models that together make up ATProcess. A logic flow chart of ATProcess
is shown on Figure 9.0, showing the major input parameters, the major calculations
performed and the output from the model. The following sections of this chapter will
describe the major equations, assumptions and numerical method solutions for each of the
sub models that are contained in ATProcess.
Mathematical Descriptions of ATProcess Model Subsections

Because each of the model subsections were adaptations of those which already exist in the literature, only the key equations, assumptions, and modifications made to each model will be shown, without a complete derivation of the equations found in the
literature. After the mathematical description, a discussion of the numerical solution algorithms will be included, where applicable, for those models which include root determination or numerical integration routines.

1.) Eulerian Control Volume, Moving Boundary Value, Eigenvalue-Eigenvector, Analytical Heat Transfer Model

The central model which makes up the core of ATProcess, is an analytical thermal analysis for the melting and consolidation of the thermoplastic resin in the prepreg composite tape during the In-Situ Consolidation process. The analysis used in ATProcess is nearly identical to that described by Ghasemi Nejhad et. al. (54), which formed the basis for this section of the total model. This analysis uses a separation of variables approach to solve the heat transfer equations analytically in a two-dimensional analysis in both the longitudinal and short transverse directions as shown on Figures 9.1 and 9.2. The width of the gas torch's impingement onto the panel is relatively wide in comparison to the tape width (impingement width> 3 tape width) being laminated, so there is little widthwise thermal variation in the process, justifying the use of two dimensional analysis for this process. In-situ composite consolidation is modeled as a moving heat source, heat transfer problem. The solution to this problem is accomplished by transforming from a fixed coordinate, Lagrangian, transient heat diffusion problem to a moving Eulerian Control Volume, which envelops the region under the influence of the heat source, as shown in Figure 9.2. This control volume moves along the laminate with the heat source, throughout the continuous lamination process. This mathematical transformation converts the problem from the difficult-to-solve moving boundary value problem to a steady-state heat transfer problem with moving coordinates. Although the model presented in the literature has the capability to compute the temperature from the input process variables at all x and y coordinates within the laminate, the y value was fixed within the ATProcess
calculation to be one ply layer down from the top surface. This was done to show the thermal profile at the interface of the tape with the laminate, where consolidation is taking place which is of greatest interest in this process. The through thickness temperature variation is not required to calculate the incident heat flux to achieve consolidation. This variation does play a much larger role in panel warpage and the macro residual stresses present after processing, as will be shown later in this chapter.

The original thermal model produced by Ghasemi Nejhad et.al. (54) was solved using SI units, while ATProcess was coded to solve the same equations with English units. This was done to eliminate any potential conversion errors in communication with process development engineers, who normally use English units.

The primary process variables which affect this heat transfer solution are;

1.) the heat flux;
2.) the width of the heat source (heat impingement zone) in the longitudinal direction;
3.) the surface convection heat transfer coefficients;
4.) the velocity of the heat source and roller;
5.) the position of the heat source/ roller relative to the laminate/tool edges;
6.) the temperature of the tool surface

Each of these process variables are shown schematically in a cross section of the consolidation process in Figure 9.1 and in Figure 9.2 on the moving Eulerian Control Volume near the heat input zone.
In this model and in reality, the length of the tape and panel is long relative to the width of the heat source, justifying the two-dimensional analysis used. To solve this transient heat diffusion problem, the transformation from a fixed set of coordinates to a moving Eulerian Control Volume influenced by a local heat source was derived by Ghasemi Nejhad (54), so that a steady state solution can be formulated. The size of the ECV was chosen in his solution to be large enough so that the boundary conditions can be satisfied. For example, the material entering the control volume has a uniform temperature distribution and its temperature is equal to that of the tool, $T_{tool}$. The Eulerian Control Volume (ECV) and the boundary conditions of this moving control volume are shown on Figure 9.2.
To simplify the analysis, the numerical processing was performed in terms of an excess temperature;

\[ T = T_{\text{TOTAL}} - T_{\text{TOOL}} \]

where the excess temperature is the \( \Delta T \) in excess of the temperature of the tool. After the eigenvalue-eigenvector summation of the excess temperature is complete, ATProcess then adds back the tooling temperature to output actual temperatures. The governing general heat transfer partial differential equation for the two dimensional anisotropic laminate, in its untransformed form is as follows;

\[ K_L \frac{\partial^2 T}{\partial x^2} + K_T \frac{\partial^2 T}{\partial y^2} + \rho U = \rho C_p V_x \frac{\partial T}{\partial x} \]

where \( K_L \) and \( K_T \) are the longitudinal and transverse thermal conductivities, respectively, of the composite laminate, \( U \) is the latent heat of fusion absorbed by the thermoplastic resin during the melting process, \( C_p \) is the heat capacity of the composite, \( \rho \) is the
composite material's density and $V_x$ is the velocity of the heat source (inert gas jet). The following transformations were applied to the general differential equations to transform it into an isotropic domain;

9.3a $\bar{x} = \left( \frac{K}{K_L} \right)^{0.5} \cdot x$

9.3b $\bar{y} = \left( \frac{K}{K_T} \right)^{0.5} \cdot y$

where $K$ is the reference thermal conductivity (54) defined to be:

9.3c $K = (K_L \cdot K_T)^{0.5}$

Using these variable transformations, the governing differential equation becomes;

9.4 $K \frac{\partial^2 T}{\partial \bar{x}^2} + K \frac{\partial^2 T}{\partial \bar{y}^2} + \rho U = \rho C_p \left( \frac{K}{K_L} \right)^{0.5} V_x \frac{\partial T}{\partial \bar{y}}$

where the $x$ and $y$ directions have been transformed by the directional thermal conductivity's. This equation can be rearranged as a homogeneous partial differential equation with a final heterogeneous, heat generation term:

9.5a $\frac{\partial^2 T}{\partial \bar{x}^2} + \frac{\partial^2 T}{\partial \bar{y}^2} - \gamma \frac{\partial T}{\partial \bar{y}} + \frac{\rho}{(K_L \cdot K_T)^{0.5}} U = 0$

The heterogeneous term in this expression results from the heat generation or absorption in the resin, $U$, during the melting process. The $\gamma$ constant is given by:

9.5b $\gamma = \frac{\rho C_p V_x}{K_L^{0.75} \cdot K_T^{0.25}}$

Therefore the solution to this governing differential equation can be separated into homogeneous and non-homogeneous components as follows;
9.6 \[ T(\bar{x}, \bar{y}) = \Theta(\bar{x}, \bar{y}) + \Phi(\bar{y}) \]

where the \( \Theta \) term is homogeneous solution as a function of both \( x \) and \( y \), and the \( \Phi \) term is the inhomogeneous solution, which in the Ghasemi Nejhad derivation (54) is a function of \( y \) only. Using the principle of superposition on the homogeneous solution, the problem can be split into \( x \) and \( y \) components and one non homogeneous boundary condition can be assigned to each component as shown below.

9.7 \[ \Theta(\bar{x}, \bar{y}) = \Theta_x(\bar{x}, \bar{y}) + \Theta_y(\bar{x}, \bar{y}) \]

The governing differential equation is now split into two equations, one for the \( x \) solution and the other for the \( y \) solution. The Differential Equation and Boundary Conditions for the \( x \) component solution, \( \Theta_x \), are as follows;

9.8 \[ \frac{\partial^2 \Theta_x}{\partial \bar{x}^2} + \frac{\partial^2 \Theta_x}{\partial \bar{y}^2} - \gamma \frac{\partial \Theta_x}{\partial \bar{x}} = 0 \]

subject to the following boundary conditions:

9.9a \[ \Theta_x(\bar{x}, \bar{y}) = 0 \quad @\bar{x} = 0 \]

which sets the Excess Temperature equal to zero (or the real temperature equal to the tool temperature) at the ECV boundary. The second boundary condition for this analysis is;

9.9b \[ \left. \frac{\partial \Theta_x}{\partial \bar{x}} \right|_{@\bar{x} = \bar{x}_r} = 0 \]

which declares that no heat transfer takes place through the second lateral boundary. (see Figure 9.2) The bottom and top surface boundary conditions are expressed as;

9.9c \[ K_T^{0.25} K_T^{0.75} \left. \frac{\partial \Theta_x}{\partial \bar{y}} \right|_{@\bar{y} = 0} = h_0 \Theta_x \quad @\bar{y} = 0 \]
9.9d \( K_T^{0.25}K_T^{0.75} \frac{\partial \Theta_x}{\partial \bar{y}} = q'' - h_2 \Theta_x \) \( \bar{y} = \bar{y}_t \)

where \( h_0 \) is the top surface convection coefficient, \( h_2 \) is the convection coefficient between the composite laminate and the tool surface and \( q'' \) is given by the following expression:

9.10 \( q'' = \frac{h_2 \rho U}{(K_LK_T)^{0.5}} \frac{y_t^2}{2} + \left( \frac{K_T}{K_L} \right)^{0.25} \cdot \rho \bar{U} \bar{y}_t + q_0 \)

The final two boundary conditions are thermal flux balances of the material conductance with the convection occurring on the top and bottom surfaces of the ECV, respectively.

A similar set of differential heat transfer and boundary condition equations exist for the thermal solution in the \( y \) direction, \( \Theta_y \) but will not be presented here because its solution does not give as great an insight into the In-situ Consolidation process, as does the \( \Theta_x \) solution presented here. The solution of the \( y \) direction system of equations is completely analogous to those presented here for the \( x \) direction. The \( y \) component solution, \( \Theta_y \), is coded into ATProcess, for analysis of panels with either thick laminates (\( y_t \) greater than 0.25") or for a low aspect ratio panels. (short panel length compared to its thickness). The source code of this program is given in Appendix II.

To complete the solution for \( \Theta_x \) requires a separation of variables approach where the overall thermal solution is broken into two component parts:

9.11 \( \Theta_x(\bar{x}, \bar{y}) = X(\bar{x}) \cdot Y(\bar{y}) \)

Substituting this expression into the \( x \) direction differential equation Eqn. 9.8, and rearranging yields the following differential equation:
9.12 \[ \frac{X''}{X} - \gamma \frac{X'}{X} = -\frac{Y''}{Y} = -\lambda^2 \]

The primes indicate derivatives of each solution function with respect to the coordinate that the solution is a function of, e.g. \(X'\) is the derivative of \(X\) with respect to \(\bar{x}\). The sign on the separation constant \(\lambda\), indicates that a Sturm-Liouville system of equations exists in the \(x\) direction for the thermal solution. The general solution to the Sturm-Liouville equation in the \(x\) direction is given by the following expression;

9.13 \[ \exp(-\gamma\bar{x})\ddot{X} - \gamma \exp(-\gamma\bar{x})\dot{X} + \lambda^2 \exp(-\gamma\bar{x})X = 0 \]

and the equation in the \(\bar{y}\) direction becomes:

9.14 \[ \ddot{Y} - \lambda^2 Y = 0 \]

The solution for the Sturm-Liouville, \(\Theta_x\) system can be shown to be a classic eigenvalue-eigenvector summation thermal solution (54);

9.15a

\[ \Theta_x(\bar{x}, \bar{y}) = \sum_{n=1}^{\infty} D_n \exp\left(\frac{\gamma}{2} \bar{x}\right) \sin \bar{x} \sqrt{\lambda_n^2 - \left(\frac{\gamma}{2}\right)^2} \times \left[ \sinh(\lambda_n \bar{y}) + \frac{K_L^{0.25} K_T^{0.75}}{h_0} \lambda_n \cosh(\lambda_n \bar{y}) \right] \]

where \(\lambda_n\) eigenvalues are roots of the following transcendental equation:

9.16a \[ \tan\left\{ \bar{x} \sqrt{\lambda_n^2 - \left(\frac{\gamma}{2}\right)^2} \right\} + \frac{\bar{x} \sqrt{\lambda_n^2 - \left(\frac{\gamma}{2}\right)^2}}{\bar{x} \left(\frac{\gamma}{2}\right)} = 0 \]

A similar eigenvalue-eigenvector solution exists for the solution in the \(\bar{y}\) direction, \(\Theta_y(\bar{x}, \bar{y})\) given by the following expressions.
9.15 b \[ \Theta_y(x, y) = \sum_{n=1}^{\infty} G_n \exp \left( \frac{y}{2} \right) \left[ \cos \left( \frac{\omega_n y}{\omega_n} \right) + \frac{H_0}{\omega_n} \sin \left( \frac{\omega_n y}{\omega_n} \right) \right] \]

\[ \times \left[ \cosh \frac{x}{\omega_n} + \left( \frac{y}{2} \right)^2 - C_x \sinh \frac{x}{\omega_n} \left( \omega_n^2 + \left( \frac{y}{2} \right)^2 \right) \right] \]

where the y direction eigenvalues, \( \omega_n \) are given by;

9.16 b \[ \tan \left( \omega_n \bar{y} \right) = \frac{\omega_n (H_0 + H_2)}{\omega_n^2 - H_0 H_2} = 0 \]

The eigenvalue dependent coefficients \( D_n \), in the x-direction eigenvector summation, Eqn. 9.15a, are determined for each of \( n \) eigenvalues through the following expressions derived by Ghasemi Nejhad (54);

9.17a \[ D_n = \frac{h_0 (q_0 \cdot S_{1n} + q_{kh} \cdot S_{2n})}{\lambda_n^2 \left( \frac{\bar{x}_r}{2} - \frac{\sin 2\bar{x}_r \Psi_n}{4\Psi_n} \right) \cdot S_{3n}} \]

where three \( S_{mn} \) coefficients that are used to calculate the overall eigenvalue-dependent coefficient, \( D_n \), are themselves dependent upon the eigenvalues. These coefficients are given by the following three expressions;
\[ S_{tn} = \Psi_n \left[ \exp \left(-\frac{\gamma}{2} \bar{x}_{bm}\right) \cos \bar{x}_{bm} \Psi_n - \exp \left(-\frac{\gamma}{2} \bar{x}_{bp}\right) \cos \bar{x}_{bp} \Psi_n \right] + \frac{\gamma}{2} \left[ \exp \left(-\frac{\gamma}{2} \bar{x}_{bm}\right) \sin \bar{x}_{bm} \Psi_n - \exp \left(-\frac{\gamma}{2} \bar{x}_{bp}\right) \sin \bar{x}_{bp} \Psi_n \right] \]

\[ S_{2n} = \Psi_n \left[ \exp \left(-\frac{\gamma}{2} \bar{x}_r\right) \cos \bar{x}_r \Psi_n \right] - \frac{\gamma}{2} \left[ \exp \left(-\frac{\gamma}{2} \bar{x}_r\right) \sin \bar{x}_r \Psi_n \right] \]

\[ S_{3n} = \left[ h_0 h_2 + K_{TL}^{.55} K_T^{1.5} \lambda_n^2 \right] \sinh (\lambda_n \bar{y}_t) + K_{TL}^{.25} K_T^{.75} \lambda_n (h_0 + h_2) \cosh (\lambda_n \bar{y}_t) \]

The constants in the above expressions are given by the final set of expressions;

\[ \Psi_n = \sqrt{\lambda_n^2 - \left(\frac{\gamma}{2}\right)^2} \]

\[ \bar{x}_r = \left(\frac{K_T}{K_L}\right)^{.25} (a + c) \]

\[ \bar{y}_t = \left(\frac{K_L}{K_T}\right)^{.25} y_2 \]

\[ \bar{x}_{bm} = \left(\frac{K_T}{K_L}\right)^{.25} (a - b) \]

\[ \bar{x}_{bp} = \left(\frac{K_T}{K_L}\right)^{.25} (a + b) \]

\[ q_{kh} = q'' - q_0 = \frac{h_2 \rho \bar{U} \bar{y}_t^2}{K_L K_T} \left(\frac{K_T}{K_L}\right)^{.25} \rho \bar{U} \bar{y}_t \]

where a, b, c, and y_2 are geometry constants of the In-Situ Consolidation process, shown in Figures 9.1 and 9.2, q_0 is the incident heat flux, h_2 is the tool surface convection coefficient in contact with the laminate and K_L and K_T are the longitudinal and transverse heat transfer coefficients of the laminate, respectively. All other parameters in these expressions have previously been described.

The major difficulty in solving the analytical heat transfer model just presented is to obtain the eigenvalue roots of the transcendental equation of Eqn. 9.16. Figure 9.3 is a plot of this equation using the heat transfer coefficients for APC-2/ IM-7 (given on Table 12.3),
showing the tangent like nature of this function. To select the real roots (eigenvalues) from the undefined sign changes, a complex numerical method approach was used to obtain accurate eigenvalues. To start the process for the first eigenvalue, the algorithm searches with a small step mesh for a sign change in the remainder of Eqn. 9.16 to find a candidate region which contains a root (eigenvalue). The value of $\lambda$ where the first sign change was found is then used as a seed value to perform a Newton-Raphson analysis to find a root whose error is set to be no greater than one part in $10^8$. Because Eqn. 9.16 is differentiable in the region where the eigenvalue roots are obtained, the actual derivative was used in the Newton-Raphson routine rather than a numerical derivative. Higher order eigenvalues (roots) are found using a predictor equation to begin the root search at $\lambda_{i0}$, for the next eigenvalue. The predictor equation, given by the following expression, was used to screen out the undefined regions and to save on computer calculation time.

$$9.18 \quad \lambda_{i0} = \lambda_{i-1} + 0.96(\lambda_{i-1} - \lambda_{i-2})$$

The predicted eigenvalue, $\lambda_{i0}$, is used as a starting point for the step search algorithm to begin a search for another sign change of Eqn. 9.16. This sign change becomes a candidate for the ith root of the equation. Once a sign change is observed, the Newton-Raphson algorithm is used to converge on the final eigenvalue. From observation of Figure 9.3, it can be observed that the distance between successive eigenvalues decreases as n increases. So that the sign change near the root candidate is always discriminated from the undefined region of the eigenvalue function, the 96% weighting was chosen to allow the algorithm to find the next period of this periodic function but not exceed the eigenvalue so the step search routine can find a candidate root. In the undefined region of the tangent eigenfunction, another sign change occurs from positive infinity to negative infinity. This sign change would give an erroneous eigenvalue unless it is screened out. This numerical methods strategy used in this analysis is summed up by the following statements.
(1.) A starting point predictor equation, Eqn. 9.18 is used to localize the root search outside of the region of undefined sign change into the next period of the eigenvalue function. This step is followed by;

(2.) A tight, mesh stepping routine is performed, which uses the equation's remainder sign change to screen for eigenvalue root candidates. This step is followed by;

(3.) A Newton-Raphson eigenvalue root convergence routine for the candidate roots to obtain precise eigenvalues from the seed eigenvalue candidates.

This procedure may be repeated up to 500 times in ATProcess to find all of the eigenvalue roots of Equation 9.16, but in practice only 150 eigenvalues are necessary to obtain a noise free thermal solution for a flat plate geometry. The roots are stored internally in ATProcess as an array to be used for computing the eigenvalue dependent constants in Eqn.9.17 a through d. The thermal solution is then obtained by the summation of the eigenfunctions of Eqn. 9.15 with all n of the eigenvalues. This summation is repeated for each of 100 values of the x variable (panel length from one edge) from one edge to the other, to create the entire thermal profile. The value of y for this analysis is fixed to be equal to the thickness of one ply thickness from the top surface, so the thermal solution is for the consolidation interface. At this interface, the hottest temperatures upon the laminate are experienced and is of the greatest interest in the analysis. The y and x dimensions in real space as shown in Figures 9.1 and 9.2, are transformed by Eqn. 9.6 to obtain a transformed coordinates system. The entire analysis in ATProcess is performed in transformed co-ordinate space and then the results are re-transformed into the real co-ordinate system for output.
Figure 9.3 Plot of the X Direction Eigenfunction and Eigenvalues

Equation Remainder

1st Eigenvalue

2nd Eigenvalue

3rd Eigenvalue

4th Eigenvalue

5th Eigenvalue

6th Eigenvalue

Steep Curve on Underside of Root Requires Small Search Step to Find Root With Sign Change Algorithm
2.) Surface Convection Coefficient Empirical Model

To calculate the thermal profile using the moving boundary value thermal analysis described in the previous section a surface convection coefficient is needed. Because natural (non forced) convection coefficients are dependent upon the $\Delta T$ between the environment and the panel, an empirical model was used to calculate this parameter. This top surface convection coefficient was calculated using the empirical correlation of the natural convection coefficients proposed by Eckert and Jackson (20) from correlation of experimental data. Their data yields one empirical expression for the convection coefficient when the air flow over the panel is laminar, and another when the air flow has transitioned to turbulent flow conditions. This transition is made in their correlation when the Grashof * Prandtl number (Gr*Pr), as defined in Equation 9.19, was equal to or greater than $10^9$ (20). The surface convection coefficients proposed by Eckert and Jackson (20), are more accurate expressions of the Lorenz (91) correlation of the Nusselt number. The primary correlation of these equations is the convective heat transfer coefficient of the surface increases with the length of the surface of the flat panel, $L$, and the difference in temperature, $\Delta T$, between the surface and the surrounding fluid (air). The first of the following expressions is the correlation for laminar flow, while the latter is for turbulent flow conditions;

$$9.19 \quad \text{Nu}_L = 0.555(Gr_L \cdot Pr_L)^{0.25} \quad \text{Gr} \cdot \text{Pr} \leq 10^9 \quad \text{Laminar Flow}$$

$$\text{Nu}_L = 0.0210(Gr_L \cdot Pr_L)^{0.40} \quad \text{Gr} \cdot \text{Pr} \geq 10^9 \quad \text{Turbulent Flow}$$
where \( \text{Nu} \) is the Nusselt Number, \( \text{Gr} \) is the Grashof Number and \( \text{Pr} \) is the Prandtl Number. Each of these "numbers" is a dimensionless number used in heat transfer correlations. The Nusselt Number is defined by the following expression:

\[
\text{Nu}_L = \frac{h_L L}{k_{\text{air}}}
\]

while the product of the Grashof and Prandtl numbers is given by the following expression:

\[
\text{Gr} \cdot \text{Pr} = \frac{\beta g C_p \rho^2 L^3 \Delta T}{k_{\text{air}} \mu}
\]

where \( h_L \) is the surface heat convection coefficient, \( g \) is the gravitational acceleration, \( \Delta T \) is the difference in temperature between the surface and surrounding air, \( L \) is the length of the panel, \( \rho \) is the density of air, \( k_{\text{air}} \) is the heat conductivity of air, \( \mu \) is the viscosity of air and \( \beta \) is the coefficient of thermal expansion of air. The final expressions are obtained by substituting Equations 9.20a and b into Eqn. 9.19 and rearranging to obtain the surface convection coefficient, \( h_L \). The resulting final expressions are:

\[
h_{2\text{lam}} = 0.555 \left[ \frac{\beta g C_p \rho^2 k_{\text{air}}^3 \Delta T}{\mu L} \right]^{0.25}
\]

\[
h_{2\text{turb}} = 0.0210 \left( \frac{\beta g C_p \rho^2 k_{\text{air}}^{1.5} L^{0.5} \Delta T}{\mu} \right)^{0.40}
\]

These final equations are coded into ATProcess. The lower surface convection coefficient for the large stainless steel tool was set to be a large number (1000 W/K m\(^2\)) at the suggestion of M.N. Ghasemi Nejhad, because the lower surface, in contact with the lay-up tool, has a near infinite thermal mass and rapid surface heat transfer, in comparison to the composite tape and laminate at the top surface. Each of these surface convection
coefficients are required to complete the analytical heat transfer calculations, described in the previous section.

The thermal properties of air at 80F were used in these formulas to perform the calculations. 80 F was chosen because this is approximately the mean temperature of the laboratory air where the panels were fabricated. Table 9.1 shows the thermal properties of air at this temperature.

3.) Near and Far-Field Hertzian Contact Stress Models

The stress distribution in the composite laminate as a result of its contact with the roller was modeled as an elastic body contact as a first approximation through use of Hertzian contact stress expressions. The stress field set up by the roller was broken up into two zones for this analysis. The near-field zone of the laminate, in direct contact with the roller was modeled using the flat plate-cylinder contact stress expression. The far-field contact stress zone expression calculates the stress in the panel at distances far away from the contact zone, with the force from the roller modeled as a point contact force on a flat panel.\(^1\)

The result of the far-field Hertzian stress calculation shows that the surface contact stress, (calculated one ply layer down, at the consolidation interface), ... concentrated at the contact zone. The far-field contact stresses outside the roller contact area are quite small (<1psi) in comparison to those within the contact zone (>100psi). From this calculation, it is therefore concluded that all potential consolidation and tape gap closure must occur under the roller where the large pressures (100 to 400 psi) are applied. Both

\(^1\) The contact zone of the roller would appear to be a point application of load when the size of the contact zone, ~0.16 inches, is compared to the total dimensions of the laminate, >20 inches. The size of the zone is given for the roller radius of 0.25" and a load application of 70 lbs. The Hertzian contact area varies according to the modulus of elasticity of the two contacting components, the roller radius and the force applied to the roller.
the near and far field contact stress expressions were derived for contact of bodies which possess isotropic materials properties. To correct this limitation for composite materials which possess directional orthotropic properties the moduli in the direction of contact were used in the analysis. The near field, Roller-Plate contact stress distribution was calculated using the low transverse elastic modulus, $E_{22} = E_{33}$ which would be present in the composite at the 800 F+ temperatures within the fusion zone, near the roller and inert gas torch.

**Near-Field Contact Stress Model**

The near-field contact stress is the pressure which exists between a cylinder (roller) in contact with a flat plate (laminate). The elastic deformation of both the plate and the contacting cylinder under an applied load creates an area of contact rather than a line of contact which would normally occur between a cylinder and flat plate that are not subjected to load. The analysis of the general problem of surface contact of two geometric bodies under load was first done by Hertz (89). Analyzing the contact of a flat plate with a cylinder, requires that the general solution of contact stress be modified by setting both the major and minor radii of curvature of the flat plate equal to infinity, and setting the minor radius of curvature of the cylinder equal to infinity. Figure 9.4 shows the geometry of a roller-flat plate contact, the contact area, and the elliptical contact stress distribution within the contact area. In this figure, the size of the roller in relation to the size of the plate is exaggerated to show the roller and the contact stress profile. In the actual process, the roller is quite small (radius = 1/4") when compared to the size of the plate (>10") so that the semi-infinite plate assumption of this Hertzian stress analysis is valid in the longitudinal direction. The assumption of a semi-infinite plate for the use of a Hertzian stress analysis begins to break down in the thickness direction where the composite laminate and the underlying tooling plate are of the order of the roller diameter. To determine the limitations imposed by the violation of this assumption, a Nike 2D Finite
Element Model analysis was run on this geometry (88). The results of this analysis showed that the contact stress distribution and peak stress of the first two plies differs considerably from that of a Hertzian analysis. However, after 3 to 4 plies have been laminated onto the tool, the results from a Hertzian semi-infinite plate analysis becomes a very good approximation to the stress distribution and peak stress observed in the finite element model.

![Figure 9.4 Schematic of Roller-Plate Hertzian Contact Stress Model](image)

After setting the radii of curvature to match the geometry of Figure 9.4, the general solution of contact stress derived by Hertz, is transformed to the following specific form for the maximum contact stress within the elliptical contact stress distribution of a roller-plate contact (72, 90);

\[
\sigma_{\text{max}} = 0.564 \sqrt{\frac{P}{aR\Lambda}}
\]

where \( P \) is the load upon the roller, \( R \) is the radius of the roller, and \( a \) is the length of the roller. \( \Lambda \) is a function of the elastic constants of the roller and laminate given by;
9.23 \[ \Lambda = \frac{1-v_L^2}{E_L} + \frac{1-v_R^2}{E_R} \]

where \( v_L, v_R, E_L, \) and \( E_R \) are the Poisson's ratios and Young's Moduli of the laminate and roller, respectively. The Hertzian contact stress equations are derived for two contacting isotropic bodies. To overcome this limitation with the use of orthotrophic materials the directional modulus of elasticity from the composite laminate were used. The modulus of elasticity used in calculating \( \Lambda \) was the out-of-plane elastic modulus, \( E_3 \) of the composite, whose value is predominantly dictated by that of the resin. At 800 to 900 F, this modulus was estimated to be a mere 1000 psi in the fusion zone of the In-Situ consolidation process. This value was estimated from a plot of the elastic modulus of the APC-2 resin with temperature out to 500 C (932 F). The Poisson's ratio used was the room temperature value of \( v_{13} \) for the composite laminate, 0.66. To check this assumption of using orthotrophic materials properties in a isotropically derived model, a Nike 2D finite element analysis of the contact stress was performed using the full orthotropic materials properties of the laminate in a composite shell element. As described earlier, the contact stress results of this analysis compares favorably to a Hertzian contact stress distribution after 4 to 5 plies have been consolidated to the laminate.

The half distance of the contact width of the roller with the flat panel is given by(72):

9.24 \[ b' = 1.13 \sqrt{\frac{PRA}{a}} \]

The elliptical distribution of the contact stress throughout the contact zone is given by:

9.25 \[ \sigma_y(x) = \sigma_{y}^{\text{max}} \sqrt{1 - \frac{x^2}{b'^2}} \]
Integrating the contact stress distribution throughout the contact zone and dividing by the contact distance, $2b'$, yields the average contact stress or pressure within the near-field contact zone:

$$
9.26 \quad \overline{\sigma}_{\text{avg}} = \frac{\pi \sigma_{y}^{\text{max}}}{4} = 0.443 \sqrt{\frac{P}{aRA}}
$$

As shown in this expression, the average stress in the distribution is 21% less than the peak hertzian contact stress. This average contact stress was used as the "consolidation pressure" term in the gap closure/goal consolidation submodel to be described in Section 5 of this Chapter.

**Far-Field Contact Stress Model**

The contact stress in the laminate in the regions outside the contact area is modeled by a contact stress formula which utilizes a concentrated normal load at the narrow point of contact of the roller with the composite plate as derived by Radimovski (59). The contact stress in the $y$ direction of a semi-infinite, isotropic material is given by;

$$
9.27 \quad \sigma_y(\theta) = \frac{2P}{\pi y} \cos^4 \theta
$$

where;

$$
9.28 \quad \theta = \sin^{-1}\left(\frac{x}{\sqrt{x^2 + y^2}}\right)
$$

Combining the previous two equations yields the far field contact stress formula which is coded into ATProcess.
\[ \sigma_y(x, y) = \frac{2P}{\pi y} \cos^4 \left( \sin^{-1} \left( \frac{x}{\sqrt{x^2 + y^2}} \right) \right) \]

The two limitations of the above expression are the violation of the semi-infinite assumption in the thickness direction and the use of a isotropically derived model for an orthotropic material once again. The results of the far-field stress calculations within ATPProcess showed that these stresses are smaller than 1 psi even very near to the contact zone in accordance with the Hertzian derivation of contact stress which states that no contact stress exists outside of the contact zone of the roller with the plate. Therefore this model confirmed that all of the consolidation that occurs in In-Situ Consolidation must occur in the contact zone of the roller with the laminate whose stress distribution is described by the near-field contact stress model in ATPProcess.

4.) Thermal Stress Calculation Model

The large thermal transient which occurs in the x-direction along the composite tape being consolidated in the ATP process sets up considerable thermal macrostresses due to the thermal gradients in this direction. These stresses result because the elastic modulus in the graphite fiber direction (x direction in Figure 9.1) remains at ~20 Msi even though the polymeric matrix is molten. The thermal distribution of the ATP process which sets up the thermal stresses is very similar to that set up by GTAW (Gas Tungsten Arc Welding) in creating a molten region constrained by a cooler, elastic region.

Constrained thermal stress elasticity solutions in several different geometric arrangements for welding, were solved by J. N. Goodier (29). These solutions included a flat plate butt weld with a thermal transient across the weld and a cold backing plate. The geometry and
physics of this welding process are nearly the same conceptually as those present in the In-situ Consolidation process.

The thermal stress analysis by Goodier is for the bending and shear stresses which occur in a simply supported flat plate as a result of a thermal excursion in the center of the plate due to a welding process. The thermal distribution along one axis of the plate which Goodier included in his paper is nearly identical to the thermal profiles analyzed for In-Situ Consolidation, having the form of a symmetrical, normal shaped distribution, as shown on Figure 10.2. The mechanical boundary conditions assumed by Goodier are those of a free standing plate whose edges are not constrained or clamped. These assumed conditions hold true for the In-Situ process, as well. Finally, Goodier’s derivation was for a isotropic material (a metal plate being welded). Our use of this equation will be for a material which is inherently orthotropic which makes its results approximate. To compensate for the isotropic assumption made in the derivation of this model, directional elastic constants were used in calculating thermal stresses with it. Because of the isotropic assumption in the derivation of this analysis, the results from the following equation will be only approximate, but as will be shown, its results are highly important to the fabrication of panels with this process.

The general longitudinal thermal stress in the panel due the thermal expansion in the heated center zone which impinges on the cooler, stiffer material surrounding it, yields the following expression for the maximum thermal stress;

\[ \sigma_x = \frac{1}{2} E_L \alpha_L \left[ T_1 + T_2 - 2T_0 + \frac{1 - v_{LT}}{3 + v_{LT}} (T_1 - T_2) \right] \]

where \( T_1 \) is the maximum temperature within the heated zone, \( T_2 \) is the temperature at the edge of the top face of the plate (which also is the minimum temperature of the front face), and \( T_0 \) is the temperature at the bottom surface of the plate. A representative
thermal profile of the panel during the In-Situ consolidation process is shown on Figure 10.2. In the In-situ consolidation process, the lay-up tool is such a good heat sink, that the heat transfer analysis yields the result that the edge temperature of the top face, $T_2$ is equal to the back face, bottom surface temperature, $T_0$ in all the analysis runs performed. (see Figure 10.2) Rearrangement of Eqn. 9.30 to reflect this additional constraint yields the final form of the thermal stress equation that is used in ATProcess.

\[ \sigma_x = \frac{-2E_L \alpha_L}{3 + \nu_{LT}} (T_1 - T_0) \]

The thermal stress calculated in the fusion zone of the ATP process is only present because the fibers in the composite keep the longitudinal elastic modulus, $E_L$ at roughly 16 Msi to 20 Msi, even at elevated temperatures. Because $T_1$ is greater than $T_0$ in the composite laminate, the resulting thermal stress should be compressive in the fusion zone, potentially causing microbuckling of the plies. Because the resin matrix has little or no elastic modulus at the temperatures found in the fusion zone, the coefficient of thermal expansion of the composite, $\alpha_L$, is therefore equal to that of the graphite fibers. At the elevated temperatures that the In-Situ process is performed at, the expansion coefficient of the fibers is small and positive (in sign) which creates compressive thermal stresses in the fusion zone.

5. Gap Consolidation Model

A target temperature in the fusion zone is needed to determine the optimal heat flux for a given roller force and head velocity. Wang and Gutowski (78) derived a model of gap closure in thermoplastic matrix composites. In this model, they determined the amount of time for gap closure in autoclave processing of these composites under a given pressure and resin viscosity (at a constant temperature). Extending their model by
substituting a thermally activated, shear-thinning model of the resin viscosity, the
temperature that is required to close a given gap size can be obtained by inverting their
final expression. The roller pressure (average Hertzian stress within the roller contact
zone) and the processing time (roller contact zone width divided by the head velocity)
from other subsections of the ATProcess model are used to calculate this goal
temperature. With this goal temperature under the roller, the model indicates that the
intertape gaps would be processed away during the time the roller passes over it and no
residual voids or laps would be present after the processing is complete.

The following derivation of the gap closure model will follow closely that of Wang
and Gutowski (78) and will amplify the assumptions and mechanics of their derivation.
This will continue until a basic rate equation for gap closure is obtained. At that point, a
more descriptive thermally activated model of resin viscosity will be proposed and
substituted into their model. The basic rate equation for gap closure will then be
reformulated to yield a goal consolidation temperature when the resin matrix has the
proper viscosity to allow the gap width between two adjacent tape layers to be closed in
the time that the roller is in contact with the material. The basic laminate geometry and
dimensions used in the Wang and Gutowski derivation are shown in Figure 9.5.
The Wang and Gutowski model begins with the fundamental equation of the shear strain rate of the resin under applied shear stress.

\[
\gamma_s = \sqrt{2 \left( \frac{\partial v_2}{\partial x_2} \right)^2 + 2 \left( \frac{\partial v_3}{\partial x_3} \right)^2 + \left( \frac{\partial v_2}{\partial x_3} \right)^2}
\]

where \(v_1, v_2,\) and \(v_3\) are the three components of resin velocity.

The equation of continuity in fluid flow:

\[
\frac{\partial v_2}{\partial x_2} + \frac{\partial v_3}{\partial x_3} = 0
\]

can be used to simplify the shear strain rate expression to obtain:

\[
\gamma_s = \sqrt{4 \left( \frac{\partial v_2}{\partial x_2} \right)^2 + \left( \frac{\partial v_2}{\partial x_3} \right)^2}
\]
Because the laminate is thin in contrast to its width and length, the characteristic dimensions, \( x_1 \) and \( x_2 \) are much larger than that in the \( x_3 \) direction (thickness). From this discussion, the following assumptions were made by Wang and Gutowski;

\[
\frac{\partial}{\partial x_3} \gg \frac{\partial}{\partial x_1} \quad \text{and} \quad \frac{\partial}{\partial x_3} \gg \frac{\partial}{\partial x_2}
\]

which further simplifies the shear strain rate equation to:

\[
9.35 \quad \dot{\gamma}_s = \sqrt{\left( \frac{\partial v_2}{\partial x_3} \right)^2} = \frac{\partial v_2}{\partial x_3}
\]

The shear strain rates are related to the shear stresses applied to the fluid through the generalized Newtonian viscosity relationship;

\[
9.36 \quad \tau_{ij} = \eta \dot{\gamma}_{ij}
\]

where \( \eta \) is the Newtonian viscosity coefficient, \( \tau_{ij} \) is the applied shear tensor and \( \dot{\gamma}_{ij} \) is the shear strain rate tensor. Fluids, where the viscosity is a function of the shear strain rate, are known as non-Newtonian in their behavior and are characterized by a power law relationship with shear strain rate. This class of fluids are also known as power law fluids. The thermoplastic resins used as composite matrices fall into this category when these materials are above their glass transition temperature. The mathematical representation of power law viscosity is;

\[
9.37 \quad \eta_{ij} = m \dot{\gamma}_{ij}^{n-1}
\]

where \( \eta_{ij} \) is the non-Newtonian viscosity, \( \dot{\gamma}_{ij} \) is the shear strain rate given above, \( m \) is the temperature dependent viscosity function, and \( n \) is the power law exponent. When the power law exponent is less than one, the fluid behavior is known as shear-thinning. All
thermoplastic resins analyzed in this thesis exhibit this type of rheological behavior as shown by the values of the exponents in Table 12.4. With the viscosity relationship and the shear strain rates, the stress tensor can be determined with Eqns. 9.36 and 9.37 for the consolidation rheology.

\[ \tau_{22} = 2m \left( -\frac{\partial v_2}{\partial x_3} \right)^{\alpha-1} \left( \frac{\partial v_2}{\partial x_2} \right) \]  

\[ \tau_{33} = 2m \left( -\frac{\partial v_2}{\partial x_3} \right)^{\alpha-1} \left( \frac{\partial v_3}{\partial x_3} \right) \]  

\[ \tau_{23} = -m \left( -\frac{\partial v_2}{\partial x_3} \right)^{\gamma} \]

where all other components of the stress tensor are equal to zero. The equation of motion in the transverse direction (2 direction in Figure 9.5) where the resin must flow to close the gap width, is given by the following equation;

\[ -\frac{\partial p}{\partial x_2} + \frac{\partial \tau_{23}}{\partial x_3} + \frac{\partial \tau_{22}}{\partial x_2} = 0 \]

where \( p \) is the applied pressure to consolidate the laminate. The last term in Eqn. 9.39 is neglected, as the second major assumption of this model. Because the shear stress gradient is related to the shear strain rate by the newtonian viscosity law, the following dimensional analysis may be performed to confirm this assumption:

\[ \frac{\partial \tau_{23}}{\partial x_3} \approx \frac{v_2}{h^2} \gg \frac{\partial \tau_{22}}{\partial x_2} \approx \frac{v_2}{b^2} \]

The panel width, \( b \), is much larger than the panel thickness \( h \), for a given fluid velocity \( v_2 \) in the transverse direction of the laminate, therefore the last term is small in comparison to
the first two terms and may be justifiably neglected. Using Eqn. 9.38c, differentiating, then substituting back into Eqn. 9.39, with the assumption of Eqn. 9.40, the following expression of the equation of motion is obtained.

\[
\frac{dp}{dx_2} = \frac{\partial}{\partial x_3} \left[ -m \left( \frac{\partial v_2}{\partial x_3} \right)^n \right]
\]

This equation gives the pressure gradient along the panel's transverse direction. By integrating the above expression twice in the thickness direction, \(x_3\), subject to the following boundary equations:

\[
\frac{\partial v_2}{\partial x_3} = 0 \quad \text{at} \quad x_3 = 0 \quad \text{and} \quad v_2 = 0 \quad \text{at} \quad x_3 = \pm \frac{h}{2}
\]

will yield the resin velocity as a function of the applied pressure; Eqn. 9.42. Simply put, these boundary equations state that at the bottom and top of the panel there is not any velocity gradient and there is not any transverse velocity in the center of the panel. The transverse velocity is given by:

\[
v_2 = \left( \frac{h}{2} \right)^{\frac{n+1}{n}} \cdot \left( \frac{-1}{m} \frac{dp}{dx_2} \right)^{\frac{1}{n}} \cdot \left( \frac{n}{n+1} \right) \cdot \left[ 1 - \left( \frac{2x_3}{h} \right)^{\frac{n+1}{n}} \right]
\]

Taking the continuity expression, Eqn. 9.33 and integrating it with the assumption of inextensibility in the fiber direction, yields a second expression for the transverse fluid velocity;

\[
\int_0^{\frac{h}{2}} v_2 \, dx_3 + x_2 \frac{h}{2} = 0
\]
Substituting into Eqn. 9.42a into Eqn 9.42 b and completing the integration results in the final expression for the pressure gradient;

\[
\left( -\frac{1}{m} \frac{dp}{dx_2} \right)^{\frac{1}{n}} = \frac{x_2(-\dot{h}/2)}{(h/2)^{\frac{(2n+1)}{n}}} \left( \frac{2n+1}{n} \right)
\]

where \( \dot{h} \) is the rate of decrease in the thickness caused by the consolidation process and the closure of the gaps. Back substitution of the pressure gradient, Eqn. 9.43, into Eqn. 9.42a yields the final expression for the velocity:

\[
v_2 = x_2 \left( \frac{-\dot{h}}{h} \right) \left( \frac{2n+1}{n+1} \right) \left[ 1 - \left( \frac{2x_3}{h} \right)^{\frac{n+1}{n}} \right]
\]

Integrating the transverse pressure gradient, Eqn 9.43, across the width of the tape yields the final expression for the pressure;

\[
p = \frac{mb^{n+1}}{n+1} \left[ \left( \frac{-\dot{h}/2}{(h/2)^{\frac{(2n+1)}{n}}} \right) \left( \frac{2n+1}{n} \right) \left[ 1 - \left( \frac{x_2}{b} \right)^{\frac{n+1}{n}} \right] \right]
\]

where \( b \) is the average width of the ply, and \( x_2 \) describes the position within the ply that the pressure is being measured. Integration of the pressure over the ply area from \(-a \leq x_1 \leq a\) and \(-b \leq x_2 \leq b\), then rearranging the equation, yields an expression for the average rate of consolidation, defined as \( \frac{\dot{h}}{h} \) ;
9.46  \( \left( \frac{\dot{h}}{h} \right)^n = \frac{FA^{n+1}(n+2)}{a_0mb^{2n+3}2^{2n+4}\left(\frac{2n+1}{n}\right)^n} \)

where \( A \) is the area (equal to \( 2bh \)). Because ply spreading is a constant volume process, the rate of transverse spreading, \( \frac{\dot{b}}{b} \), is equal to the rate of thickness consolidation, \( \frac{\dot{h}}{h} \), therefore the width of the tape can be expressed as a function of time as:

9.47  \( b^* = (1 + t^*)^{\frac{n}{2n+3}} \)

where \( b^* = \frac{b(t)}{b_0} \) is a dimensionless parameter of the ply width and \( t^* = \frac{t}{\tau} \) is a dimensionless time constant, while \( \tau \) is the characteristic time of the viscous flow process which causes the transverse ply spreading under the applied pressure. The characteristic time for this process is calculated by differentiating Eqn. 9.47 with respect to time and dividing by \( b^* \) to form the ratio \( \frac{\dot{b}^*}{b^*} \). By using the constant volume assumption once more, the following relationship is obtained: \( \frac{\dot{b}}{b} = \frac{\dot{h}}{h} = \frac{\dot{b}^*}{b^*} \)

Substitution of \( \frac{\dot{b}^*}{b^*} \) back into Eqn. 9.46 and rearranging yields an expression for the characteristic time of the ply spreading process:

9.48  \( \tau = \left( \frac{2n+1}{2n+3} \right) \left\{ \frac{2a_0 (2b_0)^{a+2} \cdot m}{F \cdot (h_0)^{a+1} \cdot (n+2)} \right\}^{1/n} \)
This ends the amplified derivation of the Wang and Gutowski transverse ply spreading model. The following derivation is an extension of this model to allow its usefulness in the In-situ Consolidation process. The physical arrangement for the gap closure process is shown on Figure 9.6.

**Figure 9.6 Schematic of Gap Consolidation Process Under Roller**

The average pressure applied to the laminate is equal to;

$$P = \frac{F}{2a \cdot 2b}$$

where the initial tape width is; $W = 2b_0$. The final tape width after the gap has been consolidated is; $2b = W + 2G$, and the initial ply thickness of the tape is; $h_0 = h_{\text{ply}}$. The factor 2 in the previous equation is included to account for shear flow into the gap and on the backside of the tape. With these changes, the characteristic time equation is transformed to;
\[ \tau = \frac{2n+1}{2n+3} \left( \frac{W^{n+2}m}{P(h_{pl})^{n+1} \times (n+2) \times (W+2G)} \right)^{1/n} \]

where \( G \) is the width of the gap between two adjacent plies in the lay-up. The complete ply spreading equation, Eqn. 9.47 is restated as:

\[ \left[ \frac{W+2G}{W} \right]^\frac{2n+3}{n} = \left[ 1 + \frac{1}{\tau} \right] \]

Rearrangement of Eqn. 9.51 yields the required time to consolidate the intertape gap:

\[ t_{cons} = \tau \cdot \left[ \left[ \frac{W+2G}{W} \right]^\frac{2n+3}{n} - 1 \right] \]

Substitution of the characteristic time equation, Eqn. 9.50 into Eqn. 9.52 completes the consolidation time equation:

\[ t_{cons} = \frac{2n+1}{2n+3} \left[ \frac{W^{n+2}m}{P(h_{pl})^{n+1} \times (n+2) \times (W+2G)} \right]^{1/n} \cdot \left[ \left[ \frac{W+2G}{W} \right]^\frac{2n+3}{n} - 1 \right] \]

A final modification to the above equation is made to include in the power law viscosity model a thermally activated process to take into account the decrease in viscosity with temperature. The following thermally activated, power law viscosity model is proposed to take into account both the shear strain rate and thermal effects on the viscosity,

\[ \mu = m_0 \cdot \exp(-\Delta H_\mu / RT) \cdot \dot{\gamma}_s^{n-1} \quad \text{or} \quad m = m_0 \cdot \exp(-\Delta H_\mu / RT) \]

where \( \Delta H_\mu \) is the Arrhenius activation energy of the viscosity, \( T \) is the absolute temperature, \( R \) is the universal gas constant and \( m_0 \) is the preexponential constant. This
model uses a Arrenhius thermal activation mechanism to account for the temperature effects on the resin viscosity. Arrenhius type materials models are used extensively for materials whose mechanical behaviour's are controlled by mechanisms which involve thermal activation energies, such as diffusion or creep. A thermal activation mechanism controls the effect of temperature on viscosity in thermoplastic resins. The change in the viscosity model modifies the consolidation time expression, Eqn. 9.53 to:

\[
9.55 \quad t_{\text{cons}} = \frac{2n+1}{2n+3} \left[ \frac{W^{n+2}m_0 \exp(-\Delta H_\mu / RT)}{\rho \cdot (h_{\text{ply}})^{n+1} (n+2) \cdot (W+2G)} \right]^{1/a} \cdot \left[ \frac{W+2G}{W} \right]^{\frac{2n+3}{a}} - 1
\]

The Hertzian contact distance of the roller with the composite tape is equal to\(^2\) \(c\), and is moving with the velocity \(v\). Therefore the time available for consolidation in the In-situ process is equal to:

\[
9.56 \quad t_{\text{cons}} = \frac{c}{v}
\]

Substituting this available consolidation time into Eqn. 9.55, the required consolidation time and rearranging yields:

\[
9.57 \quad \exp\left(\frac{\Delta H_\mu}{RTn}\right) = \frac{v \cdot (2n+1)}{c \cdot (2n+3)} \left[ \frac{m_0}{\rho \cdot (h_{\text{ply}})^{n+1} (n+2)} \right]^{1/a} \cdot \left[ \frac{W^{n+2}}{W+2G} \right]^{1/n} \cdot \left[ \frac{W+2G}{W} \right]^{\frac{2n+3}{a}} - 1
\]

One final rearrangement yields the required temperature in the fusion zone which is capable of processing out the intertapes gaps in the time and with the pressure provided by the roller:

---

2. The value \(c\) used in this expression is equal to \(2b\) which was defined in the derivation of the contact stress model. The value \(c\) is used here to avoid confusion with the \(b\) variable for tape width defined and used in the Gap Consolidation model.
9.58
\[
\frac{1}{T_{\text{cons}}} = \frac{nR}{\Delta H_\mu} \cdot \ln \left[ \frac{v(2n + 1)}{c(2n + 3)} \cdot \left( \frac{m_0}{p \cdot (h_{\text{phy}})^{n+1}} \right)^{n+1} \cdot \left( \frac{W^{n+2}}{W + 2G} \right)^{1/a} \cdot \left( \frac{W + 2G}{W} \right)^{2n+3} - 1 \right]
\]

This is the final form of the equation which is coded into ATProcess.

6.) Thermodynamic Model of Inert Gas Jet

The final submodel required to complete the characterization of the process is a thermodynamic model of the gas jet. This model relates the gas temperature as it exits from the torch, the mass flux flowing through the torch, the heat flux that the jet delivers to the panel and the width of area upon which the heated gas impinges upon the panel.

With this final subsection of ATProcess, the required heat flux and the width of heating on the panel can be transformed by a thermodynamic energy balance into the required mass (gas) flow and gas temperature settings of the inert gas jet. These settings can be used to build panels under the proper heat flux settings. This subsection of the model is not required if other heating methods such as a laser beam are used, where the power settings can be set directly from the desired heat flux.

The final subsection of ATProcess contains two relationships which relate the gas temperature, fusion zone average temperature and gas mass flux of the \( N_2 \) inert gas jet to the heat flux upon the panel. The following energy balance equation relates the heat flux into the panel to the loss of heat in the gas times the mass flux flowing over the panel;

9.59
\[
\dot{q} = \dot{m} \int_{T_{\text{gas}}}^{T_{\text{panel}}} C_p \, dT
\]
where the thermodynamic heat transferred from the torch is the integral of the gas’s heat capacity from the torch temperature to the panel temperature. These are the limits of integration in this expression. The heat capacity of N₂ gas at elevated temperature is given by the following power series in temperature;

\[ C_p = a + (b \times 10^{-3})T + (c \times 10^{-6})T^2 \]

where the power law exponents (a, b, c) are listed in a Atomic Energy Commission table (74) for most common gases and elements, including N₂. The coefficients for N₂ are:

\[ a = 6.76 \text{ cal/g or 0.434 BTU/lb} \quad b = 0.606 \text{ cal/g or 0.0389 BTU/lb} \quad c = 0.13 \text{ cal/g or 0.0084 BTU/lb} \]

Substitution of the heat capacity power series into the energy balance expression and integrating through the two temperature limits yields:

\[ \dot{q} = \dot{m} \left[ a(T_{\text{gas}} - T_{\text{panel}}) + \left( \frac{b \times 10^{-3}}{2} \right) (T_{\text{gas}}^2 - T_{\text{panel}}^2) + \left( \frac{c \times 10^{-6}}{3} \right) (T_{\text{gas}}^3 - T_{\text{panel}}^3) \right] \]

Rearranging Eqn. 9.61 in terms of the unknown gas flux, the following equation is obtained:

\[ \dot{m} = \frac{\dot{q} \varepsilon^{-1} A}{a(T_{\text{gas}} - T_{\text{panel}}) + \left( \frac{b \times 10^{-3}}{2} \right) (T_{\text{gas}}^2 - T_{\text{panel}}^2) + \left( \frac{c \times 10^{-6}}{3} \right) (T_{\text{gas}}^3 - T_{\text{panel}}^3)} \]

while holding the gas temperature, \( T_{\text{gas}} \), constant. A is the area of impingement of the jet where \( \dot{m} \) is the required mass flux to attain the desired incident heat flux onto the panel onto the panel and \( \varepsilon \) is the efficiency of energy transfer of the gas into the panel. The efficiency of the jet was found to be from a calibration experiment to be \( \sim 1/12 \). Eqn. 9.62
can be used to calculate the gas flow settings to attain a given heat flux, when using the constant gas temperature method of setting the gas parameters. The constant gas temperature is given by the heat convection correlation Eqn. 9.64.

Because the inert gas jet used on the In-situ consolidation machine has a lower limit of control at 45 standard liters per minute (SLPM), the mass flux calculated from Eqn. 9.62 will fall below this level for panels over 5-7 ply layers thick. Under these conditions, the mass flux is then held at a constant level of 45 SLPM and the gas temperature is calculated by solving the following transcendental equation. This expression is obtained through rearrangement of Eqn 9.62.

\[
9.63 \cdot \ln \left[ a(T_{\text{gas}} - T_{\text{panel}}) + \left( \frac{b \times 10^{-3}}{2} \right) \cdot (T_{\text{gas}}^2 - T_{\text{panel}}^2) + \left( \frac{c \times 10^{-6}}{3} \right) \cdot (T_{\text{gas}}^3 - T_{\text{panel}}^3) \right] - \dot{q}\epsilon^{-1}A = 0
\]

A Newton-Raphson routine is used in ATProcess to find a root for the gas temperature, \( T_{\text{gas}} \).

In ATProcess, the mass flux is varied initially using Eqn. 9.62 to keep the gas temperature at its 1700F upper limit until the mass flux drops to 45 SLPM. At this level, the mass flux becomes a fixed parameter at its lower limit and the gas temperature becomes the controlled variable to obtain the desired heat flux using Eqn. 9.63

The gas temperature to yield the proper consolidation conditions for the first laminate plies consolidation is given by the following convection law empirical correlation of the gas temperature to the incident heat flux. This relationship was derived for the geometry of the In-Situ Consolidation process with a finite element heat transfer model by Young (88).

\[
9.64 \quad \dot{q} = \epsilon h \Delta T = 0.009645 \cdot (T_{\text{gas}} - T_{\text{panel}})
\]
Implementation and Use of the Process Science Model

The goal of the In-Situ Consolidation process modeling and designed experimentation portion of this project was to find the best processing parameters for the fabrication of the composite test panels with this technology and accelerate the rate of learning. The goal was not to build the most detailed or complex, processing science model. This emphasis of the entire project was to demonstrate the strategy of process modeling followed by intelligent designed experimentation to shorten the time it takes to develop new manufacturing technologies.

The process model, ATProcess, was written in FORTRAN, a language that is well understood by a majority of engineers at Boeing, so additions can be made to it as a learning tool in the future. This code was written in user friendly fashion, as it queries the user for all of its input parameters, then outputs the data in a format capable of being plotted by other computer graphics programs, such as Cricket Graph. These plots show the thermal profile along the top most ply being laminated as a function of the process settings.

Figure 10.2 shows a representative thermal profile output of ATProcess. A minimal amount of skill is required to run and analyze processing conditions, with little or no prior knowledge of eigenvalue-eigenvector analytical thermal solutions. The one exception to this statement is the user must ask for the proper number of eigenvalues for a low noise convergence of the thermal solution, which is a function of the panel's aspect ratio. Long, thin panels, with high aspect ratios, require larger numbers of eigenvalues to obtain reasonably good temperature fidelity (N >100), while shorter or thicker panels require considerably less. Even at 150 eigenvalues, ATProcess can perform the analysis of one set of processing conditions in roughly 23 seconds on a MACINTOSH Cx and only 8 seconds on a 486/25 workstation. In the author's experience, this is considerably less than would be required by a non-linear, implicit, Thermal-Mechanical finite element analysis program of this process, with run times of an hour or more. ATProcess is considerably
less complex to use than these other modeling programs and fits better into the existing culture in manufacturing process development groups. The complete text of the ATProcess source program is included in Appendix II.

The thermal analysis of the processing conditions is performed by the user varying the input heat flux to adjust the temperature under the roller where consolidation takes place. Figure 9.0 shows a schematic diagram of the processing parameters and the logic flow of ATProcess. The manual adjustment of the heat flux is continued until the desired goal consolidation temperature is attained under the roller. Under these process conditions, consolidation is achieved through the closure of the intertaped gap. The model also gives the proper index spacing between the plies, the gas mass flow rate and the gas temperature which are then used to fabricate the test panels. A decision was made not to include a numerical Newton-Raphson heat flux optimization routine to this program, because such a solution routine would not allow the program user to get a "feel" for the effect of the processing conditions. Such an optimization program is planned for the future, to allow the model to rapidly converge on the required heat flux to obtain the goal consolidation temperature.

One of the team members in the ad-hoc process development team increased the group's ownership of this model by creating a more user friendly front end input program for ATProcess. This MACINTOSH version of the model comes complete with pull down menus for the input of processing condition data and the automatic on line plotting of the data. In this advanced form, the model is expected to be included in the laboratory in-situ ATP consolidation machine, scheduled for operation at Boeing in late 1992.
Chapter 10

Results of the Process Modeling and Process Parameters for the DOE Test Panels

Introduction

The ATRprocess process science computer model for the In-Situ composite fabrication process was run with the known processing parameters for the fabrication of two thermoplastic resin composite materials, HTA/IM-7 (poly-aryl-ether-sulfone, high temperature thermoplastic resin matrix) and APC-2/IM-7 (poly-ether-ether-ketone, thermoplastic resin matrix) to test the assumptions made in its development. This was performed to refine these assumptions to create a better process model. As a result of this refinement, several additional sub sections were added to the process model. These additions include the gap/lap size prediction and goal consolidation temperature routine, the gas temperature and mass flow energy balance routine and the inclusion of equations to predict the maximum gap spacing and required index spacing for proper tape lamination and consolidation. (These sub sections were described mathematically in Chapter 9).

These modifications brought the model's predictions into good agreement with the initial experimental test data from lamination experiments at ICI. Using the results of the early processing experiments to change the model allowed the lessons learned in these experiments to be captured in the logic of the model. Process science modeling of the process not only provides a tool for rapid learning about a process during development, but also provides a tool for technology transfer and continuous improvement at the conclusion of the development program. This chapter will document the early processing experiments and the changes made in the model, then will conclude with the evolution of the final set of Design of Experiment (DOE) test matrix.

The DOE test matrix serves two purposes for this program; first it serves as a final test to verify the process model, and most importantly it yields information on the most
optimal position in process space to run the process for the best mechanical properties. Due to the sensitivity of the matrix shear strength to processing flaws and residual thermal stresses, tensile strength tests with (±45)₆₅ laminates were chosen as the primary tests for DOE evaluation. Maximizing the tensile strength of the (±45)₆₅ DOE panels was chosen as the objective function for the process optimization.

The panels in the DOE test program were fabricated from APC-2 (PEEK)/IM-7, which served as the "model material" for this project. This selection was made because APC-2 is the thermoplastic resin matrix composite which the composite industry has had the most experience. This choice allows the comparison of conventionally layed up and autoclave consolidated APC-2/IM-7 to the In-Situ Consolidated panels of this thesis. The structure and chemistry of candidate thermoplastic resin matrices are shown on Figure 10.1. The materials properties for the base resin materials and the resulting lamina properties of a 60 volume percent high strain graphite fiber reinforced composite are shown in Tables 12.1 and 12.3, respectively. The thermal conductivities, heat capacities and longitudinal elastic moduli shown in Table 12.3 were used in the ATProcess analysis program.
**Figure 10.1** Chemical Structures and Data of Candidate Thermoplastic Resin Materials

<table>
<thead>
<tr>
<th>Generic Name</th>
<th>Trade Name</th>
<th>Processing Temperature (°C)</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyphenylene</td>
<td>PPS</td>
<td>316</td>
<td><img src="image1" alt="Structure" /></td>
</tr>
<tr>
<td>Sulfide</td>
<td>Ryton®</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Phillips Petroleum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyetherether Ketone</td>
<td>PEEK</td>
<td>390</td>
<td><img src="image2" alt="Structure" /></td>
</tr>
<tr>
<td></td>
<td>Victrex® PEEK</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>I.C.I.</td>
<td></td>
<td></td>
</tr>
<tr>
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<tr>
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<td>Union Carbide</td>
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</tr>
<tr>
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<td>PEI</td>
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<tr>
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<td>G.E.</td>
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<td>HTA®</td>
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<tr>
<td></td>
<td>I.C.I.</td>
<td></td>
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</tbody>
</table>
Results of the Modeling Analysis For The In-Situ Process

A representative thermal profile output from the ATProcess program (as shown on Figure 10.2.) shows that the temperature of the topmost ply is equal to that of the tool for most of the 20 inch panel length. In the region near the center, where the inert gas jet heat source impinges upon the surface of the panel, the temperature goes through an 800 degree F thermal excursion. The normal probability curve shape of the thermal profile output in this figure is predominantly determined by the highly conductive tool substrate. The predominant direction of heat transfer in this process is through the composite laminate from the inert gas torch source to the massive tool heat sink, with little residual heat remaining in the material after the torch passes by. A less conductive ceramic tooling substrate was simulated in the model by lowering the tool conductivity by three orders of magnitude to investigate its effect on the thermal profile. Under these conditions, the thermal profile became a step function along the panel, with the step at the forward edge of the heat source. Under these conditions, little heat being was being transferred to the tool and was retained in the material.
Figure 10.2: Representative Thermal Output Profile of In-Situ Consolidation Process
The consolidation roller in Figure 10.2 was located 1/2 inch behind the center of the heat source, as shown by the position of the pressure spike. The pressure spike is created by contact of the panel with the roller. This figure shows that the temperature at the lamination interface in contact with the roller is exactly equal to the goal consolidation temperature. When these conditions are met, the pressure and temperature are sufficient to promote enough shear flow in the resin, so that the gap between adjacent tapes is closed during the time the roller is in contact with the hot material. Care must be exercised so that the temperature is not above this goal value. When consolidation temperatures are too high, the increased amount of resin flow under the roller creates ply lap in subsequent tape laminations. The time that the roller spends in contact with a given volume of hot material is a function of the head velocity and the load upon the roller, as described mathematically by Eqn. 9.38. This time of contact is fairly short (from 1/4 to 1 second) and therefore the process requires high temperatures (825 to 1000 F) to attain the low viscosity needed to close the gap spacing between the tapes.

Identification of Critical Nature of Inert Gas Jet Consolidation Roller Co-Location

Figure 10.2 shows that co-location of the gas jet and consolidation roller are essential to attain good consolidation. For example, if the roller were moved from 1/2 inch to 1 inch from the center of the heat source, the heat flux would have to be drastically increased to attain the desired consolidation temperature. If the roller is moved in relation to the gas jet, without increasing the heat flux, the temperature under the roller would become that of the tool temperature and no consolidation would take place under these conditions. Therefore placement of the inert gas jet away from the roller would cause the loss of the visco-plastic fusion zone under the roller and create an elastic response in the composite tape with the roller contact. The hertzian contact stresses under the roller would climb from the 300 to 400 psi range as they are targeted to be in the fusion zone, to
an elastic value in the range from 18,000 to 30,000 psi. A decrease in the thermal conductivity of the tooling substrate or by laminating facesheet materials directly onto a honeycomb substrate would make the process more robust from the standpoint of positioning of the roller, because the fusion zone would be wider under these conditions. In all cases, the In-Situ consolidation process works best if the inert gas impinges onto the tape and roller in an intimate manner.

The use of an inefficient gas jet, when a perfectly efficient laser beam is available, at first glance seems to be incongruent for those not intimately acquainted with the process. An explanation for this from a process science standpoint, is the narrow width of the laser heat source would make it difficult to obtain the proper consolidation temperature under the roller, unless the laser is precisely focused at the base of the roller. Any variance in the focus of the laser away from the base of the roller, would create regions where consolidation does not occur. In contrast, the inefficient gas jet creates a broader process zone, so that the roller-heat zone spacing, while still important, is not as critical.

**Tradeoff between Consolidation Head Velocity and Composite Panel Quality**

The Design of Experiments testing of In-Situ Consolidated process explores the effect of the processing parameters on the mechanical test strength of test panels. The most important processing parameter of interest in this test program is the head velocity. The higher that velocity can be pushed, without burning the resin or degrading the panel strength, is desirable from a processing economics point of view. For this reason, three levels of head velocity; 0.5"/sec, 1"/sec, and 4"/sec, were included in the test program. Initial processing experiments had shown that consolidation of the material at these speeds was possible but the quality of the resulting laminate degraded as the processing speed increased. The composite tape in panels that are processed at higher velocities spends a smaller amount of time under the roller and therefore must have a higher maximum
temperature applied to it to consolidate out the gaps. Figure 10.3 illustrates that the effect of increasing velocity requires greater consolidation and maximum temperatures to obtain gap closure.

![Figure 10.3 Effect of Head Velocity on Required Consolidation and Maximum Panel Temperatures](image)

The higher maximum temperature that is required at a faster processing speed increases the probability that one or all the three of the polymeric degradation mechanisms\(^1\) will become kinetically significant, even for these short time exposures, (from 1/4 to 2 seconds per pass) degrading the matrix properties. Thermal degradation and the effects of residual laps or gaps should show up most significantly in the transverse strength and (+/-45) tensile strength properties of the composite. For this reason, (+/-45)\(_{6s}\) tension tests have been chosen as to characterize the results of the process DOE.

variable \(c\) is used here to avoid confusion with the \(b\) variable used for the tape width in the Gap Consolidation Model.

1. The three thermal degradation mechanisms of thermoplastic resins at elevated temperature in order of increasing temperature where the mechanisms operate are; 1) chain extension and crosslinking of the polymer chains which increases the viscosity of the resin after thermal exposure. The crosslinking mechanism is followed next at higher temperature by, 2) chain scission or breaking of the polymer chains and finally by; oxidation degradation of the resin or "burning" of the resin. The final two mechanisms are deleterious to the strength of the resin matrix.
The effect of residual laps or gaps would show up very well in transverse tensile tests using 90 degree laminates, but this test was not included in the test program.

**Observation of Hot Tool Sticking Problem**

The *ad-hoc* process development team observed the first panel fabricated on a hot tool at ICI Composite Structures. The first 5 plies of this panel were successfully laminated onto the 300 F tool, but the 6th ply would not stick to the 5 ply laminate after numerous attempts. During these attempts, the tape was observed to glow red as the tape head contacted the laminate. The red glow is an indication that the fusion zone was reaching temperatures in excess of 1400 F. The initial conclusion reached by the process development team was the ability to fabricate panels on a hot tool (and the associated thermal stress reduction) was a lost hope.

**Analysis and Solution to the Non Sticking Problem**

The processing parameters used by ICI in the fabrication of this panel were analyzed with the ATProcess model to shed some insight into the non-sticking and overtempering problems experienced. Figures 10.4 through 10.6 show the thermal profiles for these processing conditions as the number of plies built up from 3 to 6, with lamination of successive layers.

Using a conventional designed experiments methodology, ICI was using a constant heat flux on the tape as it laminated the successive ply layers. As can be seen in the figures, the first few plies attained their required consolidation temperatures. However, with each successive ply, the temperature of the tape at first contact with the roller was progressively higher. This occurs as the progressively thicker laminate becomes a thicker insulative layer. By the 6th ply, shown on Figure 10.6, the temperature in the fusion zone of the tape is nearly 1400 F, explaining the dull red glow observed during the processing. From this analysis, it was concluded that the heat flux required to consolidate the tape in
this process decreases initially fairly rapidly with each successive ply layer, eventually reaching an asymptotic value for thick laminates. It was also concluded that the use of fixed heat flux processing conditions would not yield acceptable consolidation results.

Figure 10.7 shows the results of one analysis of the required heat flux and gas mass flow distribution necessary to consolidate the laminate. This figure shows that the rapid initial decrease in the incident heat flux onto the panel and the approach of an asymptotic limit. Heat flux and mass flow plots such as this one were produced for all 15 of the DOE test panel conditions. These plots were made using a constant gas temperature that was calculated with the gas convection correlation equation, Eqn. 9.64.

At the thicker panel, asymptotic limit, a small amount of heat escapes through the panel to the tool in the short time scale of this process, so the heat flux required under these conditions corresponds to the amount of energy required to supply the resin’s latent heat of fusion. The use of a ceramic tooling substrate in the In-Situ process would cause this limiting condition to occur much sooner by preventing the heat from being lost to the substrate. Using ATProcess to analyze the processing conditions, the required heat flux to maintain the material at a constant temperature in the fusion zone throughout the process was calculated.
Figure 10.4  Thermal Analysis of 300 F Hot Tool Test Experiment 3rd Ply

Panel Temperature  Deg F

Processing Conditions
Qp = 0.2562  P = 70 lbs  Thk = 0.018"
Figure 10.5
Thermal Analysis of 300 F Hot Tool

5th Fly

Panel Temperature Deg F
Coal Temp

Gap = 0.010
G = 0.2832
T = 0.162
THK = 0.0.010
T1493 = 1493 F
Ttool = 300 F

Y = 1/sec

Processing Conditions
Figure 10.7  Representative Heat and Mass Flow Settings of Inert Gas Torch to Attain Consolidation Temperature
Panel #1  Constant \( T_{gas} = 1543 \, \text{F} \)

INCIDENT HEAT FLUX
BTU/ IN\(^2\) SEC

<table>
<thead>
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<table>
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<table>
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205
Effect of Tool Temperature on Residual Thermal Stress

The second major area of investigation in the DOE tests program is to determine the effect of the tool temperature on the mechanical properties of the test panels. This was done by fabricating the panels on a flat tool that included an internal set of heating elements and was capable of operation at temperatures up to 600 F. The series of Figures 10.8 to 10.10, shows the projected thermal profiles of panels fabricated with one set of processing parameters, highlighting the effect of increasing the tool temperature from 75 degrees F to 500 degrees F. In this set of figures, the amount of heat flux to attain the required consolidation temperature decreases considerably as the tool temperature increases. For the panel fabricated on a 500 F tool, only a small thermal boost from the gas torch is needed to reach the desired consolidation temperature in the process zone. With elevated temperature tooling, the smaller heat flux needed to reach the consolidation temperature also causes the difference between the maximum temperature and consolidation temperature to be smaller. The lower maximum temperature in this profile is less likely to create thermal degradation in the resin during consolidation.

The primary reason for including the tool temperature as a parameter in the test matrix is the substantial decrease in the temperature delta (ΔT) that the panel experiences along its length during fabrication. This temperature difference ranges from over 800 F for a room temperature tool to just 325 F with a 500 F tool. As shown on the figures, the decrease in the ΔT decreases the longitudinal thermal stress in the fusion zone of the topmost ply during processing from ~5000 psi for a tool at room temperature (75F in Tempe) to around -2500 psi at 500F. These figures show the temperature and thermal stress distributions which are present at one moment in time, as the consolidation torch passes over the material in the near center of the panel. As the material solidifies after the thermal wave has passed by, the thermal stresses are frozen into the material, creating residual stresses and panel warpage. The lower surface temperature of the panel is equal to that of the tool, therefore the bottom surface plies of the panel have thermal stresses
upon them whose magnitude is equal to those of the top plies, but are tensile rather than compressive in nature. This stress gradient across the panel runs from compression on the top surface to tension on the bottom. This is the mechanism that causes panel warpage to occur. The decrease in the delta temperature, ΔT, across the panel should decrease the warpage and macro\textsuperscript{2}, bending residual stresses left in the panels after fabrication. Therefore an increase in the tool temperature should have the effect in increasing the strength of the resulting laminates and improving their warpage quality (panel warpage is defined as being poor quality).

The compressive nature of the thermal stress profile is due to the increase of composite material's coefficient of thermal expansion from a negative value, \(-0.35 \times 10^{-6}\) at room temperature to \(0.56 \times 10^{-6}\) as material is heated to 425 F, the mid point temperature along the top surface of the panels, between the tool and fusion zone temperature. Therefore the positive thermal expansion coefficients exhibited by graphite fibers at elevated temperatures, result in thermal stresses that are compressive, as shown in the figures. At the temperatures in the fusion zone under the roller, the elastic modulus of the resin (which dominates the elastic modulus of a composite in the transverse direction) is negligible causing the transverse modulus to become small. The low elastic moduli in the transverse direction when coupled with compressive thermal stresses may cause the fibers to microbuckle or wave in the fusion zone. The predictions of this thermal stress calculation was confirmed during microscopic inspection of the In-Situ consolidated laminates. These laminates exhibited substantial fiber waviness in the in plane dimension of the plies. Muzzy and Colton (53) have shown that compressive strain in the

\textsuperscript{2} Macro thermal stresses are those which are created by thermal distributions created in the panel during processing. In composite materials "micro" thermal stresses are also present after a thermal processing cycle due to the thermal expansion mismatch between the fiber and matrix. When the temperature in processing exceeds the glass transition temperature, the matrix will stress relax so that a complex state of residual stress will result when the composite is cooled back to room temperature. An elastic-plastic micromechanical analysis of these residual microstresses for APC-2 / IM-7 with 50\% reinforcement revealed that the matrix has a Von Mises residual stress of 4.03 Ksi after cooling from the glass transition temperature. The majority of the residual stress in the longitudinal direction of the fibers. This analysis was performed with the McLamina analysis program whose general operation is described in Chapter 12.
longitudinal direction of the fiber during the forming of thermoplastic composite laminates, results in either fiber buckling or waviness. The result of such a set of circumstances would be a degraded compressive strength of the panels and a lower than predicted longitudinal elastic modulus.
FIGURE 10.8 THERMAL STRESS IN IN-SITU CONSOLIDATION PANEL WITH 75 F TOOL TEMPERATURE

GOAL CONSOLIDATION TEMPERATURE (DEG F)

PANEL TEMPERATURE (DEG F)

PRESSURE (PSI)

TOOL TEMPERATURE = 75 F

THERMAL STRESS (PSI)

PANEL #5 CONSOLIDATION CONDITIONS
P = 100 LBS V = 17 SEC PLY LAYER = 9
T TOOL = 75 F Q' = 0.136965

This Thermal-Mechanical Analysis is for one moment in time during the processing.
FIGURE 10.9 THERMAL STRESS IN IN-SITU CONSOLIDATION PANEL WITH 300 F TOOL TEMPERATURE

This Thermal-Mechanical Analysis is for one moment in time during the processing.
FIGURE 10.10 THERMAL STRESS IN IN-SITU CONSOLIDATION PANEL WITH 500 F TOOL TEMPERATURE

GOAL CONSOLIDATION TEMPERATURE (DEG F)

TOOL TEMPERATURE = 500 F

CONTACT PRESSURE (PSI)

THERMAL STRESS (PSI)

CONSOLIDATION CONDITIONS:
P = 100 LBS, V = 1"/SEC, PLY LAYER = 9,
T TOOL = 500F, Q' = 0.06152

This Thermal-Mechanical Analysis is for one moment in time during the processing.
To investigate the effect of the residual thermal stresses created by the longitudinal and through thickness thermal gradients during fabrication, each test condition in the designed experiment was run in the as-fabricated condition and after an annealing heat treatment (570 F / 4hr). The effect of a post process anneal is to attempt to remove the residual stresses created during lamination.

DOE Panel Processing Conditions and Evolution of Test Matrix

The primary processing parameters for the final Designed Experiments test matrix, along with the anticipated consolidation conditions to be experienced by the panel under these conditions are shown on Table 10.1. Likewise, the four gap width experimental panel processing parameters and their anticipated consolidation conditions are shown on Table 10.2. Using these processing conditions, the test panels of this project were fabricated at ICI Composite Structures. The final test matrix used to fabricate the panels was actually the third one proposed and analyzed for this project. In the first proposed test matrix, shown on Table 10.3, the roller load was limited to 50 pounds by the capacity of ICI's laboratory In-Situ Consolidation machine at that time. With this roller load, the anticipated consolidation temperatures ranged from 915 to over 1000 F. The maximum temperatures at the peak of the thermal profile were roughly 50 degrees higher yet. The high predicted consolidation temperatures as a result of this load limitation, would likely have resulted in all the panels having a degraded polymer matrix, or the processing speed would have had to be reduced to uneconomical levels (0.1 ips). After consulting with ICI on these results, they modified their machine to allow roller loads up to 100 lbs. These loads were used in the second proposed DOE test matrix, shown on Table 10.4. Further modification to allow even higher roller loads is still possible with the existing equipment, but at some point fracture of the graphite fibers under the roller may occur.

The second proposed test matrix shown in Table 10.4 included the assumption of a 10 mil gap spacing between adjacent plies in the panel. This assumed gap spacing comes
from the assumption that the variation in ply width does not change during lamination. As will be discussed later, this assumption was proven to be incorrect. The addition of the gap spacing calculation procedure to the model to account for the increased width variance of the consolidated tape allowed the final test matrix to be completed. This gap spacing calculation procedure will be described later in this chapter.

In the final test matrix, the load was set at 100 and 70 lbs to utilize the increased force capacity of the machine and determine the effect of load on the panels. The tool temperature was set at 75 and 300 F to determine the effect of tool temperature in lowering the residual macrostresses, for reasons described earlier in this chapter. This final matrix did not include a 500 F tool temperature setting after initial processing experiments showed this setting to be infeasible as will be described later. Finally, three processing speeds 0.5 ips, 1.0 ips and 4.0 ips to test the process throughout the full spectrum of processing speeds where initial processing trials have shown it to be feasible. Each of the 10 test condition panels were fabricated in a random order to minimize the effect of any systematic changes in the calibration of the fabrication machine on the processing effects measured in the DOE.
### Table 10.1 Nominal Processing Parameters For Design of Experiments Test Panels

<table>
<thead>
<tr>
<th>Panel</th>
<th># Panels</th>
<th>Initial Temp</th>
<th>Heat Flux</th>
<th>Load</th>
<th>Velocity</th>
<th>Deg F</th>
<th>Temp</th>
<th>SLPM</th>
<th>Flow</th>
<th>Pressure</th>
<th>Max Temp</th>
<th>Min Temp</th>
<th>Cond Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>390</td>
<td>100</td>
<td>76</td>
<td>76</td>
<td>4</td>
<td>300</td>
<td>75</td>
<td>68.44</td>
<td>888.47</td>
<td>918.2</td>
<td>828.0</td>
<td>888.47</td>
<td>888.47</td>
<td>888.47</td>
</tr>
<tr>
<td>391</td>
<td>100</td>
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<td>76</td>
<td>4</td>
<td>300</td>
<td>75</td>
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<td>888.47</td>
<td>918.2</td>
<td>828.0</td>
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<td>888.47</td>
</tr>
<tr>
<td>392</td>
<td>100</td>
<td>76</td>
<td>76</td>
<td>4</td>
<td>300</td>
<td>75</td>
<td>68.44</td>
<td>888.47</td>
<td>918.2</td>
<td>828.0</td>
<td>888.47</td>
<td>888.47</td>
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<tr>
<td>393</td>
<td>100</td>
<td>76</td>
<td>76</td>
<td>4</td>
<td>300</td>
<td>75</td>
<td>68.44</td>
<td>888.47</td>
<td>918.2</td>
<td>828.0</td>
<td>888.47</td>
<td>888.47</td>
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<tr>
<td>394</td>
<td>100</td>
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<td>300</td>
<td>75</td>
<td>68.44</td>
<td>888.47</td>
<td>918.2</td>
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<td>888.47</td>
<td>888.47</td>
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<tr>
<td>395</td>
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<td>888.47</td>
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<tr>
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<td>918.2</td>
<td>828.0</td>
<td>888.47</td>
<td>888.47</td>
<td>888.47</td>
</tr>
</tbody>
</table>

**Notes:**
- The total number of test panels will be 60.
- The 3 ply panels will include (1) 16 ply tension panel and (2) 24 ply compression panels.
Table 10.2 Nominal Processing Parameters For Gap Test Panels

<table>
<thead>
<tr>
<th>Panel #</th>
<th>Heat Flux BTU/in² sec</th>
<th>Gas Temp Deg F</th>
<th>Gas Flow SLPM</th>
<th>Pressure psi</th>
<th>Max Temp Deg F</th>
<th>Consolidation Deg F</th>
<th>Gap Mils</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel #6-1</td>
<td>0.21275</td>
<td>1700</td>
<td>48.36</td>
<td>428</td>
<td>855.04</td>
<td>845.5</td>
<td>20</td>
</tr>
<tr>
<td>Panel #6-2</td>
<td>0.22155</td>
<td>1700</td>
<td>51.32</td>
<td>428</td>
<td>883.45</td>
<td>861.38</td>
<td>30</td>
</tr>
<tr>
<td>Panel #6-3</td>
<td>0.22904</td>
<td>1700</td>
<td>53.81</td>
<td>428</td>
<td>897.57</td>
<td>874.32</td>
<td>40</td>
</tr>
<tr>
<td>Panel #6-4</td>
<td>0.235774</td>
<td>1700</td>
<td>56.28</td>
<td>428</td>
<td>910.05</td>
<td>885.73</td>
<td>50</td>
</tr>
</tbody>
</table>

For Each Panel Test Condition
3 Panels Will Be Fabricated In Each of Two Test Conditions:
As Fabricated and 570 F Annealed
Each Panel Will be Fabricated at a 300 F Tool Temperature, 100 lbs of Load and at 1 ips
The Three panels will include (1) 16 ply tension panel and; (2) 24 ply compression panels
<table>
<thead>
<tr>
<th>Panel #</th>
<th>Temp</th>
<th>Velocity</th>
<th>Heat Flux</th>
<th>Gas Flow</th>
<th>Lbf</th>
<th>psi</th>
<th>Target Temp</th>
<th>Max Temp</th>
<th>Condensation</th>
<th>Flow Rate</th>
<th>SLPF</th>
<th>DG</th>
<th>F</th>
<th>Btu/h</th>
<th>Sec</th>
<th>DG</th>
<th>F</th>
<th>Temperature</th>
<th>SPG</th>
<th>DGF</th>
<th>PSF</th>
<th>Lbf</th>
<th>psi</th>
<th>Lbf</th>
<th>psi</th>
<th>Test Parameters For 2nd Design of 24 Pplty Compression Panel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>120</td>
<td>60</td>
<td>300</td>
<td>100</td>
<td>1</td>
<td>0.5</td>
<td>100</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0.5</td>
<td>100</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
<td>100</td>
</tr>
</tbody>
</table>

The three panels will include (1) 15 Pplty tension panel and (2) 24 Pplty compression panels.
Changes in the Test Matrix as a Result of the Initial Processing Trials

Each of the initial test matrices (shown on Tables 10.3 and 10.4) included 3 sets of processing conditions consolidated on a hot tool at a temperature of 500°F. Initial processing trials at this tool temperature were judged to be unsatisfactory because the roller sunk into the hot laminate during either head stoppage or initial head contact. After consultation with ICI, it was decided to remove these test conditions from the matrix. The results of these initial trials and other processing experiments at ICI, have shown that the upper temperature limitation for use of the hot tool is the glass transition temperature of the thermoplastic resin. For the APC-2 (PEEK) resin used in this experiment, this upper use temperature is roughly 300°F. It was decided to substitute additional test conditions at the 4"/sec head velocity in place of the 500°F test conditions to gather additional information at this fast head speed and to complete a $2^3$ DOE test design. With these additional changes, the final DOE test matrix was completed and is shown on Table 10.1. The fast head speed and low pressure of the added test conditions, #9 and #10, that have been analyzed to result in the highest temperatures in the fusion zone of all the test conditions. Lamination under these conditions is hoped to yield information about the onset of thermal degradation in this process. They were also included to test the ability of the resin to flow rapidly in the short period of time allotted by the process at the high roller speeds to close the gaps. If this speed is too fast to allow complete transverse flow into the gaps, or does not allow enough time for diffusion bonding of the tape to the underlying laminate, or results in process zone temperatures that cause polymer degradation to occur then it is likely that these panels will have strengths below those of the other panels in the matrix.

The rapid, on line change in the test matrix was in line with the overall philosophy of the development program to generate good test panels and information on the limitations of the process, not just to blindly fabricate a preset test matrix with little regard to initial feedback from the processing trials.
Another unexpected result from the initial processing trials was the change in visible appearance of the panels produced with the decreasing heat flux consolidation conditions provided by the process model, as shown on Figure 10.7. Because of the increased insulation of the thicker underlying laminate and progressively lower incident heat flux processing conditions, the cooling rate of a multi-ply laminate will slow down as the number of ply layers increases. For semicrystalline thermoplastic resins, such as APC-2, the slower cooling rate will cause the polymer to begin to crystallize and appear white on observation. This is in contrast to those panels fabricated in the past which have been fabricated with a constant heat flux. Because the cooling rate changes as the ply thickness increases, so also will the degree of crystallinity. This variation in the degree of crystallinity provides another reason for a post process anneal to homogenize the resin matrix structure, in addition to relieving the thermal stresses generated during the consolidation process.

**Effect of Gap Width on Processing Parameters**

A set of 3 additional panels were fabricated with increasing gap width distances from 30 mils (0.030") up to 50 mils (0.050"). This matrix was proposed to simulate the larger intertape gap widths that would be required for curved panel fabrication and to test the processes capability to close those gaps. The increase in gap width is required to keep the plies from buckling to allow a part with contour to be fabricated. The test matrix and processing conditions for these panels are shown on Table 10.2. Figure 10.11 shows the expected goal consolidation temperatures and maximum panel temperatures for the 4 increasing gap widths of this experiment. As seen in this figure, the effect of increasing the gap width is to require higher heat fluxes and consolidation temperatures, with the increased probability that thermal degradation of the resin will take place. Thermal degradation has been seen in previous In-Situ Consolidated thermoplastic panels at temperatures above 925 F \(^4\), the limiting line in this figure. With the increased size of the
gap widths, the resin must flow further in the same amount of time in the process to close
the gap. To create this increased flow rate, the viscosity must be lower, which is achieved
by higher processing temperatures. The rapid decrease of resin viscosity with increased
temperature is shown on Figure 10.3.

![Figure 10.11 Effect of Gap Width on Consolidation and Maximum Panel Temperatures](image)

**Figure 10.11 Effect of Gap Width on Consolidation and Maximum Panel Temperatures**

Creation of a Master Gas Flow Schedule for Consolidation

With the heat flux-gas temperature convection correlation and the gas torch
energy balance equations (described in Chapter 9), the gas temperature and gas flow rate
are calculated from the heat flux which yields the desired consolidation temperature in the
model. The first strategy used to calculate these critical fabrication parameters was to
account for all differences in applied heat flux between the different processing conditions
using the gas temperature convection correlation, Eqn. 9.64. The result of this strategy
yields the gas mass flow distribution, shown on Figure 10.12. In this figure all changes in
the heat flux between successive ply layers are created by changes in the mass flow of the
gas. All changes in the heat flux between panels with different processing conditions was
effected by changing the gas temperature. The use of this method to calculate these parameters yields a master gas flow distribution that is valid for all of the panels in the test matrix.

The gas temperature in this strategy is a constant throughout the fabrication of the entire panel, but differs from panel to panel depending on the required heat flux. This strategy is an attractive one because it greatly simplifies the setting of these two process parameters to attain the desired heat flux.

The master gas flow curve and temperature correlation strategy could have been used to fabricate the DOE test panels, except that the inert gas jet in the ICI pilot unit was not capable of operation at gas flow rates below 45 Standard Liters Per Minute or temperatures above 1800 F. Figure 10.12 shows that the majority of the panel lamination with the constant temperature strategy requires gas flow rates below the 45 SLPM minimum. Therefore this strategy was not viable with the constraints of the present processing equipment.

The second method to calculate the inert gas torch settings is to hold the mass flow rate constant at 45 SLPM throughout most of the panel fabrication. Use of this second strategy requires that the energy balance in Eqn. 9.63 be solved iteratively to attain the gas temperature for the desired incident heat flux. When the gas temperature calculated from this equation exceeds 1700 F, the mass flux is then allowed to increase above 45 SLPM, while holding the gas temperature constant at 1700 F. This second strategy, though more complex, allows the needed heat flux to be attained within both the minimum gas flow and maximum temperature limitations of the inert gas jet. The 1700 F gas temperature limitation of this strategy is less than the 1800 F maximum temperature of the gas jet. This decision was made to limit the temperature at 1700 F because it provides a more controllable set of gas flow conditions in previous processing experiments at ICI. The ten heat and mass flow schedules for the main DOE test panels were created using this second strategy and are contained in Appendix I.
Figure 10.12  Master Inert Gas Flow Rate Plot
Figure 10.13 shows the gas temperature distributions of the four gap width experiments as a function of the increasing panel thickness. In this figure, as the thickness increases the gas temperature decreases to yield the lower required heat fluxes needed for consolidation.

![Figure 10.13 Effect of Ply Layer on Required Gas Torch Temperature for Consolidation](image)

It should also be noted that in this series of experiments, the decreased gap widths require lower heat fluxes and therefore lower gas temperatures.

The results of this modeling effort show that the mass flow of the inert gas jet needs to be extended in new designs to allow lower flow rates to be obtained without burning up the torch. This becomes a requirement if the simpler first strategy for calculating and controlling gas jet parameters is desired. The need for low gas flow rates had not been anticipated or designed into the jet's operating parameters, because the initial heat flux on the first ply is high because of the highly conductive steel tool just beneath it. The heat flux was originally assumed to be constant during panel fabrication using DOE methodology.
This analysis gives an example where a processing science model of the process can be used up front during process development to help design the manufacturing equipment, so the machinery has the capability to provide operating conditions which are optimal for panel fabrication. The above examples of problem solving illustrate the usefulness of process science based modeling in the workings of a process development team as a learning tool to analyze problems and equipment limitations of the process.

Analysis Of Gap Width Between Adjacent Tapes

The standard deviation of the tape width (after it has been slit to a width of 1/4") has been measured to be approximately 2 mils. To attain an acceptably low probability of an overlap of the two normally distributed, independent tapes of 13 parts per million, they need to placed next to each other with a spacing of 4.24 times the standard deviation of their widths. This low probability of overlap is the equivalent of +3 sigma tail of a normal distribution of the tape width. When each tape has a width which is 3 sigma from its mean, then an overlap will occur. Therefore the gap width to be controlled by the tape head for the second proposed set of DOE panels in Table 10.4 was set at a value of 10 mils, which yields an overlap probability less than 13 ppm.

However, preliminary lamination experiments of thermoplastic panels at ICI showed that the standard deviation of the tape width increases to 10 mils after it has been laminated with the In-Situ Consolidation process. Therefore the use of a 10 mil intertape gap width would have resulted in significant lapping of the second tape over the first tape which has an increased variability in its width. This increase in the variability of the width after consolidation should have been anticipated by either the author or ICI, but was not, providing another example of learning loops in process development. Consultation with ICI processing engineers created the following equations to define the gap width and ply thickness during panel consolidation and are the underpinnings of the third set of DOE test conditions used to fabricate the panels.
As shown in Figure 10.14, the gap width is defined as the maximum distance between the two plies that the resin must flow to create a fully consolidated composite. To prevent overlap of the plies, the resin must flow no farther than this distance.

![Figure 10.14 Schematic Diagram of Gap Spacing Between Two Roll Consolidated Tapes](image)

**Figure 10.14** Schematic Diagram of Gap Spacing Between Two Roll Consolidated Tapes

Composite Tape Ply Previously Laminated to the Panel

Gap

0.75σ

"Backside" of Tape

Frontside

Backside

Index Spacing = 2*(w/2) + (Gap + 0.75 * σ_{cons}) + Gap Width

Maximum Gap Width = Gap + 1/2*(3.0)*σ_{cons}

Adjacent Composite Tape Before Lamination

From this figure, the Gap Width is given by;

10.1 \[ \text{Gap Width} = 1.5 \cdot \sigma_{\text{cons}} + \text{Gap} \]

where \( \sigma_{\text{cons}} \) is the standard deviation of the tape width variation after tape lamination, with half of the total 3\( \sigma \) variation (of an assumed normal distribution of tape widths) assumed to be on one edge of the tape (accounts for 1.5 factor used). The Gap parameter is the additional spacing allotted between the tapes to account for the variance of the
unconsolidated tape and the additional spacing between the tapes that is required when fabricating curved panels. This additional spacing is dictated by the curved natural path of the tapes to prevent tape buckling. For flat panels, the Gap parameter is from 3 to 5 mils to account for the width variation of the unconsolidated tape. Because the resin must flow to close the gaps between the tapes, the thickness of each ply layer after consolidation is less than the unconsolidated tapes. The Gap Width of the above equation is the same as the G parameter used for the gap width in Eqn. 9.50 of the previous chapter.

The use of a constant volume assumption of the tapes before and after consolidation gives the following expression;

\[ t_{\text{ply}} \cdot w_{\text{ply}} = V = t_0 \cdot w_0 \]

Therefore the final expression for the ply thickness after expansion and consolidation has taken place is:

\[ t_{\text{ply}} = \left[ \frac{w_0}{w_0 + \text{Gap Width} + \text{Gap} + 0.75 \cdot \sigma_{\text{cons}}} \right] \cdot t_0 \]

Because of the change in the ply thickness, the panel thickness will also be affected by the change in the consolidated tape variance and Gap Width. Variations in the degree of closure of the gap width caused by variations in the processing parameters of the process as will be described in the final section of this chapter will result in local changes in the ply thickness of the consolidated tape and will result in variations in panel thickness of the resulting panels. These bumpy surfaces were measured in the thickness measurements of the DOE panels fabricated for this project. The final panel thickness is given by the following expression;

\[ \text{Panel Thickness} = (N - 1) \cdot t_{\text{ply}} + t_0 \]

where \( N \) is the number of ply layers in the panel. The last term in this equation, \( t_0 \), is added because the first layer of the laminate is a 12 inch wide thermoplastic prepreg sheet
This layer of prepreg was used to assist the adhesion of subsequent layers to the laminate. Earlier processing trials have shown that it is difficult to laminate tapes directly to the tool surface. Because this first layer is not consolidated by the roller, its thickness remains that of the prepreg tape. The addition of this equation to account for the change of ply thickness with consolidation is an important addition to the process model, because the heat flux and gas temperature required to consolidate a given ply layer is a very strong function of the panel thickness, as shown on Figure 10.13.

To achieve the proper gap width between two adjacent plies, the processing head must properly index the distance between the centers of two adjacent ply layers. The schematic representation of the geometry during lamination of two adjacent composite tapes, Figure 10.14, shows the individual geometric components which together make up the Index spacing. From the geometric parameters of this figure the index spacing is given by the following expression:

\[ \text{Index Spacing} = w_0 + \text{Gap} + 0.75 \cdot \sigma_{\text{core}} + \text{Gap Width} \]

The third proposed matrix of DOE test conditions, which was actually used to fabricate the panels, used a gap width calculated by these equations to be 20 mils. This gap width spacing calculation takes into consideration the increase of variability of the consolidated tapes (through the use of \( \sigma_{\text{core}} \)) and yields the same acceptably low risk of two adjacent plies overlapping as before.

First Processing Trials

A first set of processing trials on the gap width panels of Table 10.2 was run at ICI Composite Structures. The surprising result of these first consolidation experiments was instead of forming gaps in the panels, these panels exhibited large laps. The largest of these laps in one layer of the panel was approximately 90 mils. The formation of laps occurs whenever the temperature in the process zone significantly exceeds that of the goal.
consolidation temperature. The high applied temperature allows the "backside" of the tape to overexpand so the next tape is laminated on top of it, forming a lap. The lap spacings of the first processing trial are shown in Figure 10.15. These spacings were measured by optical methods on the laminate after lamination of each layer of tape. Analysis of this problem revealed the process model assumed that the incident heat flux occurred on the top surface of the composite tape, while in the actual process equipment the heat was incident on the bottom surface. Modification of the analysis program to reflect this physical reality, revealed that the original set of processing conditions for these first panels would result in temperatures that were approximately 100 F too hot. Using the original heat flux settings in the modified process model, yielded a predicted value of the lap size which should have resulted under these conditions. These predicted values of the lap spacing are also shown on Figure 10.15 for comparison with the experimental data. This analysis was performed by inputting the heat fluxes for the panel fabrication from into ATPProcess with the proper location of the gas torch relative to the tape and roller. These calculations revealed that the consolidation temperatures were greater than the goal temperatures which according to the gap closure model would predict that lapping of the tapes should occur because of over expansion on the backside of the tape. The gap closure model was modified to yield the residual lap (or gap) that results from non optimal processing conditions which will be used in subsequent sections of this chapter.

The use of the modified model to explain the laps on the first consolidation experiments provided an unintentional calibration check of the model, before the DOE panels were fabricated. The panel fabrication parameters in Appendix I were all updated with the modified analysis program before fabrication was started. Each of these revised data sets have lower heat fluxes than the original sets, because less heat is required to attain the goal consolidation temperature when the heat is applied directly to the consolidation surface.
The overall lesson from this unintended set of experiments was the finding that this process has a narrow range of temperature where the consolidation in the process zone must be run if good panels are to be fabricated. Processing conditions or variations which result in consolidation conditions either too hot or cool will result in detrimental laps or voids. The next section will describe how variations in the processing variables create conditions that will result in voids or laps.
Figure 10.15  Lap and Gap Distribution for Mnfr Trial Gap Panel 6-1

Goal Lap/Gap Spacing of 0.0

Measured Lap Spacings on Panel

ATProcess Prediction of Lap Spacing With Proper Location of Heat Input

# of Ply Layers
Simulation of Variation of Manufacturing Process Parameters

Processing science analysis models have the capability of analyzing the variation of the primary processing parameters on the quality of the panels. The quality in this instance is defined as the variability in the lap or gap dimension which results from processing. The ideal quality panels are those which yield a mean value with zero lap or gap with the tightest possible distribution about the zero mean. The process variables which achieve this ideal are the best from this definition of quality. This analysis provides a sensitivity check on the processing parameters to achieve this tight distribution.

The stated variability in each of the processing parameters from the machine manufacturer, Automated Dynamics Corp., of +/- 5% for each parameter, were combined around the central processing conditions of each the DOE test panels, to simulate the highest and lowest temperatures which result from the combined process variations. These variations are shown on Table 10.5.
<table>
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<th>Panel &amp; Condition</th>
<th>Load (lbs)</th>
<th>Velocity (ips)</th>
<th>Tool Temp (°F)</th>
<th>Lap or Gap (mils)</th>
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</tr>
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<td>0.475</td>
<td>310</td>
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<td>#10 High</td>
<td>105</td>
<td>3.8</td>
<td>310</td>
<td>-8.5</td>
</tr>
</tbody>
</table>
When all the parameters run together to produce a low temperature condition, the goal consolidation temperature is not met and voids between the tapes result. When these process variations combine to produce a high temperature condition, the likelihood of resin burning becomes greater and the tapes overexpand under the roller on the "backside" of the tape, so that overlap between two adjacent tapes results. The maximum lap and gap sizes given by the analysis are plotted on Figure 10.16. The maximum lap or gap sizes on this figure are the 3 sigma limits of the variance of the critical lap/gap parameters that one would expect to find on the resulting panels. For a given panel, the size of the laps and gaps can vary from zero to as large as these limits, without indication that the process is out of control. If laps or gaps greater than these limits are observed, a shift in the process is likely to have occurred because the variance would be greater than the variation in the processing parameters would be able to account for. This would be an indication that the process is out of control on a control chart. This figure shows that some of the processing conditions are more robust to process variations and result in smaller voids and laps than others and are likely to result in stronger panels. Process conditions #1, #3, #5, and #9 appear to be the best from this standpoint with lap or gap size ranges of +/- 5 mils.
The variance analysis for all 10 processing conditions was performed for every second ply layer of each test condition. The result of these analyses showed that there was no effect of ply thickness on the resulting laps and gaps, except for the panels fabricated at the highest velocity, 4"/sec and the lowest roller load, 70 lbs. Under these conditions, #7 and #8 in the test matrix, the resulting lap and gap 3 $\sigma$ limit control charts are shown on Figures 10.17 and 10.18, respectively. These plots show the control limits as a function of ply layer number. Initially, a larger range of lap/gap sizes would be possible but would become smaller as the laminate became progressively thicker. The size of the variability allowed in these processing conditions would make them poor candidates for In-Situ Consolidation.

Because of the narrow processing "window" of the in-situ consolidation process, with the formation of voids on the low side and the creation of laps on the high side, process science variability simulations may indicate that improvement in the machine's capability to hold the desired processing parameters constant during panel manufacture is required to improve the panel quality (lap or gap size). Manufacturing process variance
simulations aid in the design and specification of new process equipment by determining the amount of control of the process variables required to attain the desired quality levels.

**Figure 10.17** Lap and Gap Spacing Variation With Ply Thickness: Panel #7

**Figure 10.18** Lap & Gap Spacing Variation with Ply Number For DOE Panel #8
Chapter 11

Designed Experiment Test Results and Discussion

The mechanical testing and nondestructive inspection of the designed experiment test panels will be described in this Chapter. The analysis and fabrication of these test panels was described in the previous chapter. The nondestructive inspection and mechanical testing was to confirm the predictions of the process model; to determine the best processing conditions for the In-Situ Consolidation process; and measure the effects of the processing parameters on the strength and quality of panels fabricated with this process. The results of the (+/- 45) laminate tests were compared to those from conventionally (autoclave) consolidated APC-2/AS-4 material to yield a benchmark of this process's relative maturity and to project the amount of future development effort required on this process.

Experimental Test Program

After fabrication, the designed experiment panels were C-scan Through Transmission Ultrasonic (TTU) inspected for internal defects. Mechanical surface profilometry measurements were also taken of the surface of the panels to measure the amount of warpage that occurred during fabrication. These nondestructive inspections were performed immediately after the panels were received so their results could be used to correlate with the results of the mechanical testing. After inspection, the panels were cut with a diamond abrasive wheel into 1"(+0.010"/-0.000") x 8" strips parallel to the longitudinal axis of the DOE panels. The lay-up used in the fabrication of these test specimens was chosen to be (+/-45)_{6s} (as described in Chapter 10) to produce maximum shearing force in the in plane direction and provide a test of the process's ability to laminate the tapes together to resist delamination. This laminate design was chosen over other structurally important laminates (such as a quasi-isotropic laminate) because the goal
of the program was to optimize the process, not to provide structural test data. 0.070" thick, (0/90) Fiberglass tabs were bonded onto the specimen ends to prevent crushing in the grips and 3/8", 5% strain gauges (Micro-Measurements EA-06-125AD-120) were bonded onto the center of test area in accordance with established strain gauge application techniques (45). The fiberglass tabs were bonded on with a room temperature curing, two part structural adhesive, (Scotchweld 2216) to prevent potential residual stress relaxation during a high temperature cure of the non-annealed test panels. A schematic of the complete mechanical test specimen is shown on Figure 11.1.

**Figure 11.1  (+/-45)ₜₜ Tensile Specimen Geometry**

The specimens were mechanically tested with a MTS 442, analog controlled, 100 KIP electro-servo hydraulic testing machine at room temperature, in laboratory air with an approximately constant, 72% relative humidity. Each specimen was tested in stroke control with a constant ramp rate of 1" in 1000 seconds to yield an approximate strain rate of 2.5 x 10⁻⁴ to a maximum potential strain of 25%. In all cases, the specimens failed
before this maximum strain limit was reached. All specimens failed near the center of the specimens; no instances of fiberglass tab pulloff or failure in the grips were observed. For the specimens tested to failure, to obtain the complete stress-strain curve, the data was collected with an Apple Mac II computer running Lab View using a data scan rate of 1Hz to balance the needs of data fidelity against the size of the storage files.

The Elastic Modulus in the longitudinal direction (long axis of the 8"x 5" panel) for each of the processing condition test panels was determined from a separate test of one specimen to a strain level of approximately 5000 microstrain (0.5% strain). The Elastic Modulus was determined from regression analysis of the Stress-Strain data with the strain data coming from the strain gauge which was bonded to the specimens, as the most accurate method to measure the strain on the specimen. In these tests, the data was collected from the test machine at 4 Hz, 4 times the normal data collection rate. The large number of data points gathered in the initial elastic region allowed the stress and strain data to be analyzed with a linear regression program, to determine the best value of the initial tangent elastic modulus. This initial modulus, at a low strain in the composite, was determined with an analysis technique developed by Vizzini (93) and Lagace (44) for thermoset matrix composites which exhibit non linear behavior after the initial straight line region. The tangent modulus is taken in the initial straight line region.

The load cell used for load data collection was a MTS 100 KIP load cell, recently calibrated with a NBS standard load cell. On the 10 KIP range used for load measurement in these experiments, the error in measurement of the maximum load ranged from one part in 150 to one part in 400 depending on the maximum load achieved in testing the various specimens.

The large plastic deformations measured in these tests, up to 20%, required the use of a clip-on extensometer with the capability to measure strains up to 18.3 %. All stress and strain data reported in this thesis is engineering stress and strain and as such does not
account for the reduction in the cross section or elongation in the gauge length as does true stress and strain data.

The microcrack detection was performed by the test operator positioned 6" from the specimen to detect the acoustic emissions emanated by the specimens. The cracks detected by the operator were able to correspond very accurately to the stress perturbations exhibited in the stress-strain curves. Index signals were manually input into the data log of the test when these cracks were audibly detected. This allowed the cracks to be related with the specimen strain when they were detected. The occurrence of the signals was plotted on the Stress-Strain curves as shown in Figure 11.2

Mechanical Test Results For The DOE Test Panels

The results of the mechanical tests of the Non-Annealed DOE panels is shown on Table 11.1. The results for the Annealed DOE panels is shown on Table 11.2. The Ultimate Tensile Strength of each composite specimen was determined at the maximum stress level attained in the test before the first large load drop occurred. These load drops were always associated with severe delamination cracking of the specimen at strain levels greater than that where the ultimate tensile strength occurred. The final failure mode observed was ply delamination and was the same for all the specimens tested. The ultimate tensile strength and the load drop exhibited in these tests are shown on Figure 11.2. This figure is a representative stress-strain curve of one of the specimens subjected to the in-plane mechanical test. This figure also shows the deformation energy, which is defined to be the energy under the stress-strain curve (obtained by computer numerical integration of this curve) from the origin to the strain level associated with the load drop. During each mechanical test, the strain levels that were associated with the first several audible microcracks detected were recorded.
FIGURE 11.2 REPRESENTATIVE STRESS-STRAIN CURVE OF MECHANICAL TESTS
SPECIMEN 1-AN-1

Stress (psi)

Ultimate Tensile Strength = 26,375 psi @ 7.5% Strain
Audible Microcracks Detected
Load Drop

Longitudinal
Microstrain

0 1.000 10^4 2.000 10^4 3.000 10^4 4.000 10^4 5.000 10^4 6.000 10^4 7.000 10^4 8.000 10^4 9.000 10^4 1.000 10^5 1.100 10^5 1.200 10^5 1.300 10^5 1.400 10^5 1.500 10^5 1.600 10^5 1.700 10^5 1.800 10^5 1.900 10^5 2.000 10^5 2.100 10^5 2.200 10^5 2.300 10^5 2.400 10^5 2.500 10^5 2.600 10^5 2.700 10^5 2.800 10^5 2.900 10^5 3.000 10^5
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<th>Elastic Modulus (ksi)</th>
<th>Eng. Ultimate Tensile Strength (ksi)</th>
<th>Eng. Strain at Load Drop (%)</th>
<th>Deformation Energy in-lb/in^3</th>
<th>Strain at First Crack (Eng.) %</th>
<th>Average Tensile Strength and Coeff. of Variation Kσ %</th>
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<td>1,3345</td>
<td>1.69</td>
<td>1.48%</td>
</tr>
<tr>
<td>1-AN-3</td>
<td></td>
<td>26287</td>
<td>5.77</td>
<td>1,235</td>
<td>3.57</td>
<td></td>
</tr>
<tr>
<td>2-AN-1</td>
<td>1.79</td>
<td>24116</td>
<td>10.71</td>
<td>2,393</td>
<td>1.10</td>
<td>23445</td>
</tr>
<tr>
<td>2-AN-2</td>
<td></td>
<td>23346</td>
<td>6.097</td>
<td>1,194</td>
<td>6.25</td>
<td>2.67%</td>
</tr>
<tr>
<td>2-AN-3</td>
<td></td>
<td>22874</td>
<td>5.246</td>
<td>950.1</td>
<td>1.47</td>
<td></td>
</tr>
<tr>
<td>3-AN-1</td>
<td>1.70</td>
<td>25443</td>
<td>13.74</td>
<td>3,061</td>
<td>12.5</td>
<td>25547</td>
</tr>
<tr>
<td>3-AN-2</td>
<td></td>
<td>25449</td>
<td>12.8</td>
<td>2,818</td>
<td>12.25</td>
<td>0.68%</td>
</tr>
<tr>
<td>3-AN-3</td>
<td></td>
<td>25748</td>
<td>11.74</td>
<td>2,422</td>
<td>11.95</td>
<td></td>
</tr>
<tr>
<td>4-AN-1</td>
<td>1.99</td>
<td>27233</td>
<td>11.568</td>
<td>2,930</td>
<td>6.0</td>
<td>26887</td>
</tr>
<tr>
<td>4-AN-2</td>
<td></td>
<td>26615</td>
<td>9.731</td>
<td>2,360</td>
<td>2.7</td>
<td>1.17%</td>
</tr>
<tr>
<td>4-AN-3</td>
<td></td>
<td>26814</td>
<td>12.11</td>
<td>2,872</td>
<td>11.08</td>
<td></td>
</tr>
<tr>
<td>5-AN-1</td>
<td>2.24</td>
<td>22798</td>
<td>5.862</td>
<td>1,324.</td>
<td>1.91</td>
<td>23653</td>
</tr>
<tr>
<td>5-AN-2</td>
<td></td>
<td>23048</td>
<td>7.953</td>
<td>1,582</td>
<td>2.64</td>
<td>5.37%</td>
</tr>
<tr>
<td>5-AN-3</td>
<td></td>
<td>25114</td>
<td>9.233</td>
<td>1,943</td>
<td>1.38</td>
<td></td>
</tr>
<tr>
<td>6-AN-1</td>
<td>1.93</td>
<td>19334</td>
<td>5.58</td>
<td>1,043</td>
<td>2.94</td>
<td>19165</td>
</tr>
<tr>
<td>6-AN-2</td>
<td></td>
<td>18602</td>
<td>4.16</td>
<td>703.7</td>
<td>1.06</td>
<td>2.61%</td>
</tr>
<tr>
<td>6-AN-3</td>
<td></td>
<td>19558</td>
<td>5.94</td>
<td>1,189</td>
<td>1.71</td>
<td></td>
</tr>
<tr>
<td>7-AN-1</td>
<td>1.33</td>
<td>8648</td>
<td>12.73</td>
<td>1,068.</td>
<td>0.35</td>
<td>9146</td>
</tr>
<tr>
<td>7-AN-2</td>
<td></td>
<td>9670</td>
<td>4.97</td>
<td>642.8</td>
<td>0.52</td>
<td>5.59%</td>
</tr>
<tr>
<td>7-AN-3</td>
<td></td>
<td>9122</td>
<td>11.71</td>
<td>1,058.</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>8-AN-1</td>
<td>Not Valid</td>
<td>9741</td>
<td>1.68</td>
<td>193.1</td>
<td>0.72</td>
<td>9823</td>
</tr>
<tr>
<td>8-AN-2</td>
<td></td>
<td>9507</td>
<td>1.525</td>
<td>234.3</td>
<td>0.45</td>
<td>3.71%</td>
</tr>
<tr>
<td>8-AN-3</td>
<td></td>
<td>10222</td>
<td>1.7</td>
<td>229.0</td>
<td>0.46</td>
<td></td>
</tr>
<tr>
<td>9-AN-1</td>
<td>1.56</td>
<td>7578</td>
<td>7.52</td>
<td>545.2</td>
<td>0.15</td>
<td>7112</td>
</tr>
<tr>
<td>9-AN-2</td>
<td></td>
<td>6813</td>
<td>3.22</td>
<td>401.0</td>
<td>0.05</td>
<td>5.75%</td>
</tr>
<tr>
<td>9-AN-3</td>
<td></td>
<td>6944</td>
<td>7.1</td>
<td>984.7</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>10-AN-1</td>
<td>Not Valid</td>
<td>4170</td>
<td>2.3</td>
<td>Not Valid</td>
<td>0.02</td>
<td>4003</td>
</tr>
<tr>
<td>10-AN-2</td>
<td></td>
<td>4006</td>
<td>1.2</td>
<td>Not Valid</td>
<td>0.03</td>
<td>4.18%</td>
</tr>
<tr>
<td>10-AN-3</td>
<td></td>
<td>3834</td>
<td>1</td>
<td>Not Valid</td>
<td>0.01</td>
<td></td>
</tr>
</tbody>
</table>
Analysis of Test Data With A Designed Experiment Analysis Methodology

The ultimate tensile strength of the (+/- 45) test specimens was analyzed using a statistical technique described by Montgomery (Chapter 12 in (50)) for the $2^3$ and $2^2$ test matrices contained within the 10 panels of the two sets (annealed and non-annealed) of panels fabricated. The nomenclature used in the previous sentence indicates that three processing variables were tested at two levels in the first matrix $2^3$, and that two processing variables were tested at two levels in the second, $2^2$. The design of experiments analysis methodology outlined in this reference allows the determination of statistically significant effects within designed experiment test matrices by use of a F test statistic which is a comparison of the magnitude of the mean squared error of each of the effects of the test matrix to the mean squared error of the noise of the overall matrix. If this F test for a given processing variable exceeds a preset value\(^1\) in the ANOVA (Analysis of Variance) (50) tables, then the effect is determined to be significant and the magnitude of this effect is included in the empirical correlation "model" of the process parameters generated by this analysis procedure. The effects that are not determined to be significant are not included in this empirical "model". An underlying assumption of this approach is that the effects of the process variables on the objective functions are linear functions. Therefore for these empirical "models" to be fit the observed data, the ranges over which they apply must be small and extreme care should be taken whenever $x$ or $y$ are used to extrapolate outside of the empirical test data ranges. Their usefulness in process development comes from the fact that they point to the direction in process space where more optimal processing conditions may be found.

---

\(^1\) The value of the F test parameter is based on the allowable probability of a Type II error (which is one that occurs when one determines that an effect is significant when it actually is not) and degrees of freedom of the effect and the noise in the matrix. The degrees of freedom of the noise or error is determined by the size of the test matrix (number of processing variables, levels of the processing variables that were tested at and number of specimen replicates)
The designed experiment approach may also be used with quarter or half factorial screening experiments as well as full factorial test programs such as this one. The advantage of full factorial tests is the higher level interaction effects are not "aliased" together and the effects of each can be determined separately. The disadvantage of full factorial experiments is they are more costly and time consuming to perform. The use of this methodology was used for the strength and residual stress data for each of the annealed and non-annealed test panels fabricated for this program.

Analysis of the Non-Annealed Designed Experiment Test Matrices

The main effects, sum of the squares, and the F tests for each of the primary processing variables for the three factor non-annealed DOE panels is shown on an ANOVA (Analysis of Variance) table, Table 11.3. From this table, all three of the main effects (Tool Temperature, Load and Head Velocity) along with the two factor V-P, velocity-pressure interaction effect, were significant at a probability level of a Type II error of less than 1% in the three factor test matrix. This data shown in the Table 11.3 is for process conditions 3-NA through 10-NA. The significant processing effects in the three factor designed experiment yields the following empirical equation for the Ultimate Tensile Strength of the (+/- 45) specimens.

\[
\sigma_{\text{ips}, \text{NonAnnealed}} = 14,333 - 4.766(T - 187.5) - 4078(V - 2.5) - 28.04(P - 85) + 9.215(V - 2.5)(P - 85)
\]

From this equation, it can be seen that the maximum failure stress in the three factor experiment is obtained at the minimum value of each of the primary processing variables, which corresponds to process condition #3-NA in the \(2^3\) test matrix. When the process parameter values at this process condition are substituted in Eqn.11.1, the result is the following expression;
11.2 $\sigma_{N_{an}}^{\text{NouAno}}_{\text{ips}} = 14,332 + 536.2 + 6,118 + 420.6 + 207.3 = 21,614$

mean tool temp velocity pressure V-P interaction

where the second term is the effect of the tool temperature, the third is the effect of the head velocity, the fourth is the effect of the pressure and the final term is due to the two factor velocity-pressure interaction. Equation 11.2 shows the predominant effect of the velocity in determining the strength of these panels in this experiment. The designed experiment analysis in Eqn. 11.2, calculates the strength of the #3-NA panels to be 20,614 psi, where the actual average strength of these panels was 21,280 psi. The good agreement between the calculated and actual strength of the panels is due to the relatively small amount of the mean squared error in the ANOVA table (Tables 11.3 and 11.4) when compared to the Mean Squared values of the significant effects.
### Table 11.3 ANOVA Analysis of the Processing Variables of the Non-Annealed Test Panels
Three Factor Designed Experiment; Test Conditions 3 through 10

<table>
<thead>
<tr>
<th>Processing Variable</th>
<th>Effect</th>
<th>Sum of the Squares</th>
<th>Degrees of Freedom</th>
<th>Mean Squared Error</th>
<th>F Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool Temp T</td>
<td>-1120.0 psi</td>
<td>7.526 E+06</td>
<td>1</td>
<td>7.526 E+06</td>
<td>121.21</td>
</tr>
<tr>
<td>Head Velocity V</td>
<td>-12235 psi</td>
<td>8.983 E+08</td>
<td>1</td>
<td>8.983 E+08</td>
<td>2531.72</td>
</tr>
<tr>
<td>Load P</td>
<td>-841.33 psi</td>
<td>4.247 E+06</td>
<td>1</td>
<td>4.247 E+06</td>
<td>11.97</td>
</tr>
<tr>
<td>TV</td>
<td>-695.3 psi</td>
<td>2.901 E+06</td>
<td>1</td>
<td>2.901 E+06</td>
<td>8.18</td>
</tr>
<tr>
<td>TP</td>
<td>-584.3 psi</td>
<td>2.049 E+06</td>
<td>1</td>
<td>2.049 E+06</td>
<td>2.77</td>
</tr>
<tr>
<td>VP</td>
<td>829.3 psi</td>
<td>4.127 E+06</td>
<td>1</td>
<td>4.127 E+06</td>
<td>11.53</td>
</tr>
<tr>
<td>TVP</td>
<td>-149.3 psi</td>
<td>1.338 E+05</td>
<td>1</td>
<td>1.338 E+05</td>
<td>0.38</td>
</tr>
<tr>
<td>ERROR</td>
<td></td>
<td>5.677 E+06</td>
<td>16</td>
<td>3.548 E+05</td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>9.249 E+08</strong></td>
<td><strong>23</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

At a 1% probability of a Type II error, the critical value of F is 8.53
Bold F values indicates effect passes the above significance test and is a significant parameter

### Table 11.4 Two Factor, Low Velocity Designed Experiment ANOVA Table:
Test Conditions 1,2,5 & 6 Non-Annealed

<table>
<thead>
<tr>
<th>Processing Variable</th>
<th>Effect</th>
<th>Sum of the Squares</th>
<th>Degrees of Freedom</th>
<th>Mean Squared Error</th>
<th>F Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool Temp T</td>
<td>-2297.2 psi</td>
<td>1.583 E+07</td>
<td>1</td>
<td>1.583 E+07</td>
<td>52.71</td>
</tr>
<tr>
<td>Head Velocity V</td>
<td>-3291.5 psi</td>
<td>3.250 E+07</td>
<td>1</td>
<td>3.250 E+07</td>
<td>108.365</td>
</tr>
<tr>
<td>TV</td>
<td>1447.8 psi</td>
<td>6.289 E+06</td>
<td>1</td>
<td>6.289 E+06</td>
<td>20.967</td>
</tr>
<tr>
<td>ERROR</td>
<td></td>
<td>2.399 E+06</td>
<td>8</td>
<td>2.999 E+05</td>
<td>1</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>5.702 E+07</strong></td>
<td><strong>11</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

At a 1% probability of a Type II error, the critical value of F is 11.26
Bold F values indicates effect passes the above significance test and is a significant parameter

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The second, non-annealed designed experiment analysis, contained on Table 11.4 is for the $2^2$ test matrix which was run at slow processing speeds (0.5 ips and 1.0 ips), and at a constant 100 lbs of load. The ANOVA analysis for this second test matrix shows that the effect of both the primary processing variables, tool temperature and head velocity, are significant along with the two factor, T-V, tool temperature-velocity interaction effect. From the magnitude of the effects shown on this table, the following empirical equation for the (+/-45) strength of the panels is derived;

\[
\sigma_{\text{ip}}^{\text{NA-slow}} = 21,255 - 10.21(T - 187.5) - 6582(V - 0.75) + 12.87(T - 187.5)(V - 0.75)
\]

Once again, the lowest levels of velocity and temperature (given processing condition #1-NA) yield the optimal strength levels of all the non-annealed DOE test panels. When these levels of processing conditions are substituted into Eqn. 11.3, the following equation results;

\[
\sigma_{\text{ip}}^{\text{NA-slow}} = 21,255 + 1,149 + 1,646 + 362 = 24,412 \text{ psi}
\]

which is a designed experiment analysis calculation of the (+/-45) tensile strength at processing condition #1-NA. The calculated value at this condition was 24,411 psi which compares favorably with the experimental average strength of this panel of 24,774 psi. The good correlative capability of the empirical process "model", Eqn. 11.3, is due once again to the relatively small level of the mean squared error to that of the significant effects in this test matrix. This analysis of the slow speed, $2^2$ DOE test matrix shows that lowering the tool temperature is nearly as large an effect as the decrease in head velocity at slower velocities. Therefore at lower processing velocities, the effect of decreasing the head velocity further is not as dominant an effect in relation to the tool temperature as it was at higher processing velocities. Another interesting result from this analysis is the increase in tool temperature actually decreases the strength of the panels. If the thermal
stresses (present under the roller during fabrication) controlled the strength of the panels, the negative effect of tool temperature measured in this experiment would not likely have been observed.

**Analysis of the Annealed Designed Experiment Test Matrices**

A second set of DOE panels were fabricated under conditions identical to those of the first set with the addition of a post processing annealing operation. Annealing the panels was accomplished by heating the panels to 570 F and holding the panels for four hours, in an attempt to remove the residual stresses created during processing and also to homogenize the resin microstructure. The annealing process was performed by using the internally heated vacuum tool that the panels were laminated on as the furnace to heat the panels to the annealing temperature. Therefore only one processing tool was required during fabrication. The vacuum holddown force on the laminates was continued during annealing process, in an attempt to produce flat laminates. The annealing process works through the action of viscoelastic stress re\textsuperscript{a}laxation in the resin of the macro residual stresses created during fabrication. For this reason, the annealing process is performed at temperatures significantly above the glass transition temperature of the resin. The temperature chosen, 570 F was selected as a compromise to allow the resin matrix to stress relax within a reasonable time period (4 to 6 hours), but not hot enough to allow gross deformation of the laminate under gravitational forces. The temperature chosen was selected on the recommendation of ICI Composite Structures from their extensive experience with APC-2 composites. As the data will show, this temperature may not be optimal for the annealing out of the residual stresses, but forms a first attempt to investigate this secondary process.

An ANOVA analyses of the two annealed panel, designed experiment test matrices are shown on Tables 11.5 and 11.6.
### Table 11.5 ANOVA Analysis of the Processing Variables of the Annealed Test Panels
Three Factor Designed Experiment; Test Conditions 3 through 10

<table>
<thead>
<tr>
<th>Processing Variable</th>
<th>Effect</th>
<th>Sum of the Squares</th>
<th>Degrees of Freedom</th>
<th>Mean Squared Error</th>
<th>F Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool Temp T</td>
<td>-1395.75</td>
<td>1.169 E+07</td>
<td>1</td>
<td>1.169 E+07</td>
<td>0.256</td>
</tr>
<tr>
<td>Head Velocity V</td>
<td>-12036 psi</td>
<td>8.678E+08</td>
<td>1</td>
<td>8.678 E+08</td>
<td>19.022</td>
</tr>
<tr>
<td>Load P</td>
<td>-4368.6</td>
<td>1.145 E+08</td>
<td>1</td>
<td>1.145 E+08</td>
<td>2.51</td>
</tr>
<tr>
<td>T V</td>
<td>178.25 psi</td>
<td>1.906 E+05</td>
<td>1</td>
<td>1.906 E+05</td>
<td>0.004</td>
</tr>
<tr>
<td>T P</td>
<td>-2404.4 psi</td>
<td>3.469 E+07</td>
<td>1</td>
<td>3.469 E+07</td>
<td>0.76</td>
</tr>
<tr>
<td>V P</td>
<td>439.41 psi</td>
<td>1.158 E+06</td>
<td>1</td>
<td>1.158 E+06</td>
<td>0.025</td>
</tr>
<tr>
<td>T V P</td>
<td>510.25 psi</td>
<td>1.562 E+06</td>
<td>1</td>
<td>1.562 E+06</td>
<td>0.034</td>
</tr>
<tr>
<td>ERROR</td>
<td>7.300 E+08</td>
<td>16</td>
<td>16</td>
<td>4.562 E+07</td>
<td>1</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1.762 E+09</td>
<td>23</td>
<td>23</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

At a 1% probability of a Type II error, the critical value of F is 8.53

Bold F values indicates effect passes the above significance test and is a significant parameter

### Table 11.6 Two Factor, Low Velocity Designed Experiment ANOVA Table:
Test Conditions 1,2,5 & 6 Annealed

<table>
<thead>
<tr>
<th>Processing Variable</th>
<th>Effect</th>
<th>Sum of the Squares</th>
<th>Degrees of Freedom</th>
<th>Mean Squared Error</th>
<th>F Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool Temp T</td>
<td>-3800.17 psi</td>
<td>4.332 E+07</td>
<td>1</td>
<td>4.332 E+07</td>
<td>71.788</td>
</tr>
<tr>
<td>Head Velocity V</td>
<td>-3592.16 psi</td>
<td>3.871 E+07</td>
<td>1</td>
<td>3.871 E+07</td>
<td>64.145</td>
</tr>
<tr>
<td>T V</td>
<td>-688.5 psi</td>
<td>1.422 E+06</td>
<td>1</td>
<td>1.422 E+06</td>
<td>2.356</td>
</tr>
<tr>
<td>ERROR</td>
<td>4.828 E+06</td>
<td>8</td>
<td></td>
<td>6.035 E+05</td>
<td>1</td>
</tr>
<tr>
<td>TOTAL</td>
<td>8.828 E+07</td>
<td>11</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

At a 1% probability of a Type II error, the critical value of F is 11.26

Bold F values indicates effect passes the above significance test and is a significant parameter
The analysis of the three factor test matrix, Table 11.5, showed that the mean squared error term of the annealed panels is much greater than in the previous non-annealed test matrices. For this test matrix, only two significant effects were determined, the head velocity and the load. (The load is very marginally significant) These significant processing variables yield the following empirical expression for the (+/-45) tensile strength in the three factor, annealed test matrix;

\[
\sigma_{\text{ipoa}}^{\text{Ann}} = 15,667 - 4009(V - 2.5) - 145.6(P - 85)
\]

Comparison of this equation with Eqn. 11.1, shows that the effect of the annealing process increases the mean (+/-45) tensile strength by 1334 psi. The annealing process did not statistically change the effect of head velocity significantly and only a slight change was observed in the main effect of the applied load (second term). The shift in the mean value shows that the annealing process improves the strength of all the panels in this matrix over their non-annealed counterparts. This was true for most of the panels except #9-NA and #10-NA which were fabricated at the fastest processing velocity, 4 ips. For these conditions the panels actually were degraded by the annealing process and ply layers actually fell off these laminates before they could be tested. The thermal expansion in heating up and cooling down these poorly bonded laminates may have caused the observed delamination and lower (+/-45) tensile strength. However for most of the panels, the annealing process was beneficial in increasing the degree of bonding between the ply layers and/or increasing the strength by reducing the residual stresses.

It is interesting that the effect of the tool temperature was not found to be a significant effect in this test matrix, as it was in the non-annealed test matrices. The tool temperature was shown to be a major factor controlling the magnitude of the thermal and residual stresses in Chapter 10. The annealing process has the potential to remove the residual stresses from the panel, therefore the annealing process has the potential to
remove much of the effect of the tool temperature from the mechanical properties. This is a likely explanation for the insignificance of the tool temperature effect for the three factor, annealed test panels. Inspection of Eqn. 11.5 shows that the maximum value of the (+/-45) tensile strength is again obtained at low values of load and head velocity in the three factor DOE test matrix. Therefore for the processing conditions of #3-AN and #4-AN, the maximum (+/-45) tensile strength is calculated with Eqn. 11.5 to be:

\[
\sigma_{\text{mean}}^{\text{ana}} = 15,667 + 6013 + 2184 = 23,864 \text{psi}
\]

The actual mean value of the (+/-45) tensile strength at these processing conditions was 26,217 psi. The larger difference between the actual mean strength and the calculated values for the annealed panels is due to the larger mean squared error noise shown in the experimental data of the ANOVA tables, Tables 11.5 and 11.6. In Eqn. 11.6, the effect of the head velocity once again predominates over the other significant effects as it did in the non-annealed panels.

Because the optimum strength in the three factor experiment occurred at the lower corner point in the test matrix, an EVOP (evolutionary operation) designed experimental technique would indicate that further experimentation is required at slower processing speeds to search for optimum processing conditions. A slow speed, \(2^2\) two factor, designed experiment similar to that run for the non-annealed panels, was also run for the annealed panels. The test results of this second annealed test matrix are reported on Table 11.6. At the slow processing speeds in this matrix, the primary processing effects for the annealed panels were the head velocity and tool temperature. From the magnitudes of the significant processing variables, the following empirical "process model" is obtained for the slow speed annealed DOE test matrix.

\[
\sigma_{\text{ips}}^{\text{ana-slow}} = 23,205 - 7184(V - 0.75) - 16.89(T - 187.5)
\]
As with the non-annealed, slow velocity, two factor experiment, the maximum strength is found at the minimum values of the tool temperature and head velocity. Substituting the values of these process conditions at Condition #1-NA into Eqn.11.7 yields the following expression:

\[ C_{\text{ips-Low}}^{\text{Ana}} = 23,025 + 1,796 + 1900 = 26,721 \text{psi} \]

Comparison of this expression with Eqn. 11.4 shows that the effect of annealing is to increase the mean strength of the panels in the two factor experiment by 2309 psi and increase the magnitude of the effect of the tool temperature. As can be seen from the above expression, the effect of head velocity did not change significantly with annealing process, while the tool temperature effect increased significantly to make it the dominant effect near the optimal processing condition of all the panels tested, #1-AN. The magnitude of the increase in strength after the annealing process at slow head velocities of 0.5 ips (2309 psi) is considerably larger than the 1334 psi increase in the slower three factor experiment. From this data the conclusion may be drawn that the effect of annealing is more significant at slow processing speeds. The calculated value of #1-AN in Eqn. 11.8 from the DOE effects analysis, 26,721 psi, is fairly close to the average of the experimental test data for this process condition, 26,997 psi. Finally, at the slower processing speeds of the 2² matrix, the annealing process was not able to remove the effects of the tool temperature on the +/- 45 panel strength from statistical significance, as it was able to do at higher processing speeds.

**Analysis of Panel Warpage Data**

Surface measurement of the test panels was carried out at 9 regularly spaced points along the panel surface in a rectangular array to determine the degree of warpage using the surface profilometry method. This method uses a mechanical measurement
device to determine the elevation of the surface relative to a standard. Measurement points were taken at each of the 4 corners, at the center and at the midpoint along each of the 3 longitudinal arcs (left and right and center) of the panels. These data points allowed the surface curvature to be measured along three arcs parallel to the longitudinal axis of the composite panel (along the left and right sides and in the center). Trigonometric manipulation of the three data points of each arc allowed the radius of curvature of the panel to be calculated for each arc. Most of the panel warpage occurred in the longitudinal direction of the panel as cylindrical bending. The residual stresses in cylindrical bending parallel to the longitudinal axis of the panel are calculated with wide beam theory from the radius of curvature through the following set of equations:

11.9a \[ \sigma_{\text{long}} = \frac{Mc}{I} \]

where \( M \) is the "effective applied moment" due to the residual thermal stress on the beam, \( c \) is the distance to the outer fiber from the midplane and \( I \) is the moment of inertia of the wide beam. Wide beam theory gives the following expression:

11.9b \[ \frac{E_1}{1 - v_{12}^2} \frac{d^2y}{dx^2} = M \]

where \( E_1 \) is the longitudinal elastic modulus and \( v_{12} \) is the in-plane Poisson's ratio. The panel's radius of curvature, \( R \), is by definition equal to;

11.9c \[ \frac{d^2y}{dx^2} = \frac{1}{R} \]

The final expression for the residual stress for a panel in cylindrical bending is therefore:

11.9d \[ \sigma_{\text{long}} = \frac{E_1 c}{(1 - v_{12}^2)R} \cdot \frac{h}{I} = \frac{E_1 \cdot h}{2 \cdot (1 - v_{12}^2) \cdot R \cdot \frac{bh^3}{12}} \]
The residual stress and radius of curvature data for the non-annealed panels are shown on Table 11.7. The data for the annealed panels are shown on Table 11.8. The measured longitudinal moduli values in Tables 11.1 and 11.2, along with a $v_{12}$ value of 0.66 calculated from a laminate plate theory analysis of the $(+/-45)_6$ laminate, were used to calculate the residual stresses. A cursory analysis of the data of these figures, shows that the residual stresses are lower for those processing conditions which yielded high mechanical strength. This data also shows that the annealed test panels showed significantly lower residual stresses than the non-annealed panels, as was expected. The panel warpage data for both the annealed and non-annealed panels and was analyzed with the same designed experiments analysis format as the mechanical test data. This format allowed a determination of the significant processing effects on the residual stresses of these panels. Table 11.9 presents an ANOVA table for the determination of the significant processing effects on residual stress for the Non-Annealed panels.
### Table 11.7 Non-Annealed DOE Panel Curvature Data

<table>
<thead>
<tr>
<th>DOE Panel #</th>
<th>Left Side</th>
<th>Center</th>
<th>Right Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-NA</td>
<td>425 psi / 456&quot;</td>
<td>464 psi / 416&quot;</td>
<td>435 psi / 445&quot;</td>
</tr>
<tr>
<td>2-NA</td>
<td>142.6 psi / 1595&quot;</td>
<td>142.6 psi / 1595&quot;</td>
<td>130.8 psi / 1740&quot;</td>
</tr>
<tr>
<td>3-NA</td>
<td>459 psi / 486&quot;</td>
<td>471 psi / 473&quot;</td>
<td>484 psi / 460&quot;</td>
</tr>
<tr>
<td>4-NA</td>
<td>278 psi / 810&quot;</td>
<td>319 psi / 709&quot;</td>
<td>305 psi / 740&quot;</td>
</tr>
<tr>
<td>5-NA</td>
<td>253 psi / 798&quot;</td>
<td>285 psi / 709&quot;</td>
<td>232 psi / 870&quot;</td>
</tr>
<tr>
<td>6-NA</td>
<td>480 psi / 430&quot;</td>
<td>526 psi / 392&quot;</td>
<td>492 psi / 420&quot;</td>
</tr>
<tr>
<td>7-NA</td>
<td>846 psi / 262&quot;</td>
<td>884 psi / 252&quot;</td>
<td>920 psi / 242&quot;</td>
</tr>
<tr>
<td>8-NA</td>
<td>190 psi / 1276&quot;</td>
<td>365 psi / 660&quot;</td>
<td>365 psi / 660&quot;</td>
</tr>
<tr>
<td>9-NA</td>
<td>1212 psi / 171&quot;</td>
<td>1224 psi / 169&quot;</td>
<td>1279 psi / 162&quot;</td>
</tr>
<tr>
<td>10-NA</td>
<td>193 psi / 1068&quot;</td>
<td>182 psi / 1126&quot;</td>
<td>227 psi / 916&quot;</td>
</tr>
</tbody>
</table>

### Table 11.8 Annealed DOE Panel Curvature Data

<table>
<thead>
<tr>
<th>DOE Panel #</th>
<th>Left Side</th>
<th>Center</th>
<th>Right Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-AN</td>
<td>165 psi / 2257&quot;</td>
<td>376 psi / 452&quot;</td>
<td>188 psi / 903&quot;</td>
</tr>
<tr>
<td>2-AN</td>
<td>84.3 psi / 2580&quot;</td>
<td>48.2 psi / 4516&quot;</td>
<td>36.1 psi / 6021&quot;</td>
</tr>
<tr>
<td>3-AN</td>
<td>205 psi / 951&quot;</td>
<td>422 psi / 463&quot;</td>
<td>75.8 psi / 2581&quot;</td>
</tr>
<tr>
<td>4-AN</td>
<td>45.9 psi / 4321&quot;</td>
<td>207 psi / 960&quot;</td>
<td>80.3 psi / 2469&quot;</td>
</tr>
<tr>
<td>5-AN</td>
<td>461 psi / 430&quot;</td>
<td>571 psi / 347&quot;</td>
<td>592 psi / 334&quot;</td>
</tr>
<tr>
<td>6-AN</td>
<td>169 psi / 1390&quot;</td>
<td>104 psi / 2258&quot;</td>
<td>52.1 psi / 4515&quot;</td>
</tr>
<tr>
<td>7-AN</td>
<td>558 psi / 420&quot;</td>
<td>493 psi / 475&quot;</td>
<td>363 psi / 645&quot;</td>
</tr>
<tr>
<td>8-AN</td>
<td>701 psi / 263&quot;</td>
<td>793 psi / 233&quot;</td>
<td>650 psi / 284&quot;</td>
</tr>
<tr>
<td>9-AN</td>
<td>24.3 psi / 9037&quot;</td>
<td>921 psi / 238&quot;</td>
<td>1430 psi / 153&quot;</td>
</tr>
<tr>
<td>10-AN</td>
<td>687 psi / 317&quot;</td>
<td>566 psi / 384&quot;</td>
<td>542 psi / 403&quot;</td>
</tr>
</tbody>
</table>
Table 11.9 ANOVA Analysis of the Effect of the Processing Variables on the Warpage and Residual Thermal Stress of the Non-Annealed Panels

<table>
<thead>
<tr>
<th>Processing Variable</th>
<th>Effect</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Mean Squared Error</th>
<th>F Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool Temp T</td>
<td>-385.33</td>
<td>890930.</td>
<td>1</td>
<td>890930.</td>
<td>466</td>
</tr>
<tr>
<td>Head Velocity V</td>
<td>275.41</td>
<td>455080.</td>
<td>1</td>
<td>455080.</td>
<td>238</td>
</tr>
<tr>
<td>Load P</td>
<td>58.285</td>
<td>20383</td>
<td>1</td>
<td>20383</td>
<td>10.6</td>
</tr>
<tr>
<td>T V</td>
<td>-421.67</td>
<td>1,066,900</td>
<td>1</td>
<td>1,066,900</td>
<td>558</td>
</tr>
<tr>
<td>T P</td>
<td>-11.960</td>
<td>858.27</td>
<td>1</td>
<td>858.27</td>
<td>0.448</td>
</tr>
<tr>
<td>V P</td>
<td>66.46</td>
<td>26513</td>
<td>1</td>
<td>26513</td>
<td>13.86</td>
</tr>
<tr>
<td>T V P</td>
<td>-218.48</td>
<td>286400</td>
<td>1</td>
<td>286400</td>
<td>150</td>
</tr>
<tr>
<td>ERROR</td>
<td></td>
<td>30589</td>
<td>16</td>
<td>1911.8</td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>2,777,600</td>
<td>23</td>
<td>120,770</td>
<td></td>
</tr>
</tbody>
</table>

At a 1% probability of a Type II error, the critical value of F is 8.53. Bold F values indicate effect passes the above significance test and is a significant parameter.

From Table 11.9, it can be observed that the primary effects controlling residual stress are the tool temperature and head velocity. A T-V, (tool temp.-velocity) two factor effect, and a T-V-P, (tool temp-velocity-pressure) three factor interaction effect are also significant factors affecting the warpage of the panels in this matrix. The following expression is a mathematical representation of the residual stress as a function of the processing variables identified in Table 11.9.

\[
\sigma_{\text{residual}}^{NA} = 519 - 1.7133(T - 187.5) + 91.779(V - 2.5) - 0.625(T - 187.5)(V - 2.5) - 0.01079(T - 187.5)(V - 2.5)(P - 85)
\]
Eqn. 11.10 shows that the smallest thermal stress (which corresponds to the least amount of panel warpage) occurs when the tool temperature is at 300 F, the velocity is 1 ips or less and the head load P is at 70 lbs. When these values of the processing parameters are substituted into Eqn. 11.10, the following expression results:

\[ \sigma_{\text{residual}}^{\text{NA}} = 519 - 193 - 137.7 + 105.4 - 27.3 = 266.3 \text{ psi} \]

Mean Temp Velocity T-V Interaction T-V-P Interaction

This expression shows that the increase in the tool temperature is the largest single factor in reducing the residual stresses in the laminate after processing in these non-annealed panels as is expected from the arguments in Chapter 10 on residual stresses. The reduction in the macro residual stresses in the panel is due to the decrease in both the longitudinal and through thickness thermal gradients during processing. Eqn. 11.11 also shows that a decrease in head velocity decreases the thermal residual stresses and panel warpage, the second most important factor. As was shown on Figure 10.3, the increase in head velocity requires higher goal and maximum consolidation temperatures which would increase the \( \Delta T \) in the panel and the residual thermal stresses. The experimental average residual stress for Panel 4-NA is 301 psi, while the calculated thermal stress given by Eqn. 11.11 for this panel is 266 psi, showing the reasonable fit of the empirical correlation "model" to the measured residual stress data. Finally, the calculated residual stress value in Eqn. 11.11 is a factor of 4.5 less than the maximum residual stress measured in Panel 9-NA which was processed at a high velocity and consolidation temperature coupled with a low tool temperature. This demonstrates the amount of variance in the degree of panel warpage and residual stress that is possible with the change of the processing variables.

The Annealed test panels were measured and analyzed in the same way as the Non-Annealed panels. The results of the designed experiment analysis of the derived residual stress for the annealed panel are shown on Table 11.10. This ANOVA table shows the significant process variables in this experiment. As expected, the results show
that the annealing process has removed the strong tool temperature major effect and two higher order interaction effects which included tool temperature (T-V and T-V-P) that were present in the non-annealed panels. The head velocity remains as the only strong effect parameter affecting warpage and residual stress in the annealed panels. The empirical equation of the residual stress for the annealed panels is:

\[ \sigma_{\text{residual}}^{\text{Ann}} = 446.5 + 131.82(V - 2.5) + 0.02764(T - 187.5)(P - 85) \]

Comparison of this equation with Eqn. 11.10, shows that the annealing process has relieved 72.5 psi of the internal stress through its decrease of the mean effect. This equation also shows that the lowest head velocity, and the lowest head load, represented by processing condition #1-AN yields the least amount of panel warpage and residual stress. Substitution of these processing conditions into Eqn. 11.12 yields the residual stress under these conditions to be:

\[ \sigma_{\text{residual}}^{\text{Ann-low}} = 446.7 - 197.7 - 46.6 = 202.3 \text{psi} \]

The warpage of the panel produced with processing condition #1-AN, which exhibited this low level of residual stress, was only +/- 4 mils, a fairly small value. However even at these low levels of residual stress, larger panels produced with this process would exhibit significant deflections.

The use of slow head velocities during fabrication and the use of post processing annealing will be required to minimize the effect of the internal stresses in warping the panels. Fortunately these processing conditions also create panels which possess the maximum +/- 45 tensile strength.
Table 11.10 ANOVA Analysis of the Effect of the Processing Variables on Residual Stress and Warpage of the Annealed Panels

<table>
<thead>
<tr>
<th>Processing Variable</th>
<th>Effect</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Mean Squared Error</th>
<th>F Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool Temp T</td>
<td>-126.55</td>
<td>96097</td>
<td>1</td>
<td>96097</td>
<td>1.123</td>
</tr>
<tr>
<td>Head Velocity V</td>
<td>395.58</td>
<td>719150</td>
<td>1</td>
<td>719150</td>
<td>8.4104</td>
</tr>
<tr>
<td>Load P</td>
<td>127.48</td>
<td>97515</td>
<td>1</td>
<td>97515</td>
<td>1.1404</td>
</tr>
<tr>
<td>TV</td>
<td>151.93</td>
<td>138500</td>
<td>1</td>
<td>138500</td>
<td>1.6197</td>
</tr>
<tr>
<td>TP</td>
<td>-186.55</td>
<td>208820</td>
<td>1</td>
<td>208820</td>
<td>2.4421</td>
</tr>
<tr>
<td>VP</td>
<td>-24.929</td>
<td>3729.1</td>
<td>1</td>
<td>3729.1</td>
<td>0.04361</td>
</tr>
<tr>
<td>TVP</td>
<td>-31.706</td>
<td>6032.4</td>
<td>1</td>
<td>6032.4</td>
<td>0.07055</td>
</tr>
<tr>
<td>ERROR</td>
<td></td>
<td>1,368,100</td>
<td>16</td>
<td>85506</td>
<td>1</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>2,637,900</td>
<td>23</td>
<td>114690</td>
<td></td>
</tr>
</tbody>
</table>

At a 1% probability of a Type II error, the critical value of F is 8.53
Bold F values indicates effect passes the above significance test and is a significant parameter

Discussion of the Mechanical Test Results

The dominant processing effect found in all four of the mechanical test matrices was the effect of head velocity. Two potential mechanisms were identified in the analysis to explain the decrease in the (+/- 45) strength at higher processing speeds. These mechanisms will be detailed in the following paragraphs.

The first mechanism identified for the lower (+/- 45) strength at higher processing speeds is caused by the higher consolidation temperatures required for gap closure between adjacent tapes at higher processing speeds. After the consolidation temperature exceeds 875 F, degradation of the resin could cause the observed lower strengths.
Because the failure mechanism observed was delamination of the plies in each specimen, the strength measured in the mechanical tests of this project is dependent upon the strength of the bond between adjacent plies in the laminate. The bond strength is dependent on the strength of the resin matrix between the plies. Therefore degradation of the resin's properties should lower the bond strength between the plies and therefore the interlaminar strength in these specimens. Figure 11.3 shows the change in the tensile strength of the test panels as a function of the analyzed consolidation temperature. As the temperature exceeds 875 degrees F, the (+/- 45) strength of the laminate decreases rapidly.

The failure mode observed in all the (+/- 45) strength tests was the delamination of the ply layers from each other during the test, resulting in a "brushy" fracture surface. In effect, the interlaminar stresses upon the specimens effectively tore the lamina layers from each other. Figure 11.4 contains photographs of fracture surfaces of specimens fabricated with process conditions 3-AN, and 7-AN. In each case, this figure shows the specimens failed by interply delamination. It may also be observed from this figure that the first plies to delaminate were the topmost plies, which were the last to be laminated, at the coolest processing conditions. This is less pronounced for Specimen # 3-AN than for 7-AN. The analysis of the fracture surfaces in this figure confirms that the strength in this (+/- 45) test was controlled by the interlaminar strength between the ply layers.

At the highest processing velocity, 4 ips, where panel 7-AN was fabricated, a small residence time would exist where the tape is in contact with the underlying laminate and the pressure of the roller. The strongly negative effect of the processing velocity in the DOE analysis would indicate that longer residence times are required to effect strong "diffusion bonds" (terminology borrowed from the titanium bonding literature) which translates into high (+/-45) strengths, from the argument in the previous paragraph. Figure 11.5 shows the mechanical strength of the test specimens as a function of their residence time under the roller. This plot shows that the (+/-45) strength increases as the
residence time under the roller increases. Because a diffusion bonding model of thermoplastic lamina was not included in ATProcess, the effect of velocity on the interface bond strength was therefore not predicted by the process model. Subsequent work to develop such a model is required to fully understand the (+/-45) strength behavior of In-Situ processed thermoplastic composites.

It is quite possible that both the residence time and consolidation temperature mechanisms operate in this process and together create the strongly negative effect of increasing velocity on the (+/-45) strength. From the data of this test program, it would appear that head velocities above 1 ips cannot be contemplated for acceptable composite resistance to delamination.
Figure 11.4  Delamination Failure Surface of In-Situ Consolidated Specimens

Panel 3-AN

Panel 7-AN

3-AN

7-AN
Figure 11.5 Contact Time Under Roller Versus Strength
Classification of Stress -Strain Curves

on Figure 11.6, is representative of the behavior of most of the specimens tested. This type of mechanical behavior was designated as Type I behavior. In this test, the first microcracks were detected at low strain levels from 1.0 to 2.5%, corresponding roughly to the initial onset of plasticity in the thermoplastic resin matrix of these (+/- 45) specimens. The elastic yield strain of the matrix occurs at a longitudinal strain level of 1.8% in these panels. During the observation of these tests, the detection of audible interlaminar microcracks corresponded to the delamination of plies occurring in the specimen. For specimens with especially poor bonding, such as #9-AN, the delamination occurring during the detection of a interlaminar crack caused surface plies to fall from the specimen. The low strain level for these first few interlaminar microcracks is indication of significant variance in the interlaminar strength (either shear or face tension) between the plies. As shown on this figure, the first plies delaminate at roughly one third of the maximum strength in the panels. The low shear or face tension strength of these weakly bonded plies is additional evidence that some plies are not as well bonded as others during processing.

The weakly bonded plies were observed to occur most frequently at the top surface of the specimen for those specimens whose ultimate strengths did not exceed 10 Ksi. These topmost plies were consolidated to the laminate with the lowest heat flux setting. For the processing conditions where Type I mechanical behavior and low strengths were observed, this is evidence that a higher heat flux setting is required as the panel thickness builds up than was used in consolidating the panels. A potential reason for these poorly bonded top plies is the model calculates that the laminate is a better insulator than it really is. With the low transverse thermal conductivity used, the model would decrease the heat flux more rapidly with increasing thickness than it should. The result of a low heat flux setting would be a low temperature in the fusion zone and the presence of intertape gaps.
This would be more pronounced at faster processing speeds, where the material is exposed to the heat flux for a shorter period of time. Better transverse and longitudinal coefficients of thermal conductivity may improve the model's predictions for the last plies in thick lay-ups.

As the strain level increases in this figure, progressively more interlaminar microcracks are detected as more interfaces delaminate. The specimen increases in strength to a maximum value where a large crack is detected and a large drop in stress occurs after this peak. After these large cracks propagated the compliance of the specimen increased so the stress the specimen was able to hold at a given strain was less. Although the specimen continued to hold load at higher strain levels after this maximum level was reached, the maximum stress and the strain corresponding to it were chosen to represent failure, in an engineering sense if not in an absolute sense. Specimens exhibiting this behavior are listed in Table 11.11.

<table>
<thead>
<tr>
<th>Type I</th>
<th>Avg. Strength</th>
<th>Type II</th>
<th>Avg. Strength</th>
<th>Type III</th>
<th>Avg. Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-NA</td>
<td>24770</td>
<td>7-NA</td>
<td>8812</td>
<td>3-AN</td>
<td>25550</td>
</tr>
<tr>
<td>2-NA</td>
<td>21030</td>
<td>9-NA</td>
<td>9483</td>
<td>4-AN (2 of 3)</td>
<td>26920</td>
</tr>
<tr>
<td>3-NA</td>
<td>21280</td>
<td>5-NA (1 of 3)</td>
<td>19428</td>
<td>2-AN (2 of 3)</td>
<td>23730</td>
</tr>
<tr>
<td>4-NA</td>
<td>21290</td>
<td>7-AN</td>
<td>9147</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-NA (2 of 3)</td>
<td>20350</td>
<td>2-AN (1 of 3)</td>
<td>22874</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6-NA</td>
<td>19190</td>
<td>4-AN (1 of 3)</td>
<td>26814</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8-NA</td>
<td>7680</td>
<td>8-AN</td>
<td>9823</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10-NA</td>
<td>6934</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-AN</td>
<td>23650</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>6-AN</td>
<td>19160</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9-AN</td>
<td>7112</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The second type of stress-strain curve, shown on Figure 11.7, is characterized as "sawtooth", Type II, fracture. Type II behavior differs from that of Type I shown on the
previous figure by the presence of several load drops in their stress-strain curve. Each of these successive points of maximum stress occur at levels which are greater than the previous value. At each point of maximum stress an interlaminar microcrack was detected which caused the load to drop. In this second type of behavior, the stress in the specimen begins to build up once again after the load drop, building to another maximum stress level. This is in contrast to type I behavior where after the first load drop the stress in the specimen never approaches that of the first point of maximum stress. The major difference between this type of behavior and Type I, is the much earlier onset of non-linear stress-strain behavior and extensive interlaminar cracking. The stress-strain curve of Type II behavior resembles a "sawtooth" pattern of increasing stress during the progressive straining followed by delamination relieving the stress after the next maximum stress level is reached. As with Type I specimens, the stress level for the first interlaminar microcrack was quite low, indicating that some plies in the laminate were poorly bonded. Although Type II specimens were able to attain respectable levels of deformation energy and strain to their maximum load drop, most of these specimens were not exceptionally strong and in most cases inferior to those exhibiting Types I and III behavior.

The final type of stress-strain curve, which typifies Type III behavior, is shown on Figure 11.8. This behavior was exhibited by the strongest specimens in the test program. The following processing conditions, #2-AN, #3-AN and #4-AN generated stress-strain curves of this type. These processing conditions are at slow head velocities and yielded mechanical strengths of approximately 25 Ksi. In contrast to the previous types, interlaminar microcracks were not detected at low values of strain in these specimens, indicating that all plies in these laminates have interlaminar strengths above some minimum value. When the first plies in this type of specimen delaminated, they all began to delaminate. In contrast to type I specimens, the top most plies in these specimens were as well bonded as the initial plies, indicating that the gas temperature schedule for panel fabrication of these panels yielded the proper results. These specimens exhibited over
10% (in most cases 12 to 13%) strain before the load drop was detected. As shown on
the figure, the level of strain where the first cracking was observed corresponded to the
point where the maximum stress was observed. These specimens not only exhibited the
highest strength and strain to load drop, but they also possessed the highest deformation
energy (by a factor of two to ten) over specimens whose deformation behavior is
characterized by the previous two classifications. Finally, those specimens which best
exhibited Type III behavior (conditions #3) also were analyzed to have the lowest
variability in their lap/gap sizes, as shown on Figure 10.16. To attain Type III mechanical
behavior, a small variation in interlaminar bond strength and lap/gap sizes is required in
addition to high interlaminar bond strength. This type of mechanical behavior will be
required from the materials created with the optimum processing conditions.
FIGURE 11.6 CATEGORY I MECHANICAL TEST BEHAVIOR:
PROGRESSIVE CRACKING TO AN ULTIMATE TENSILE STRESS
FOLLOWED BY A LOAD DROP
SPECIMEN 5-AN-1

Stress (psi)

0
5000
1.000 x 10^4
1.500 x 10^4
2.000 x 10^4
2.500 x 10^4

Ultimate Tensile Strength = 22,798 psi @ 5.86% Strain

Audible Microcracks Detected

Longitudinal Microstrain

1.000 x 10^-4
2.000 x 10^-4
3.000 x 10^-4
4.000 x 10^-4
5.000 x 10^-4
6.000 x 10^-4
7.000 x 10^-4
8.000 x 10^-4
FIGURE 11.7 CATEGORY II MECHANICAL TEST BEHAVIOR:
"SAWTOOTH" FRACTURE
SPECIMEN 7-AN-1
FIGURE 11.8 CATEGORY III MECHANICAL TEST BEHAVIOR: NO MICROCRACKING UNTIL ULTIMATE TENSILE STRENGTH IS REACHED SPECIMEN 3-AN-3

Stress (psi)

Longitudinal Microstrain
Maturity of the Process and the Effect of Fiber Waviness on Modulus of Elasticity

Observation of Tables 11.1 and 11.2 shows that the initial elastic modulus measured for the In-Situ consolidated materials range from 2.2 to 1.8 Msi. These modulus values are substantially below that which is predicted for a +/- 45 degree laminate of APC-2/AS-4 of 2.35 Msi as shown in Figure 11.9. This carpet plot of Elastic modulus values with increasing cross ply angles was calculated using laminate plate theory and manufacturer-supplied lamina data (34) as input as shown on Table 11.12.

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<td>σ₁₂</td>
<td>27</td>
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</table>

To explain this substantial variance in the observed modulus in the In-Situ consolidated specimens from their predicted values, three potential hypotheses were considered. The first is the presence of residual voids in the laminate after processing. A rule of mixtures analysis of the longitudinal direction modulus would indicate that a 30% void volume would have needed to be present for the void content to explain the reduction in composite modulus that was observed. Measurement of the density of the test specimens showed that the as-consolidated material was within 5% of theoretical density, so that a 30% void volume content was not possible. The second hypothesis considered was the angle of ply lay-up differed significantly from the desired 45 degree orientation. As shown on Figure 11.9, if the ply angle is increased from 45 degrees to over 50 degrees,
the modulus of the laminate would decrease from 2.85 Msi to the observed range of the specimens. This hypothesis was ruled out by measuring the ply orientations of all the specimens under a 15 power stereoscope with a protractor. From the data measured, the ply angle was;

\[ \text{Ply Angle} = 46.04 \pm 1.011 \text{ Degrees (66\% Probability of Mean Between Bounds)} \]

which indicates that the panels were fabricated with the proper ply angle, 45 degrees. In this measurement the desired mean is within one standard deviation of the measured mean. Therefore this hypothesis can be ruled out as the mechanism for the low observed specimen modulii. During observation of the panels under the stereoscope revealed that the fibers were no longer straight with respect to the tape boundaries. The observed fibers exhibited substantial waviness, appearing sinusoidal in shape with an amplitude approximately equal to the wavelength. This was predicted in Chapter 10 (on Figures 10.8 through 10.10) in the analysis of compressive thermal stresses in the fusion zone during fabrication. In that chapter the compressive thermal stresses were postulated to cause microbuckling and waving of the fibers.
FIGURE 11.9 CARPET PLOT OF APC-2/IM-7
LONGITUDINAL ELASTIC MODULUS WITH PLY ANGLE

LONGITUDINAL ELASTIC MODULUS (MSI)

PREDICTED MODULUS FOR A +/- 45 LAMINATE
APC-2' AS-4 LAMINATE

LONGITUDINAL ELASTIC MODULUS OF (+/- ANGLE)

PLY ANGLE (+/- DEG)

2.5 3 3.5 4
38 40 42 44 46 48 50 52 54
2 2.5 3 3.5 4
The micromechanical model of Gillespe et al. (23) was used to describe the effects of the waviness on elastic modulus of the resulting laminate to determine if fiber waviness in the laminates was responsible for the low elastic modulus. In this model, the fibers are modeled to be sinusoidal in their shape within the consolidated laminate. The following modified equation gives the local elastic modulus as a function of the local fiber angle, at any point in a wavy ply:

\[
\frac{1}{E_x(\theta)} = \frac{\cos^4(\theta)}{E_{11}} + \left[ \frac{1}{G_{12}} \frac{2v_{12}}{E_{11}} \right] \sin^2(\theta) \cos^2(\theta) + \frac{\sin^4(\theta)}{E_{22}}
\]

where \( \theta \) is the local angle of the fiber to the longitudinal axis of the fiber. Numerically integrating the above equation through one-half wavelength of a sinewave allows the determination the average elastic modulus of the wavy ply that would be exhibited in a mechanical test. The results of this analysis shows that the elastic modulus of a ply is a function of the amplitude to wavelength ratio, as shown on Figure 11.9b. This figure demonstrates that when the amplitude of the wavy fibers is approximately equal to one wavelength, a 30% reduction in the elastic modulus of the ply results.

The observed sinusoidal amplitude of the fibers in the topmost plies of In-situ consolidated panels was approximately 0.05", while the wavelength was also 0.05". These amplitudes and wavelengths were measured with a 15X optical stereoscope while measuring the ply angles. From Figure 11.9b, the observed waviness of the fibers in these topmost plies would yield an elastic modulus whose magnitude is 70% of that which would be obtained if the fibers had remained straight. This model demonstrates that fiber waviness is substantially responsible for the observed 30% decrease in the modulus of In-Situ consolidated laminates as compared to conventional autoclave processed thermoplastic materials, where the fibers remain straight. Not all of the plies in the laminate were wavy because the first ply in the laminate was a layer of prepreg which was not consolidated during processing. It is likely that all the other plies in the laminate were
wavy although only the last ply's surface could be viewed directly. Because of the changes in processing conditions during consolidation, the fiber waviness is likely to be a function of thickness.

Data from ICI Fiberite (the material's manufacturer) on APC-2/AS4 (34) shows that autoclave consolidated prepreg of this material in the +/-45 lay-up orientation has a ultimate strength of 56 Ksi and a strain to failure in this test of 17%. The best mechanical test specimens in this test program, from processing conditions #1-AN and #4-AN, had ultimate tensile strengths of 26 to 27 Ksi, roughly half that of the autoclave processed material. The low measured modulus of elasticity in the In-situ consolidated panels would account for approximately 5 ksi of the lower (+/-45) tensile strength, but the remaining 20 ksi difference will require further improvements in bonding between plies to attain parity with the autoclave process. This may be accomplished with some combination of higher applied loads or slower processing velocities (below 0.5 ips). The strain-to-failure of
these materials will be improved through the elimination of the low strain cracking caused by the poor bonds. Elimination of these defects will have the effect of pushing out the strain level where catastrophic cracking occurs (load drop) and increasing the maximum tensile strength. Obviously, the slower processing speeds make In-Situ Consolidation less attractive from an economic standpoint, so a tradeoff between economy and panel strength will have to be established.

C-Scan TTU Analysis of Test Panels

C-scan TTU non destructive inspection utilizes an ultrasonic acoustic sound wave which is transmitted through the composite test panels. On the opposite side of the panel an ultrasonic transducer picks up the transmitted energy and measures the amount of attenuation in the signal after it has passed through the panel. The emitter and transducer are rastered across the panel to yield a video image of the amount of attenuation to the position on the panel where the signal was measured. Previous experience with this inspection system has shown that the degree of attenuation is proportional to the amount of defects that are present in a composite panel. Voids, gaps, and delamination defects all reflect the acoustic sound waves and increase the amount of attenuation measured. In the video image of the panel those regions which have a dark image correspond to regions which have a low amount of attenuation and are of high quality, while those regions which appear white have high amounts of attenuation and correspondingly higher densities of defects within them. The ideal inspection scan of a composite panel would reveal a completely dark output with few (or no) defects being present.

The C-scan TTU outputs of the composite panels were roughly in line with the results of the mechanical tests. At the 18 dB level of absorption shown in the Figures 11.10 and 11.11, the two panels #1-AN and #2-AN which exhibited strong +/- 45 strength are relatively free of areas of defects at this level of acoustic attenuation except along the panel edges. (an 18 dB level of attenuation is indicated by a white area; a black
background is shown on the figure if the attenuation is less than 18 dB) The weak panels, which are classified by Type II mechanical behavior and exhibit interlaminar micro cracking at low applied strains or stresses (represented in this case by #9-AN), show high levels of internal absorption throughout the entire panel. This level of attenuation is indicative of poorly bonded tape lamina or tape delaminations. From these figures, it is apparent that the In-Situ Consolidation process does not yet exhibit the consistency required to attain (+/-45) tensile strength values equal to those of the autoclave consolidated panels. These figures do show that significant progress is made toward achieving the consistency at the lower tape head speeds.
Figure 11.10 a  18 Db C-Scan TTU Non Destructive Inspection of Panels Exhibiting Type III Mechanical Behavior Panel 2-AN
Figure 11.10 b  18 dB C-Scan TTU Non Destructive Inspection of Panels Exhibiting Type III Mechanical Behavior
Panel 4-AN
Figure 11.11  18 dB C-Scan TTU Non Destructive Inspection of Panels Exhibiting Type I Mechanical Behavior

Panels 8-AN and 9-AN
The panels fabricated in the DOE test matrices were of two lay-ups, +/- 45 laminates for testing resistance to interlaminar delamination, and 0/90 laminates to provide a representative structural lay-up. Unfortunately, the 0/90 laminates yield very little useful information in the optimization of the process because of the dominant nature of the 0 degree plies in determining the strength of the panel. To fully test the lap/gap consolidation model in ATProcess, it would have been necessary to fabricate 90 laminates which would be most sensitive to any residual gaps or voids which result from incomplete consolidation or laps which result from overexpansion and subsequent overlay of adjacent tapes. Subsequent optimization DOE testing with this process should include additional (+/- 45) or (+/- 30/90) panels which provide an indirect measure of the effects of the interlaminar diffusion bond between plies in the short transverse direction. This testing should also include 90 degree in-plane transverse strength panels to provide data on the degree of residual lap/gap and its variability. Lastly, a $G_{Ic}$ test should be included in the program to test the interply crack propagation resistance of the laminate. This test will provide another useful determination of the degree of bonding between the ply layers. It is interesting to note that these tests that are most useful for process optimization are generally not desired by the structural design community and points out the differing requirements of the two communities. Using the laminates of interest to the structural test community, as has been traditional practice, will not lead to efficient process optimization. After the process is optimized using the previously mentioned three tests, the representative structural laminate panels should be fabricated and tested to create the structural property data necessary for design.
Conclusion

The results of the designed experiments test matrices showed that the largest variable effecting both the mechanical strength and the residual stress/warpage analyses was the head velocity. In each of these cases, the head velocity should be maintained below 1 ips for the best consolidation. The effect of tool temperature was present only at the lowest processing speeds, but its negative effect on (+/-45) strength leads to the conclusion that elevated temperature tooling is not beneficial. Their was some benefit of elevated tool temperatures in reducing the internal thermal stresses during processing and the residual stresses after processing. However under no circumstances were elevated temperatures in the tool (limited by the glass transition temperature of the resin) able to remove the compression residual stresses in the fusion zone and eliminate the fiber waviness problem, so the effectiveness of adding internally heated tooling (with its additional expense) is in serious question. The annealing process after In-Situ Consolidation was helpful in its ability to the to increase the mechanical strength of the composite panels and decrease the degree of warpage. This secondary process could be accomplished with a heat pad laid over the panel to eliminate the cost and complexity of the internal heating. The other major finding of this test program established annealing as a subsequent processing step to increase the mechanical strength and decrease the amount of warpage and internal stress. The results of the +\- 45 degree laminate mechanical tests were compared to those from conventionally (autoclave) consolidated APC-2/AS-4 to yield a benchmark of this process's relative maturity and provide a projection of the amount of future effort required, in line with the development philosophies proposed for a process development team.
Chapter 12
Simultaneous Materials and Manufacturing Process Development

The Process Science model developed in Chapters 9 and 10 then used to create a DOE test matrix is also useful as a tool to screen developmental materials for their suitability in a manufacturing process. This analysis will yield an prospective group of initial processing conditions to speed the optimization of the new materials in the process. This chapter will demonstrate the steps taken to introduce two potential candidate materials into the In-Situ Consolidation process. Simultaneous materials and manufacturing process development allows the newly developed processes to use state-of-the-art materials. Through the use of process modeling, the knowledge gained in developing older materials in the process is leveraged to make the development of the new materials more rapid.

Requirements For Thermoplastic Resin Materials

The DOE test panels were fabricated using the 60 volume percent APC-2/IM-7 material which was laminated onto the panels in the form of 1/4" wide tape. To achieve the vision of the project and the goal of a process development team to simultaneously develop both materials and manufacturing processes together, additional analysis was performed with ATRprocess to understand the suitability of two high temperature amorphous thermoplastic resins for the In-Situ Consolidation process. The two amorphous resin candidates are Ultem 5001, a poly-ether-imide copolymer and HTA, (stands for high temperature amorphous resin) a poly-aryl-ether-sulfone resin. The molecular structure of each of these resins is shown on Figure 10.1. The glass transition temperature, $T_g$, of Ultem 5001 is 422F, while that of HTA is 500F, allowing each resin to withstand sustained exposure to temperatures of 300F or more, which can be expected for aircraft which fly above Mach 2. Besides thermal resistance, these amorphous resins must
also possess other properties to be considered as candidate materials for commercial and military aircraft applications. These additional requirements are:

1.) Resistance to common solvents used around commercial aircraft.
2.) Ductility and toughness in the polymeric matrix to provide impact resistance to the composite and the maintenance of this ductility after exposure to elevated temperature.

Cost and Solvent Resistance of Amorphous Thermoplastic Resins

Before a thermoplastic material can be considered as a candidate for use on aircraft, screening tests of its suitability in the environmental conditions are necessary before either process modeling or materials procurement should take place. Most amorphous thermoplastic resins are not resistant to many common, nonpolar, organic solvents used around aircraft such as Skydrol, a common hydraulic fluid, and JP-4, a kerosene-based jet fuel. To withstand these solvents, semicrystalline thermoplastic resins, such as PEEK, have been used as the resin matrices in thermoplastic composites. The unfortunate thing about the semicrystalline polymers is they are relatively complex in their derivation chemistry and are also specialized as aerospace materials in their applications. Therefore they are not produced in large quantities and are expensive. In contrast, Ultem 5001 is a relatively low cost, PEI co-polymer, developed by its manufacturer, the General Electric Company, to be a chemically resistant amorphous resin. Used for the new, all-plastic automotive headlamps, this new resin sells in quantity for only $8.00 per pound, considerably less than the current $70 per pound for PEEK. During this project, ICI Fiberite was able to manufacture prepreg tape of this resin with IM-7 graphite fibers, demonstrating that this resin is capable of being utilized as a composite matrix providing that it can withstand the environmental conditions. The low cost of this resin makes it an attractive candidate for aircraft applications.
Environmental Stressed Beam Experiment For Solvent Resistance

To prove the utility of this resin for use in the Skydrol hydraulic fluid, a stressed beam experiment with environmental exposure was pioneered for composites at the Boeing company. In this experiment, a 4 point bending specimen was clamped to a circular mandrel with a radius calculated to strain the specimen to one half of its failure strain. The tensile surface of this specimen was continually exposed for one month to the Skydrol hydraulic fluid within a wicking substrate\(^1\). This experimental setup allowed exposure to a tensile loaded surface without allowing exposure to the cut specimen sides, where solvent could enter more easily. Since exposure of specimen sides to the solvent would not occur in use, this experimental setup prevented this from occurring. After exposure, the 5 specimens in each batch were tested to failure to determine the residual strength of the specimens. The residual strengths of the exposed specimens were compared to control specimens which had not been exposed.

The results for injection molded Ultem 5001/30 volume % discontinuous fiberglass reinforcement showed a mere 2% decrease in strength after exposure to Skydrol.

Ultem 5001, exhibits a 70% strain to failure of the neat resin, more than adequate ductility for excellent transverse impact resistance. The only other low cost, solvent resistant, amorphous resin system is Pyton, a poly-phenylene-sulfide resin. This resin does not meet the requirements of this project, due to a lack of thermal resistance, ( a \(T_g\) of only 180 F) and a ductility of only 1% under the most optimistic processing conditions. By a process of elimination, the "ad-hoc" PDT identified Ultem 5001 as the most promising candidate material for a low cost, tough, high temperature amorphous thermoplastic material, which was proved to be resistant to the two most common organic solvents which exist in its operating environment.

\(^1\) A feminine hygiene napkin was used to absorb and retain the fluid and to continually expose the stressed beam to the solvent without allowing the cut sides from being exposed.
Analysis of Candidate Thermoplastic Materials

Each of the candidate resin materials (Ultem5001 and HTA) with high strain graphite fiber reinforcement have limited amounts of composite lamina and laminate thermal and mechanical property data available for analysis of their performance in structures or manufacturing processes. Aircraft structural applications usually dictate the use of new, high strain graphite fibers, such as IM-7 and IM-8, which limits the amount of data typically available. To run the ATProcess analysis for In-Situ Consolidation, the thermal and mechanical properties for these candidate materials were projected using a micromechanical analysis program. This program, McLamina, predicts the lamina composite properties from the constituent fiber and resin properties as input. Tables 12.1 and 12.2 show the constituent thermal and mechanical properties of candidate graphite fiber reinforcements and thermoplastic resins, respectively. These data were input into McLamina, a 3D, elastic-plastic, micromechanical composite properties prediction code developed by the author as a proprietary code of the Boeing Company.

---

2 These are all thermoplastic resins except Fiberite 934, which is a common, epoxy, thermoset resin.

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Description of McLamina Composite Micromechanics Analysis Program

McLamina was originally developed for Metal Matrix Composites, and includes routines to analyze the three-dimensional thermal residual stresses as a result of the differential thermal expansion of both the fiber and matrix on cooling and the effect of these residual stresses on the mechanical properties of the composite. To calculate the 3D thermal microstRESS field about the cylindrical fibers, an Eshelby inclusion technique was used to determine the displacement field around the fibers. From the displacement fields, the elastic or plastic strain fields in the matrix are determined.

The strength and thermal properties projections of the program are made with modified versions of Chamis's ICAN (Intergrated Composite Analysis program). The strength equations of this program were extensively modified to include provisions for matrix plasticity and for the effects of the 3D thermal microstresses around the fiber.

The moduli values of the material for the lamina are estimated using a Hill's transversely isotropic composite model, which utilizes a matrix inversion technique to obtain all of the elastic constants of the composite. The choice of this elastic constant micromechanics model has been shown to overestimate the transverse elastic modulus by 25%, but other constants are in line with their experimental values.

Results of the McLamina Micromechanical Analysis

The use of an elastic-plastic micromechanics analysis program with residual stresses has not generally been use in polymeric composites, because the majority of these materials have brittle, low temperature, epoxy matrices. With high temperature, thermoplastic matrices, the residual thermal stresses become large enough to be significant, at values which range from 3 to 4.5 Ksi. These residual stresses show an effect mainly upon the transverse direction properties of the lamina. The matrix plasticity provision of McLamina was not needed, because of the low modulus of the thermoplastic resins; i.e. the fibers in the longitudinal direction fail (at 2% strain) before the resin yields.
Therefore this analysis supports the conclusion of Jackson (7) and Lagace (43) that the toughness of a thermoplastic resin is not translated into the longitudinal direction of a composite material because of the constraint of the fibers. This toughness does show up however in off-axis properties such as in the material's resistance to delamination and cracking caused by an impact. The projected lamina composite lamina properties of Ultem 5001 and HTA resins with candidate graphite fiber reinforcements are shown on Table 12.3.

Tools such as McLamina and other materials preliminary development tools developed by the author and others are invaluable in the simultaneous materials, design and manufacturing activities to screen potential candidate composite materials for their useful properties before the investment in time and funds is made to develop the materials and obtain the properties.

Analysis of HTA and Ultem 5001 for Suitability in In-Situ Consolidation Process

The visco-plastic materials properties of both HTA and Ultem 5001 are required as inputs to the ATProcess gap closure subroutine. Since these properties are not always available in the literature or in manufacturers data sheets, these properties were obtained in this project by experimental measurement using a dual plate, rotating viscometer.
Table 12.3 Mechanical and Physical Property Database of Candidate Thermoplastic Composite Lamina
(Projected By McLamina)

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<td>5.44 I</td>
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<td>S12</td>
<td>KSI</td>
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<td>20.901</td>
<td>22.621</td>
</tr>
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<td>-0.0481</td>
<td>0.1824</td>
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<td>-0.07348</td>
</tr>
<tr>
<td>CTE22</td>
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<td>26.3</td>
<td>26.81</td>
<td>30.98</td>
<td>25.88</td>
<td>27.65</td>
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<tr>
<td>K11</td>
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<td>35.005</td>
<td>31.02</td>
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<td>34.765</td>
</tr>
<tr>
<td>K22</td>
<td>BTU/IN-F-FT&quot;2</td>
<td>6.6488</td>
<td>5.7267</td>
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<td>SIGMdt</td>
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<tr>
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<td>435</td>
<td>421</td>
<td>289.4</td>
<td>500</td>
</tr>
<tr>
<td>DENSITY</td>
<td>LB/IN&quot;3</td>
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<td>0.055095</td>
<td>0.055095</td>
<td>0.05582</td>
<td>0.05654</td>
</tr>
</tbody>
</table>

F DENOTES FAILURE  
P DENOTES PLASTIC DEFORMATION  
D DENOTES COMPRESSION DELAMINATION FAILURE  
I DENOTES FIBER-MATRIX INTERFACE FAILURE; COUPLING AGENTS MAY IMPROVE THIS LOW VALUE
In these experiments, the resins were tested continually throughout a temperature spectrum from 150 C to 450 C to obtain information on the glass transition temperatures and the Arrhenius activation energies of the resin viscosity. Multiple temperature spectrum tests were performed under at least 4 rotational frequencies to allow the determination of the shear-thinning coefficients of these resins. Table 12.4 shows the activation energies and shear-thinning coefficients for each of the candidate thermoplastic resins. These are the coefficients in the thermally activated shear-thinning viscosity model used within the Gap Closure model (see Chapters 9 & 10.)

| Table 12.4 Thermoplastic Resin Viscosity Coefficients For Determination of Lap/Gap Closure in ATProcess |
|-------------------------------------------------|----------|----------|----------|----------|----------|
| Coefficient          | Resin     | PEEK     | PEKK     | PEAS     | PEI Co-polymer Ultem 5001 |
| Delta H /R (1/K)     | Thermal   | -9603.2  | -12207.65| -20168   | -10065   |
| Activation Energy    |           |          |          |          |          |
| m (psi-sec)          | Pre-exponential Constant | 1.12E-05 | 9.39E-08 | 6.41E-12 | 2.03E-04 |
| n (dim)              | Shear-Thinning Constant | 0.3      | 0.3      | 0.167    | 0.167    |
| Tg (F)               | Glass Transition Temperature | 291 F    | 313 F    | 500 F    | 420 F    |

With the experimental and projected mechanical, thermal and viscosity properties for these advanced materials, it was then possible to run each in the ATProcess analysis to determine their suitability in the In-situ Consolidation process.

3 The viscosity data for PEEK and PEK were obtained from the literature. (12)
The thermal profile for consolidation of HTA/IM-7 under one set of processing parameters is shown on Figure 12.1. This result was initially surprising because the required consolidation temperatures to close the inter-tape gaps are about the same as those predicted for PEEK (APC-2/IM-7). HTA with its substantially higher glass transition temperature, \( T_g \) of nearly 500 F, was thought to require much higher temperatures in the fusion zone to process out the gaps and prevent void formation. Our initial guess was that it would not be possible to in-situ consolidate HTA without thermal degradation occurring. The reason that the analysis indicates that high process temperatures are not required to consolidate HTA is the very high Arrenhius activation energy of the resin of \( \sim 20 \) Kcal/mole K (shown on Table 12.4). High thermal activation energies cause the viscosity to drop very sharply with increasing temperature, so that the viscosity of HTA is about equal to that of PEEK at 850 F, even though it was substantially higher at 500 F. Subsequent experimental tests of in-situ consolidation with HTA at ICI Composite Structures bore out these conclusions, and they too were surprised by the results.
Figure 12.1 Thermal Profile for HTA / IM-7 Composite at Representative Processing Conditions
Ultem 5001 was also analyzed for its suitability in the in-situ ATP process and the results of the best processing conditions for this material are shown on Figure 12.2. In this figure, it is observed that the goal consolidation temperature is still 1125 F even though the load was at its maximum value of 100 lbs, the gap width was held to 10 mils (0.010") and the head velocity was slowed to an uneconomical one twentieth of an inch per second (0.05 ips). The high viscosity of Ultem 5001 at high temperatures, causes it to suffer the fate which we feared that HTA might suffer. Because it is unlikely that in-situ consolidation can be done on this material without thermal degradation, it is no longer a candidate for this rapid process. Because of its other potential cost and performance advantages, it remains a strong candidate for autoclave and double diaphragm forming operations which are slower and operate at lower temperatures. Consolidation and forming should occur in one to two hours at 750 F with this material.

From these analyses, a key materials requirement of the viscosity and its change with processing temperature, was identified for a material's suitability in the In-Situ Consolidation process, as is demonstrated by Figure 12.3. For consolidation to take place in the roughly 0.10 to 2.0 seconds allotted to it by the roller, the viscosity of the resin must be quite low, as shown by the target viscosity line on this figure. Materials with moderate glass transition temperatures like PEEK (APC-2) may have their viscosity fall off moderately with temperature and still be able to cross the target viscosity line before thermal degradation sets in. Materials with higher T_g 's, such as Ultem 5001 and HTA, must have a rapid rate of decrease of their viscosity to enable consolidation without degradation. As was mentioned in Chapter 10, materials whose viscosity's fall off rapidly with increasing temperature (higher activation energies) will be more susceptible to processing variations in In-Situ consolidation, because the change in processing temperature set up by a given variance in processing parameters will be reflected by larger voids or laps in the resulting material.
Figure 12.2 Thermal Profile for Ultem 5001/IM-7 at Slow Consolidation Processing Speeds

Temperature °F

and Pressure psi

Processing Conditions
T_{\text{gas}} = 1805°F
T_{\text{tool}} = 500°F
V = 0.057/sec
C_{\text{in}} = 0.0662
P = 100 lbs
Gap = 0.010
Figure 12.3  Effect of Temperature on Thermoplastic Resin Viscosity and Required Viscosity to Close Gaps
For these higher temperature materials, it is likely that the process parameter variation of the In-Situ Consolidation machine may need to be tightened to obtain acceptable results. With these simple rules and this figure as a guide, a PDT should be able to screen candidate materials rapidly for suitability for the In-Situ process or determine the amount of effort required to modify the process to accommodate these new candidate materials.

Conclusion

Materials/processing science based rules should be created for each process developed by a PDT. Once these rules have been established, all existing and subsequent new materials can be quickly screened for their suitability in the process. These rules will also allow materials suppliers to modify their materials to fit the process, if other attractive features of the material such as cost, resistance to solvents, or thermal stability are present. For example, it may be possible to modify Ultem's thermal activation energy of viscosity through molecular weight changes in the resin which would allow it to be processed with In-Situ Consolidation. To do this would show the attainment of the goal to use a "materials by design" philosophy in subsequent materials and process development activities. In this philosophy the material is "designed" or "engineered" to perform optimally in both the application and process.
Chapter 13
Recommendations For Future Work on In-situ Consolidation Process

A new designed experiments test program should be undertaken in subsequent work to optimize the In-Situ Consolidation process for APC-2/IM-7. This experiment should include test conditions at three relatively slow head velocities, 0.25 ips, 0.50 ips and 1.0 ips. The load applied should be set at 70 lbs, 120 lbs, and 170 lbs to test the effects of the new higher force capacity machines, at the near optimum head velocities. From the discussion in the previous section, all panels should be fabricated on a room temperature tool. Three sets of panels should be fabricated under these 9 test conditions described above, one non-annealed, one at 570 F for 4 hours (used in the present experiment) and a final condition at a higher annealing temperature above 600 F, to more completely relieve the residual stresses in the panel after fabrication. The warpage and residual stress of the panels after processing should be measured and analyzed in a similar fashion to that performed in the present program.

The mechanical strength of these designed experiments panels should be tested with either (+/- 45) or (+/-30/90) strength tests to test indirectly the interlaminar strength of the laminates and the use of 90 degree transverse tensile strength tests to improve the process for lap/gap consolidation. This test will also measure the effect of process parameter variance on lap/gap spacing and its effect on the transverse strength. Finally, this test will be capable of experimentally testing the lap/gap consolidation model used to set the goal consolidation temperature in ATP Process. The use of 3 replicates at each processing condition was shown to be effective in the present test program and should be continued in the subsequent process optimization matrix. Together the 3 sets of 9 process conditions using 2 tests and 3 replicates yields 162 total mechanical test specimens, approximately 3 times greater than the present screening DOE.

300
Since it is unlikely that 1/4" wide tape will ever be used for gentle contours of the majority of wing and fuselage components, the optimization DOE should be run with either 1" or 3" tape when tape heads are completed to accommodate these wider tape widths. Because it now seems very unlikely that processing speeds of over 1 inch per second can be achieved with acceptable properties with this process, the larger tape widths will increase the total composite laydown rate to improve the economic performance of this process.

This optimization DOE testing should be undertaken after a fuzzy logic, adaptive process control system has been developed and installed to control the gas temperature and gas flow of the inert gas jet. A proposed fuzzy logic control system is shown in Figure 13.1. In this system, the controller continuously varies the gas temperature and flow rate initially to create an internal "model" of the process dynamics, so that it can subsequently maintain the temperature under the roller in the process zone equal to the goal consolidation temperature. At this temperature, no residual gaps or laps remain after processing. This controller will be able to adjust the temperature in the tape under the roller to compensate for changes in the other processing variables (such as head velocity or load) and remove the problem of poor consolidation or resin burning due to the increase of the thermal insulative property of the laminate as it gets thicker.
The sensor used for feedback in this proposed system is a light pipe thermal sensor developed by Accufiber Inc., which uses a Planck function fitting of the light spectrum emitted by hot objects to calculate an extremely accurate temperature measurement of the surface. The light gathered from the source is brought to the detector through the use of glass light pipe. The sensor may either be placed to "look" at the base of the roller- tape contact interface directly or to measure the temperature of the consolidation roller. If the latter method is chosen, then the roller must be drilled on one side to create a blind hole in its center to create a blackbody cavity for accurate measurement of its temperature. Use of this indirect route also requires a three dimensional finite element analysis of the roller laminate contact with heat input to determine the $\Delta T$ (change in temperature) between the light pipe sensor positioned in the roller and the temperature at the consolidation interface. As shown in the figure, this $\Delta T$ would be embedded into the controller system as a constant temperature offset of the goal consolidation temperature. The direct route of
measuring of the tape-laminate interface is conceptually less difficult to put in place, except that it involves placing a light pipe down the bore of the gas jet. The use of sapphire light pipe should allow it to withstand the thermal environment of its application. Finally, the high reentrant angle at the interface of contact between the tape and the laminate, when coupled with the high surface emissivities of graphite fiber composites ($\varepsilon = 0.95-0.99$) should yield a reasonable approximation to a black-body condition for accurate temperature measurement.

With the second round of DOE testing at low processing speeds, and the use of a fuzzy logic process controller to maintain a constant temperature in the consolidation zone, it should be possible to optimize the process at the slow processing speeds with the use of subsequent annealing. The use of several annealing temperatures in the test matrix will optimize this subsequent process as well.

With this secondary round of DOE testing, the process should be optimized and ready for the scaled-up facilities now under development. The concerted effort to model, test and develop new materials for this process may bear fruit in readying this process for use in the manufacture of aerospace composite parts within 5 years on a next generation aircraft.
Chapter 14
Conclusion

This thesis was written to answer the three major questions involving the development of a strategy to create strategic advantage from process development activities. These questions were posed in the first two pages of Chapter 1. The theme of this entire thesis was to provide the evidence and data to answer these three fundamental questions:

1.) Can a strategy to develop fundamental new process technology be successful to innovate new complex assembled products, such as aircraft, to create strategic advantage for the firm?

2.) Can new methods of process development be undertaken to more rapidly develop manufacturing technology?

3.) Is it possible to form new multidisciplinary organizations of design and manufacturing engineers capable of developing new processes more rapidly?

The creation of a manufacturing process development strategy was shown in Chapter 2 to be important for competitive survival in the aerospace industry as the dominant design transitions from aluminum to composite structures. This transition was shown in this chapter to be proceeding more rapidly in the military segment of this industry than in the commercial segment. A model of industrial transformation was presented in Chapters 2 and 5 to describe the changes that occur in mature industries with the emergence of new dominant designs. These models predict that after the appearance of the new dominant design, several generations of rapidly evolving process technologies need to be implemented by the surviving firms in the industry. The objective of the new
competitive against the old technology and to also fully utilize its performance advantages. Failure to implement the new process technologies has been a cause of competitive failure of firms which were formerly dominant in the untransformed industries. During the current materials transition in the commercial aircraft industry several generations of new manufacturing processes will likely be needed until this transformation is complete. For industries undergoing changes in the dominant design, Manufacturing Process Development is strategic to the survival of a firm.

The current literature on enhancing the development of manufactured products as presented by Clark and Fugimoto; (10) Hayes, Wheelwright and Clark (30) and others (71, 84) have emphasized that concurrent engineering concepts of simultaneous manufacturing and engineering participation in the product development activities of manufacturing firms will increase their rate of development and enhance the number of innovations in new manufactured products. This literature indicates that this method of project organization is a key element for a firm to maintain competitive against World Class competitors, along with "lean", flexible factory operations. These studies have concentrated nearly exclusively on the product development activities of mature manufacturing firms and have paid little or no attention to the development of the underlying process technology on which these firm's manufacturing rests. The accelerated product development projects promoted by these references precludes the development of fundamentally new process technology concurrently with the product. Chapters 3 and 4 of this thesis document that this product-driven paradigm of process development is currently in use in the aerospace industry and has led to a low amount of implementation of new process technology. One of the key conclusions of this thesis is that the use of concurrent engineering in new product development alone is not sufficient to raise the degree of innovation in engineered products. Evidence presented in Chapter 4 of this thesis indicates that the use of concurrent engineering teams, when combined with the
schedule-driven nature of such projects and conservative manufacturing engineers vetoing innovative designs, may lead to a situation where innovation in mature companies may be impeded by their use, rather than enhanced.

This thesis proposes to overcome these shortfalls of concurrent engineering product development teams, by the formation of a three tiered heirarchy of team based organizational structures, as shown in Figure 14.1. With the heirarchy shown on this figure, the PDT creates a flow of technology and trained individuals to stock the "technology pantry" for subsequent use in product development (DBT) and factory production (PE) teams. The final team structure, known as a Process Engineering (PE) team, will be responsible for implementing the new technology within a factory, then to continuously monitor and improve the productivity of the process throughout its life. This team structure would consist of individuals with backgrounds in manufacturing process engineering, industrial engineering, scheduling, planning and finance as a final multidisciplinary organization. It is intended in this system of team structures that skilled individuals should transfer along with the process to maintain the technical continuity as the process transitions through its states of maturity. From the evidence presented in this thesis, it is postulated that each of these three team-based structures are necessary to obtain the desired increase in innovation and technology in manufactured products, not just a product development team.
The implementation of these three team structures will bring about a fusion of the engineering and manufacturing cultures (63) throughout three key activities of a manufacturing firm:

- Technology development
- Product Development
- Factory Operations

The use of a manufacturing process development strategy outlined in this thesis will require the firms to loosely couple their process technology activities to future product development. This is in sharp contrast to existing firms operating with the old paradigm who attempt with varying degrees of success to drive technology development with their product development activities. Under this tightly coupled system, a process technology program is not undertaken unless it meets the needs of an existing product development program. With a process development strategy, the proposed new manufacturing technology efforts are loosely tied to future parameters of advanced aircraft, not to the definitive needs of aircraft programs under development. This strategy
allows the new manufacturing technology to evolve the future products through their capabilities and in some cases enable entirely new types of aircraft or new levels of performance that would not have been possible without the development of the manufacturing technology. The use of a manufacturing process development strategy increases the time horizon of the technology development efforts of a firm from 1 to 3 years (with a product-driven strategy) to 5-10 years. The organizational structures and philosophies proposed in this thesis are required to keep the long range research and development focused on the future business needs of the firms, in an attempt to derive strategic advantage from these development efforts.

The work in Chapters 8 through 13 was undertaken to answer Question # 2 on whether new methods of development such as process modeling followed by designed experiment testing are capable of increasing the rate of development of new processes. The faster development rate will act to increase the profitability from process development activities and also to decrease the time horizon that process development is effective in implementing new technologies into a production environment. The reduced time horizon allows a process development strategy to meet the time horizon that it is reasonable to forecast future aerospace industry market opportunities. Once these two activities have similar time horizons, it is then possible to use process development strategy to stock a "technological pantry" and to enable new products in the future. Once similar time horizons have been achieved, a process development strategy would be successful in increasing the future innovation in complex assembled products. The development strategy and methods used on this project should point the way where these techniques can be used on other process development projects. The fast development of strategic technologies, when coupled with a process development strategy to identify, develop and implement new manufacturing technologies has the potential to create long term competitive advantage for the firm engaged in these practices. This strategic advantage is
gained through the reinvigoration of their product line, lowering of the intrinsic costs of manufacturing, and the ability to achieve rapid increases in quality. The increase in the amount of innovation in this and other mature industries provides the answer to question #1.

The last question posed in Chapter 1, involving the creation of multidisciplinary organizations to develop manufacturing processes more rapidly was answered in Chapters 3, 4, 6 and 7 where the structure, philosophy, skill makeup and development strategies of Process Development team structures were presented. The ideal structure and culture for such a team team fits the model of a "holographic" (51) team. The creation of this type of team structure and culture are proposed in this thesis as a means to speed the development and implementation of new process technologies throughout an organization and create new core competencies. To demonstrate the effectiveness of such a team structure to develop a specific new manufacturing process, an ad-hoc team was formed utilizing the philosophy, development strategies and skill makeup of the proposed team organizations to investigate In-Situ Roll Consolidation. During the development of this process, this team structure demonstrated its effectiveness in learning rapidly about the process to speed its development. The major lessons learned in the development and analysis of this process are contained in Chapters 10, 11 and 12 with the recommendations for further development of this process presented in Chapter 13. It is the author's belief that the mix of individuals with different backgrounds in different skill areas, when coupled with a strategy of process modeling followed by experimental testing was more effective than a unidisciplinary group of individuals using either experimental or analytical methods exclusively. The increased development group learning rate led to a greater maturity of the process after 1 year of development than would have been possible with conventional approaches to development. These types of process development organization along with the use of advanced methods to develop manufacturing processes speed the development
process so that a loosely-coupled, longrange process development strategy can succeed in enhancing innovation in manufacturing industries.

As competition in the aerospace industry becomes increasingly global in nature this enhancement in innovation becomes strategic to survival of the American firms. A recent paper published by the Association Europeen des Constructeurs de Materiel Aerospatial (AECMA) (92) on the critical issues facing the European aerospace industry stated the following on the implementation of new technology: "Technology alone cannot guarantee the success of an aeronautical company, but no aeronautical company can hope to produce fully competitive products without immediate access to state of the art technology. This argument relates not only to the user characteristics of the product, but also to the flexibility and economics of production. Because technology is a prime ingredient of competiveness, there is unceasing pressure to acquire improved technology which can be exploited to make a superior / more economical product". This statement is as true for the American industry as it is for its European counterpart and sums up the importance of process development for competitiveness and survival of aerospace firms in the global market of the next decade. Firms which are able to develop and implement advanced process technologies, then couple these new technologies to innovative new structural or aerodynamic designs and efficient factory operations will attain a long term, sustainable, competitive advantage over their rivals. This is the promise and threat posed by a process development strategy.
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## Appendix I

### Complete Listing of Consolidation Conditions

For DOE Test Panels

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**Figure Appendix I.1 Heat Flux Variation as a Function of Ply Thickness**

**Panel #1 (Random Order of Fabrication 3rd)**

<table>
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<th>Ply #</th>
<th>Thickness Inches</th>
<th>Heat Flux BTU/in<strong>2</strong>/sec</th>
<th>Gas Temp Deg F</th>
<th>Mass Flux SLPM</th>
<th>Temp Consol Deg F</th>
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</thead>
<tbody>
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<td>2</td>
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<td>0.29261</td>
<td>1700</td>
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<td>45</td>
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</table>

- Index Spacing = 0.2725*
- Gap Spacing = 0.0200*
- Goal Consolidation Temperature = 825.32 F
- Load = 100 lbs
- Head Velocity = 0.5*/sec
- Tool Temp = 75 F
### Figure Appendix I.2 Heat Flux Variation as a Function of Ply Thickness

**Panel #2 (Random Order of Fabrication 6th)**

<table>
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<tr>
<th>Ply #</th>
<th>Thickness inches</th>
<th>Heat Flux BTU/in²<em>2</em>sec⁻¹</th>
<th>Gas Temp Deg F</th>
<th>Mass Flux SLPM</th>
<th>Temp Consol Deg F</th>
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Index Spacing = 0.2725"
Gap Width = 0.0200"
Goal Consolidation Temperature = 825.33 F
Load = 100 lbs
Head Velocity = 0.5"/sec
Tool Temp = 300 F

### Figure Appendix I.3 Heat Flux Variation as a Function of Ply Thickness

**Panel #3 (Random Order of Fabrication 2nd)**

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Index Spacing = 0.2775"
Gap Spacing = 0.0200"
Goal Consolidation Temperature = 868.76 F
Load = 70 lbs
Head Velocity = 1"/sec
Tool Temp = 75 F
### Figure Appendix I.4  Heat Flux Variation as a Function of Ply Thickness
#### Panel #4 (Random Order of Fabrication 9th)

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Index Spacing = 0.2725"
Gap Spacing = 0.0200"
Goal Consolidation Temperature = 868.75 F
Load = 70 lbs
Head Velocity = 1"/sec
Tool Temp = 300 F

### Figure Appendix I.5  Heat Flux Variation as a Function of Ply Thickness
#### Panel #5 (Random Order of Fabrication 10th)

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<td>SLPM</td>
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Index Spacing = 0.2725"
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Goal Consolidation Temperature = 845.50 F
Load = 100 lbs
Head Velocity = 1"/sec
Tool Temp = 75 F
### Figure Appendix I.6  Heat Flux Variation as a Function of Ply Thickness

Panel #6-1 (Random Order of Fabrication 1st)

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Index Spacing = 0.2725"
Gap Spacing = 0.0200"
Goal Consolidation Temperature = 845.50 F
Load = 100 lbs
Head Velocity = 1'/sec
Tool Temp = 300 F

### Figure Appendix I.7  Heat Flux Variation as a Function of Ply Thickness

Panel #7 (Random Order of Fabrication 7th)

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Index Spacing = 0.2725"
Gap Spacing = 0.0200"
Goal Consolidation Temperature = 912.62 F
Load = 70 lbs
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Tool Temp = 75 F
### Figure Appendix I.8  Heat Flux Variation as a Function of Ply Thickness

#### Panel #8 (Random Order of Fabrication 5th)

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Index Spacing = 0.2725"
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Goal Consolidation Temperature = 912.62 F
Load = 70 lbs
Head Velocity = 4"/sec
Tool Temp = 300 F

### Figure Appendix I.9  Heat Flux Variation as a Function of Ply Thickness

#### Panel #9 (Random Order of Fabrication 8th)

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<td>45</td>
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Index Spacing = 0.2725"
Gap Spacing = 0.0200"
Gap Consolidation Temp = 887.82 F
Load = 100 lbs
Head Velocity = 4.0"/sec
Tool Temp = 75 F
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<th>Heat Flux BTU/in²<em>2</em>sec</th>
<th>Gas Temp Deg F</th>
<th>Mass Flux SLPM</th>
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</table>

Index Spacing = 0.2725"  
Gap Spacing = 0.0200"  
Goal Consolidation Temperature = 887.82 F  
Load = 100 lbs  
Head Velocity = 4"/sec  
Tool Temp = 300 F
Appendix II
Source Code Listing Of ATProcess
Computer Program

PROGRAM ATProcess
IMPLICIT REAL*8 (A-H,O-Z)
INTEGER*4 I1,I2,IRANGE,IRANG
REAL*8 LAMDA,LAMDA1,LAMDA2,LAMDA0,LMADAO,K11,K22,KAXRR,
$LOAD,LIMIT,MU12,LEFT,M0,N1,N2,LOWER,KONST
CHARACTER*15 IFILE,DFILE,DFIL

C DIMENSION EIGENX (500)
C DIMENSION EIGENY (500)
C DIMENSION ATEMPS (200)
C DIMENSION ATENPS (200)
C DIMENSION APRESSX (200)
C DIMENSION APRESSY (200)
C DIMENSION AX(200)
C DIMENSION AY(200)
C DIMENSION STRESSX (200)
C DIMENSION STRESSY (200)
C
C THIS PROGRAM USES A SEPARATION OF VARIABLES APPROACH TO
C SOLVE A 2D HEAT TRANSFER PROBLEM MODELING THE HEAT FLOW
C AND TEMPERATURE OF THE ADVANCED TOW PLACEMENT PROCESS.
C THIS MODEL ASSUMES DIRACUTE DISCONTINUOUS BOUNDARY CONDITIONS
C AND A MOVING HEAT SOURCE IN AN ANISOTROPIC HEAT CONDUCTION
C HEAT SOURCE. THE X AND Y SOLUTIONS OF THE TEMPERATURE PARTIAL
C DIFFERENTIAL EQUATIONS ARE FORMED BY A SEPARATION OF THE
C THERMAL SOLUTION INTO X AND Y COMPONENTS THEN CREATING
C A STURM-LIOUVILLE SYSTEM OF EQUATIONS TO CONVERT
C PARTIAL DIFFERENTIAL EQUATIONS INTO SINGLE VARIABLE REGULAR
C DIFFERENTIAL EQUATIONS WITH EIGENVALUE-EIGENVECTOR SOLUTIONS.
C THE CONSOLIDATION PRESSURE CALCULATION IS CALCULATED WITH A
C HERTZIAN CONTACT STRESS OF A ROLLER ON A FLAT
C PLATE. A GOAL CONSOLIDATION TEMPERATURE IS CALCULATED WITH THE
C MATERIAL'S VISCOSITY COEFFICIENTS AND A GAP CONSOLIDATION MODEL.
C BRAD LEE KIRKWOOD MAR 1992 VERSION #1.5
C
C OPEN STATEMENTS AND SELECTION OF DATA INPUT AND OUTPUT FILES
C
IC=0
ID=6
IH=8
IJ=9
WRITE(IC,1)
WRITE(IC,2)
WRITE(IC,3)
WRITE(IC,4)
READ(IC,20)
1 FORMAT(1X,'WELCOME TO THE ADVANCED TOW PLACEMENT',/,
$ 5X,'IN-SITU COMPOSITE CONSOLIDATION',/,'X',
$ 'THERMAL-MECHANICAL ANALYTICAL ANALYSIS PROGRAM',/,'X')
2 FORMAT(10X,'HOW WOULD YOU LIKE TO INPUT DATA ?')
3 FORMAT(1X,'#1. INPUT DATA INTERACTIVELY THROUGH KEYBOARD')
4 FORMAT(1X,'#2. INPUT DATA USING AN EXISTING FILE')
5 FORMAT(11)
IF(1B .EQ. 1) THEN
WRITE(IC,6)
6 FORMAT(1X,'KEYBOARD INPUT DATA STORAGE FILE NAME IS?
$. (FILENAME.ATP) ')
READ(IC,7) DFILE
OPEN(UNIT=IN,FILE=DFILE,FORM = 'FORMATTED',STATUS = 'NEW')
IA=IC
ELSE
WRITE(IC,8)
7 FORMAT(15)
8 FORMAT(1X,'FILE NAME FOR DATA INPUT IS? (FILENAME.ATP) ')
READ(IC,7)IFORM
OPEN(UNIT=IN,FILE=IFORM,FORM = 'FORMATTED',STATUS = 'OLD')
IA=IJ
END IF
WRITE(IC,9)
9 FORMAT(1X,'PROGRAM DATA OUTPUT FILE IS? (OUTFILE.OUT)')
READ(IDC,7)OFILE
OPEN(UNIT=1D,FILE=OFILE,FORM='FORMATTED',STATUS='UNKNOWN')
C
C
C READ RHO,HEATCAP,K11,K22,PLYTHK// IMAXX, IMAXY, I1MAX, ITER,
C READ VEL,GQ,TMPTL,TPAM8,A,B,C,Y2,AIRVEL,CONV2
C
C WRITE(IC,91)
91 FORMAT(1X,'DO YOU WANT A FULL LISTING OF TEMPERATURE OUTPUT?',//,
$1X,'1 = NO; SUMMARY OUTPUT ONLY',//,'1X,'2 = YES; FULL LISTING OF',
$1X,'THERMAL OUTPUT')
READ(IDC,*1) ISKIP
C
C WRITE(IDC,10)
WRITE(IDC,10)
10 FORMAT(1X,'INPUT COMPOSITE MATERIAL NAME (MATRIX/FIBER) ')
READ(IDC,11) COMPN
WRITE(IDC,11) COMPN
WRITE(IDC,11) COMPN
IF(IDC .EQ. 1) THEN
WRITE(IDC,11) COMPN
END IF
C
C WRITE(IDC,12)
WRITE(IDC,12)
12 FORMAT(1X,'INPUT COMPOSITE DENSITY .(LB/ CU IN) ')
READ(IDC,*1) RHO
WRITE(IDC,*1) RHO
WRITE(IDC,*1) RHO
IF(IDC .EQ. 1) THEN
WRITE(IDC,*1) RHO
END IF
C
C WRITE(IDC,13)
WRITE(IDC,13)
13 FORMAT(1X,'INPUT LONGITUDINAL ELASTIC MODULUS: E1...(PSI) ')
READ(IDC,*1) E1
WRITE(IDC,*1) E1
WRITE(IDC,*1) E1
IF(IDC .EQ. 1) THEN
WRITE(IDC,*1) E1
END IF
C
C WRITE(IDC,15)
WRITE(IDC,15)
15 FORMAT(1X,'INPUT LONGITUDINAL EXPANSION COEFFICIENT: ALPHA1 S...',(IN/IN^F) ')
READ(IDC,*1) ALPHA1
WRITE(IDC,*1) ALPHA1
WRITE(IDC,*1) ALPHA1
IF(IDC .EQ. 1) THEN
WRITE(IDC,*1) ALPHA1
END IF
C
C WRITE(IDC,17)
WRITE(IDC,17)
17 FORMAT(1X,'INPUT POISSON''S RATIO: NU12.....(DIM) ')
READ(IDC,*1) NU12
WRITE(IDC,*1) NU12
WRITE(IDC,*1) NU12
IF(IDC .EQ. 1) THEN
WRITE(IDC,*1) NU12
END IF
WRITE(IC,18)
WRITE(ID,18)
18 FORMAT(1X,'INPUT TOWREG OR PREPREG WIDTH.......(INCHES) ')
READ(AA,*') WIDE
WRITE(IC,*') WIDE
WRITE(ID,*') WIDE
IF(IB .EQ. 1) THEN
WRITE(IN,*') WIDE
END IF
C
C
WRITE(IC,19)
WRITE(ID,19)
19 FORMAT(1X,'INPUT STD. DEV. OF AS CONSOLIDATED TAPE WIDTH.
$....(INCHES)'
READ(AA,*') VAR
WRITE(IC,*') VAR
WRITE(ID,*') VAR
IF(IB .EQ. 1) THEN
WRITE(IN,*') VAR
END IF
C
C
WRITE(IC,20)
WRITE(ID,20)
20 FORMAT(1X,'INPUT COMPOSITE HEAT CAPACITY CP .....(BTU/LB.-F)'
READ(AA,*') HEATCAP
WRITE(IC,*') HEATCAP
WRITE(ID,*') HEATCAP
IF(IB .EQ. 1) THEN
WRITE(IN,*') HEATCAP
END IF
C
C
WRITE(IC,21)
WRITE(ID,21)
21 FORMAT(1X,'INPUT THE SHEAR THINNING RATE CONSTANT......(DIM)'
READ(AA,*') N1
WRITE(IC,*') N1
WRITE(ID,*') N1
IF(IB .EQ. 1) THEN
WRITE(IN,*') N1
END IF
C
C
WRITE(IC,22)
WRITE(ID,22)
22 FORMAT(1X,'INPUT THE TEMP PREEXPONENTIAL ZERO SHEAR RATE VISCOSITY
$ COEFFICIENT.........(PSI.-IN)'
READ(AA,*') MO
WRITE(IC,*') MO
WRITE(ID,*') MO
IF(IB .EQ. 1) THEN
WRITE(IN,*') MO
END IF
C
C
WRITE(IC,23)
WRITE(ID,23)
$.....(DIM)'
READ(AA,*') DELH
WRITE(IC,*') DELH
WRITE(ID,*') DELH
IF(IB .EQ. 1) THEN
WRITE(IN,*') DELH
END IF
C
C
WRITE(IC,24)
WRITE(ID,24)
24 FORMAT(1X,'INPUT THE NOMINAL GAP BETWEEN TAPES ......(INCHES)'
ix
READ(IA,"\") GAPTape
WRITE(IC,"\") GAPTape
WRITE(ID,"\") GAPTape
IF(IB .EQ. 1) THEN
WRITE(IH,"\") GAPTape
END IF
C
----------------------------------------------
C
WRITE(IC,25)
WRITE(ID,25)
25 FORMAT(1X,'INPUT THE LONGITUDINAL HEAT TRANSFER COEFFICIENT:
S...(BTU/SEC-\-IN**2)')
READ(IA,"\") K11
WRITE(IC,"\") K11
WRITE(ID,"\") K11
IF(IB .EQ. 1) THEN
WRITE(IH,"\") K11
END IF
C
----------------------------------------------
C
WRITE(IC,28)
WRITE(ID,28)
28 FORMAT(1X,'INPUT THE LATENT HEAT OF FUSION OF THE RESIN MATRIX:
S.....(BTU/LB)')
READ(IA,"\") DELTAU
WRITE(IC,"\") DELTAU
WRITE(ID,"\") DELTAU
IF(IB .EQ. 1) THEN
WRITE(IH,"\") DELTAU
END IF
C
----------------------------------------------
C
WRITE(IC,30)
WRITE(ID,30)
30 FORMAT(1X,'INPUT THE TRANSVERSE HEAT TRANSFER COEFFICIENT:
S...(BTU/SEC-\-IN**2)')
READ(IA,"\") K22
WRITE(IC,"\") K22
WRITE(ID,"\") K22
IF(IB .EQ. 1) THEN
WRITE(IH,"\") K22
END IF
C
----------------------------------------------
C
WRITE(IC,32)
WRITE(ID,32)
32 FORMAT(1X,'INPUT THE COMPOSITE TOWPREG PLY THICKNESS:
S.....(INCHES)')
READ(IA,"\") PLYTHK
WRITE(IC,"\") PLYTHK
WRITE(ID,"\") PLYTHK
IF(IB .EQ. 1) THEN
WRITE(IH,"\") PLYTHK
END IF
C
----------------------------------------------
C
WRITE(IC,35)
WRITE(ID,35)
35 FORMAT(1X,'INPUT THE NUMBER OF X EIGENVALUES IN THE THERMAL',1X,
S'CALCULATION...20 TO 200...(DM)' )
READ(IA,"\") MAXX
WRITE(IC,"\") MAXX
WRITE(ID,"\") MAXX
IF(IB .EQ. 1) THEN
WRITE(IH,"\") MAXX
END IF
C
----------------------------------------------
C
WRITE(IC,40)
WRITE(ID,40)
40 FORMAT(1X,'INPUT THE NUMBER OF Y EIGENVALUES IN THE THERMAL',1X,
X
$'CALCULATION...20 TO 500...(DIM)'$
READ(I4,*) MAXY
WRITE(IC,*) MAXY
WRITE(ID,*) MAXY
IF(IB .EQ. 1) THEN
  WRITE(IH,*) MAXY
END IF

C
C
C
WRITE(IC,45)
WRITE(ID,45)
45 FORMAT(1X,'INPUT THE MAXIMUM NUMBER OF ITERATIONS IN A NEWTON"S'
$ ','ROUTINE (DIM)')
READ(I4,*) ITER
WRITE(IC,*) ITER
WRITE(ID,*) ITER
IF(IB .EQ. 1) THEN
  WRITE(IH,*) ITER
END IF

C
C
C
WRITE(IC,50)
WRITE(ID,50)
50 FORMAT(1X,'INPUT THE NUMBER OF ANALYSIS POINTS IN THE X & Y',1X,
$ 'DIRECTIONS...10 TO 200...(DIM)'$
READ(I4,*) IMAXX
WRITE(IC,*) IMAXX
WRITE(ID,*) IMAXX
IF(IB .EQ. 1) THEN
  WRITE(IH,*) IMAXX
END IF

C
C
C
WRITE(IC,55)
WRITE(ID,55)
55 FORMAT(1X,'INPUT THE RANGE OF ANALYSIS FOR THE EIGENVALUE ROOT',
$ ','SEARCH...500 TO 5000...(DIM)'$
READ(I4,*) IRANG
WRITE(IC,*) IRANG
WRITE(ID,*) IRANG
IF(IB .EQ. 1) THEN
  WRITE(IH,*) IRANG
END IF

C
C
C
WRITE(IC,60)
WRITE(ID,60)
60 FORMAT(1X,'INPUT THE ERROR TOLERANCE IN THE NEWTON"S ROUTINE CALC'
$ 'ULATION')
READ(I4,*) MAXERR
WRITE(IC,*) MAXERR
WRITE(ID,*) MAXERR
IF(IB .EQ. 1) THEN
  WRITE(IH,*) MAXERR
END IF

C
C
C
WRITE(IC,101)
WRITE(ID,101)
101 FORMAT(1X,'INPUT THE X VELOCITY OF THE TOW PLACEMENT HEAD'
$ '.(IN/SEC)')
READ(I4,*) VEL
WRITE(IC,*) VEL
WRITE(ID,*) VEL
IF(IB .EQ. 1) THEN
  WRITE(IH,*) VEL
END IF
IF(IB .NE. 0) GO TO 190

C
C
C
WRITE(IC,115)
WRITE(10,115)
115 FORMAT(1X,'INPUT THE INCIDENT HEAT FLUX....(BTU/IN**2 SEC)')
READ(IA,*), QO
WRITE(ID,*), QO
WRITE(1D,*), QQ
IF(IB .EQ. 1) THEN
WRITE(1H,*), QQ
END IF
IF (I3 .NE. 0) GO TO 190
C
C
120 WRITE(1C,121)
WRITE(1D,121)
121 FORMAT(1X,'INPUT THE TEMPERATURE OF THE LAYUP TOOL',
$1.-----------------(DEG F)')
READ(IA,*), TMPTL
WRITE(1C,*), TMPTL
WRITE(1D,*), TMPTL
IF(IB .EQ. 1) THEN
WRITE(1H,*), TMPTL
END IF
IF (I3 .NE. 0) GO TO 190
C
C
125 WRITE(1C,126)
WRITE(1D,126)
126 FORMAT(1X, 'INPUT THE AMBIENT TEMPERATURE .....(DEG F)')
READ(IA,*), TMPAMB
WRITE(1C,*), TMPAMB
WRITE(1D,*), TMPAMB
IF(IB .EQ. 1) THEN
WRITE(1H,*), TMPAMB
END IF
IF (I3 .NE. 0) GO TO 190
C
C
130 WRITE(1C,131)
WRITE(1D,131)
131 FORMAT(1X,'INPUT THE LOAD ON THE ROLLER',
$1.-----------------(LBS)')
READ(IA,*), LOAD
WRITE(1C,*), LOAD
WRITE(1D,*), LOAD
IF(IB .EQ. 1) THEN
WRITE(1H,*), LOAD
END IF
IF (I3 .NE. 0) GO TO 190
C
C
135 WRITE(1C,136)
WRITE(1D,136)
136 FORMAT(1X,'INPUT THE CONSOLIDATION ROLLER RADIUS...(IN)')
READ(IA,*), RAD
WRITE(1C,*), RAD
WRITE(1D,*), RAD
IF(IB .EQ. 1) THEN
WRITE(1H,*), RAD
END IF
IF (I3 .NE. 0) GO TO 190
C
C
140 WRITE(1C,141)
WRITE(1D,141)
141 FORMAT(1X,'INPUT THE DISTANCE FROM THE CENTER OF THE HEATING NOZZLE
$ TO THE CENTER OF THE ROLLER...(IN)')
READ(IA,*), XPRIME
WRITE(1C,*), XPRIME
WRITE(1D,*), XPRIME
IF(IB .EQ. 1) THEN
WRITE(1H,*), XPRIME
END IF
IF (I3 .NE. 0) GO TO 190
C
C
xii
WRITE (IC, 151)
WRITE (ID, 151)
151 FORMAT (1X, 'INPUT THE UPSTREAM DISTANCE FROM THE TOW PLACEMENT',
$1X, 'HEAD .... ('A' IN INCHES) ' )
READ (IA, *) A
WRITE (IC, *) A
WRITE (ID, *) A
IF (IB .EQ. 1) THEN
WRITE (IH, *) A
END IF
C
C
WRITE (IC, 161)
WRITE (ID, 161)
161 FORMAT (1X, 'INPUT THE PANEL LENGTH ('L' IN INCHES) ')
READ (IA, *) PNLT
WRITE (IC, *) PNLT
WRITE (ID, *) PNLT
IF (IB .EQ. 1) THEN
WRITE (IH, *) PNLT
END IF
IF (IS .NE. 0) GO TO 190
C
WRITE (IC, 166)
WRITE (ID, 166)
166 FORMAT (1X, 'INPUT NUMBER OF PLYS IN LAMINATE...(# OF PLYS)')
READ (IA, *) NO
WRITE (IC, *) NO
WRITE (ID, *) NO
IF (IB .EQ. 1) THEN
WRITE (IH, *) NO
END IF
IF (IS .NE. 0) GO TO 190
C
WRITE (IC, 171)
WRITE (ID, 171)
171 FORMAT (1X, 'INPUT THE WORKING TEMPERATURE OF THE MATRIX RESIN....
$..... ('TW' IN DEGREES F)')
READ (IA, *) TW
WRITE (IC, *) TW
WRITE (ID, *) TW
IF (IB .EQ. 1) THEN
WRITE (IH, *) TW
END IF
IF (IS .NE. 0) GO TO 190
C
WRITE (IC, 181)
WRITE (ID, 181)
181 FORMAT (1X, 'INPUT BOTTOM SURFACE HEAT TRANSFER COEFFICIENT',1X,
$ 'FOR HEAT TRANSFER TO TOOL....(BTU/ DEG R*IN**2-SEC)')
READ (IA, *) CONVO
WRITE (IC, *) CONVO
WRITE (ID, *) CONVO
IF (IB .EQ. 1) THEN
WRITE (IH, *) CONVO
END IF
IF (IS .NE. 0) GO TO 190
C
WRITE (IC, 188)
WRITE (ID, 188)
188 FORMAT (1X, 'INPUT THE NUMERICAL METHODS HEAT SENSITIVITY FACTOR
$.... (DIM)')
READ (IA, *) DIVFACTOR
WRITE (IC, *) DIVFACTOR
WRITE (ID, *) DIVFACTOR
IF (IB .EQ. 1) THEN
WRITE (IH, *) DIVFACTOR
END IF
IF (IS .NE. 0) GO TO 190
C
CALCULATION OF SURFACE HEAT CONVECTION COEFFICIENTS

DELTAT = TW - TMSPMB
C = PNLTH - A
GRPR = 1.5567309E+02 * (PNLTH**3.0) * (DELTAT / 2.0D)
IF (GRPR .LE. 1.0E+09) THEN
  LAMINAR SURFACE HEAT CONVECTION
CONV1 = (4.9308788E-07 / PNLTH) * 0.555D0 * ((GRPR)**0.25D0)
ELSE
  TURBULENT SURFACE HEAT CONVECTION
CONV2 = (4.9308788E-07 / PNLTH) * 0.021D0 * ((GRPR)**0.20D0)
ENDIF

END IF
GAP = 1.5D0 * VAR + GAPTAPE
TINDEX = WIDE + GAP + (1.5D0 * VAR/2.0D) + GAPTAPE
Y2 = (WIDE/(WIDE + GAP + GAPTAPE + (1.5D0 * VAR/2.0D))) * PLYTHK
$ = DFLOAT (NO - 1) + PLYTHK
B = 3.0 * RAD
PI = 3.1415935636D0
CP = HEATCAP / DIVFACTOR
GAMMA = RHOCP**VEL/((K11**0.75D0) * (K22**0.25D0))
XR = ((K22/K11)**0.25D0) * (A+C)
XBM = ((K22/K11)**0.25D0) * (A-B)
XB = ((K22/K11)**0.25D0) * (A+B)
YT = ((K11*K22)**0.25D0) * Y2
HO = CONV1/((K11**0.25D0) * (K22**0.75D0))
H2 = CONV2/((K11**0.25D0) * (K22**0.75D0))
DELTAU = DELTAU/ DIVFACTOR
QKH = H2 * RHO * DELTAU * (YT**2.0D0) / (2.0D0*DSQRT(K11*K22)) + $RHO * DELTAU * YT * ((K22/K11)**0.25D0)
J1 = 0
J2 = 0
WIDTH0 = 0.00010D0
WIDTH = WIDTH0
REM1 = 0.1D0
LAMDA00 = (GAMMA/2.0D0)
LAMDA0 = LAMDA00
I1 = 0
IRANGE = IRANG * 10

CALCULATION OF X DIRECTION EIGENVALUES FOR THE HEAT TRANSFER SOLN

DO 203 I1 = 1,IRANGE,1
LAMDA = LAMDA0 + WIDTH * DFLOAT(I1)
SORLAM = DSQRT((LAMDA**2.0D0) - ((GAMMA/2.0D0)**2.0D0))
REM2 = DTAN (XR*SORLAM) + 2.0D0 * SORLAM/GAMMA
IF(J1 .LE. 3) THEN
  LIMIT = 50.0D0
ELSE
  LIMIT = DREM * WIDTH * 1.5D0
ENDIF
IF(REM2/REM1 .LE. 0.0D0) THEN
  IF( ABS (REM2) .LE. LIMIT) THEN
    REM1 = REM2
    GO TO 210
  END IF
ENDIF
REM1 = REM2
202 IF(I1 .GT. IRANGE) THEN
  MAXX = J1
  GO TO 230
END IF
203 CONTINUE
204 J1 = J1+1
IF(J1 .GT. MAXX) GO TO 230
EIGENX(J1) = LAMDA2
REM1 = 1.0D0
IF (J1 .GT. 1) THEN
  J3 = J1 - 1
  DELTALAM2 = (EIGENX(J1) - EIGENX(J3))
ENDIF
IF( DELTALAM2 .GT. 10*DAMADO) THEN
  DELTALAM1 = DELTALAM2
ENDIF
LAMDAO = EIGENX(J1) + 0.96D0 * DELTALAM1
IF (J1 .GT. 5) THEN
  WIDTH = WIDTH0/5.0D0
ENDIF
IF (J1 .GT. 40) THEN
  WIDTH = WIDTH0/10.0D0
ENDIF
IF (J1 .GT. 80) THEN
  WIDTH = WIDTH0/50.0D0
ENDIF
ELSE
  LAMDAO = LAMDAO + 1.5D0 * EIGENX(J1)
ENDIF
GO TO 200
NEWTON - RAPHSON ROUTINE FOR ROOT REFINEMENT AND SELECTION

210 LAMDA1 = LAMDA
  DO 220 I3 = 1,ITER,1
  SQRSLAM = DSGRT((LAMDA1**2.0D0) - ((GAMMA/2.0D0)**2.0D0))
  REM1 = DTAN (XR**SQRSLAM) + 2.0D0 * SQRSLAM/GAMMA
  DREM = (LAMDA1/SQRSLAM) * (2.0D0/SQRSLAM + XR/DCOS(XR**SQRSLAM)**2.0D0)
  LAMDA2 = LAMDA1 - REM1/DREM
  IF( ABS((LAMDA2-LAMDA1)/LAMDA2) .LE. MAXERR) THEN
    GO TO 204
  ELSE
    LAMDA1 = LAMDA2
  END IF
  CONTINUE
CALCULATION OF THE Y DIRECTION EIGENVALUES FOR THE HEAT TRANSFER SOLN

230 IF(XR/YT .GE. 20.0D0) THEN
  IFLAG = 1
  GO TO 280
ELSE
  IFLAG = 0
ENDIF
V1 = - 0.013D0
WIDTH = 0.013D0
J2 = 0
I2 = 0
I2 = I2 + 1
OMEGA = WIDTH * DFLOAT(I2)
REM2 = OMEGA*(HO*H2)/(OMEGA**2.0D0) - HO*H2 - DTAN(OMEGA*YT)
IF (REM2/REM1 .LE. 0.0D0) THEN
  IF( ABS(REM2) .LT. 5.0D0) THEN
    REM1 = REM2
    GO TO 280
  END IF
ENDIF
REM1 = REM2
GO TO 250
J2 = J2+1
IF(J2 .GT. MAXY) GO TO 280
EIGEN (J2) = OMEGA2
250 IF(I2 .GT. IRANGE) THEN
  MAXY = J2
  GO TO 280
ELSE
  GO TO 235
END IF
NEWTON RAPHSON CALCULATION ALGORITHM OF Y EIGENVALUES

260 OMEGA1 = OMEGA
DO 270 14 = 1,ITER,1
FOMEGA = OMEGA1**2.00 - HO*H2
FREM = OMEGA1*(HO+H2)/FOMEGA - DTAN(OMEGA1*Y1)
DFREM = ((HO+H2)/FOMEGA) * (1.00 - (2.00 * OMEGA1**2.00)/FOMEGA)
$ - YT*(DCOS(OMEGA1*Y1)**2.00)
OMEGA2 = OMEGA1 - FREM/DFREM
IF (ABS((OMEGA2-OMEGA1)/OMEGA2) .LE. MAXERR) THEN
   GO TO 269
ELSE
   OMEGA1 = OMEGA2
END IF

CONTINUE

CALCULATION OF X DIRECTION TEMPERATURE PLOT (Y VALUE FIXED AT ONE PLY
THICKNESS)

280 XGAIN = XR/DFLOAT(1MAXX)
TEPMAX = 0.000
ICOUNT = 0
TEMSUN = 0.000
DO 290 IX = 1,1MAXX,1
YBAR = ((K11/K22)**0.25D0) * (Y2 - PLYTHK)
XBAR = XGAIN * DFLOAT(IX)
TEMPX = 0.00
DO 299 J1 = 1,MAXX,1
PSI = DSQRT((EIGENX(J1)**2.00) - (GAMMA/2.00)**2.00)

CALCULATION OF X EIGENVALUE DEPENDENT COEFFICIENTS

S1 = PSI*(DEXP(-GAMMA*XBM)/2.00) * DCOS(PSI*XBM) -
$ DEXP((-GAMMA*XBP)/2.00) * DCOS(XBP*PSI)) + (GAMMA/2.00)*
$ (DEXP((-GAMMA*XBM)/2.00) * DSIN(XBM*PSI) - DEXP((-GAMMA*XBP)
$ /2.00) * DSIN(XBP*PSI))

S2 = PSI*(1.00 - DEXP((-GAMMA*XR)/2.00) * DCOS (XR*PSI))
$ (GAMMA/2.00) * DEXP((-GAMMA*XR)/2.00) * DSIN (XR*PSI)

S3 = (CONVO*CONV2 + (K11**0.500) * (K22**1.500) *
$ (EIGENX(J1)**2.00)) * DSINH (EIGENX(J1)*YT) + (K11**0.25D0) *
$ (K22**0.75D0) * (CONV0*CONV2) * EIGENX(J1) *
$ DCOSH (EIGENX(J1)*YT);

DENOM = S3*(EIGENX(J1)**2.00) * (XR/2.00) -
$ (DSIN(2.00*XR*PSI) / (4.00*PSI)))
DJ1 = CONVO * (G0*S1 + QKH*S2)/ DENOM

CY = DSINH (EIGENX(J1) * YBAR) + ((K11**0.25D0) *
$ (K22**0.75D0)*CONV0 * EIGENX(J1) - DCOSH (EIGENX(J1) * YBAR)

TEMPX = TEMPX + DJ1 * CY * DEXP((GAMMA*XBAR)/2.00) *
$ DSIN (XBAR*PSI)

CONTINUE

CALCULATION OF LOCAL HERTZIAN STRESS AND WRITE PRESSURE AND TEMPERATURE
TO ARRAYS

ATEMPX(IX) = TEMPX + TMPTL
STRESS(IX) = -2.00 * E1 * ALPHAT*(ATEMPX(IX)-TMPTL)/(3.00 + N12)
X = XBAR/((K22/K11)**0.25D0)
Y = PLYTHK
BPRIME = 4.67451575E-02 * DSQRT(LOAD * RAD)
XPRESS = (C*XPRIIME) * ((K22/K11)**0.25D0)
TRPRESS = DNINT (XPRESS / XGAIN)
IPRESS = IDINT (TRPRESS)
IF( IX .EQ. IPRESS ) THEN

xvi
C CONTACT PRESSURE LOAD INSIDE ROLLER CONTACT ZONE
C
APRESSX(IX) = 21.41610652 * DSQRT(LOAD/RAD)
PRESS = APRESSX(IX)
AX(IX) = X
TCONS = ATEMPX(IX)
ELSE
C CONTACT PRESSURE OUTSIDE ROLLER CONTACT ZONE
C
CONTX = X - (C*XPRIME)
THETA = DATAN(ABS(CONTX)/Y)
APRESSX(IX) = (2.00*LOAD/(PI*Y)) * (DCOS(THETA)**4.00)
AX(IX) = X
END IF
C CALCULATION OF AVERAGE THERMAL STRESS AND GAS TEMPERATURE OF TORCH
C INSIDE THE GAS TORCH HEATING REGION
C
IF(ABS(X-C) .LE. B) THEN
   TEMPSUM = TEMPSUM + ATEMPX(IX)
   ICOUNT = ICOUNT + 1
   IF(ATEMPX(IX) .GT. TEMPMAX) THEN
       TEMPMAX = ATEMPX(IX)
   END IF
END IF
C CALCULATION OF GAS TORCH PROCESS PARAMETERS AND THERMAL STRESS
C
DELTATMAX = TEMPMAX - TMPL
STRESSMAX = -2.00 * E1 * ALPHA1 * DELTATMAX/(3.00 + NU12)
AVGTEMP = TEMPSUM / DFLOAT(ICOUNT)
TGAS = AVGTEMP + (1.03680E+04 * Q0)
IF(TGAS .GT. 1800) THEN
   TGAS = 1800.000
END IF
TG = TGAS + 459.67
TAMB = AVGTEMP + 459.67
LOWER = 2.413079E-01 * (TG - TAMB) + 6.008900E-06 * (TG**2.00 - 
       TAMB**2.00) + 4.774215E-10 * (TG**3.00 - TAMB**3.00)
GFLOWR1 = ((2.00 * Q0) * (2.00 * B) * (3.00 * WIDE)) / LOWER
GFLOWR2 = 23768.353300 * GFLOWR1
RATEL = 45.00
C
C NEWTON-RAPHSON CALCULATION OF GAS TEMPERATURE AT LOWER
C LIMIT OF GAS FLOW
C
IF(GFLOWR2 .LE. RATEL) THEN
   TG1 = TG
   GFLOWR = RATEL
   DO 295 J4 = 1,ITER,1
   LOWER = 2.413079E-01 * (TG1 - TAMB) + 6.008900E-06 * (TG1**2.00 - 
                     TAMB**2.00) + 4.774215E-10 * (TG1**3.00 - TAMB**3.00)
   CON1 = 23768.353300 * ((2.00 * Q0) * (2.00 * B) * (3.00 * WIDE))
   GREN = GFLOWR * LOWER - CON1
   DGREN = GFLOWR * ((2.413079E-01 + 1.201780E-05) * TG 
                      + 1.432265E-09 * (TG1**2.00))
   TG2 = TG1 - GREN/DGREN
   IF((TG2-TG1)/TG2 .LE. MAXERR) THEN
      GO TO 296
   ELSE
      TG1 = TG2
   END IF
295 CONTINUE
296 TGAS = TG2 - 459.67
GFLOWR2 = GFLOWR
GFLOWR1 = GFLOWR/23768.353300
END IF
C
C CALCULATION OF COAL TEMPERATURE TO PROCESS OUT GAPS
C
C0 = 1.00/N1
C1 = N1 + 1.00

xvii
C2 = N1 + 2.00
C3 = 2.00*N1 + 1.00
C4 = 2.00*N1 + 3.00
LEFT = (C3*VEL(C4*TPRINE)) * (HO/(PRESS * C2 * PLYTHK**C1)**C0
RIGHT = (WIDE**C2/WIDE+GAP)**C0 *
$ ((WIDE+GAP)/WIDE)**(C4/N1) - 1.00)
GOALTEMP = 1.00/
((N1/DHEL) * DLGO(LEFT*RIGHT))
GOALTEMP = 1.8000 * GOALTEMP - 459.6700
IF (TCONS .GT. GOALTEMP) THEN
VOID = 0.00
GO TO 298
END IF
ABSCONS = (5.00/9.0) * (TCONS *459.6700)
KONST = (1.00/LEFT) * DEXP(DHEL/(ABSCONS * N1))
C5 = (N1 + 1.00) / N1
G1 = GAP
C***************************************************************
C FIND VOID SIZE IF TCONS IS LESS THAN GOALTEMP
C***************************************************************
DO 297 J5 = 1,1ITER,1
GEM = (WIDE + G1)**(2.00*C5) * WIDE**(-1.00*C5) - WIDE**(C2/N1) *
$(WIDE + G1)**(-1.00*C0) - KONST
OGEM = 2.00 * C5 * WIDE**(-1.00*C5) * (WIDE + G1)**(C2*C0)
$ + C0 * WIDE**(2.00*C2) * (WIDE + G1)**(-1.00*C5)
G2 = G1 - GEM/OGEM
IF ( ABS((G2-G1)/G2) .LE. MAXERR) THEN
VOID = GAP - G2
GO TO 298
ELSE
G1 = G2
END IF
297 CONTINUE
298 IF (IFLAG .EQ. 1) GO TO 302
C***************************************************************
C CALCULATION OF Y DIRECTION TEMPERATURE PLOT
C***************************************************************
YGAIN = YT/ DFLOAT(IMAXX)
DO 300 IY = 1,IMAXX,1
XBAR = XR/2.00
YBAR = YGAIN * DFLOAT(IY)
TEMPY = 0.00
DO 299 J2 = 1,MAXY,1
C***************************************************************
C CALCULATION OF Y EIGENVALUE DEPENDENT COEFFICIENTS
C***************************************************************
OMEGASQ = EIGENY(J2)**2.00
OMEGAYT = EIGENY(J2) * YT
COMEQA = DSORT( OMEGASQ + (GAMMA/2.00)**2.00)
C***************************************************************
S4 = HO + EIGENY(J2) * DSIN (OMEGAYT) - HO * DCOS (OMEGAYT)
C***************************************************************
S5 = EIGENY(J2) * (OMEGASQ * (YT**2.00) - 2.00) *
$ DSIN(OMEGAYT) + (2.00 * YT) * OMEGASQ * DCOS(OMEGAYT)
$ + 2.00 * HO * YT * EIGENY(J2) * DSINC(OMEGAYT)
$ - HO * (OMEGASQ * (YT**2.00) - 2.00) *
$ DCOS(OMEGAYT) - 2.00*HO
C***************************************************************
S6 = (1.00/2.00) * ((OMEGASQ + HO**2.00) *
$ (YT + H2/(OMEGASQ + H2**2.00) +HO)
C***************************************************************
UK = (RHO * DELTAL)/(2.00 * OMEGASQ * (K11**0.500) *
$ (K22**0.500))
C***************************************************************
CX1 = (GAMMA/2.00) * DCOSH(XR*COMEQA) + COMEQA * DSINH(XR*COMEQA)
CX2 = (GAMMA/2.00) * DSINH(XR*COMEQA) + COMEQA * DCOSH(XR*COMEQA)
CXR = CX1/CX2
C***************************************************************
GJ2 = ((TMTPL - TMPAMB) * S4 + UK * S5)/ S6
C***************************************************************
CX3 = DCOSH(XBAR * COMEQA)
CX4 = CXR * DSINH(XBAR * COMEQA)
CX = CX3 - CX4
C***************************************************************
TEMPY = TEMPY + GJ2 * CX * DEXP((GAMMA*XBAR)/(2.00)) *
299 CONTINUE
C CALCULATION OF LOCAL HERTZIAN STRESSES AND WRITING Y TEMPERATURE AND
C PRESSURE TO ARRAYS
C
ATENPY(IY) = TEMPY + TMPL
X = XBAR/((K22/K11)**0.25D0) * 2.0D0
Y = YBAR/((K22/K11)**0.25D0)
CONTX = X - (C - XPRIME)
THETA = DATAN(ABS(CONTX)/Y)
APRESSY(IY) = (2.0D0*LOAD/(PI*Y)) * (DCOS(THETA)**2.0D0)
AY(IY) = Y
300 CONTINUE
C
C CREATION OF A PLOT FILE FOR TEMPERATURE AND PRESSURE
C
301 IF (ISKIP .EQ. 1) GO TO 600
DO 500 IM = 1,IMAXX,1
WRITE(IC,699) AX(IM),ATENPY(IM),APRESSX(IM),STRESSX(IM),
$AY(IM),ATENPY(IM),APRESSY(IM)
C
WRITE(ID,699) AX(IM),ATENPY(IM),APRESSX(IM),STRESSX(IM),
$AY(IM),ATENPY(IM),APRESSY(IM)
C
499 FORMAT(TR1,F7.3,TR1,F14.6,TR1,F14.6,TR1,F14.6,/,TR1,F14.6,TR1,F14.6,TR1,F14.6)
500 CONTINUE
GO TO 600
302 IF (ISKIP .EQ. 1) GO TO 600
DO 504 IM = 1,IMAXX,1
WRITE(IC,503) AX(IM),ATENPY(IM),APRESSX(IM),STRESSX(IM),GOALTEMP
WRITE(ID,503) AX(IM),ATENPY(IM),APRESSX(IM),STRESSX(IM),GOALTEMP
503 FORMAT(TR1,F7.3,TR1,F14.6,TR1,F14.6,TR1,F14.6,TR1,F14.6)
504 CONTINUE
C
C PARAMETER CHANGES FOR NEW ATP PROCESSING CONDITIONS
C
600 WRITE(IC,601) BPRIME,APRESSX(IPRESS),TINDEX,TCONS,STRESSMAX,TGAS,
$AVGTEMP,GOALTEMP,GFLOWR2,GAP,VOID,Y2
WRITE(ID,601) BPRIME,APRESSX(IPRESS),TINDEX,TCONS,STRESSMAX,TGAS,
$AVGTEMP,GOALTEMP,GFLOWR2,GAP,VOID,Y2
601 FORMAT(TR1,'ROLLER CONTACT WIDTH =',F7.5,/,TR1,
$'AVG. ROLLER PRESSURE IN CONTACT AREA =',F14.6,/,TR1,
$'THE INDEX BETWEEN ADJACENT PLYS =',F14.6,/,TR1,
$'THE TEMPERATURE UNDER CONSOLIDATION ROLLER =',F14.6,/,TR1,
$'MAXIMUM THERMAL STRESS IN HEATED REGION =',F14.6,/,TR1,
$'THE GAS FLAME TEMPERATURE =',F14.6,/,TR1,
$'THE AVERAGE TEMPERATURE IN THE HEATED ZONE =',F14.6,/,TR1,
$'THE REQUIRED CONSOLIDATION TEMPERATURE IN HEATED ZONE =',F14.6,/,TR1,
$'THE MASS FLOW RATE OF N2 GAS (SLPM) =',F14.6,/,TR1,
$'THE GAP WIDTH BETWEEN ADJACENT PLYS =',F14.6,/,TR1,
$'THE VOID SIZE REMAINING IN GAP AFTER CONSOLIDATION =',F14.6,/,TR1,
$'THE PANEL THICKNESS =',F14.6 )
C
C WRITE(IC,1100)
WRITE(IC,1101)
WRITE(IC,1102)
WRITE(IC,1103)
WRITE(IC,1104)
WRITE(IC,1105)
WRITE(IC,1106)
WRITE(IC,1107)
WRITE(IC,1108)
WRITE(IC,1109)
WRITE(IC,1110)
WRITE(IC,1111)
WRITE(IC,1112)
WRITE(IC,1113)
WRITE(IC,1114)
C
xix
1100 FORMAT(1X,'WHICH VARIABLE DO YOU WISH TO CHANGE FOR THE NEXT',/,,
        $1X, 'ATP THERMAL AND CONTACT PRESSURE ANALYSIS ?')
1101 FORMAT(1X,' #1. X DIRECTION VELOCITY OF THE HEAD')
1102 FORMAT(1X, '#2. THE INCIDENT HEAT FLUX IS')
1103 FORMAT(1X,' #3. TEMPERATURE OF THE LAYUP TOOL')
1104 FORMAT(1X, '#4. AMBIENT TEMPERATURE')
1105 FORMAT(1X, '#5. LOAD ON THE ROLLER')
1106 FORMAT(1X,' #6. RADIUS OF THE ROLLER')
1107 FORMAT(1X,' #7. GAS NOZZLE TO ROLLER DISTANCE')
1108 FORMAT(1X, '#8. UPSTREAM DISTANCE FROM TOW PLACEMENT HEAD')
1109 FORMAT(1X, '#9. PANEL LENGTH')
1110 FORMAT(1X, '#10. NUMBER OF LAMINATE LYS')
1111 FORMAT(1X,' #11. WORKING TEMP OF MATRIX RESIN')
1112 FORMAT(1X,' #12. BOTTOM HEAT TRANSFER COEFFICIENT')
1113 FORMAT(1X, '#13. HEAT CAPACITY SENSITIVITY FACTOR')
1114 FORMAT(1X, '#14. EXIT FROM PROGRAM')
C
READ(1C,*) IC
WRITE(1C,*) IC
WRITE(1D,*) ID
WRITE(1C,1001)
WRITE(1D,1001)
1001 FORMAT(1X,'-----------------------------------------------')
$-----------------------------------------------$
IF(IC .LT. 15) THEN
  IA = IC
  IB = 0
END IF
C
IF(IC .EQ. 1) GO TO 100
IF(IC .EQ. 2) GO TO 110
IF(IC .EQ. 3) GO TO 120
IF(IC .EQ. 4) GO TO 125
IF(IC .EQ. 5) GO TO 130
IF(IC .EQ. 6) GO TO 135
IF(IC .EQ. 7) GO TO 140
IF(IC .EQ. 8) GO TO 150
IF(IC .EQ. 9) GO TO 150
IF(IC .EQ. 10) GO TO 165
IF(IC .EQ. 11) GO TO 170
IF(IC .EQ. 12) GO TO 180
IF(IC .EQ. 13) GO TO 185
IF(IC .EQ. 14) GO TO 2000
C
2000 STOP
END